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DEEP ROTARY CORE DRILLING IN ICE

G. Robert Lange

February 1973

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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PREFACE

This report was prepared by Mr. G. Robert Lange, Geologist, Applied Research Branch (Mr. Albert F. Wuori, Chief), Experimental Engineering Division (Mr. Kenneth A. Linell, Chief), U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). The work described was directed by Mr. Lange and supervised by Mr. W. Keith Boyd, then Chief, ARB.

The ice coring operations accomplished in Greenland during 1956 and 1957 were designated as CE Project No. 25, *Deep Drilling in Ice*, and were part of the U.S. Army Corps of Engineers Greenland Research and Development Program. This work was preliminary to and in preparation for the coring accomplished at Marie Byrd Station, Antarctica, in 1957-58 and at Little America V, Antarctica, in 1958-59. The Antarctic portion of the work was designated IGY Glaciological Project 4.7, *Antarctic Drilling.*

The entire investigation was a joint project of the U.S. Army Snow, Ice and Permafrost Research Establishment* and the Glaciology Panel, U.S. National Committee, International Geophysical Year (IGY). The Applied Research Branch of USA SIPRE was responsible for the investigation of drilling and coring techniques and the drilling operations (SIPRE Project 22.4-6, *Drilling in Ice* and 22.4-13, *Drilling in the Antarctic*). The Basic Research Branch, USA SIPRE, was responsible for the analysis of the core; this work is described elsewhere.

Field support was provided in Greenland by the U.S. Army Engineer Arctic Task Force and in the Antarctic by U.S. Navy Task Force 43. The field operations in the Antarctic were supervised by Mr. R.W. Patenaude, then of the Applied Research Branch, USA SIPRE. Preliminary reports of those operations were written by Mr. Patenaude and published as a portion of SIPRE Technical Report 60, *Deep Core Drilling in Ice, Byrd Station, Antarctica*, and SIPRE Technical Report 70, *Deep Core Drilling in the Ross Ice Shelf, Little America V, Antarctica.* Much of the information in this report regarding the Antarctic operations has been abstracted from these reports and Mr. Patenaude's notebooks.

This report has been technically reviewed by Mr. Kenneth A. Linell, Chief, Experimental Engineering Division, USA CRREL.

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* USA SIPRE was merged with the Arctic Construction and Frost Effects Laboratory to form USA CRREL on 1 February 1961. In this report USA SIPRE will be used in referring to this organization.

CONTENTS

CONTENTS (Cont'd)

ILLUSTRATIONS

TABLES

DEEP ROTARY CORE DRILLING IN ICE

by

G. Robert Lange

INTRODUCTION

Previous work

A thorough understanding of the large ice masses of the world requires detailed study of samples from various depths. However, the difficulty of sampling at the depths required has been a deterrent to the progress of this field of investigation. Attempts to obtain usable samples from depths greater than 100 ft have usually been defeated by factors of remote location, short season, inadequate financing, and the great weight and bulk of the drilling plants.

Hand and light engine-powered equipment developed at ACFEL and SIPRE (ACFEL Technical Reports 25, 46 and 50) has been used to secure good samples to depths of up to 100 ft. By starting from a pit 100 ft deep, SIPRE investigators obtained good quality cores to a depth of 158 ft in northwest Greenland (Bader et al. 1954).

Thermal boring (which did not produce core) has been used to produce holes of over 1000 ft in both temperate and polar glaciers.

Several attempts have been made to secure core with conventional rotary drilling equipment. In most cases, diamond drill rigs with mechanical screw feed were used with little or no modification of rig, circulating fluid system, or drilling tools. Results have been generally discouraging, with little or no usable core reported (Miller 1954, Heuberger 1954 and others).

Anticipating the opportunities for glaciological research that would be afforded by the IGY, the U.S. Army Engineer Research and Development Laboratory (at the direction of SIPRE and Office of the Chief of Engineers) contracted for an investigation of the feasibility of the project with the George E. Failing Company of Enid, Oklahoma. The Failing report (Contract No. DA-44-009, 1950) demonstrated that special steel bits could be used to cut cores from samples of artificial ice. They strongly recommended the use of compressed air, and made many other suggestions that have been extremely valuable.

General plan

Plans for the glaciological program of the International Geophysical Year (IGY) called for samples from considerable depths in both the Ross Ice Shelf and the high polar ice mass in Marie Byrd Land. Since the SIPRE research program in northwest Greenland, which was carried out in an environment similar to that of Marie Byrd Land, also required data at greater depths, a combined effort was planned. SIPRE agreed to procure a rig and tools based on the recommendations made by the Failing Co. and to carry out initial trials in northwest Greenland during July and August of 1956. However, the Greenland trials actually required both the summers of 1956 and 1957. A duplicate rig and basic tools were to be sent to the Antarctic in August of 1956, for use during the Antarctic field season of 1956-57. This part of the plan was later modified because of difficulties in transportation and procurement so that the drilling in the Antarctic was initiated in Marie Byrd Land during the Antarctic field season of 1957-58.

Scope and objectives

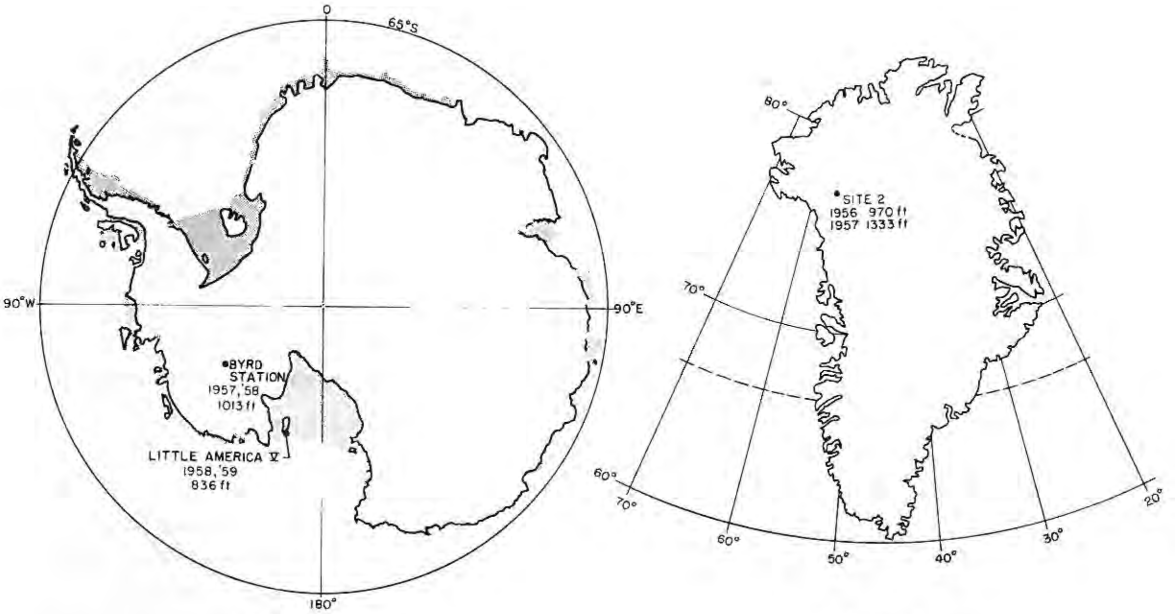
The plan called for two seasons of field operations in both Greenland and the Antarctic. Continuous coring to depths of 1000 ft to 2000 ft was required. The first season in Greenland was to be experimental and the remaining seasons were designated as operational, i.e. the prime objectiv would be to furnish core for glaciologists. This report includes the work and results of the four field seasons.

The project had as its initial objective the development of methods and equipment for securin continuous core samples from depths as great as 2000 ft in high polar glaciers. Subsequent to the developmental stage the resulting equipment and experienced crew were put at the disposal of glaciological teams.

EQUIPMENT DESIGN AND SELECTION

Preliminary considerations

Surface environment. The USA SIPRE research facility in northwest Greenland (Site II) was located approximately 200 miles east of Thule Air Base (Thule, Greenland) at an elevation of 7000 ft. The site is underlain by approximately 6800 ft of ice and is situated well above the firn line. The ice cap attains its maximum thickness of 10,000 ft roughly 200 miles further east (Fig.



a. Antarctica b. Greenland

Figure 1. Maps of Greenland and Antarctica showing borehole locations with dates of drilling and total depths.

Drilling equipment was to be transported by air to Thule Air Base and then by tractor train over the ice cap to the research station. No resupply could be expected during the season and it was necessary to provide for all conceivable breakdowns. The only water available at the site was obtained by melting snow.

Ambient air temperatures during the working season range from 0°F to 30°F. While temperatures were not often low enough to interrupt operations, winds ranging up to 90 mph caused operations to be suspended from time to time, particularly during the summer of 1956. High winds carrying loose, dry surface snow decreased visibility, preventing travel from the camp to the rig, and caused drifting that occasionally interfered with the functioning of equipment.

Properties of ice from polar glaciers. The drilling was done from the bottom of a trench approximately 15 ft below the surface. Temperatures of the snow and ice below this level varied between -11.2°F and -13.8°F (see Fig. 2).

Data obtained from the deep pit and hand cored hole of 1954 were extremely useful in planning the casing program. High air permeabilities were expected near the surface and extrapolation of the data mentioned showed that zero permeability might be expected in the neighborhood of 175 ft (Bader et al. 1955, Chap. XI).

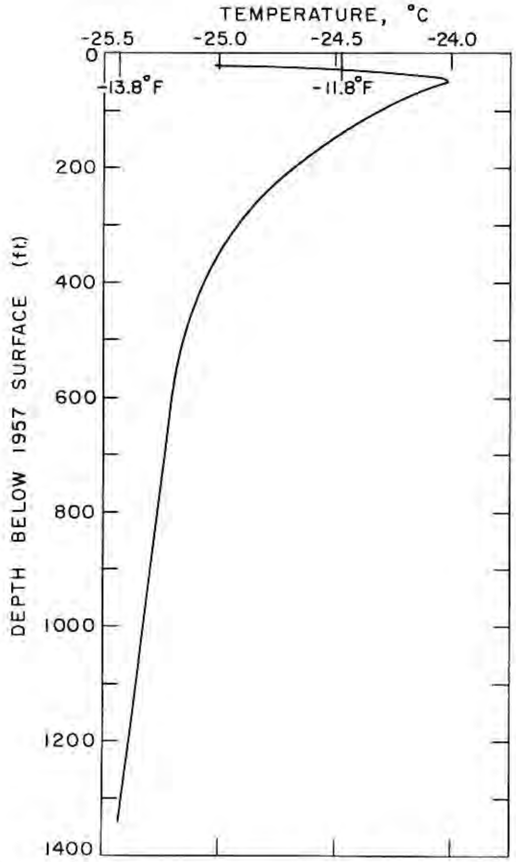


Figure 2. Temperature vs depth, Site II, Greenland, 1956-57 (from Hansen and Landauer 1958).

Cores from the bore hole have not been subjected to strength tests, but an indication of the strength of commercial ice and lake ice at the temperatures mentioned above can be found in SIPRE Research Report 18 (Butkovich 1956) and SIPRE Research Paper 11 (Butkovich 1954.) Crushing (unconfined compression) strength is given as 900-1000 psi, tensile strength 225 psi and shear strength 250 psi. The above data are given to illustrate only the approximate mechanical properties of the material sampled.

Density vs depth curves from the 1954 deep pit are given by Bader et al. (1955, Chap. I). Density determinations on core from the deep bore hole of 1956-57 (Langway 1952) did not vary appreciably from those mentioned above. It was found that density becomes nearly constant at a depth of approximately 200 feet (see Fig. 3).

Overburden load data from the deep pit of 1954 are given in Bader et al. (1955, Chap. X). Density data from the deeper bore holes of 1956-57 can be used to show that the overburden load will exceed the tensile strengths given above in the neighborhood of 600 ft. Assuming that tensile stresses equal to the original load are developed as the core is cut, it could be reasonably expected that unbroken cores below this depth would be nearly impossible to obtain from an airfilled hole, provided that there is not time for creep to occur.

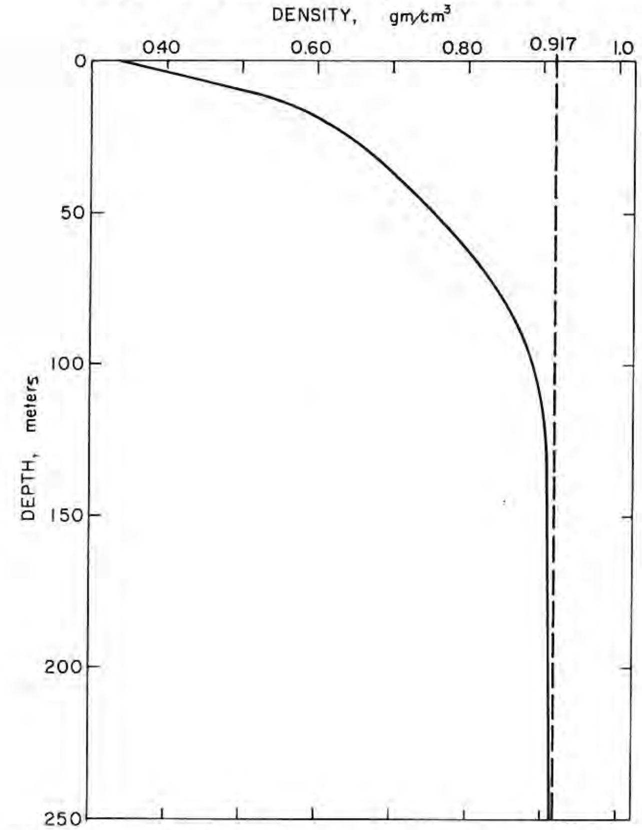


Figure 3. Density vs depth, Site II, Greenland (from Langway 1958).

Choice of a drilling fluid

The choice of compressed air as the circulating fluid was obvious in view of the problems inherent in the other alternatives: oils and oil-based fluids, and water and water-based fluids (i.e. brines and brine-based muds). The possibilities of contaminating the core and of fire, and problems of transporting large quantities of oil raised major objections to the use of diesel oil and kerosene. The concentration of brine necessary to prevent freezing in such a deep, cold bore hole would have required special protective clothing and gloves to prevent skin irritation and would have caused deterioration of core and hole walls by melting. Air offered no difficulties of supply and would not freeze in the hole or contaminate or destroy core.

Compressor and compressor capacity

Computations indicated that an uphole velocity of approximately 1500 feet/min would be necessary to properly clean the hole of ice chips of approximately 0.1 in. diameter. Hole diameter would be about 5½ in. in order to obtain a 4-in. core with the DCDMA* Large Series core barrels. These dimensions were later modified to $3\frac{7}{8}$ in. × $5\frac{3}{4}$ in.

Compressor displacement could be computed by: $CD = VA$

where:

CD = compressor displacement (ft^3/min)
V = uphole velocity of air stream (ft/min)
A = area of annulus between drill pipe and hole wall (ft^2)

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* Diamond Core Drill Manufacturers Association.

Corrected for an altitude of 7000 ft, 290 ft^3/min is required.*

The largest capacity compressors available for Army depots were Joy model WK 80 driven by IH UD-16 diesel engines with capacity of 315 ft^3/min. To allow for all contingencies, which included complete breakdown of compressor or engine, cuttings larger than 0.1 in., the loss of some of the air flow to permeable snow, and the inaccuracy of the calculations, two of these machines were procured.

Air cooling

It was recognized that air compressed to the pressure required to overcome frictional head losses would be warm enough to cause melting of both hole wall and core. Although it seemed likely that coring, even to 1500 ft, would not require the full pressure available from the two-stage compressors chosen, it was decided to design a cooling system capable of handling the maximum flow at maximum pressure. Data from compressor manufacturers indicated that final air temperatures, even from compressors supplied with intercoolers, would be in the neighborhood of 250°F. Initial requirements for a cooling scheme called for cooling 630 ft^3/min (of free air at 7000 ft)* at 100 psi from 250°F to some temperature below the freezing point. The possibilities of cooling the air further, to the temperature of the ice (–12 or –13°F) were to be investigated in order to reduce the time required for temperatures in the bore hole to come to equilibrium.

It was obvious that the most plentiful coolants available would be snow and air. Of the two the snow was colder, particularly a few feet below the surface. A plan for laying long coils of compressed air lines in the snow was briefly investigated. It was noted that a cooling curve (temperature vs length of coil) for the compressed air under these conditions would be asymptotic to and several degrees warmer than the temperature of the coolant. Thus, since the coolant would quickly become a slush-water mixture at +32°F, air no cooler than +38° or +40°F could be expected with a reasonable length of cooling coil.

Mean maximum temperatures of the ambient air would seldom exceed +25°F and mean temperatures would rarely exceed +20°F during the summer working season. An air-to-air heat exchanger was procured whose specifications called for cooling 630 ft^3/min (of free air) at pressures up to 125 psig, from temperatures as high as 250°F to within 10°F of the ambient air temperature (see Fig. 4). A pressure loss of 5 psi across the cooler was allowed. The tube and fin principle was used, similar to the radiator of an internal combustion engine except that compressed air is carried in the tubes instead of antifreeze. The radiator unit is 5 ft tall, 5 ft wide and about 12 in. deep, with three rows of tubes making five passes. Ambient air is pulled through by a 48-in. six-bladed fan driven by a 12-hp gasoline engine.

Figure 4. Air-to-air heat exchanger (left) and two 315-ft^3/min compressors (right).

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* *Compressed Air Handbook.*

It was recognized that icing would occur if the air were cooled below freezing and that the amount of ice would depend upon the amount of moisture available in the ambient air. Provision was therefore made for defrosting the heat exchanger with a Herman-Nelson aircraft heater.

Drill pipe

The choice of drill pipe was governed mainly by consideration of the weight per unit length and frictional pressure losses anticipated in the flow of the compressed air down the bore of the drill pipe. Initially, three types of drill pipe were considered: N Acme,drill rod, 2⅜-in. internal upset drill pipe with A.P.I. regular tool joints, and 2⅜-in external upset drill pipe with internal flush tool joints. In the first two, the pressure losses at the tool joints were found to be high and although only rough approximations could be made, the losses due to constriction at the tool joints appeared to be as high as the frictional pressure losses in the rest of the pipe. The lack of constriction in the external upset pipe with internal flush tool joints made this an obvious choice for the 1956 operation. Table I gives pressure loss data and critical dimensions of this pipe and tool joint.

Table I. Pressure loss (psi/100 ft) in drill pipe.

Pressure loss is computed from the equation:

$$f = \frac{0.1025\, L\, Q^2}{r\, d^{5.31}}$$

Where:

f = pressure loss (psi)
L = length of pipe (ft)
Q = compressor displacement (ft^3/min)
r = compression ratio (initial pressure/14.7)
d = inside diameter of pipe (in.)

Compressor displacement (ft^3/min)	*Initial pressure (psig)*			
	*2⅜-in. external upset**		*2⅜-in. API IF†*	
	60	*100*	*60*	*100*
300	1.0	0.64	2.1	1.3
600	4.1	2.6	8.3	5.2

* External upset tubing, 20-ft sections weighing 5.2 lb/ft with 1.995-in. ID. Joints were API IF bored out to 1.995 in. (see Fig. 5).

† API IF drill pipe, 20-ft sections weighing 7.1 lb/ft with 1.750 to 1.800-in. ID. Joints were internal flush tool joints.

Continued investigation of types of drill pipe revealed that it was fairly common practice to use light-walled tubing fitted with tool joints for slim hole production drilling. This scheme gives a more advantageous ratio of the weight of the drill string to the bore cross section area. The specifications and pressure loss data for a 2⅜-in. external upset tubing with 2⅜-in. API internal flush tool joints (normally 1¾-in. ID) bored out to 1.995 in. are given in Table I. The bored out tool joint is illustrated in Figure 5. One thousand feet of tubing was procured for use on a trial basis in 1957.

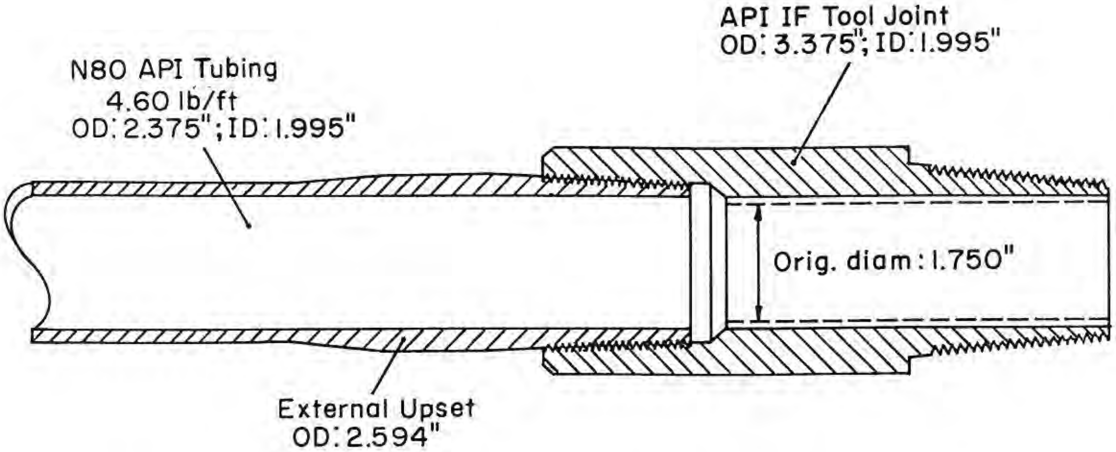


Figure 5. External upset tubing with API IF tool joint bored out to 1.995 in. ID.

For continuous deep coring, the "tool joint type" of drill pipe with its outside shoulders has great advantage over the outside flush joint drill rod commonly used in engineering exploration. Elevators and slips which are quickly set may be used in making round trips, greatly decreasing the time required for each connection. This type of joint is also a good deal stronger in flexure, decreasing the possibility of "twist off."

Rig

The larger (Failing 314) of the two rigs available from Army stock was chosen. This was equivalent to the skid-mounted Failing Model 1500 with a 27-ft mast, with mud pump, drawworks and rotary driven by a Buda HP-217 55-hp engine (Fig. 6).

The rig was modified to allow the use of the longest core barrels and drill pipe possible. The 28-ft mast was replaced by a 38-ft mast so that 20-ft core barrels could be used to make 20-ft coring runs continuously with 20-ft lengths of drill pipe. The mud pump was removed and a 6-in. blower from a cotton gin was substituted. The suction side of the blower was connected to a **T** connection fitted to the top of the casing with 6-in. hose, and cuttings from the casing annulus were drawn through hose and blower and deposited 20 ft from the rig.

In the interest of efficiency, a power breakout table was provided. An 8-in. opening in the breakout table was specified so that 6-in. casing could be handled through it.

With a mast capacity of 40,000 lb and a maximum hook load rated at 25,000 lb, it would be theoretically possible to handle 3000 ft of the 7 lb/ft drill pipe with core barrel and drill collar.

Core barrels, bits and lifters

DCDMA 4 × 5½-in. core barrels, 20 ft long, were slightly modified by enlarging the annulus between the inner and outer tube extension to reduce the constriction to air flow (Fig. 7). Ten-foot inner and outer tubes were provided as well in case the 20-ft runs proved too long. A complete duplicate 20-ft barrel assembly was included as insurance against loss of the entire core barrel in the hole. The barrels were fitted with sludge barrels to collect cuttings that might be too large to be carried up the hole by the air stream and to collect the cuttings that would settle if the air stream suddenly failed during coring. A special 7-ft handling sub, or length of drill pipe, was provided to

Figure 6. Failing 314 mounted on 10-ton sled prior to installation in trench.

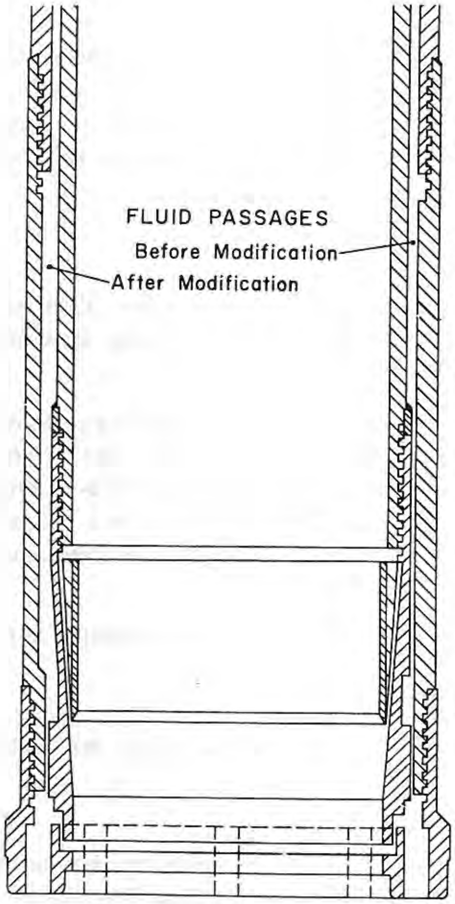
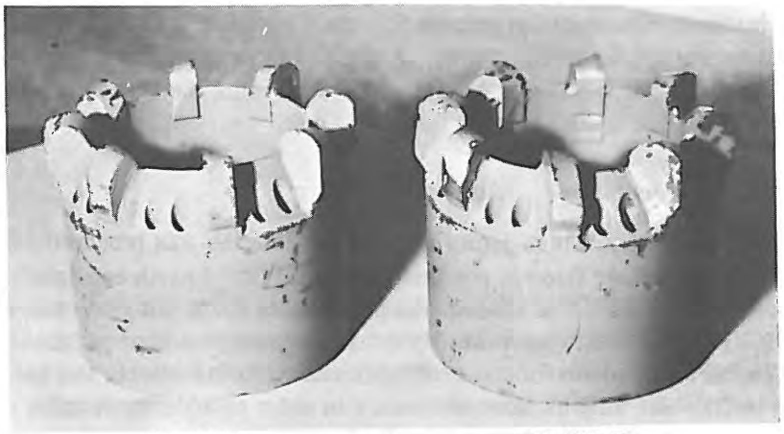


Figure 7. Core barrel for deep rotary core drilling in ice. (Drawing furnished by G.E. Failing Company, Enid, Oklahoma.)

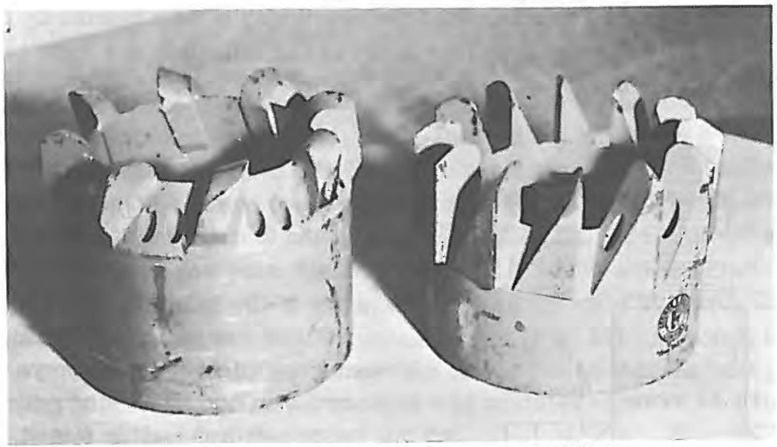
avoid disassembly of the sludge barrel from the core barrel when the core barrel was connected to the drill pipe. The entire assembly, consisting of core bit, core barrel, sludge barrel and handling sub, was 29.7 ft long. Several extra inner and outer tube extensions were provided in anticipation of damage to these parts by pipe wrenches while disassembling to extract the core.

Five bit types were provided for the 1956 season: B-413-A, B-413-B, B-413-C, B-413-D and B-413-DA. The first three of these were suggested by the results of the Failing Company's investigation previously mentioned. B-413-D and B-413-DA were adaptations of the cutting head of the USA SIPRE hand auger to fit the core barrel. Experience with these led to the design of six more bits for the 1957 season: B-413-E, B-413-F, B-413-G, B-413-H, B-413-J and B-413-K (Fig. 8). As no rock materials were expected, the bits were made of fairly soft (4140 and 1020) steel and were not hardened. The bottom discharge principle was used throughout to afford maximum protection for the core. Several blank bits were provided for the execution of bit designs suggested in the field.

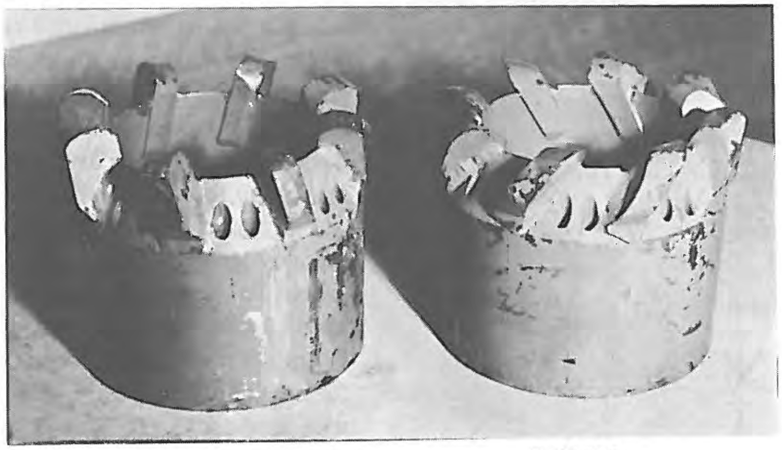
Three types of core lifter were procured for 1956, designated B-412, B-412-A and B-412-B. Of these, B-412 and B-412-B were of standard split ring and basket design. B-412-A was especially designed during the early Failing in-



B-413-E B-413-F



B-413-G B-413-K



B-413-J B-413-H

Figure 8. Ice coring bits B-413-E through B-413-K used in coring operations at Site II, Greenland, 1957, and subsequent operations in the Antarctic.

vestigation to provide a more positive grip on the smooth surface of the core than was afforded by the conventional basket and split ring types. A special inner tube extension (B-411-B) was required for the proper functioning of B-412-A. A fourth lifter, utilizing the standard inner tube extension, B-412-C, was designed and tested in 1957.

Other drilling tools and equipment

Standard 6-in. casing with flush joints in 4- to 5-ft lengths was procured. Casing threads for the 1956 work were six square threads per inch, while in 1957 four-thread joints were found more expedient. Approximately 250 ft of casing was provided in the event that more than one attempt would be necessary, even though permeability data indicated that zero permeability would be reached at a depth of 175 ft. Since plans for the 1956 work called for advancing the casing by "drilling in" between coring runs, short lengths were necessary in order to add new lengths under the drill head. A casing bit was made in the field from a length of casing.

Reamers were provided to guard against the possibility of hole closure by plastic flow of the ice during drilling. They had the same tool joints as the drill pipe and could be inserted in the drill string at any point (Fig. 9).

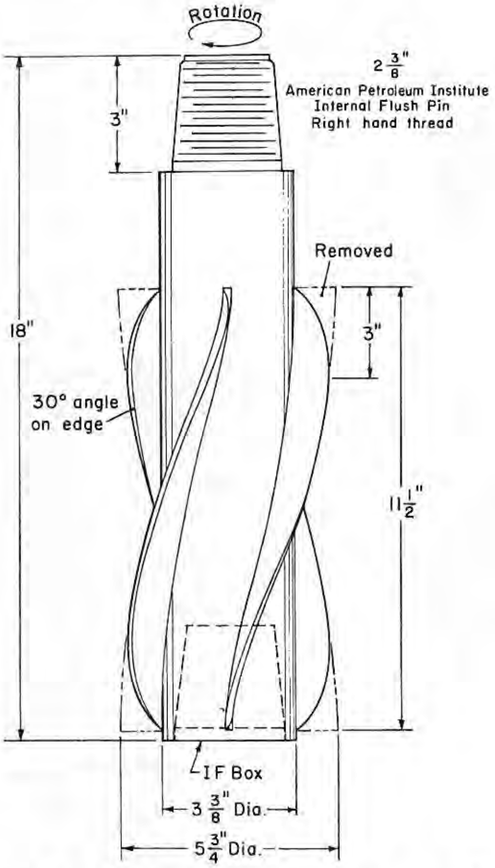


Figure 9. Reamer. (Drawing furnished by G.E. Failing Co., Enid, Oklahoma.)

Standard rock and drag bits, both $5\frac{5}{8}$-in. and $7\frac{7}{8}$-in., were obtained in several types since they were to be used in open hole drilling below 1000 ft and to clean out the hole at intervals. The larger size was used to obtain a hole for the setting of the initial string of casing. It was also felt that experience in drilling open hole on the ice cap might someday prove valuable. Pilot, two-wing and three-wing drag bits were used, as were soft and medium formation (long and short teeth) rock bits.

A combination standby generator and electric welder driven by a small gasoline engine was procured. The welder, mounted near the rig, had leads long enough to reach most of the working floor area and the entire mast. Weighing less than 1000 lb, this unit provided 200 amps ac welding capacity and 4.5 kw at 115 volts ac of standby power. Sufficient power was produced for rig lighting, power drill and grinders in the shop and the core laboratory on an emergency basis. A much heavier 5-kw generator was used for normal power during 1956 and a 10-kw generator was used for the increased power requirements in 1957.

A full complement of hand tools such as snow shovels, picks, saws, hammers and sledges, wrecking and pinch bars were provided, in considerably greater number than the estimated need to allow for breakage and loss in the soft snow.

Mechanical tools sufficient for most repairs, including a full master mechanics tool kit was available. An oxyacetylene welding and cutting outfit, power drills and a power grinder were also provided.

GREENLAND 1956

Introduction

Work commenced at Site 2 on 23 June 1956 with the arrival of project personnel. Most of the drilling equipment had been previously transported from Camp Tuto by tractor train. While one party unloaded equipment and mounted the rig and compressors on 10-ton cargo sleds, another started to prepare a shelter for the drilling operation and core laboratory. A trench approximately 70 ft long, 15 ft wide and 15 ft deep was dug with the Peter snow miller. Ramps were constructed at both ends to allow the rig sled to be towed into the trench by a crawler tractor. An 8-ft-wide trench approximately 60 ft long was excavated at one end to serve as storage for core and drill pipe. From this trench, a core analysis laboratory was dug by hand. After the rig was positioned near one end of the trench on 2 July a timber and plywood roof of arch bent construction with removable center keys was constructed over the 16-ft-wide part of the trench (Fig. 10). The 8-ft-wide part was covered with 8 × 8 beams and canvas to allow snow to accumulate and eventually gain enough strength to support itself. The center panels of the roof were made removable so that the rig could be moved for the second hole projected for 1957 and so that it could be removed at the end of the work in 1957. The mast projected through one of the panels, which was removed. The helpers platform in the rig mast was approximately at the same level as the snow surface. The compressors were placed at the surface and covered by a canvas shelter (Fig. 11). Although it would have been desirable to place the compressors below the surface it was feared that the heat generated by them would cause thawing of the snow walls. A wanigan was modified to serve as a tool house and shop and was pulled into the wider trench in front of the rig.

Figure 10. Trench excavated, rig in place and roof under construction, Site 2, 1956.

Figure 11. Rig and roof in place, compressor shelter on left, Greenland, 1957.

Operations

Drilling was begun on 19 July. Thirteen feet of open hole was drilled, starting from the floor of the trench some 15 ft below the surface of the snow, in order to start the casing. Several cores were taken to advance the hole to 64 ft. The chief difficulty in the first coring runs lay in the dimensions of the bit and lifter. While the coring bits had been set to cut core $3\frac{7}{8}$-in. in diameter, lifters had been set to engage core of the standard 4-in. diameter. Consequently, lifters failed to engage on the hard, smooth surface of the core and a good deal of core was dropped before the lifters were modified. Core was generally in good condition except where damaged or lost because of the difficulty with the lifters.

With the casing advanced to 13 ft and the open hole at a depth of 64 ft, air circulation was lost to the permeable hole walls, cuttings collected around the core barrel and stuck the tools in the hole. The tools were recovered by jarring and hoisting and preparations were made to advance the casing. The bottom of the casing had been formed to a slight bell shape on the bottom to facilitate the entry of tools during hoisting. This prevented further advance of the casing so it was pulled and a casing bit was made by cutting saw teeth on the bottom of a piece of casing. It was hoped that the casing bit would ream its own hole, by drilling in the casing after coring below the bottom of the casing. Thus, coring was continued until circulation was lost, coring tools were pulled from the hole and the casing was advanced by rotating and feeding weight with the hydraulic feed. The cuttings formed by the casing bit fell into the open hole made by the previous coring. Generally, it was necessary to remove the cuttings from the bottom of the hole with a drag bit before resuming coring. The core that was recovered was generally in good condition, but a good deal was dropped when loss of compressed air circulation caused the core barrel to stick in the hole and the subsequent jarring required to loosen the tools caused the core to drop from the barrel.

Rotating and advancing the casing in the manner described above became increasingly difficult because of the friction of the sand-like snow grains of the hole wall on the tightly fitting casing. The casing, although flush on the outside, was 6¹⁄₁₆-in. OD and was following the hole made by the coring bit which was 5¾-in. in diameter. The teeth on the casing bit were set to the same diameter as the outside of the casing. Two lower kelly subs were twisted off before a scheme was devised for rotating the casing with the breakout table by means of a log chain wrapped about the casing and attached to the table. The casing was eventually advanced to 143 ft in this way with the circulation gradually improving. It is unlikely that the casing would have been advanced to a greater depth by this or any other means except underreaming. Since the hole was now cased to 158 ft from the surface, which was close to the predicted depth of zero permeability (175 ft), attempts to advance the casing were abandoned.

Although some difficulties with circulation persisted, they were not severe and could not be traced to insufficient penetration of the casing. Cuttings were found to be accumulating at the top of the sludge barrel. This was eliminated by drilling two small (³⁄₁₆-in.) holes through the wall of the handling sub, angled upward 30° from the vertical an inch or two above the top of the sludge barrel. The small air jets thus created probably gave enough additional velocity to cuttings about to drop in the fallout zone to allow them to continue up the hole. The normally very sharp transition of velocity of the uphole air stream at the top of the sludge barrel was smoothed by the jet holes.

On 25 July the clutch on one of the compressors became damaged and could not be repaired until replacement parts were available on 14 August. Immediately upon starting the repaired machine the voltage regulator burned out, rendering the machine inoperative for the balance of the season. Thus, all of the coring from 123 ft to the final depth of the hole was done with one compressor, i.e. 315 cfm.

Coring was continued with the major circulation difficulties resolved. A program of experimentation was followed in an attempt to learn the relationship between the variables of the coring operation and the condition of the core. All of the available bit designs were tried and some new designs were fabricated in the field. Speed of rotation and rate of penetration were varied according to a more or less systematic program. Most of the lifter designs were tested and one design was modified in the field. The results of this experimentation will be discussed later. Although principles of bit and lifter design evolved from this program, definite conclusions regarding an optimum rate of rotation and of penetration were not obvious, probably because of variations in the properties of the ice and its confining pressure. No variations in air flow rate were attempted since it was felt that with only one compressor in use, the air flow was near the minimum safe level. To further decrease the air flow rate would be to risk sticking the tools in the ever-deepening hole. A full range of rpm was not available as the kelly had become bent in shipment and could not be rotated much faster than 80 rpm.

Hydraulic pressure was never necessary for coring, even at the top of the hole; the weight of the drill string was more than enough to make the bit cut. Consequently, the load on the bit was controlled by the brake on the main hoist line. A single sheave traveling block was rigged upon reaching a depth of 200 ft and a double sheave block was used after reaching 685 ft, to give better control of the weight on the bit and to handle the increasing weight of the drill string with safety. At a depth of 740 ft, when the drill string weighed a little more than 6000 lb, it became impossible to maintain a uniform rate of feed with the brake, which tended to "stick" or grab in the same manner as wet automobile brakes. It is not known what caused this, but it undoubtedly was a contributing factor to the poor quality of core at depth. A needle valve had been installed on the exhaust side of the otherwise standard hydraulic feed system to allow uniform rate of feed by clamping the kelly in the chuck and allowing the weight of the tools to force fluid from beneath the pistons. The rate of penetration was then controlled by the rate of flow of oil from the cylinders, which in turn could be controlled by the needle valve. Since the long, slender kelly was bent, excessive whip was experienced at any rpm unless the entire kelly was held in tension, so that it was impossible to utilize the hydraulic feed system for weight control.

By 27 August the hole had advanced to 971 ft by continuous coring. At this depth, progress averaged approximately two round trips per day, or about 36 ft. In order to explore the problems of open hole drilling, and of coring at depths greater than 1000 ft, it was decided to attempt to drill open hole to approximately 1500 ft (since this could be done in a day or two) and to attempt one or two coring runs at that depth before the end of the field season. A Hughes tricone, roller type rock bit was substituted for the core barrel assembly and open hole drilling was begun at 971 ft. The bit shortly became stuck in the hole and all eforts to extract it were in vain. It appears likely that a long-toothed, soft formation rock bit made chips too large to be lifted by the air stream from the one compressor that was available, and that they formed a collar of ice on the top shoulder of the bit, or at the reamer just above the bit. After three days of nearly continuous pulling, jarring and rotating, the tools could be lifted approximately 30 ft above the bottom of the hole and could be rotated, but both motions required great effort. One 20-ft length of drill pipe was removed from the top of the string and the operation was concluded for the season.

Results

Core. Appendix B shows the quality and amount of core obtained in 1956. Since there was no precedent for the use of relative terms such as "poor," "good" etc. to describe the ice cores, it was realized during the 1956 operations that observers' criteria for these terms were probably changing as the difficulties of obtaining satisfactory core increased with depth. Consequently, photographs of a great deal of the core were taken in 1957 to serve as a record of its condition. Sample photographs are shown in Figure 12 to illustrate these word descriptions approximately as they were used in 1956.

Appendix C reproduces the complete drilling operations log for three sample runs to illustrate the operational data taken and the way in which they were collected.

Upon close examination, the core exhibited two distinct types of cracks, both of which increase in frequency at greater depths. One type (Fig. 13a), distinctly flat and regularly spaced and normal to the axis of the core cylinder, may be associated with the scratches or machine marks made by certain bits. These bits were characterized by sharp corners on the cutting edges which caused the scratches, which in turn concentrated stresses. If this hypothesis of the origin of this type of crack is correct, then redesign of the bit teeth so that only smoothly curving cutting surfaces are presented to the core should eliminate the cracks to some degree. The same form of crack also resulted from excessive rates of penetration (Fig. 13a).

The second type of crack (Fig. 13b) was conchoidal or irregularly curved, as opposed to the typically flat form mentioned above. The general orientation of the curved type was generally normal to the axis of the core. There appeared to be no association between this conchoidal type and the coring tools and technique. Because of their increasing frequency with depth it was suspected at the time that these resulted from the abrupt release of the core sample from the confining pressure of the overlying ice.*

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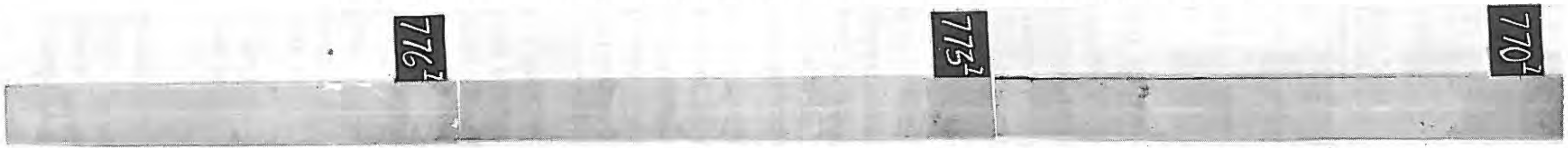
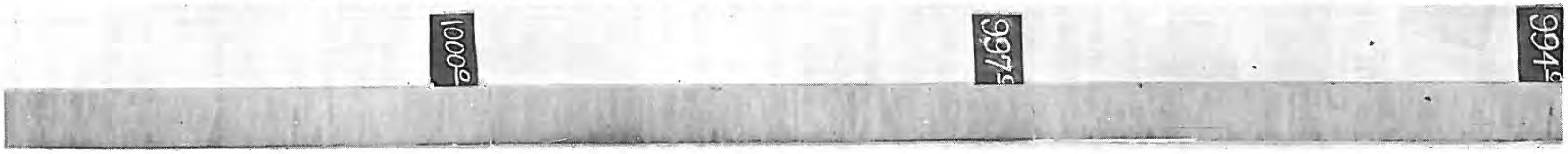
* Core disking in rock has been interpreted by others (Obert and Duval 1967) as a result of stress relief due to coring. However, in rocks that behave more or less in an elastic manner the disks are generally saucer shaped, concave upward and of uniform thickness, while stress relief cracks in viscoelastic ice cores are roughly horizontal. Stress relief cracks in ice cores show less parallelism than rock core disks and the detail of the fracture surface texture is conchoidal.

a. *Excellent quality core: run 58, 690.5 to 699.5 ft, few or no cracks, no core loss.*

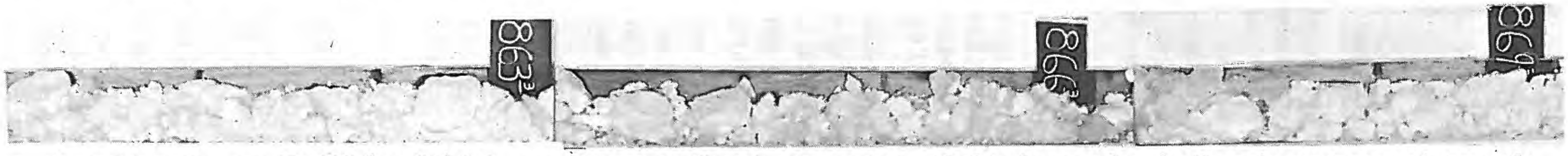


b. *Good quality core: run 62, 670.5 to 778.7 ft, a few conchoidal cracks, irregularly spaced, no core loss.*



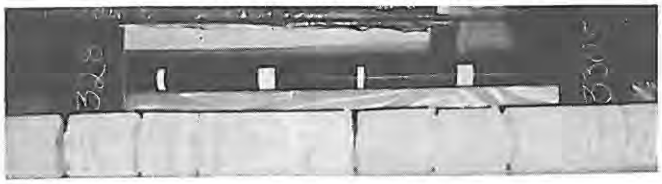
c. *Fair quality core: run 75, 994.0 to 1002.7 ft, more conchoidal cracks, fairly regularly spaced, some flat cracks, little or no core loss.*

d. *Poor quality core: run 76, 1161.0 to 1168.5 ft, many closely spaced conchoidal and flat cracks, many breaks in core, up to 5% core loss.*

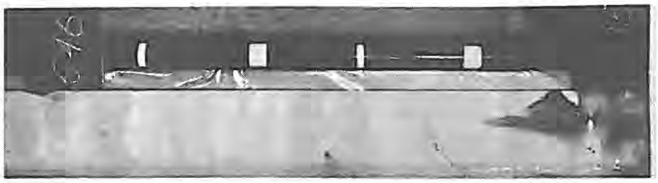


e. *Unusable core: run 67, 863.3 to 871.5 ft, some large irregular chunks, some crushed to ice powder, depth assignment approximate only, occurred rarely in Greenland and not at all in Antarctica, less cannot be measured.*

Figure 12. Various grades of core quality, Site II, 1957



a. *Cracking resulting from scratches made by bits with sharp inside (core-cutting) corners.*



b. *Cracking or disking resulting from release of overburden load.*

Figure 13. Core cracking.

Equipment. The difficulties with the casing made mandatory a search for some other means of advancing the casing between coring runs without pulling it. The underreamer described under *Equipment (1957)* was procured, modified and used in subsequent seasons.

Some correlation is possible between the rate of penetration and the frequency of cracking. The desirability of a uniform rate of feed with a range of rates available is obvious in considering a coring operation in nearly perfectly homogeneous but weak and fragile material. The single drum brakes of the rig were not adequate to afford the completely smooth braking action required to feed several thousand pounds of drill string at a uniform rate.

It was often noted that the top part of the core was in worse condition than the bottom of the run. Although there could be other causes for this condition, it was strongly suspected that the top of the core barrel was weaving during rotation and that better core might have been obtained if the rotation of the core barrel could have been steadied, perhaps by drill collar run just above the core barrel.

A mechanical line scale or weight indicator had been procured in order to measure the weight on the bit, but although it had the lowest range of any available, it proved entirely unreliable. This was probably because drill string loads never exceeded 8500 lb and, thus, only the lower 20% of the instrument's range of 40,000 lb was used.

When it was discovered that the inner tube was turning, by the observation of helical scratches on the core made by core lifter teeth, the head of the core barrel was disassembled and the grease which lubricates the thrust bearing was replaced by diesel fuel. It is recommended that this practice be followed whenever a double tube, swivel type barrel is run in such a cold borehole.

Although not always obvious from the data given here, the most valuable results obtained in the first season's operations in Greenland were the changes in techniques and equipment design which suggested themselves.

To summarize the results of the first season's operation: It was demonstrated that core could be obtained to depths of 1000 ft in a high polar glacier by the method described and, although the quality of the core produced left a good deal to be desired, it appeared certain that improvements in quality and amount recovered could be assured by modification of equipment.

GREENLAND 1957

Equipment modifications

Several modifications of the equipment were suggested by the results of the first trials in 1956. Schemes were investigated for obtaining a more uniform rate of feed that would be independent of the friction brakes of the main hoist. This meant that a device had to be designed that would feed the "dead" end of the main hoist line which was normally anchored to the rig. The first and most obvious of these is a long hydraulic cylinder with a valve to control the flow of oil from the exhaust end and with the "dead" end of the hoist line tied to the piston. With the brake on the hoist line drum set, the weight of the tools would then be supported by the oil pressure in the cylinder. By bleeding this oil with the valve, the rate of descent of the tool string could be closely controlled. However, a double sheave traveling block and a "four part" line were required and it will be seen that an 80-ft cylinder would be required for an uninterrupted 20-ft coring run. It was learned that 20-ft cylinders were available and in use for this purpose in the deep exploration programs in the iron ranges of Upper Michigan. Even if four strokes of a 20-ft cylinder were used, a high speed pump would be required to quickly return the oil after each 5-ft advance of the drilling tools. In addition to the other requirements mentioned the method had to provide for storage of the 80 ft of line required to feed the tools 20 ft. This was eventually accomplished by the use of a truck winch driven by a small electric motor through a hydraulic transmission. The transmission allowed nearly infinitely fine variation of ratios from 1:1 to 100:1. Thus, with the main hoist brake set, the electric motor would drive the truck winch at any required speed and that speed could be very closely controlled by the handwheel speed ratio adjustment of the transmission. Further, the great range of speed ratios available allowed rapid rewinding of the line on the drum (Fig. 14).

Core bit teeth were redesigned to present a smoothly curved cutting edge to the core. Examples of the resulting bits that were used in 1957 are shown in Figure 8.

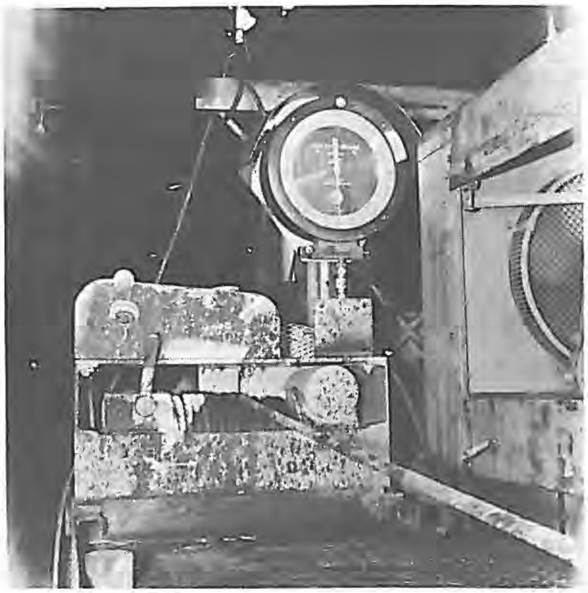


Figure 14. Constant-rate feed device.

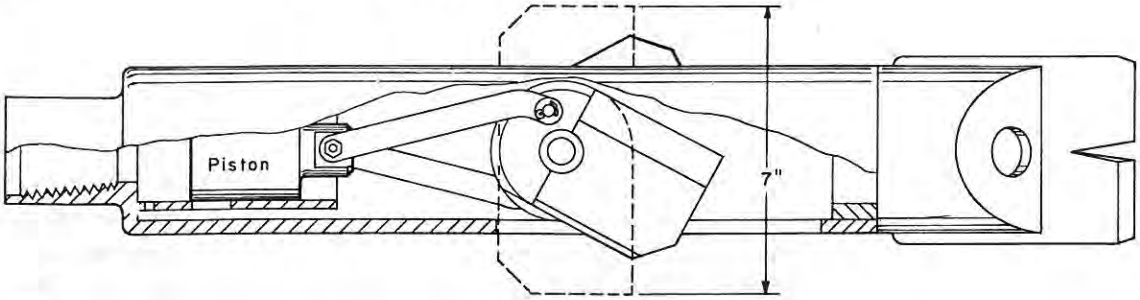


Figure 15. Failing underreamer No. U-120-A-12.

Difficulties encountered while "drilling in" casing in 1956 suggested the use of an underreamer the following season. The blades were opened by air pressure and were cut to ream a 7-in. hole (Fig. 15).

The drill collar which was intended to steady the rotation of the core barrel was procured in 10-ft lengths with 2⅞-in. API Regular tool joints so that several lengths could be made up together to present a flush surface, affording no opportunity for lodging of cuttings. The drill collar OD matched the core barrel OD, and the top end of one of the lengths of collar was fitted with threads to accommodate the sludge barrel. Thus, the entire assembly, from the top of the core bit teeth to the top of the sludge barrel, presented a flush surface along which the cuttings moved upward at great velocity due to this small annulus. Cuttings too large to be lifted by the lower velocity air stream above the top of the sludge barrel, where the annulus section increased, were collected in the sludge barrel.

An additional 350-cfm compressor insured against the possibility of breakdown since it had been found that one compressor did not provide sufficient capacity to keep the hole clean except when coring at low rates of penetration.

Operations

As soon as personnel arrived at the site in early June, attempts were made to retrieve the 940 ft of drill pipe stuck in the hole drilled in 1956. It became apparent that only a part of the pipe might be recovered and that valuable time would be consumed in the operation. Since the drill pipe would serve as casing to protect the hole from complete closure, it was decided to leave it in place so that temperature measurements could be made at depth within the bore of the pipe.

The center section of the roof was removed and the rig was moved 38 ft up the trench. Several days were required to open the trench so that a tractor could enter to move the rig, install the compressors in a new shelter at the surface, repair the roof, and re-rig. Figure 16 shows the rig in place for the 1957 operation.

Although it was realized that approximately 150 ft of casing would be required, only 80 ft was available. An open hole was drilled to that depth, and the 80 ft of casing set. Additional casing and all of the new equipment were delayed in shipment and were not available until early August. Coring was begun with the original equipment from the 1956 season on 15 July. Fairly good cores were obtained to 400 ft although regular cracking was beginning to appear. Two 10-hour shifts were initiated on 25 July. Uncertain air circulation plagued the operation up to this point since the casing only extended to 80 ft. It was hoped that upward-flowing fine cuttings might seal the permeable zone below the bottom of the casing. This did not happen, and additional casing was set to 160 ft shortly after it arrived on 1 August.

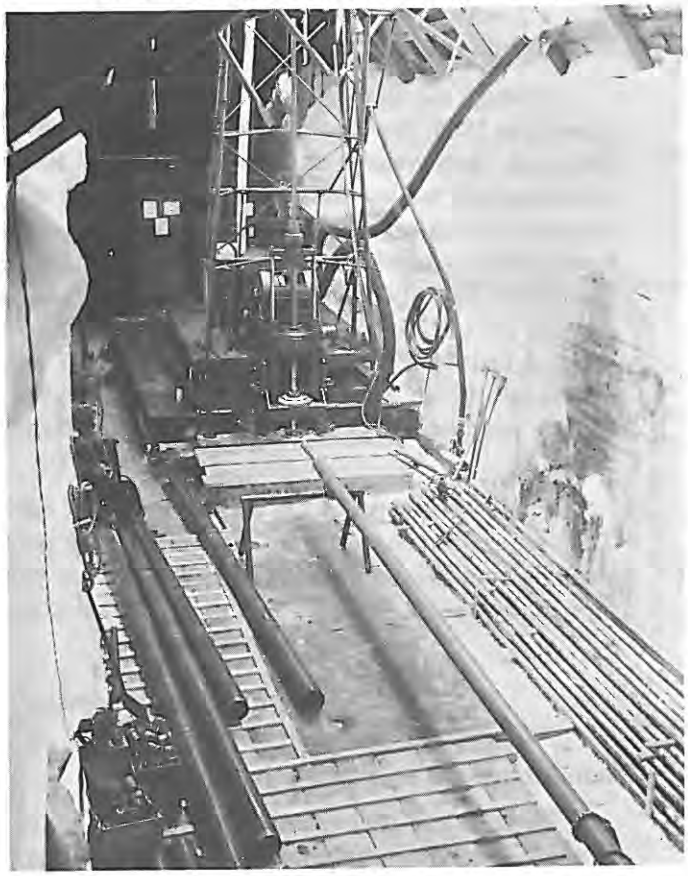


Figure 16. Rig in place in trench, Site II, 1957.

Utilization of the new equipment which arrived in mid-season immediately improved the condition of the core. Twenty feet of 5¼-in. drill collar (60 lb/ft) was run directly above the core barrel and the tendency of the core to deteriorate at the top of each run was markedly reduced. The new bits (Fig. 8) with the smoothly curved cutting edges produced much smoother core, which in turn seemed less apt to fracture. Unfortunately, the uniform feed device was so delayed in shipment that it was not available during the 1957 Greenland season. Minor and remediable difficulties caused the loss of some core between 500 and 1000 ft. In general, core quality was much improved over core recovered from similar depths in 1956.

Brakes of insufficient capacity and the generally worn condition of the 15-year-old rig caused increasing difficulties between 500 and 1000 ft as the weight of the tools increased. It became impossible to feed the drill string at the slow, uniform rate required to produce good core from these depths.

Continuous coring was terminated at 1000 ft and open hole was drilled to 1155 ft where one coring run was made that produced fair core. Open hole was continued to 1316 ft where a final coring attempt produced some usable core. This core is shown in Figure 17. The hole was bottomed at 1334 ft since the condition of the brakes no longer allowed the heavy (10,000 lb) string of tools to be safely lowered into the air-filled hole.

Summary of results

Although the quality of the core was generally improved over that recovered in 1956, the tendency of the core quality to deteriorate at depth persisted. Improvement in core quality was at least in part due to improved bit design and the use of the drill collar. Some improvement must also be attributed to the experience gained by project personnel in 1956. The enormous difficulty experienced in 1956 in attempting to "drill in" the casing was almost entirely overcome by the use of the underreamer in 1957. Casing was set to 150 ft in approximately two days as opposed to several weeks required in 1956. Two shifts were used in 1957 with a considerable increase in efficiency. This was probably due to the fact that the operation became nearly continuous and difficulties in starting cold engines were reduced.

Figure 12 illustrates the various grades of core quality taken in 1957. They are used to illustrate the word criteria for core quality used in 1956 when no photographs were taken. The improved techniques and equipment already mentioned resulted in large quantities of excellent core.

BYRD STATION 1957-58

Introduction and logistics

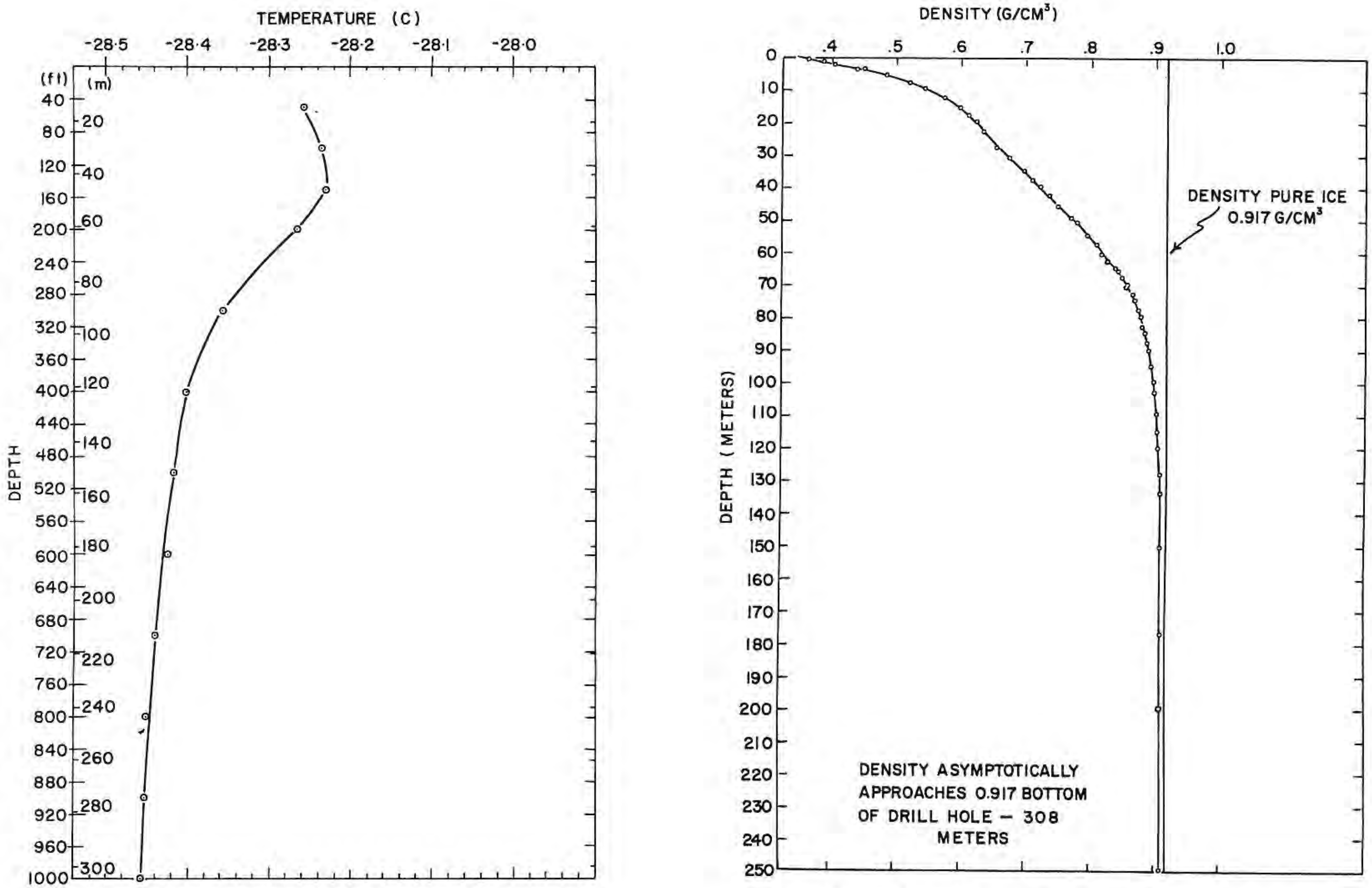
Location and environment. Byrd Station is located on a high plateau of Marie Byrd Land in the interior of the Antarctic continent at 80°S, 120°W at an elevation of 5000 ft, 900 air miles from McMurdo and 400 miles from the nearest coast (Fig. 1). Mounting a drilling operation at this remote site represented a formidable logistic problem (see below). Heavy items could be delivered only by a 650-mile Cat train haul and the largest airplane that could be landed at the site was a C-47. A good deal of equipment could be airdropped from C-124 Globemasters flying from McMurdo Sound.

It was expected that the ice would be approximately 8000 ft thick and that the depth vs density relationship and the level of zero permeability would be similar to subsurface conditions encountered in northwest Greenland. With a mean annual temperature of –28°F, summer season temperatures occasionally came within 3 to 4° of freezing. Maximum wind velocities to be expected in summer were 60 mph. An annual net accumulation of 5.5 in. of water equivalent indicates a much drier climate than that of northwest Greenland (Fig. 18).

Logistics. The drilling program at Byrd Station was scheduled on the premise that personnel and equipment would be at the drilling site by the middle of October. The personnel were in New Zealand at the end of September, and the driller and driller's helpers arrived at Byrd Station 7 November 1957.

Twenty-six tons of basic equipment consisting of the drill rig, two compressors, an air cooler, drill pipe and casing arrived at Little America by ship in December 1956. This equipment was transferred to a tractor train and arrived at Byrd Station by 26 October 1957. In addition, 13 tons of supplemental drilling equipment was forwarded from the United States to Christchurch, New Zealand, by ship in 1957, arriving in late October; and finally 3700 lb of equipment used in the 1957 Greenland operation was flown direct

Figure 17. Core from run 79, Site II.



Borehole temperatures to 1000 ft depth at Byrd Station.

Depth density curve for Byrd Station borehole.

Figure 18. Borehole temperatures to 1000-ft depth and depth-density curve, Byrd Station (Bender and Gow 1961).

from Thule, Greenland, to Christchurch by Military Air Transport Service. About 5000 lb of this material, which was flown to NAF McMurdo by USAF Globemasters, was landed at Byrd Station by a ski-equipped U.S. Navy R4D (C-47). The remainder, consisting of 72 separate items, was dropped by Globemasters at Byrd Station on 1 and 4 December 1957.

A few items were lost or damaged in transport. All were replaced from field stocks or repaired. One critical replacement item was flown from the U.S. on an emergency basis.

Equipment. The drilling equipment used in Greenland and described in detail earlier was completely duplicated with two major additions. The core feed device previously mentioned was available for field trial for the first time. Because there would be neither time nor equipment to construct a subsurface shelter as was used in Greenland, a prefabricated shelter was provided for erection on the surface (Fig. 19). A framework of lightweight steel tubing covered by a very strong fabric was designed similar to oilfield rig shelters. This arrangement covered the sled-mounted rig and compressors, and provided extra space for tool storage. It was designed to be snow-tight and to withstand winds of up to 80 mph.

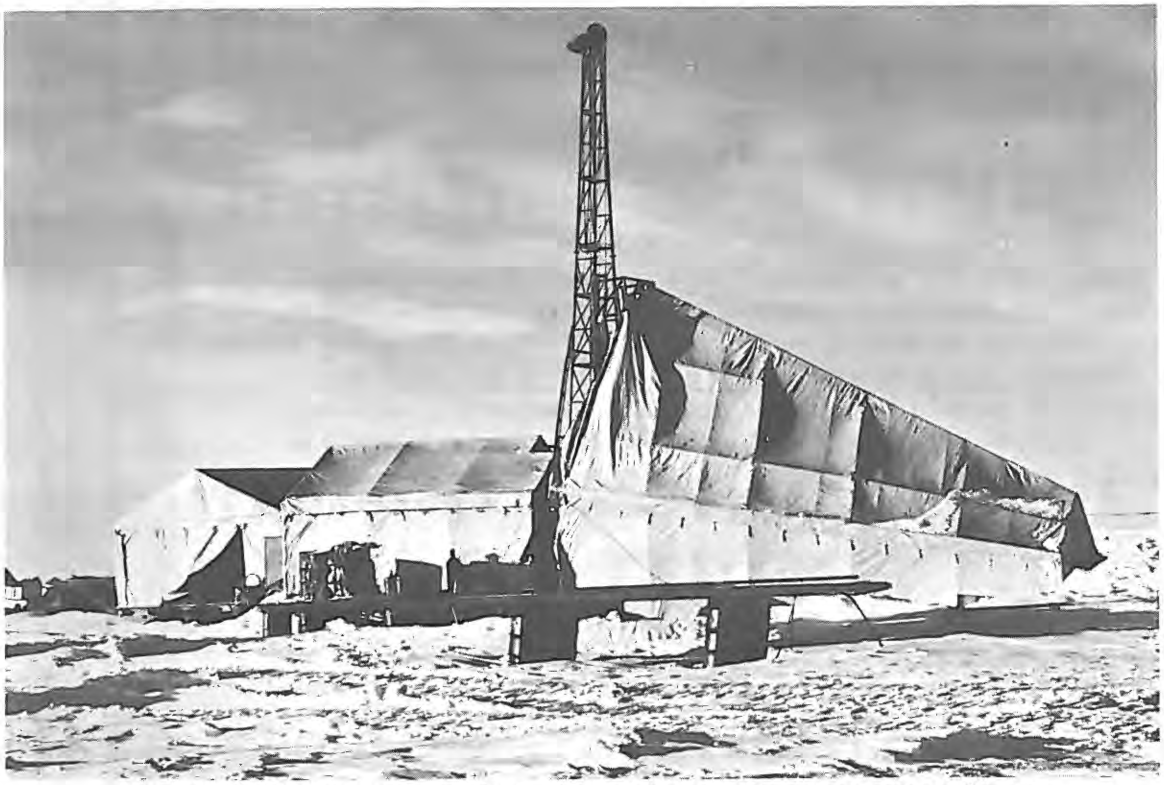


Figure 19. Drilling plant in place with tubular steel frame and Nacion fabric shelter at Marie Byrd Station, 1957-1958.

Operations

Drilling operations were begun on 16 December 1957 and completed on 26 January 1958. An abbreviated operational log follows.

16 Dec	Completed setting up the equipment and shelter. Drilled open hole to 40 ft.
17	Attempted coring at 40 ft but lost circulation. Drilled open hole to 63 ft.
20	Casing set to 62 ft. Cored to 95 ft and again lost circulation. Set casing to 84 ft.

23	Shut down with burned-out bearing in rig.
26	Bearing repaired.
30	Cored to 134 ft and lost circulation.
1 Jan	Set casing to 115 ft.
2	Cored to a depth of 180 ft. Recovered the first unbroken core, 18 ft in length.
4	Cored to 338 ft. Recovered the last unbroken core, 19 ft in length.
8	Cored to 509 ft. Recovered unbroken lengths of core up to 8 ft in length at this depth.
11	Completed installation of core feed device (509 ft).
26	Cored to 1013 ft without incident. Recovered core in unbroken segments as much as 2 ft in length at 1000 ft. Conchoidal tension fractures from release of overburden load became evident at 600-700 ft, increasing in frequency at depth.

Results

Core was recovered for 98% of the distance; most of this was good quality. The tendency to conchoidal cracking due to the release of the overburden load was evident, but greatly reduced compared to the cracking at depth in Greenland in 1957. The use of the constant rate-of-feed or core feed device accounted for this improvement. Core was almost entirely of "excellent" quality to 600 ft, "good" quality to approximately 750 ft and "fair" to "poor" quality to the bottom of the hole (see Fig. 12). It is believed that the results, in terms of quality and amount of core recovered, represent the optimum for rotary coring with compressed air in a high polar ice cap.

LITTLE AMERICA V, 1958-1959

Introduction

Location and environment. Little America V is located about two miles from the seaward edge of the Ross Ice Shelf (78° 11' S, 162° 10' W) (Fig. 1), a sheet of glacier ice floating on the Ross Sea. The shelf is attached to the continent of Antarctica at its landward edge and is known to be grounded at several places. At the drilling site, which was approximately 150 ft above sea level, the shelf ice was expected to be about 1000 ft thick and floating in about 2000 ft of water. The mean annual temperature is −11°F and summer season temperatures occasionally rise above freezing. Maximum wind speeds of 40-60 mph could be expected during the field season. While the depth vs density relationship and the depth of the level of zero permeability were not known, these conditions were expected to be roughly similar to those encountered at Byrd Station and in Greenland, except that annual net accumulation was expected to be about 8.3 in. of water (Fig. 20).

Logistics. The drilling equipment was transported from Byrd Station to Little America V by tractor-train in February 1958 after completion of the Byrd Station drilling program. The drill party arrived at Little America Station on 13 October 1958. The equipment was unloaded from sleds, the prefabricated compressor and rig shelters previously described were erected, a Jamesway hut was set up for use as a tool house and shop, and an undersnow core storage vault and laboratory were constructed at the rear of the drill shelter.

Equipment. The drilling plant was the same as that used at Byrd Station, with one important addition. Since the question of whether the shelf was growing thicker by the accretion of sea ice at the bottom or wasting by melting of glacier ice would be quickly settled by an examination of

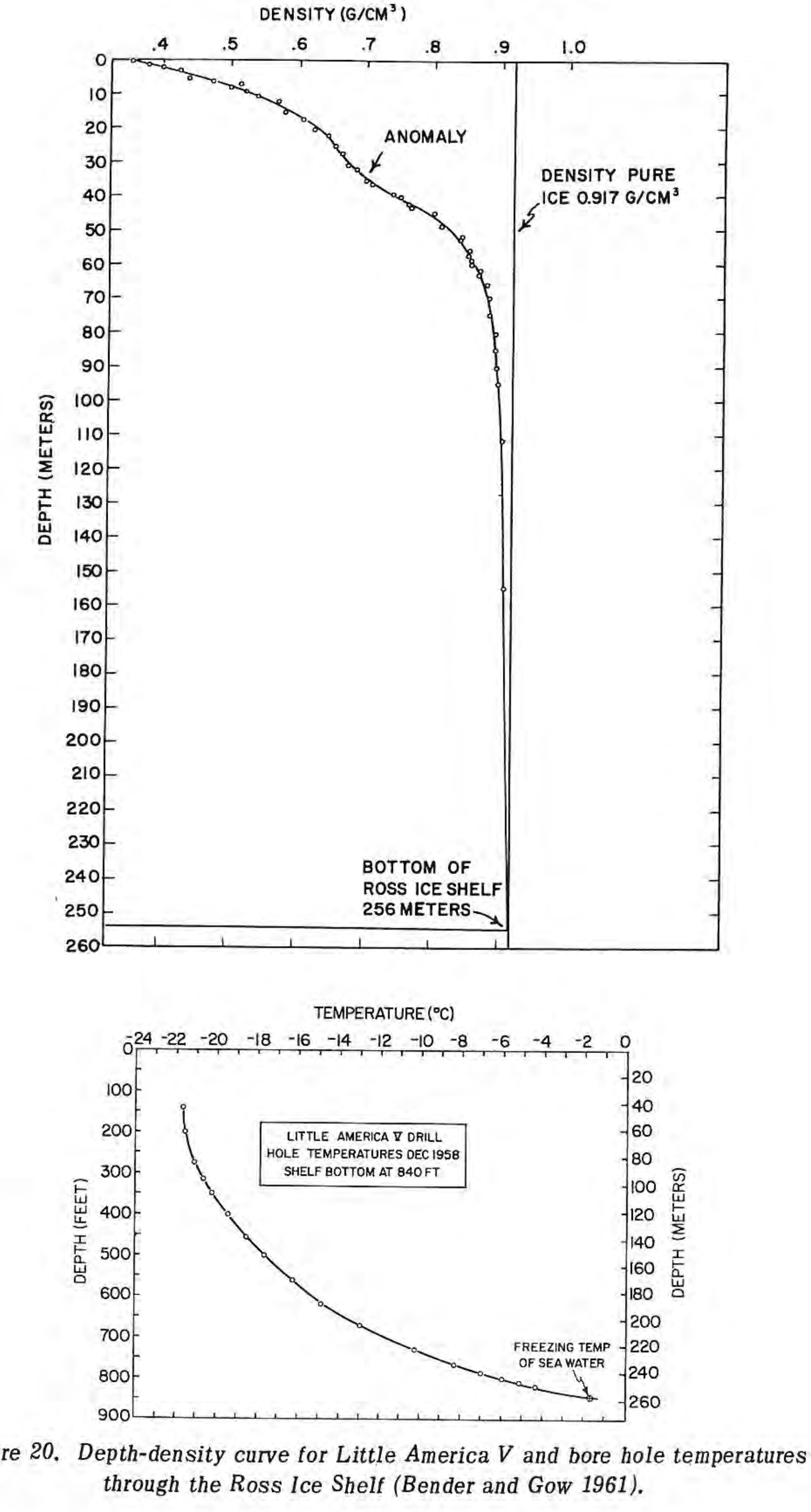


Figure 20. Depth-density curve for Little America V and bore hole temperatures through the Ross Ice Shelf (Bender and Gow 1961).

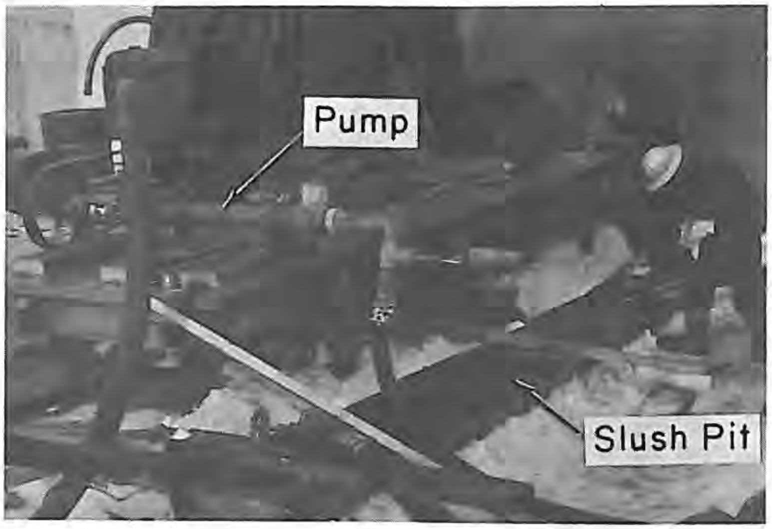


Figure 21. Moyno pump and slush pits rigged for the use of diesel fuel, Little America V, 1959.

core from near the ice/sea water interface, an attempt was to be made to core completely through the shelf to the sea water beneath. The surface of the shelf was 145 ft above sea level; therefore, it was expected that sea water would invade the hole and rise to sea level. For this reason a pump was provided so that a liquid could be used as the circulating fluid to balance the pressure of the sea water. A Moyno progressing cavity type was chosen for its simplicity and efficiency (Fig. 21). The model 3L6-CSQ weighed 150 lb and at 900 rpm delivered 36 gpm at 225 psi, required 7½ hp input and was 78% efficient. It was driven by the 15-hp air-cooled engine that powered the large fan in the air to air heat exchanger. The only liquid available in quantity that had a low freezing point and that was not an aqueous solution was diesel fuel. Because of the large quantities of liquid involved the pump and diesel fuel were to be used only near the bottom of the shelf when the penetration of the shelf seemed imminent. As before, cooled compressed air would be used as the circulating fluid for the upper part of the hole.

Operations

Drilling began at 1630 on 31 October 1958. Open hole was drilled to 22 ft, where coring was attempted. Circulation could be maintained for only a few feet at a time in the permeable upper snow. Casing was initially set to 39 ft. It became necessary to advance the casing four times to a total depth of 130 ft by underreaming before it was possible to maintain air circulation. As at Byrd Station and in Greenland, the bits used at Little America Station cut a 3⅞-in. core and a 5¾-in.-diam hole. Also, as in the previous ice coring, the casing was $6\frac{1}{16}$-in. ID.

Cooled compressed air was used as a drilling fluid from the surface to 818 ft. Drilling was not attempted during the infrequent times that the temperature of the compressed air exceeded 25°F at the drill. While drilling with air, the drill string was rotated from 50 to 60 rpm and advanced at the rate of 5 to 6 in./min.

Increasing ice temperatures (Fig. 20) may have accelerated hole closure near the bottom of the shelf. On retrieving the core barrel after a 10-ft run had been made to 808 ft, bit B413J backed off at a point estimated to be 40 ft above bottom. This bit has teeth inclined in such a manner (positive axial rake) that if they were dragged on an undersized hole wall in hoisting the resulting rotation would turn the bit off the core barrel. However, it had consistently produced better core than any other type. The bit was recovered by running a grapple made from a turnbuckle down through the bit on the sand line. For the remainder of the drilling, this bit was replaced by bit B413E, which is similar except for vertical teeth (0° axial rake), and therefore less likely to unscrew. Return circulation had been good, but the drilling had progressed slowly during the preceding several days because of the necessity for taking frequent bore hole temperature measurements in order to accuratel predict the thickness of the shelf before it was penetrated by the bit.

When the drilling had advanced to 818 ft increasing bore hole temperatures together with seismic evidence indicated the possibility of encountering the bottom of the shelf in another 20 or 30 ft. It was decided to drill the balance of the hole with diesel fuel. The possibility of losing part of the hole to salt water encroachment was realized, as the collar of the hole was 140 ft above sea level and about 700 ft of salt water (density 1.025 g/cm^3 at 0°C) would weigh more than 840 ft of Arctic diesel fuel (density 0.813 g/cm^3 at 5°F). Preparations were made to load the hole with diesel fuel on the assumption that it would be possible to drill out any resulting ice plug.

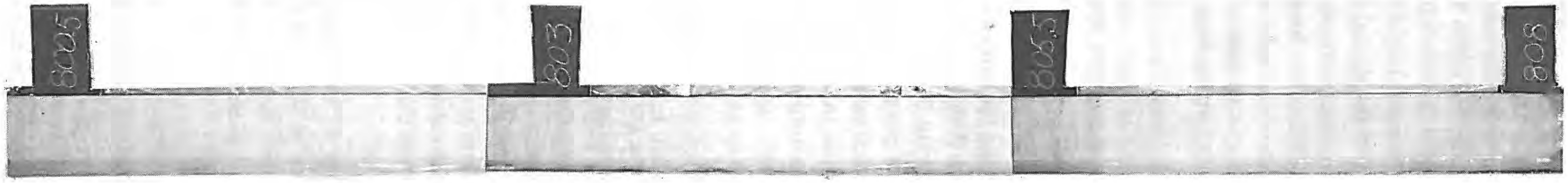
The Moyno pump was put in service. A slush or settling pit was fabricated of three 55-gal fuel drums cut in half lengthwise and welded end to end to form a six-compartment tank. Filter screens of common house screening were placed in each compartment.

The hole was cored to 836 ft using diesel fuel. During the coring run, the drill string was rotated from 60 to 65 rpm and advanced at 6 in./min. The pump pressure averaged 100 psi and the circulation averaged 50 gpm. The temperature of the diesel fuel was 6°F. While retrieving the drill string from the hole, a return flow of diesel fuel, roughly equivalent to the previous pump circulation rate, continued while the first five or six lengths of drill pipe were in the slips. This flow ceased while the string was being raised between joints. When the core barrel was recovered, about 4 in. of core projected below the bit, and to this was frozen an irregular, diesel-fuel-contaminated layer of salt ice ½ to ¾ in. thick. The core recovered from this run is shown in Figure 22c.

The diesel fuel head in the drill hole was measured shortly after removal of the core and was found to be 32 ft from the surface. The computed volume loss due to removal of the tools was 82 ft. A weight was run down the drill hole on the sand line and some resistance was encountered between 600 and 620 ft. The weight was recovered with ice particles on it that tasted strongly of salt. As the bottom of the core terminated in a clean break, it appears that a fracture may have been encountered or developed in the bottom of the shelf, providing access for the salt water. It was decided to wait several days for the salt water to freeze and then to redrill the salt ice that would probably form in the hole because temperature and closure measurements could be required through the entire thickness of the shelf.

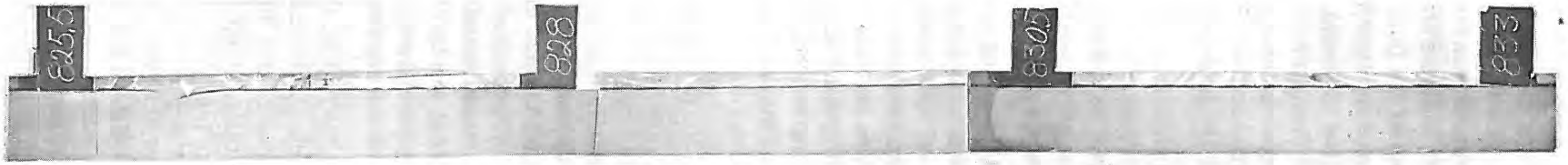
The coring run with diesel fuel was made on 5 December and drilling was not resumed until 15 December, principally because of a storm. By the evening of 16 December, the hole had been redrilled to 760 ft using a 5⅝-in. drag bit. The cuttings from 600 to 760 ft consisted almost entirely of thin, flat, transparent plates up to ½ in. in diameter. They appeared to be crystal fragments, indicating that the salt water had frozen in a crystal mush. The circulation while drilling averaged 50 psi and 50 gpm and the temperature of the diesel fuel was 5°F. The drilling tools were rotated at 60 and 70 rpm and advanced about 6 in./min.

It was presumed that the loose salt ice structure might continue to the bottom of the hole, and might not be of sufficient strength or impermeable enough to prevent the sea water from entering the hole. For this reason, it was decided to stop drilling open hole and to attempt to core this ice plug, after which the drilling would be stopped and the hole would be left loaded with diesel fuel.



a. *Run 46, 800.5 to 808.0 ft, frequent cracking, core quality fair to poor, taken with compressed air.*

b. *Run 47, 810.5 to 817.5 ft, frequent cracking, core quality fair to poor, taken with compressed air.*



c. *Run 48, 825.5 to 833 ft, core quality excellent, taken with diesel fuel.*

Figure 22. Representative cores from 800 to 833 ft at Little America V, 1959.

It was necessary to ream the redrilled portion of the hole with the core barrel because the salt ice had been drilled out with a 5⅝-in. bit and the core bit is 5¾-in. OD. During the morning of 17 December, the hole was reamed from 600 to 660 ft. From this point onward, ice chips that failed to settle out in the slush pits and were recirculated repeatedly lodged in the restricted clearances of the core barrel and blocked off the fluid circulation. It was evident that a much larger settling pit would have to be constructed to allow the fine ice particles to settle out of the diesel fuel. Since it was late in the season and the supply of diesel fuel had been depleted, the decision was made to shut the project down. The depth of the drill hole was measured at 727 ft. The loss from the previous depth of 760 ft represented cuttings that had fallen to the bottom of the hole while reaming with the core barrel. To secure the hole for possible future use, 15 ft of casing was added above snow level to the original 130 ft of casing in the hole and the entire casing string was capped.

Results

Core recovery amounted to 98% of the footage drilled. A major part of the core loss resulted while experimenting with a new bit design when 4.5 ft of a 19-ft coring run from 320 ft was lost and the remainder of the run was badly fragmented.

As with the previous ice coring it was found that variations in drilling techniques at shallow depths, especially rate of penetration and rpm, appear to be less critical than in the deeper ice. These rates could be varied widely without affecting the snow core. During the coring from 38 to 138 ft, the rotational speed was varied from 50 to 110 rpm and the rate of penetration from 6 to 12 in./min without affecting the condition of the core. A symmetrical spiral faceting of the core was observed in two runs at 75 rpm and 138 to 165 ft, which may have been due to resonance developing in the lengthening string of tools. Beyond 165 ft, the rotation was maintained at 60 rpm and the rate of penetration at 6 in./min, as this combination had produced the best core in the previous ice coring.

The core from 150 to 300 ft was infrequently broken, with unbroken segments often more than 15 ft long. Beyond 300 ft, release, by coring, of the increasing overburden load resulted in shorter segments of unbroken core down to 600 ft, where the segments averaged 1 ft in length. Beyond 600 ft, the core condition gradually improved, i.e. the length of the unbroken segments increased, probably because the increasing temperature resulted in decreasing fragility of the ice. At depths greater than 500 ft the core exhibited the incipient conchoidal fractures that are presumed to result from the release of the overburden load (Fig. 13b). Conchoidal cracks normal to the axis of the core, which are characteristic of cores taken from an air-filled hole at depth, appeared at 500 ft with the most careful drilling, and by 600 ft there were perhaps a dozen fractures per foot of core length. The number of incipient fractures per unit length increased with depth down to 818 ft, where air no longer was used as a drilling fluid.

The core from 818 to 836 ft (Fig. 22c), taken while using diesel fuel as a drilling fluid, did not contain the cracks normally characteristic of the cores taken with air at this depth, but had small, irregular surficial cracks that did not penetrate more than ½ in. into the core. This suggests that cracking might be virtually eliminated if diesel fuel is used as the circulating fluid while drilling in the impermeable ice.

DISCUSSION OF RESULTS WITH RECOMMENDATIONS FOR FUTURE OPERATIONS

Circulating fluid

The choice of the proper circulating fluid, delivered at an adequate pressure and rate of flow, is probably the most important single factor in insuring the success of any drilling program.

The use of cold compressed air as a drilling fluid produced good results and the decision to use it was a sound one in view of the experience available at that time. The original computations for the flow and pressure required appear to have been approximately correct. Air pressure measurements made in the receivers at the surface during drilling operations validated the pressure drop calculations.

When cuttings were produced too rapidly or a few over-large cuttings were produced, the uphole airstream became overloaded and the cuttings froze to the hole wall, reducing the diameter of the hole above the core barrel. The tools were then hoisted with great difficulty or not at all. Usually this condition was recognized early enough so that the tools could be loosened by moderate pulling and bumping. However, serious difficulties were encountered from this source when the drill pipe was stuck at the end of the 1956 season in Greenland.

The air-to-air heat exchanger described furnished adequate cooling of the compressed air except for a few days at Little America V during which the ambient temperatures rose above approximately +20°F. Defrosting of the heat exchanger afforded little or no problem when a dependable Herman Nelson heater was available and heat from it applied as soon as compressed air pressure began to rise, indicating that accumulating ice was constricting the heat exchanger tubes.

Since the work reported here has been accomplished, a second stage of compressed air cooling has been developed. A mechanical refrigerator has been designed and built for refrigerating diesel fuel and compressed air to be used as drilling fluids in permafrost. By using this as a second stage of cooling, following the air-to-air heat exchanger, compressed air at approximately the environmental temperature of the ice that is being cored could be delivered to the bit. This would allow borehole temperature, usually measured at intervals during the drilling of the hole, to approach equilibrium in a very short time. The colder air would also reduce the thermal shock to the core while it is being cut. The degree to which thermal stresses contribute to the total stresses on the core is not known, so that the resulting improvement in core condition can not be predicted. A second stage of cooling would definitely be required for ice coring using compressed air from a surface environment in which ambient air temperatures more than occasionally rose above +25°F. Defrosting difficulties are much more severe in the brine-to-compressed-air heat exchanger than in the air-to-air heat exchanger.

While good arguments against the use of diesel fuel as a drilling fluid were advanced at the beginning of this work, there is now good evidence that at depths below the level of zero permeability, the use of chilled diesel fuel would greatly improve the physical condition of the core. Part of this evidence is contained in the core taken with diesel fuel at the bottom of the Ross Ice Shelf at Little America (Fig. 22c). There are no serious cracks in the entire core. It is believed that this remarkable improvement in core quality is due to two effects. First the diesel fuel, being a great deal more viscous than air, damps the many and various mechanical shocks and vibrations transmitted to the core by the bit and core barrel. Second, but perhaps more important, if the hole is loaded with diesel fuel the pressure at the bottom of the hole where the core is being cut is nearly equal to the hydrostatic pressure in the ice or the environment from which the core is cut. Thus the hydrostatic or original confining pressure on the core is relieved fairly slowly as the core is hoisted up through the pressure gradient in the oil-filled hole. In an air-filled hole the confining pressure is relieved rather abruptly when the core is cut. It is likely that the rapidly increasing temperature of the ice towards the bottom of the shelf contributed in some small degree to the absence of cracks in this core; but only in a small way, because the temperature gradient is smooth, as it must be, and the absence of cracking is markedly abrupt. Figure 22c shows the core taken in run 48, with the diesel fuel, and the cores taken in the previous runs using air are shown in Figures 22a and b. All of the runs previous to and including run 47 show the gradually increasing frequency of cracking mentioned previously, while run 48 exhibits little or no cracking.

For drilling and coring to depths greater than a few hundred feet in a glacier, by any method now envisioned, diesel fuel would almost certainly be chosen as the basic fluid. Some liquid would be required below two or three thousand feet, in order to inhibit hole closure enough to permit the passage of the drilling tools in and out of the hole. The promise of increased core quality manifest in the last run taken with diesel fuel at Little America is indeed attractive.

Some sort of casing would have to be set to or near the level of zero permeability before the diesel fuel could be used. This might be accomplished by the use of compressed air as before, but the great cost and weight of a suitable compressor and the logistic problem of fuel supply for compressor engines justifies a search for some other method. Open hole has been made by augers to depths of 120 ft at Camp Century in Greenland with little difficulty. Cores have been taken by auger type core barrels at these depths. Thus it seems likely that augering tools driven by the basic drill rig might well be used to set the casing deep enough to insure the circulation of the diesel fuel without loss to the snow, thereby completely eliminating compressed air and its attendant problems.

While the presence of diesel fuel is not objectionable in certain physical tests, it does cause serious contamination of the surface of samples prepared for accurate chemical analysis. It appears likely that this difficulty may eventually be overcome with refinement in core analysis techniques.

Subsequent experience with diesel fuel in drilling and coring in permafrost rocks and soils has somewhat dispelled the earlier fears of the fire hazard. However, the diesel fuel has been found somewhat unpleasant to handle and prolonged exposure can cause minor, but annoying, skin irritation.

Compressors and pumps

The compressors used, both in Greenland and the Antarctic, were chosen mainly because they were available without cost. While they had presumably been overhauled before they left the Army depot from which they were obtained, frequent breakdowns often left the total success of each of the projects in grave doubt until each hole was finished. Furthermore, these breakdowns caused delays which materially added to the time required for the completion of the projects. It is strongly recommended that only new machines be obtained for future work, particularly in remote locations. It is further recommended that the man responsible for the operation and maintenance of the compressors carry out a long "break-in" run on the machine under factory supervision. The use of rotary compressors is also recommended because of their greater efficiency and their simplicity of design relative to reciprocating types.

It would seem that if diesel fuel is used as a circulating fluid, the rather slight difference between the density of the cuttings and the density of the drilling fluid (ice = 0.917 g/cm^3, diesel fuel = 0.815) would allow the use of slow uphole fluid velocities and consequently pumps of a small capacity. Thus, 50 gpm was sufficient to keep the hole clean during the last coring run at Little America. This discharge gives an uphole velocity of 42 ft/min with 2⅜-in.-OD drill pipe in 5¾-in.-diam hole and therefore the cuttings require 24 minutes to rise to the surface from the bottom of a 1000-ft hole. This means that the pump must be run for perhaps 25 minutes after each coring run is completed in order to flush all of the cuttings from the hole before hoisting the tools. If a pumping plant is to be selected for future work, consideration should be given to the delay thus caused and some compromise pump discharge figure chosen.

Rig

For continuous coring to depths of over a few hundred feet in a remote location with a short working season, the highest mast possible should be used. This will allow a maximum length of core barrel and coring run and thus a minimum number of hoisting trips. Also a high mast will allow the stacking of longer joints of pipe and thus reduce the number of connections to be made in each hoisting trip. The length of mast, then, will be limited by economic and logistic considerations. The 38-ft mast described earlier, which allowed the use of 20-ft core barrels and 20-ft lengths of drill pipe, would theoretically allow a program of continuous coring to be carried to 1000 ft in a fairly short time, assuming a rate of penetration of 4-6 in./min and allowing 1 minute for each connection of each joint on a round trip. However, to allow for the inevitable breakdowns and other delays, the figure so estimated should be multiplied by a factor of from 5 to 10.

Line pull available from the drawworks and mast strength (or hookload capacity) will be properly matched by the manufacturer and should be adequate to handle any anticipated drill pipe loads with a safety factor of perhaps two. The additional hoisting capacity is then available for pulling on stuck pipe. Difficulty was encountered with sticking brakes when handling drill pipe loads on the order of 8000 to 10,000 lb in the air-filled bore hole. In fact, this condition, which results in dangerous shock loads on the mast when the tools are lowered and hoisted, determined the depth limit of the equipment and the final depth of the holes in all cases except at Little America where the ice shelf was penetrated. The use of a liquid as a drilling fluid would extend the depth limit because the shock loading would be considerably damped by the higher viscosity liquid and the buoyancy of the liquid would reduce the effective load on the mast.

When the constant rate of feed device was finally available for use at Byrd Station a definite improvement in the condition of the core was noted. Core taken with the device was of markedly better quality than core taken from similar depths in previous holes.

Drill pipe and drill pipe handling

During the first operations in Greenland in 1956, a special type of breakout slip was used in conjunction with the breakout table. Because this type of slip gripped the drill pipe joint, it was impossible to use drill pipe elevators and a hoist plug was used. In order that elevators could be used to increase the speed of the hoisting operation, slips which gripped the drill pipe tubing rather than the tool joint were used in all later operations. Since the sharp die points could cut through the thin walled tubing, this was not considered good practice; however a worthwhile saving was made in the round trip hoisting times.

Torque for breakout was provided in the manner described above, using the engine-driven breakout table. A hand-held 24-in. heavy duty pipe wrench was used for backup. Make-up torque was applied by a pair of 24-in. wrenches, one backed solidly against the rig and the other struck one or two moderate blows with an 8- to 10-lb sledge.

Coring bits and core lifters

Bits B-413-A through B-413-D and DA were developed from the original investigation accomplished by the Failing Co. for ERDL and were taken to Greenland for initial trials in 1956. Experience thus gained resulted in the design and fabrication of bits B-413-E through B-413-K (Fig. 8) which were available for the 1957 Greenland work and subsequent work in the Antarctic. The second series of bits incorporates the principle of presenting only a smoothly curving sharp edge to the core surface in order to avoid scratches which afford opportunity for stress relief. It will be noticed that each bit of the second series represents a variation of the angle of axial or radial rake. It is felt that types 413-J and K represent the best of the designs tested. It should be pointed out that the negative axial rake feature of 413-J caused the loss of that bit when hoisted in the tight hole at Little America.

All the bit designs used are of the face or bottom discharge type. No evidence of inadequate cleaning of the bit teeth by the air stream was ever noticed nor was there any evidence of the air stream eroding the core. Thus, no definite change could be recommended in this aspect of the design; however it is felt that the use of the internal discharge principle might also give good results with either air or diesel fuel.

The bits were made of mild steel (1020) and painted. Very little paint was worn from any of the teeth although some of them were used to cut hundreds of feet of core (see Fig. 8). Apparently clean glacier ice has little or no abrasive effect. It was noted by Abel (1961) that small fractions of soil grains embedded in the ice caused considerable wear to the tungsten carbide teeth of mining machinery used in glacier ice. In coring sea ice by hand considerable abrasion was noted, usually when the ice was colder than -23°C, i.e. when salt crystals were present.*

Several standard types of core lifter including collet, basket, dog and standard split ring types were tried during the first operations in Greenland in 1956. None of these types provided positive initial engagement to the core until the standard outside spline, split ring type normally used for coring in hard rocks was modified by notching out each of the webs approximately ⅜-in. deep with a hacksaw and bending the resulting tab inward about 30 to 45 degrees. The upper ends of the tabs should then drag slightly on the core at full diameter and may be sharpened or burred for more positive engagement. The lifter was used in all subsequent operations and proved completely successful.

Drill string

The selection of drill pipe was discussed in detail earlier and it is believed that the 2⅜-in. external upset tubing with 2⅜-in. internal flush tool joints mentioned represents the best choice available at this time for use with either air or diesel fuel. If a higher mast is used, of course, the longest length of pipe joint that is commensurate with the mast height should be used.

The use of drill collar improved the balance of the drill string, i.e. moved the null point, or point of zero compression and tension, lower in the string. When drilling in rock, drill collar is used to aid in keeping the hole straight among other reasons; it is not required for this reason in ice. So little weight is required on the bit that almost the entire string is in tension and straight hole is easily maintained. However, the drill collar did appear to steady the rotation of the bit and core barrel and this resulted in improved condition of the core. As mentioned previously, the upper drill collar should be threaded to receive the sludge barrel.

The steel 6-in. casing with flush joints described previously proved to be entirely satisfactory when advanced by underreaming. Since advancement by underreaming requires very little casing strength, and in view of the very considerable weight of steel casing required (3000-4000 lb) it is quite possible that some sort of plastic or other material of lighter weight and of moderate strength might be substituted.

The reamers provided were usually run just above the handling sub at the top of the sludge barrel. These, in conjunction with the small jet holes in the handling sub usually prevented the accumulation of cuttings due to the sudden annular cross-section enlargement at this point. Several reamers were also run at intervals in the drill string when there was any evidence of tight hole in order to keep the hole scraped to full diameter. Tight hole appeared to be due to accumulation of cuttings rather than plastic closure of the hole. The only possible exception to this explanation is the tight hole encountered near the bottom of the Ross Ice Shelf which may have been caused at least in part by the increased plasticity of the ice due to the increasing temperature near the bottom of the shelf. In addition the reamers stabilize and centralize the drill pipe in the hole.

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* A. Assur, personal communication.

The DCDMA large series 4 × 5½-in. core barrel served very well and it is estimated that the modification illustrated by Figure 7 decreased the pressure drop by at least 5 psi at maximum flow and pressure. This modification is recommended for use with air or diesel fuel. As with the drill pipe, for maximum efficiency a core barrel of the maximum length allowed by the mast should be used. It is likely that, when using compressed air, a longer core barrel will cause some extra core damage due to the additional vibration involved in the longer core run. This would not be likely to occur if diesel fuel is used because of the damping effect of the fluid.

Technique and operations

It is one of the principal purposes of this report to provide guidance to those who may be required to drill and core to considerable depths in glaciers. As much of the experience gained as is possible and all of the recommendations that resulted are recorded here for the benefit of those who must plan and carry out future operations of this sort. However, a great deal of the "know how" gained in these operations must of necessity remain a part of the skill of the driller. These skills of the experienced driller are a most vital part of any drilling operation, but in the case of an unprecedented operation in the most remote areas of the world, the entire success of the operation sometimes daily depends upon the ingenuity, experience and dedication of the drilling foreman. Thus it is difficult if not impossible to give detailed instructions for drilling and coring in ice. However a few general principles can be mentioned.

A wide range of rpm and rate of penetration was used in initial trials in Greenland and it seems apparent that the best cores are consistently taken at about 50-70 rpm and 4-6 in./min. It is often more convenient to consider these two variables as feed rate, i.e. in terms of revolutions/inch. Thus a range of 8-20 rev/in. is recommended. Less than 50 rpm often caused chattering, especially during the second half of a 20-ft coring run. Fine or slow rates of feed develop finer cuttings and are recommended when uphole fluid velocities may be marginal. Coarse or rapid rates of feed may conversely create cuttings too large to be handled by the uphole fluid velocities available. Exceeding 100 rpm usually caused vibration of the drill string that was deleterious to the highly stressed core from depths below 400-500 ft. Cores of snow, i.e. from the zone above the level of zero permeability, were not at all sensitive to variations in drilling techniques and could be taken successfully at almost any variation of rpm and rate of penetration within the capabilities of the drill rig. As noted in preceding sections of this report, sensitivity of the core quality to variations in technique increased rapidly at depth, and the more specific of the above recommendations apply to the more sensitive core at the greater depths. It should also be noted that the foregoing conclusions and recommendations are based upon the use of compressed air as the drilling fluid. It is likely that higher rpm and feed rates may be used without deleterious effects upon the core if diesel fuel is used.

The problem of the release of the overburden load and the resulting cracking of the core has been discussed in detail in earlier sections of this report. This problem will be largely overcome in future operations through the use of diesel fuel as the drilling fluid and the uniform feed device.

If possible, working shifts should be arranged so that the equipment is running 24 hours per day, except for maintenance shutdowns. The importance of a foreman with a broad background of drilling experience cannot be overemphasized. Members of the drilling crews should be directly responsible to the foreman and should be provided with some incentive. For both of these reasons military personnel assigned as casual labor are not satisfactory. Men of good emotional balance and some degree of maturity are required to work long shifts in remote locations. Needless to say, living quarters, messing facilities, and food should be the best that can be provided. Men not experienced as "roughnecks" or drillers' helpers must be carefully instructed in safe procedures and constantly checked on as the work progresses to insure that safe working habits have been instilled. The most effective way of insuring that safe working procedures become habitual in a crew is the example set by the supervisory personnel.

Both the undersnow shelter used in Greenland and the special tubular steel and fabric shelter used in the Antarctic provided satisfactory protection from the weather for both crews and equipment. In either case care must be taken to seal all cracks against the drifting of the blowing snow.

In the design of a shelter, either on or under the surface, sufficient room should be allowed to swing the long core barrel out away from the rig so that it may be laid down in a horizontal position in order to transfer the core from the barrel to the core trays. The ice cores are too fragile to transfer to the trays with the core barrel hanging in a vertical position. Space should be provided for the long core trays and it is usually desirable to photograph and measure the core on waist-high benches rather than on the floor.

If drilling is to be carried out in other than the summer season, as may well be required in future operations, it is recommended that the entire drilling plant and working area be contained in an insulated and ventilated undersnow shelter. In this case provisions must be made for maintaining the temperature of the drilling fluid at the desired level and for protecting the core from above-freezing temperatures.

It is becoming common practice among drilling contractors in arctic Canada to use diesel engines throughout the entire drilling plant. This practice has a considerable advantage over the use of gasoline in terms of power produced per pound of fuel transported. The advantages in regard to fire hazard and use of a single fuel are obvious. Diesel engines, however, require a higher order of maintenance and repair skill than gasoline engines. The single fuel advantage will not likely be completely realized since some auxiliary engine such as a light plant or delivery pump will invariably require gasoline.

All of the core, except that from the 1956 Greenland operation, was photographed to obtain a permanent record. The core was laid in a tray marked at 1-ft intervals and a small chalk board indicating the depth from which the core was taken was included in each photo. A 35mm single reflex camera was used and each photo included slightly more than 2 ft of core. Uniform illumination was provided by photoflood lamps. Thus, when properly matched and assembled, a continuous photograph of the entire 20-ft run of core is available at a scale of about 1 in. = 1 ft. All the core photographs in this report were obtained in this way. In subsequent coring investigations when photos of core of frozen rock and soil were required a 2¼ × 2¼ single lens reflex camera was used and negatives were developed in a fine grain developer. The remarkable resolution of detail possible with this system recommends its use, particularly if structural details must be recorded.

Recommendations for 10,000-ft drilling by rotary methods

As previously suggested, if drilling and coring to depths greater than 1000 ft is contemplated diesel fuel should be used as the drilling fluid. While the buoyant effect will only reduce the effective weight of the drill pipe by 10%, the viscous damping property of the diesel fuel should reduce the shock loading encountered in the air-filled hole to the point where equipment of the capacity described here could probably be safely used to penetrate to 2000 ft. There is no reason why this type of equipment with increased capacity, properly designed to overcome the greater drill pipe loads and frictional pressure losses in the circulating system, could not be used to penetrate any known ice thickness in the world, i.e. on the order of 10,000 ft. However, the logistic problems of moving such heavy equipment to remote locations would be enormous. The 100-ft mast and substructure required would weigh about 25 to 30,000 lb and measure 60 ft long in the collapsed position. Drawworks and power plant, pumping plant, 10,000 ft or more of drill pipe, and all of the required tools and accessories might total on the order of 150 tons. Since a large part of the heavy equipment mentioned above is required to pump and conduct the drilling fluid to the bottom of the hole and hoist the string of drill pipe, an investigation is presently being carried out to investigate the feasibility of methods in which the drill pipe and circulating fluid may be eliminated.

SUMMARY

A method of drilling holes and obtaining core to depths of 1500 ft in high polar glaciers was required for SIPRE and IGY glaciological investigations. Rotary drilling equipment was modified and sent to Greenland and the Antarctic. Principal modifications included the use of chilled compressed air as a circulating fluid and specially designed coring bits. During initial trials in northwest Greenland in 1956 nearly continuous core was obtained to 970 ft but the core was badly cracked at depth. A second season in Greenland produced much more continuous core to 1000 ft, and single coring runs at the 1100-, 1200- and 1300-ft levels produced usable core. Core cracking at depth persisted although it was less severe. During the Antarctic field season of 1957-58 similar equipment was used to take continuous core to 1000 ft at Byrd Station for the IGY glaciological program. The use of a special constant rate of feed device for coring and improved techniques based on experience gained in Greenland resulted in further improvements in core condition and rate of recovery. In 1957-58 the Ross Ice Shelf was penetrated (840 ft) at Little America V with equally good results. One core taken with diesel fuel at the bottom of the ice shelf was remarkably free from the cracking which had previously resulted from the rapid release of overburden load in the air-filled hole. This strongly suggests that increased depths and much better core will be obtained if diesel fuel is used as the circulating fluid. Coring to depths of 10,000 ft should be possible with much heavier rotary drilling equipment and similar techniques, but logistic and other considerations suggest that the feasibility of a wire line method rather than drill pipe be investigated.

CONCLUSIONS

It has been demonstrated that good quality cores may be taken and open hole may be drilled to depths of nearly 1500 ft in cold polar glaciers using cold compressed air and other modifications of the conventional rotary drilling system. It is suggested that, if diesel fuel is used as the drilling fluid, core quality may be greatly improved and the depth limit of the equipment described may be extended by perhaps 25%. While coring to depths of 10,000 ft in ice could be accomplished by heavier rotary equipment, investigation of methods that eliminate the use of drill pipe is suggested.

LITERATURE CITED

ACFEL (1950) Development of ice mechanics test kit – Final report. U.S. Army Arctic Construction and Frost Effects Laboratory (USA ACFEL) Technical Report 25, 116 p. AD 712490.

ACFEL (1954) Investigation of construction and maintenance of airdromes on ice, 1954. Development of power ice coring rig. USA ACFEL Technical Report 46, 106 p. AD 712537.

ACFEL (1954) Investigation of construction and maintenance of airdromes on ice, 1953-1954. Project Mint Julep, Investigation of a smooth ice area of the Greenland Ice Cap, Pt. IV. USA ACFEL Technical Report 50, 77 p. AD 073243.

Bader, H., R.W. Waterhouse, J.K. Landauer, B.L. Hansen, J.A. Bender and T.R. Butkovich (1955) Excavations and installations at SIPRE test site, Site 2, Greenland. U.S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE) Technical Report 20, 32 p. AD 123155(d).

Bender, J.A. and A.J. Gow (1961) Deep core drilling in Antarctica. Symposium on Antarctic glaciology, General Assembly of Helsinki, International Association of Scientific Hydrology Publication 55, p. 132-141. [See also U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) Miscellaneous Paper 56.]

LITERATURE CITED (Cont'd)

Butkovich, T.R. (1954) Ultimate strength of ice. USA SIPRE Research Report 11, 12 p. AD 050514.

Butkovich, T.R. (1956) Strength studies of high-density snow. USA SIPRE Research Report 18, 19 p. AD 122665.

Calciati, M. (1945) Drilling on the Housand Glacier. *Boll. Comitato. Glaciol. Ital.*, vol. 23, p. 19-26.

Flusin, G. and C. Bernard (1909) Glacier drilling to great depths. *Etudes Glaciologiques*, vol. 1, p. 1-31 (French).

Hansen, B.L. and J.K. Landauer (1958) Some results of ice cap drill hole measurements. Symposium of Chamonix, *International Association of Scientific Hydrology Publication 47.*

Heuberger, J.C. (1954) *Greenland glaciology, Vol. I: Borehole studies on the ice cap.* Paris: Hermann & Cie, 64 p. (French with English and German summaries.)

Kasser, P. (1951) A light-weight thermal ice drill for preparing albation measurements on glaciers. *Verhandl. Scheiz. naturforsch Ges.*, vol. 131, p. 95-96 (German).

Langway, C.C., Jr. (1958) A 400-meter-deep ice core in Greenland, Preliminary report. *Journal of Glaciology*, vol. 3, no. 3, p. 216-217.

Mercanton, P.L. (1905) Glacier drilling. *Arch. Sci. Phys. Nat.*, Series 4, vol. 19, p. 367-379 (French).

Miller, M.M. (1954) Mechanical core drilling in firn and ice. With a report on Related Investigations in the Taku Glacier, 1950-53. Unpublished manuscript prepared for the E.J. Longyear Co., the Eastman Oil Well Survey Co., and the Geological Society of America.

Nizery, A. (1951) Electrothermic rig for the boring of glaciers. *Transactions of the American Geophysical Union*, vol. 32, p. 66-72.

Obert and Duval (1967) *Rock mechanics and the design of structures in rock.* New York: Wiley & Sons, p. 426.

Remenieras, M.G. and M.M. Terrier (1951) The electrothermic E.D.F. drill for glacier boring. Union of Geodesy and Geophysics, General Assembly of Brussels, *Proceedings of the International Association of Scientific Hydrology*, vol. 1, p. 254-260 (French).

Schytt, V. (1949) Re-freezing of the melt-water in the surface of glacier ice. *Geografiska Annaler*, vol. 31, p. 222-227.

Schytt, V. (1954) Glaciology in Queen Maud Land. Work of the Norwegian-British-Swedish Antarctic expedition. *Geographical Review*, vol. 44, p. 70-87.

Schytt, V. (1954) Report on glaciological investigations during the Norwegian-British-Swedish Antarctic expedition, 1949-1952. *International Association of Scientific Hydrology*, vol. 4, p. 236-243.

Schytt, V. and G. de. Q. Robin (1953) The Norwegian-British-Swedish Antarctic expedition, 1949-52. I: Summary of the glaciological work, preliminary report. II: Summary of seismic shooting investigations in Dronning Maud Land. *Journal of Glaciology*, vol. 2, p. 204-210.

Seligman, G. (1941) The structure of a temperate glacier. *Geographical Journal*, vol. 97, p. 295-317.

Ward, W.H. (1952) The glaciological studies of the Baffin Island expedition, 1950. Part III: Equipment and techniques. *Journal of Glaciology*, vol. 2, p. 115-121.

Ward, W.H. (1954) Studies in glacier physics on the Penny Ice Cap, Baffin Island, 1953. Part II: Portable ice boring equipment. *Journal of Glaciology*, vol. 2, p. 433-436.

The following handbooks were used and are recommended:

Rotary Drilling Handbook, by J.E. Brantly, Palmer Publications, New York, 1961.

Flow of Fluids through Valves, Fittings and Pipes, Crane Company, Technical Paper No. 410.

LITERATURE CITED (Cont'd)

Hydraulics in Rotary Drilling, Hughes Tool Company Bulletin No. 1-B, 1957.

Cameron Hydraulic Data, by Shaw and Loomis, Ingersoll-Rand Company, 1951.

Standards, Diamond Core Drill Manufacturing Assn., Bulletin No. 2.

Diamond Drill Handbook, by J.D. Cumming, J.K. Smit & Sons, Canada, 1951.

Sub-Surface Sampling for Engineering Purposes, by H.J. Hvorslev, Harvard University and Waterways Experiment Station, Vicksburg, Mississippi.

Compressed Air Handbook, Compressed Air and Gas Institute, 1947.

APPENDIX A: GLOSSARY

API:	American Petroleum Institute – designates standard dimensions, particularly of threads and tabular materials for the oil industry.
Breakout:	Loosening and disconnecting the threaded connections of drill pipe, casing, core barrel or any other threaded joints.
Breakout Table:	A device similar to a rotary table and powered by the rig engine which may be reversed in order to break out the joints of drill pipe more easily than by hand.
Bottom Discharge:	A principle of core bit design in which the fluid is discharged directly at the root of the bit teeth or directly to the cutting face and does not contact the core, as opposed to *internal discharge* in which the fluid stream is vented to the inside of the core barrel a short distance above the bit teeth. Bottom discharge is normally used to protect soft, weak or erodable core.
Casing:	Pipe used to line the hole in order to prevent collapse of the hole wall and to seal the wall against the loss of drilling fluid to permeable formations.
Chips (also cuttings):	Small particles cut by the bit from the material being drilled.
Chuck:	Similar to a lathe chuck and used to clamp the kelly in the drill head so that force upwards or downwards may be transmitted to the drill pipe while it is rotating.
Circulating fluid (also drilling fluid or drilling mud):	In this report includes compressed air and diesel fuel, pumped down the bore of the drill pipe and to the bit teeth, then returned to the surface in the drill pipe - bore hole annulus; serves principally to remove cuttings from the hole, and to clean and cool the bit.
Core Lifter:	A ring-shaped device fitted in the bottom of the inner tube through which the core slides as it is being cut by the core barrel. It engages the core at the end of the coring run to prevent the core from falling from the core barrel during hoisting.
DCDMA:	Diamond Core Drill Manufacturers Association, used to designate standards of design and dimensions in the diamond drill industry.

Drag Bit:	A steel bit which cuts by the scraping action of two or more hardened steel blades on the bottom of the hole.
Drawworks:	The hoisting winches and their prime movers of the rig; includes main hoist, sand line, cathead and brakes.
Drill Collar:	Weighted drill pipe, designed for maximum weight per unit length; used to keep the drill pipe in tension.
Drilling:	Includes drilling open hole and coring.
Drill pipe (also drilling shaft):	Pipe used to connect rig at surface with bit and other tools at bottom of hole. Serves to transmit rotation to bit, to hoist and lower bit and tools, and to transmit circulating fluid to bottom of hole. Called *drill rod* in diamond drill industry.
Drill string:	All of the tools which are suspended from the mast and rotated and lowered during drilling, i.e. drill pipe, drill collar, core barrel, sludge barrel, swivel, kelly and drilling and coring bits.
Elevators:	A hinged split ring with a spring loaded lock that will close over the drill pipe tubing but will not pass the tool joint shoulder; used for hoisting and lowering drill pipe and casing.
Hoist Plug:	A dummy plug, threaded to fit drill pipe or casing threads and suspended on a swivel used to hoist drill pipe or casing where an outside shoulder is not available for the use of elevators. Commonly used with diamond drill rod.
Kelly:	The uppermost piece of the drilling shaft, which is usually splined, square or hexed so that it may transmit rotation from the rotary to the drill pipe and at the same time be lowered or hoisted through the rotary table.
Makeup:	The threading on and tightening of drill pipe, casing etc.
Mud Pit (also slush pit):	A pit or tank of large cross;sectional area through which the circulating liquid is passed upon its exit from the top of the annulus of the hole. The resulting decrease in velocity causes cuttings to settle so that they may be removed from the fluid stream.
Mud Pump:	Used to pump any of the liquid drilling or circulating fluids.
Rock Bit (also rolling cutter bit):	A steel bit which breaks material from the bottom of the hole by the chipping action of hardened teeth mounted on two, three or four rollers or cones which "walk" on the bottom of the hole as the bit is turned; used in this project for open hole drilling only.

Rotary (also rotary table and drill head):	That part of the drill rig which transmits rotation to the kelly and drill string, essentially a ring and pinion gear.
Round Trip:(also trip):	The operation which consists of interrupting the drilling or coring, pulling the entire string from the hole, and replacing it in the hole, usually for the purpose of removing core from the barrel or replacing worn bit.
Run (also coring run):	The length or distance cored in one round trip of the core barrel; usually a distance slightly shorter than the capacity of the core barrel.
Slips:	Usually a pair of grips faced with hardened and pointed dies that, when set in a conical bowl at the surface, are used to hold the drill string while the elevators are removed from the drill pipe and returned to pick up the next length of pipe. Also used to hold casing and drill collar in similar manner.
Sludge Barrel:	An open-topped container located at the top of the core barrel or drill collar which collects cuttings too large to be lifted by the fluid stream. The uphole fluid velocity is sharply reduced at this point because of the abrupt increase in annular flow cross section from core barrel to drill pipe.
Substitute (also sub):	An adapter or connector for joining two parts of the drill or casing string, usually of unlike threads.
Tool Joint:	A coupling or collar threaded or welded to the ends of lengths of drill pipe to facilitate making connections. If joint has an outside shoulder it facilitates hoisting by means of elevators. See handbooks for drawings and dimensions of various types mentioned.
Underream:	To drill a hole of larger diameter starting below the surface from a hole of smaller diameter; must be accomplished by bit with expanding blades, i.e. underreamer.
Wing:	A blade of a drag bit.

APPENDIX B: TABULAR RESULTS OF ICE CORING, GREENLAND 1956

Run	*Depth finish* (ft)*	*Percent recovered*	*Quality*	*Run*	*Depth finish* (ft)*	*Percent recovered*	*Quality*
1	23.0	100	exc.	31	448.8	63	
2	34.5	96	good	32		Drag bit to clean hole	
3	44.9	100	exc.	33	470.1	77	good
4	54.9	75	good	34	488.7	78	good
5	62.9	75	good	35	502.0	74	fair
6	67.2			36	521.1	73	fair
7	77.0	100	exc.	37	540.1	79	poor
8	87.0	100	exc.	38	559.1	16	poor
9	97.0	Stuck tools lost core		39	578.1	59	poor
10	101.0	100		40	591.9	30	poor
11	110.2			41	610.7	90	poor
12	126.3			42	629.2	84	fair
13	140.7	95	exc.	43	648.2	89	fair
14	160.6	100	fair	44	667.2	83	good
15	181.2	50		45	686.2		good
16	191.8	100	good	46	705.3	99	good
17	211.6	100	fair	47	724.3	99	good
18	224.9		poor	48	743.4	91	good
19	243.6	89	good	49	762.4	89	fair
20	261.8	100	good	50	781.3	74	poor
21	281.7	48	good	51	800.3	25	poor
22	291.8	100		52	819.3		
23	311.8	100	good	53	838.3	90	good
24	331.0	100	good	54	851.3	74	poor
25	351.5	95	exc.	55	876.3	97	fair
26	370.1	70	poor	56	895.3	97	fair
27	389.5	29		57	914.3	84	fair
28	395.9	78	poor	58	933.3	97	good
29	411.9	89	fair	59	952.3	95	fair
30	429.8	92	good	60	971.3	43	poor

* Depth below rig floor at end of run.

APPENDIX C: ICE CORING OPERATIONAL DATA SHEET, SITE II, 1956

RUN	TIME		WEIGHT		DEPTH					AIR		CORE		
8/24	IN	2000	D.P.	5780	826.0	BIT	B-413C rebuilt mill tooth	RPM	80	PRESS	45-50	RUN	19.0	DESCRIBE CORE
8/25	BOTTOM	0900	C.B.	850	29.7			R.P.	3-5	TEMP	+13°	REC	18.4	Not so many regular cracks - irregular cracks spaced ½-3".
	START	0910	KELLY	300	+1.6	LIFT	Split ring modified	FEED	16-27	AMB.	+7°	%	97%	
55	FINISH	1012	TOTAL	6930	857.3							COND	Fair - Good	
	OUT	1125	FINISH		876.3									
	REMARKS: Best core yet at this depth.													
RUN	TIME		WEIGHT		DEPTH					AIR		CORE		
8/25	IN	1330	D.P.	6000	846.0	BIT	B-413C as above	RPM	40	PRESS	50	RUN	19.0	DESCRIBE CORE
56	BOTTOM	1440	C.B.	850	29.7			R.P.	4	TEMP	+13°	REC	18.5	A little better - some irregular cracks.
	START	1453	KELLY	300	+0.6	LIFT	Split ring modified	FEED	10	AMB.	+3°	%	97%	
	FINISH	1620	TOTAL	7150	876.3							COND	Fair - Good	
	OUT		FINISH		895.3									
	REMARKS: Down for 45 min. in middle of coring run - tried antifreeze on tool joints to keep ice out of threads - works well - need brake and hydraulic feed.													
RUN	TIME		WEIGHT		DEPTH					AIR		CORE		
8/26	IN	1230	D.P.	6150	866.0	BIT	B-413C as above	RPM	80	PRESS	50	RUN	19.0	DESCRIBE CORE
	BOTTOM	1330	C.B.	850	29.7			R.P.	8	TEMP	+12°	REC	16.0	Irregular cracks spaced 1-2"
57	START	1345	KELLY	300	-0.4	LIFT	Split ring modified	FEED	10	AMB.	+3°	%	84%	
	FINISH	1430	TOTAL	7300	895.3							COND	Fair - Good	
	OUT	1530	FINISH		914.3									
	REMARKS: Used brakes and hydraulic system in combination - worst core at top.													

D.P. = drill pipe; LIFT = core lifter; FEED = revolutions/inch; AIR PRESS = at rig; AMB. = ambient air temp (°F); C.B. = core barrel assembly; R.P. = rate of penetration (inches/min.); TEMP = °F; REC = length recovered.

EXPLANATION OF OPERATIONAL DRILLING LOG

Runs: numbered consecutively and include trips into the hole with drag and rock bits for cleaning the hole and drilling open hole.

Time:

In: the time of day when lowering of the string of tools was started. This and the following times were recorded as a time and motion study of sorts since the short season made the hoisting and lowering time required for the continuous coring critical.

Bottom: the time that the string reached the bottom of the hole.

Start: the starting time of the coring run.

Finish: time at the end of coring run; elapsed time from start to finish is actual time spent cutting core.

Out: time that drill pipe was all stacked and core barrel was ready for disassembly. Elapsed time between finish and out includes time spent setting core lifter and preparing to hoist core out of the hole.

Weight: Total weight of the string of tools was computed chiefly so that personnel would not lose an appreciation of the magnitude of the slowly accumulating weight of the drill string. Originally, the weight on the bit was to be taken by measuring the weight on the hoisting lines and subtracting the weight of the tools as calculated in this column, but the line scale proved to be unsatisfactory.

Depth: the length of the drill string in position to start coring, from the bit teeth to the breakout table.

Bit and *Lifter:* parts numbers were used where known.

RPM and *R.P.* (rate of penetration in in./min) and *Feed* (rev/in.): those values which prevailed during most of the run if they were varied during the run.

Air:

Temperature and *Pressure* were measured in a special receiver adjacent to the driller's position.

Ambient: refers to the ambient air temperature taken just in front of the air intake of the air-to air heat exchanger, i.e., the temperature of the coolant.

Core:

Run: difference between "total" and "finish" under the Depth column.

Recovered: actual length of core recovered. The length was estimated even if completely crushed.

"%" (recovered): recovered/run, expressed as %.

Condition: relative terms described on p. 14 are used (good, fair, etc.).

Describe core: the physical characteristics of the core that were thought to be pertinent to the drilling, i.e., the type and frequency of cracks, etc. Geologic features of the core were recorded and interpreted by another group.

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13. ABSTRACT
Rotary drilling equipment was modified and used to obtain cores from glaciers i Northwest Greenland, Byrd Station and Little America V, Antarctica. Using cold compressed air, specially designed bits and other modifications, cores were obtained to 1345 feet in Greenland, 1000 feet at Byrd Station and the Ross Ice Shelf was penetrated to a depth of 840 feet at Little America V. In all locations cracks in the core appeared with increasing frequency at depth due to the sudden release of the overburden load when the core was cut in the air-filled hole. Special equipment and techniques developed dealt with the problem with some success. It is suggested that better cores and greater depths may be obtained by using diesel fuel as the circulating medium. A wireline system instead of drill pipe is suggested for coring to 10,000 foot depths in polar glaciers.

14. KEY WORDS

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