CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 12

DIAMOND DRILLING IN PERMAFROST AT RESOLUTE BAY, NORTHWEST TERRITORIES

BY

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QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1955

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Peter C. Bremner

ABSTRACT

In the summer of 1948 a number of high-resistance ceramic thermometers were placed in shallow holes drilled in the permanently frozen ground at Resolute Bay (latitude 74° 41′ N, longitude 94° 54′ W). During the next year the temperature of the soil was measured daily by Department of Transport officers. The interest engendered by this work led to the suggestion that an attempt be made to drill deep holes and to place temperature-measuring elements at regular intervals to a depth of 1,000 feet. This project was carried out during the four summers of 1950-53, its object being to drill the holes and install thermometers in them. The reading of the thermometers, the determination of temperatures at various levels and the analysis of the results in terms of heat flow from the earth was to be undertaken by the Department of Transport in cooperation with Professor A. D. Misener at the University of Western Ontario.

The program was carried out under great difficulties. Because of transportation problems a relatively light drill was used and because of the low temperature of the ground the drilling water often froze in the hole and seized the rods, necessitating the use of hot water heated to an initial temperature of 190°F. Even this was not sufficient at depths in excess of 600 feet, for the water had cooled almost to the freezing point before it returned to the surface. The work was hampered by caving formations which could not be cased off because of the small size (1½ inches) of the hole being drilled. Due to all these difficulties it was necessary to be content with a maximum depth of 650 feet.

Although the original aim of the work was to drill at least one hole of 1,000 feet, the object of determining the temperature gradient at Resolute Bay was almost as well served by the 10 holes successfully completed from 5 to 650 feet in depth, and equipped with temperature elements at 5-foot intervals to 70 feet, at 10-foot intervals thence to 100 feet and at 50-foot intervals to the maximum of 650 feet.

Cores were taken at all depths to 100 feet and at approximately 50-foot intervals to 650 feet. Some of these cores have been submitted to the Geological Survey of Canada for examination, while the thermal properties of others are being studied at the University of Western Ontario in connection with the general analysis of the project.

INTRODUCTION

During the summer of 1948 the writer travelled to Resolute Bay to investigate the possibility of installing a seismograph station[1] there. In order to determine the depth to bedrock a small diamond drill was required. This, with an operator, was supplied by the Arctic Section of the Defence Research Board. Mr. Andrew Thomson of the Meteorological Division, Federal Department of Transport, suggested that it would be of interest to install soil thermometers in any holes drilled in order to study the temperature and its seasonal variations within the permanently frozen ground and he offered to supply the necessary temperature elements. Seven of these, together with a separate array to measure air temperatures were installed during the summer of 1948, and during the following year temperature observations were made by the staff of the weather station.

From this small beginning grew the program described in this paper. The initial proposal, first advanced by Mr. Thomson, was that 2 holes be drilled to depths of 100 feet and 1,000 feet respectively, and that multi-element temperature cables be installed in each. By comparing the temperature gradient extrapolated from the 100-foot hole

[1] Bremner, P. C., "The Dominion Observatory Seismic Station at Resolute Bay, Northwest Territories", *Publications of the Dominion Observatory*, Vol. XVI, No. 2, 1952.

with that actually observed at greater depths, it would be possible to ascertain whether the observed temperature gradient was a consequence of present day climatic conditions or whether there were effects remaining from a previous epoch, and to study the general question of heat loss from the earth's crust under Arctic conditions. The Dominion Observatory undertook to supply the drill and all necessary auxiliary equipment. The Meteorological Division of the Department of Transport, with some financial assistance from the United States Weather Bureau, hired the drilling personnel and arranged for their board and lodging at Resolute. The United States Weather Bureau also supplied the two multi-element temperature cables and numerous other items of equipment, besides arranging for the transportation of the original equipment to Resolute Bay. Subsequent delivery of equipment, including emergency transportation of supplies, was undertaken by the Air Transport Command, Royal Canadian Air Force. The Canadian Longyear Company supplied the drilling equipment and offered advice and special service far beyond their commercial obligation.

The program began during the summer of 1950 under the supervision of the writer, who was at Resolute Bay to install the seismograph station. What had been planned as a one-year program actually continued throughout the four summers of 1950-53 due to the extreme difficulty experienced in drilling in the permafrost. It was continued on the same co-operative basis as outlined above, with additional financial assistance during the final season through the Associate Committee on Soil and Snow Mechanics of the National Research Council. The original program had to be modified repeatedly because of the difficulties encountered, so that instead of the 2 holes originally proposed, 21 holes were drilled, the maximum depth at which a temperature measuring element was placed being 650 feet.

Part of the cores obtained in the course of the project were supplied to the Geological Survey of Canada and others were sent to Professor A. D. Misener of the Department of Physics, University of Western Ontario. Professor Misener has undertaken to report on the thermal properties of these cores and on the interpretation of the temperatures measured in the holes.

The present paper is limited to a description of the actual drilling, an analysis of the difficulties encountered and recommendations based on that analysis. It is hoped that the experience gained in drilling in permafrost will be of assistance to others who may have similar drilling problems.

DESCRIPTION OF EQUIPMENT

Drilling Equipment

Elementary Description

For the benefit of those not acquainted with diamond drilling techniques, a diagram of a drill is reproduced in Figure 1. The complete drilling rig consists of the drill with a tripod, bearing a sheave at its apex, mounted above it. A wire rope passes from the draw works of the drill up through the sheave in the tripod and may be used to raise or lower the drill rods.

The drill itself consists of four essential parts, an engine to supply power, a transmission to carry this power to the drilling head, the draw works already mentioned and the drilling head. The drilling head may be rotated, so that the hole may be drilled at any desired angle. The drill pipe, as indicated in the figure by a broken line, passes through the drill head, entering through the feed screw at the top and emerging through the chuck at the bottom. In lowering rods into the hole they are let down by means of the draw works until the bottom of the hole is reached; then a set screw in the chuck is tightened and the rotation of the chuck is so transmitted to the rods. The feed screw can be advanced as the hole is drilled.

The drill rod, which is hollow, terminates at its lower end in a bit—which may be either a core bit or a solid bit of one of several varieties—and at its upper end in a water swivel. Water is pumped through the swivel, down the drill rod, and out through holes in the bit, where it carries away the cuttings and forces them to the surface on the outside of the drill pipe. In discussing the equipment assembled for the project, the drilling rig, the drill rods, the pumping and the water heating equipment are described, the last named being of prime importance because of the freezing action of the permafrost.

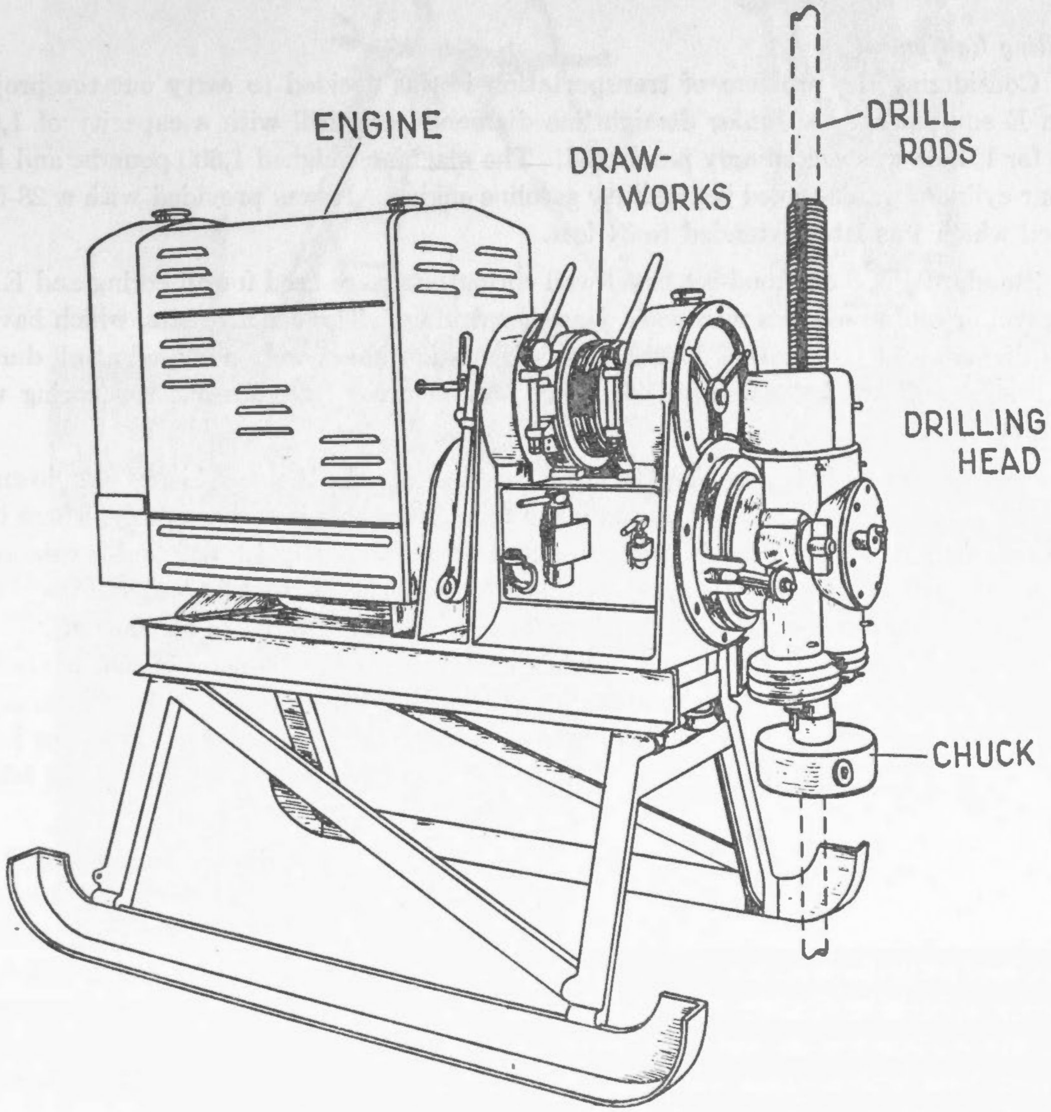

FIGURE 1.—Diamond core drill, screw feed advance. Rated at 1,000 feet of $1\frac{7}{8}''$ hole recovering $1\frac{5}{16}''$ core.

Equipment Designations

It is convenient in the following description to refer to equipment dimensions in the standard nomenclature. This nomenclature may be defined in terms of four casing sizes, designed to fit one inside the other. The smallest casing, designated EX, has an inside diameter of $1\frac{1}{2}$ inches, an outside diameter of $1\frac{13}{16}$ inches. The next size, AX, has an inside diameter of $1\frac{29}{32}$ inches, and an outside diameter of $2\frac{1}{4}$ inches. There are two larger sizes, BX and NX, with which we are not concerned. Other equipment is designated in terms of the casing through which it will pass. For example, an EX bit will pass through EX casing, an AX reaming shell will pass through AX casing.

The above designations are those of United States manufacturers. Canadian firms use the same casing sizes, so that Canadian tools will pass through the related casing size. For most other equipment Canadian specifications differ but slightly from those of United States manufacturers, but are distinguished by the addition of the letter T, as AXT and EXT. An EXT bit, either coring or bull-nosed, has an outside diameter of 1·460 inches.

Drilling Equipment

Considering the problem of transportation it was decided to carry out the project with E equipment. A Junior Straightline diamond core drill with a capacity of 1,000 feet for E hole was accordingly purchased. The machine weighed 1,600 pounds, and had a four-cylinder water-cooled heavy-duty gasoline engine. It was provided with a 28-foot tripod which was later extended to 34 feet.

Standard EXT diamond-set bevel-wall coring bits were used for all coring and EXT concave, or bull-nosed bits were used for other drilling. The concave bits, which have a solid diamond-set face except for the water-circulation holes, were not used at all during the first season, all holes being drilled for core. During later seasons less coring was attempted.

In taking cores it is necessary to use a core-barrel. As the core bit travels down, a cylindrical piece of rock passes into the inner tube of the core barrel assembly, where it is held from falling out by a small spring, called a core lifter. Rigid type, double tube core barrels of various lengths were used in the project. The circulating water flows down between the inner and outer tubes of these barrels and is delivered to the face of the bit through small holes at the lower end of the inner tube. As the diameter of the core barrel ($1\frac{1}{16}$ inches) is slightly greater than the diameter of the drill rods ($1\frac{5}{16}$ inches) it tends to restrict the return flow of water. Special core barrels were constructed, three feet long, with a spiral water groove cut along their length and these were used during the latter part of the project.

The initial pumping equipment purchased consisted of 2 duplex pumps, rated at 1,000 gals/hr., and driven by a 4-cycle $6\frac{1}{2}$ h.p. gasoline engine. It was intended that one of these would be used in drilling, the other to pump water to the drill site from a fresh-water lake some distance away. The pump units were not capable of delivering sufficient pressure when deep drilling was being done and higher capacity pumps were borrowed from the weather station and incorporated into the water system. The most important of these were 2 three-stage centrifugal pumps with a rated capacity of 200 gals/min. through a 300-foot head.

FIGURE 2.—Drill set-up showing tripod and two coil water heaters.

The water-heating equipment used during the first summer proved completely inadequate for the purpose. It consisted of a coil made from many lineal feet of copper tubing. This coil was set in an insulated jacket and mounted about 15 inches above a combustion chamber where it was heated by the hot exhaust gases. Fuel oil was delivered into the fire pot, the quantity being controlled by a carburetor similar to those used on commercial space heaters. The unit was rated to raise 300 gallons of water per hour through 50°F.

When the unit was new it delivered hot water at about the specified rate but after burning for half a day the temperature of the output dropped considerably. The decrease in efficiency was due to incomplete combustion of the fuel oil, which resulted in a layer of carbon about $\frac{1}{8}$ inch thick being deposited on the coil. All efforts to obtain complete combustion by increasing the draft and by preheating the fuel oil met with little success. The efficiency of the heater was increased by reducing the quantity of oil entering the fire-box but the overall heating effect was decreased because of the smaller fire. A better supply of hot water might have been forthcoming if it had been feasible to clean the coil while the fire was burning, but to reach the coil the stove had to be shut down and dismantled. Even after the carbon had been removed the coil was covered again within three hours.

The arrangement ultimately arrived at for heating water proved capable of raising 350 gals./hr. from 40°F up to 190°F. It consisted of 2 units working in series. The first unit was a coil heater, weighing about 350 pounds, constructed from a commercial type water-heater coil mounted in a 45-gallon drum lined with fire brick. The unit was fired with fuel oil and a strong draft was induced by a 16-foot smoke stack. The coil through which the water circulated was at the top of the combustion chamber where the flames could burn off any excess carbon which might deposit on the tubing. In addition, the draft stack could be removed readily to allow the operator to clean the coil with a wire brush. The second unit consisted of an oil-fired marine type boiler with an electric burner and thermostat controls. It weighed one ton, had dimensions 75 inches x 43$\frac{1}{4}$ inches x 34$\frac{1}{2}$ inches, and was rated to raise 410 gals./hr. through 100°F. Its performance was satisfactory, but considering its size and weight a series of the simpler heaters might have been more satisfactory.

Because of supply difficulties, troubles were anticipated as much as possible and duplicate parts and fishing tools of various sorts were ordered. The use of these is mentioned from time to time in another section.

Temperature Measuring Equipment

The temperature-measuring equipment supplied during the life of the project is listed in Table I, which also indicates the ultimate use made of the several cables. The hole numbers referred to are described in Table III in a later section.

TABLE I

Temperature Measuring Elements and Cables Supplied for the Project

Type of Element or Cable and Year Supplied	Element or Cable Designation	Supplier	Ultimate Use See Table III
1948			
Ceramic Resistance Thermometers	Elements No. 1-13	D. of T.*	See Table II
1950			
100 foot Multi-Element	No. 146	U.S.W.B.†	Hole No. 1
(Temperature measuring elements at 5 foot intervals from 0 feet to 70 feet and at 80 feet, 90 feet, 100 feet)			
1,000 foot Multi-Element	No. 147	U.S.W.B.	Hole No. 20
(Temperature measuring elements at 50 foot intervals from 150 feet to 1,000 feet)			
Ceramic Resistance Thermometers	No. 1	D. of T.	Hole No. 5
	No. 2	"	Hole No. 2
	No. 3	"	Hole No. 4
	No. 4	"	Hole No. 3
	No. 5	"	Surface
	No. 6	"	Hole No. 6
1951			
300 foot Single Element	No. 170	U.S.W.B.	Hole No. 9
500 foot Single Element	No. 171	"	Hole No. 14
1,000 foot Single Element		"	Accidentally destroyed while in storage
1953			
750 foot Single Element		U.S.W.B.	Hole No. 21

* Meteorological Division, Department of Transport, Canada.

† United States Weather Bureau.

ACCOUNT OF THE DRILLING OPERATIONS

At the time of the writer's first visit to Resolute Bay in the summer of 1948, the Meteorological Division, Department of Transport, supplied 13 high-resistance ceramic thermometers, numbered 1 to 13. In order to have a complete record in one place the disposal of these elements is listed in Table II, below, although these preliminary studies were not, properly speaking, part of the program described in this paper.

TABLE II

Temperature-Measuring Elements Installed in 1948

Element Number	Disposal
2	Mounted in a radiation shield on the radio antenna. Height 22 m.
3	Mounted in a radiation shield on the radio antenna. Height 11 m.
4	Mounted in a radiation shield on the radio antenna. Height 2 m.
5	Mounted in screen. Screen dry.
6	Mounted in screen. Screen wet.
7	Placed in disturbed soil in pit. Depth 42 cm.
8	Placed in disturbed soil in pit. Depth 85 cm.
9	At surface.
10	In drilled, uncased, hole. Depth 10 cm.
12	In drilled, uncased, hole. Depth 20 cm.
11	In drilled hole, cased with rubber garden hose. Depth 45 cm.
1	In drilled hole, cased with rubber garden hose. Depth 100 cm.
13	In drilled hole, cased with rubber garden hose. Depth 150 cm.

The sections that follow trace the progress of the drilling program throughout the four summers operations. This account seems necessary in order that the drilling techniques ultimately arrived at will be understood and their necessity appreciated. The information is summarized in Table III.

TABLE III

Hole No.	Year Drilled	Depth of Hole (feet)	Depth of Temperature Element (feet)	Type and Designation of Temperature Element	Core Recovery Range (feet)	Remarks
1	1950	103	100	100-feet Multi-Element	5—103	Surface casing, from 1 foot to 7 feet, could not be removed.
2		23	21½	Ceramic No. 2	6½— 23	
3		52	50½	Ceramic No. 4	6½— 50	
4		30	28	Ceramic No. 3	6½— 30	
5		11	10	Ceramic No. 1	6½— 11	
6		6	5	Ceramic No. 6	—	
7		130	—		7—130	Drill rods seized in hole due to freezing. Recovered 70 feet.
8		188			20—188	Hole abandoned at 188 feet because of close of season. Filled with pure anti-freeze and capped.
	1951				188—190	Hole was re-entered at start of 1951 season but rods became frozen in the hole. 60 feet of rods and 10 foot core barrel lost.
9		300	300	300-foot Single Element		
10		385				Drill rod seized when pump failed. 320 feet of rods and 10 foot core barrel lost.

TABLE III (*Concluded*)

Hole No.	Year Drilled	Depth of Hole (feet)	Depth of Temperature Element (feet)	Type and Designation of Temperature Element	Core Recovery Range (feet)	Remarks
11	1951	355				Hole abandoned because of cave. No loss of equipment.
12		385				Rods stuck, apparently due to sludge accumulated in the hole. 340 feet of rods and core bit lost.
13		300				Hole lost at 300 feet. 10 foot core barrel left in hole but all rod recovered.
14		450	450	500-foot Single Element		So much drill rod had been lost during the season that it was necessary to install element at 450 feet rather than the 500 feet proposed.
15	1952	682				Drill rods stuck by frost action. 300 feet of rods and 2 foot core barrel left in hole. Attempts to drill over rods with casing unsuccessful.
16		512				Drill rods stuck by frost action. 110 feet of rods lost. Attempt to free rods by drilling over them with casing discontinued when expansion of casing joints increased pump pressure dangerously.
17		662				Hole reamed to AXT whenever increasing pump pressure indicated poor circulation. Drill rods stuck by caving rock at 660 feet. Core barrel and 10 feet of rods lost. An additional 600 feet of rods were lost in attempting to fish core barrel.
18		740			5 ft.-10 ft. cores, at 50 ft. intervals, down to 600 feet.	Reaming technique continued. Failure of thread on rods resulted in loss of 265 feet of rods.
	1953					An attempt was made to fish these rods at the beginning of the 1953 season by washing over them with casing with left-hand thread. Efforts were defeated by repeated cave at a depth of about 200 feet.
19		687				Hole reamed at same time as it was drilled by mounting reamer above bit. Pressure built up at depth of 687 feet and in attempting to free rods a rod coupling was sheared, leaving 527 feet of rod and the reaming bit in the hole. 230 feet of rods were recovered by fishing.
20		675	650	Multi-Element No. 147		Same technique as Hole 19. Rods jammed at 675 feet and rod coupling sheared leaving 180 feet of rods in the hole. All but 20 feet of these were fished out and temperature cable was lowered to depth of 650 feet.
21		300	115			Hole drilled at angle of 45° under ocean. Depths indicated were measured along hole, not vertically.

Summer of 1950

Description of Work

The diamond drill and its accessories were sent to Resolute Bay by sea, arriving on August 20, 1950. By this time the seismograph station had been installed and the writer was free to devote most of his time to the drilling program.

During the next week a drill-shelter, 12 feet long, 9 feet wide, and 8 feet high, made from dunnage off the beach, was erected on a sled. The wooden shelter, which was later covered with tar paper, was designed to accommodate the drill, one water heater, and an oil-fired space heater. A 28-foot steel pipe tripod was set up for hoisting and lowering the rods and the remaining equipment was made ready for immediate operation. The 2 new water pumps and the new drill engine were carefully run in to avoid delay when the drillers arrived.

The two diamond drill operators arrived at Resolute on August 30. Work began at once on the problem of supplying water for use at the drill. As a continuous supply of hot water was required at a rate of 400 gallons per hour it was decided to pump the water to the drill from the fresh water lake 1,500 feet west of the station. A 1,500-foot line, made up of 25-foot lengths of flexible steel hose, was laid from the drill to the water pump, which was housed in a wooden shelter at the lake. This system delivered plenty of water but the day after it was started the weather turned cold and the water quickly froze in the steel hose.

To continue with this system meant either heating the water before it passed through the line or, alternately, heating the line. An attempt was made to do the latter by using an arc welder as the power supply for an electrical heater in which the steel pipe represented the heating coil. Though this idea proved quite successful when applied to individual lengths it could not be used over the whole line since rubber gaskets in the hose couplings insulated consecutive lengths from each other. It was decided to put a 1,000-gallon tank on a sled by the drill and keep the machine supplied with water hauled from the lake.

This system was satisfactory if the pump in the station water-wagon did not break down. The water was sucked from the 1,000-gallon tank by one of the two pumps located at the drill, and forced through the coil heater into a 50-gallon reservoir also located inside the drill shelter. The second pump took hot water from the reservoir and pushed it down the hole. A system of valves and lines enabled the operator to circulate water from the tank through the coil heater and back into the cold water reservoir if the drilling was stopped and the 50-gallon hot water tank was full.

With the problem of water supply solved, final adjustments were made at the drill set-up before beginning the first hole, which was to accommodate the 100-foot cable. On September 3, the hole was started. A 2½-inch pipe was driven down to bedrock, about 5½ feet below the surface, by thawing the ground with water and using a 350-lb. drive block. The overburden was frozen gravel and the rate of penetration through the last 18 inches was extremely slow due to the rock-like hardness of the permafrost Flush joint EX casing was drilled down 7 feet, and the drilling was commenced.

At the end of the second day the hole was down 68 feet. It was then pumped full of fuel oil and left over-night. The following morning the hole was frozen solidly to within 14 feet of the surface. Either the oil had not reached the bottom of the hole or the water had percolated down, displacing the lighter fuel oil. In the next shift the ice was re-drilled and the hole was continued to 103 feet, the extra 3 feet being allowed for ice which formed while the rods were being hoisted.

The hole was then deep enough to receive the 100-foot multi-element cable, but there was so much cave at regular intervals that cement was poured in to prevent further restrictions from forming. Though the cement mixture was very fluid and free of any lumps it only hardened in the first 15 to 20 feet of the hole. Next day the cement and ice were drilled out and the rods raised and lowered until the restrictions were cleared. After each run to clear the hole, 3 or 4 feet of new ice had to be re-drilled. The reel containing the temperature cable was mounted inside the shelter so that the unit could be quickly lowered. Before inserting the thermometer a brass weight was lowered on a strong line to determine whether or not the passage was open. After two trials with the weight, separated by delays in which the new ice was re-drilled, the cable was lowered.

Since the temperature elements were closely spaced from the surface down, it was most desirable to remove the 7 feet of casing. However, all attempts to do this failed. A steam jet thawed out the permafrost to bedrock and warm water even circulated out of the top of the rod. After this, pipe wrenches and even the force of the tractor fork-lift were applied but the casing had apparently become securely cemented in the rock. It was therefore cut off about 12 inches below the ground surface and the gravel carefully replaced to make the material over the elements as much like the undisturbed ground as possible. The 200-foot lead-in cable was encased in a wooden conduit which led from the drill hole into the administration building. Observations were begun at once to record the "settling" of the drill hole.

A similar drilling procedure was used to place the ceramic elements supplied by the Meteorological Division at depths of 0, 5, 10, 21½, 28, and 51½ feet. However, for these shallow holes the flush joint casing was successfully removed as follows: while the hole was still "warm" from the drilling, a pipe wrench was clamped on the casing and tied to a heavy rope leading over the tripod sheave wheel to the hoist drum. A second pipe wrench was used to rotate the casing while the hoist applied the necessary tension to pull the casing up over the thermometer cable. These elements were installed at the rate of one a day, and observations were started without delay.

The drilling arrangement was slightly altered before making a first attempt to drill the 1,000-foot hole. The tripod legs were increased from 28 to 34 feet, permitting the rods to be pulled and broken in 20-foot sections rather than 10 as had been done in the 100-foot hole. The 1,000-gallon tank and its associated pump were enclosed in a canvas shelter and all other equipment was checked before continuing the operation.

Following the usual procedure, a section of 2½-inch pipe was driven down 7 feet to bed rock with the aid of warm water and the 350-lb. driving hammer. The casing was then drilled down 20 feet to reduce the possibility of cave caused by the shattered condition of the surface layers. At the end of the shift the hole was down 40 feet, fuel oil was poured down the rods as they were raised and decoupled one at a time. Between shifts water percolated into the hole and by morning the cavity was frozen. The ice was drilled out and boring was continued to a depth of 90 feet. This time the hole was filled with a solution of anti-freeze and water in the ratio of 8 quarts of anti-freeze to 12 quarts of water.

This solution proved much more successful and at the beginning of the next shift the first 72 feet of the hole were clear, while the bottom 18 feet were slush. The rods were lowered, without hot water being circulated, as far as they would go. The core barrel became clogged with ice, making it necessary to hoist the rods at once. No difficulty was experienced in removing the rods and after the core barrel was changed they were let down a second time, being stopped every 30 feet or so to test whether or not water could be circulated. Drilling was then continued to a depth of 130 feet with no complications. Ice was now starting to form rapidly at the bottom of the hole during the time when the rods were being hoisted and the core barrels interchanged, but as yet the rods showed no tendency to freeze to the walls of the hole. The temperature of the drilling water was probably around 75°-85°F.

At 130 feet the hole was again filled with anti-freeze which, this time, kept it completely free of ice. The following morning a T-joint was put on the top of the casing to facilitate the recovery of the solution, as the supply of anti-freeze was limited. The rods were lowered to the bottom and the water swivel attached. Water circulation was not possible. The hoisting plug was quickly replaced, but unlike the previous occasion, the rods rose a foot or two and then became seized in the hole.

By the time the first three or four 10-foot lengths of rod had been removed with the rod spear, the rest of the string was frozen solidly in the hole and the spear was of no further use. It was decided to try to free the rods by drilling down over them with flush joint casing. This yielded good results until at 70 feet the joints of the casing began to spread and this procedure had to be abandoned. Some 60 feet of drill rod, a core barrel, and the diamond bit were left in the ground.

The second attempt to drill a 1,000-foot hole was abandoned when it became evident that deeper bore holes could be completed only if the drilling was continued day and night until the required depth was obtained. Filling the hole with anti-freeze and allowing it to stand overnight had resulted in delays and near losses of equipment, which could not be tolerated. As in the earlier drilling no severe difficulties were encountered in the first 100 feet or so. However, considerable time was wasted in drilling ice which formed each time the rods were hoisted to change a core barrel. At depths over 150 feet as much as 40 or 50 feet of hard ice was often drilled. This would take several hours as the drilling head was not equipped with high speed reaming gears which would have been ideal for boring ice. Had extremely hot water been available the rods could have been lowered more quickly without fear of freezing them in the ground.

Another serious delay occurred at the beginning of each shift, when the rods were let down after the hole had cooled for about 12 hours. As soon as the anti-freeze solution was forced out, the danger of frost seizing the rods was great. On several occasions the drilling tools were nearly frozen in the ground. Apparently the tendency of the rods to freeze is caused by the presence of ice crystals on the walls of the drill hole. When the rods are lowered after a small delay the core barrel pushes the frost ahead of it like a plough until ice blocks the circulating channel between the inside of the rod and the outside of the core tube. Finally, the quantity of slush ahead of the rods may become so great and tightly packed as to prevent the string from further descent. It is impossible to circulate water, consequently the rods must be hoisted. As the upward journey starts the remaining frost on the wall begins to gather around the guide ring on the core barrel, and perhaps in the narrow space between the core barrel and the wall of the hole. Quickly the friction increases, ice wedges against the core barrel, and the string seizes in the hole.

To combat this effect the technique was developed of lowering the rods through the drill head rather than simply lowering them from the tripod sheave and of attaching the water swivel and circulating hot water for thirty seconds or so after each rod was attached. However, this procedure was time-consuming and as much as a half of each day's working time had to be devoted to opening up the hole already drilled. It was decided to attempt to circulate hot water through the drill hole all night, but shortage of manpower made this unfeasible. Therefore the hole, which was 188 feet deep, was filled with pure anti-freeze and stopped with a metal cap.

Little difficulty was encountered in logging core for the 103-foot and 188-foot holes. Special boxes were provided for storing the samples, which were made up entirely of fossiliferous limestone. Near the surface only small pieces of core were recovered, but after reaching a depth of 100 feet, long unbroken pieces were obtained, indicating that the rock was more solid.

Analysis of the Summer's Difficulties

The measurement of soil temperatures made as a result of the first season's work revealed the cause of many of the drilling complications and suggested modifications of technique. The first 50 feet of frozen ground exhibit seasonal variations with temperature, but at a depth of 50 feet an unvarying temperature of $-13°\cdot5$ C. ($7°\cdot7$ F.) is found. This is believed to be the coldest ground temperature on record.

Because of these extreme temperatures a supply of more and hotter water was recognized as a necessity and it was also apparent that drilling should proceed on a 24-hour basis so that the hole would have no opportunity to cool off. To reduce the amount of time required in removing the rods it was decided that less core-drilling be attempted and that the effort be directed principally towards making hole rather than obtaining core.

Summer of 1951

Description of the Summer's Work

The difficulties experienced during the 1950 season suggested that it might not be practical to drill a single 1,000-foot hole and to insert the multi-element cable in it. The program was accordingly modified. It was agreed that efforts should be directed towards drilling holes to depths of 300 feet, 500 feet and 1,000 feet and to insert single-element cables in them. In this way something could be accomplished even if the 1,000-foot hole could not be completed.

The recommendation, based on 1950 experience, of 24-hour operation was met by sending sufficient drilling personnel to operate two 12-hour shifts. It had been recommended that a third man be available on each crew to service the pumps and heating equipment but this could not be arranged. The writer again supervised the project and was responsible for installing the temperature cable.

FIGURE 3.—Drill set-up showing location of the three water pumps, water heaters and the diamond drill.

The drilling crew arrived at Resolute on July 7. The new heating equipment, consisting of the coil heater and marine boiler already described were set up in an open line system between the 1,000-gallon cold water reservoir and the 50-gallon reservoir for hot water. This system reduced the danger of bursting hose lines and of injury to the drillers and did not require the use of pressurized hoses except for the swivel hoses leading from the pressure pumps to the drill rods. For depths up to 150 feet, only the marine boiler was used as water temperatures around 140° were sufficient to drive the frost back from the walls of the hole. At greater depths, or if delays were frequent, both heaters were used in series to produce water between 150° and 190°F.

The circulating system used during the second season proved very satisfactory and was not subsequently modified. The details are shown in Figure 4. It included a spare pump to be switched into the line if either the pressure or supply pump failed. The pressure pumps must be built to withstand the continual hot water and great stresses on the plungers. Water pressures at the face of the bit varied between 175 and 200 lbs. per square inch; in holes up to depths of 450 feet the rate of water flow was finally raised to between 300 and 450 gallons per hour.

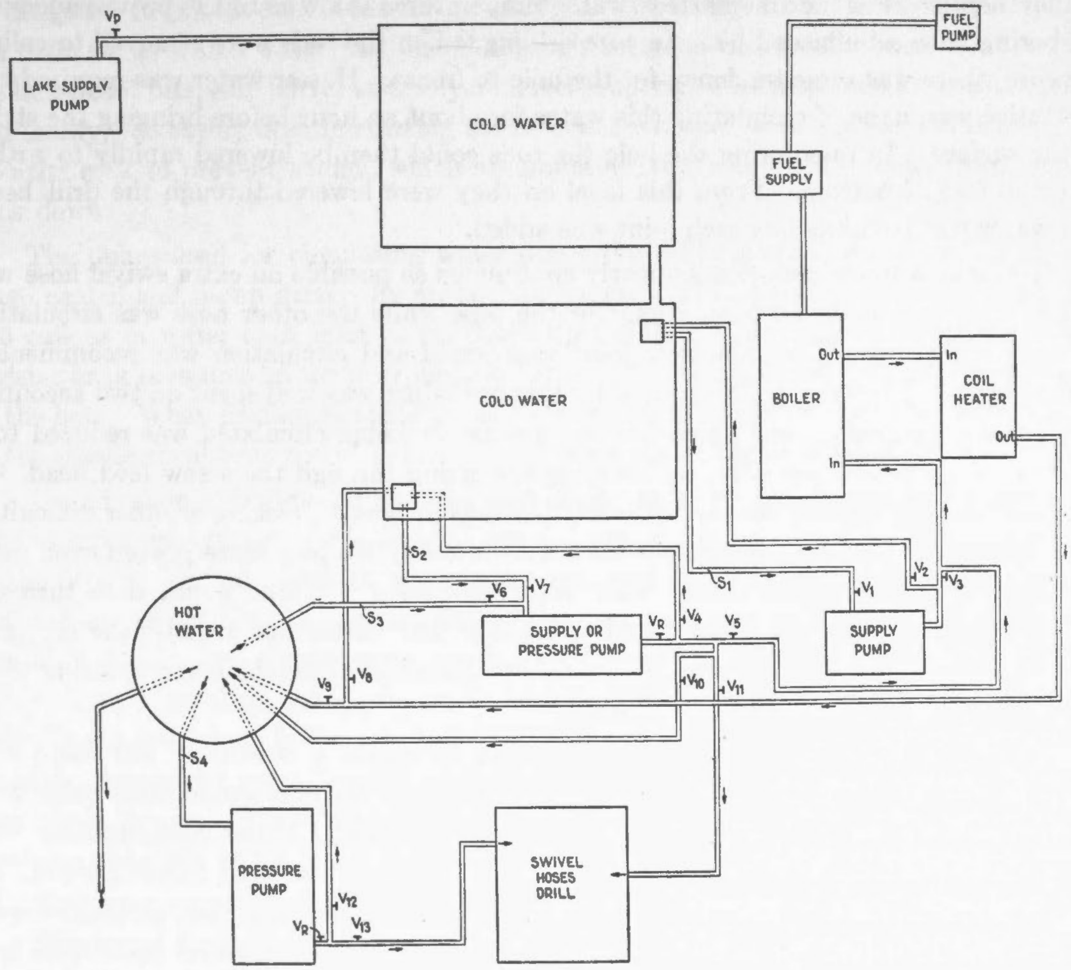

Figure 4.—Circulatory system for heating water and providing continuous flow through the drill hole.

A careful study of Figure 4 shows that each of the fifteen valves included play an important part in ensuring rapid and close control over the supply of hot water to the drill. Valves V_2 and V_3 on the output side of the supply pump together regulate the rate of flow through the heaters, ensuring that only the required volume of water is heated. When the rods are to be hoisted, and hot water is not required for several minutes, valves V_8, V_9 return the hot water to the 1,000-gallon reservoir, conserving water and heat. A similar system is used at the pressure pumps to regulate the pressure and rate of flow down the hole, and to re-claim the hot water when there is no flow through the rods. A third system of valves enables the spare pump to be used either for pressure or supply. On the intake side of this pump are two suctions, one for cold water the other for hot. On the output side, two separate sets of valves channel water through the heaters or through the swivel hose.

After a satisfactory heating unit and an efficient circulating system had been assembled drilling was commenced on a basis of 24-hour operation during the drilling of each hole. Although the 188 foot hole, which was left full of anti-freeze in October 1950 was lost, along with considerable drill rod, because the hole was re-entered too quickly, it soon became evident that the improved technique had eliminated permafrost complications at shallow depths. For the first 200 feet, water temperatures as low as 130°F. proved adequate for boring with a bullnosed bit. In core drilling, when the rods were removed to collect the core, there was some tendency for the hole to freeze. Hotter water was required and a practice was made of circulating this water for about an hour before bringing the string to the surface. In re-entering the hole the rods could then be lowered rapidly to within 50 or 60 feet of bottom. From this level on they were lowered through the drill head, and water was circulated as each joint was added.

To make water circulation as nearly continuous as possible an extra swivel hose was used. This was made up to one joint of the pipe while the other hose was circulating through the string. Then the new joint was added and circulation was recommenced immediately. The extra time required by this procedure was well spent on two accounts. Firstly, the interval during which hot water was not being circulated was reduced to a fraction of a minute; secondly, by lowering the string through the screw feed head, the machine could be used at once to withdraw the rods if signs of freezing or other difficulties were apparent. When complications were encountered, this procedure proved even more successful if the rods were turned with wrenches during the time required to turn the drill chuck down over the rods to permit another lift. Attempts to hoist the string as soon as difficulties were indicated, without first reversing the machine and rotating them back several feet, often met with failure.

About 48 hours of drilling were required to reach a depth of 300 feet with the bullnosed bit. After circulating hot water for 3 hours the first temperature cable with a single element was lowered and readings were commenced. Minor complications were encountered but none of these could be attributed to the permanently frozen ground.

Attempts to reach a depth of 500 feet were less successful and serious difficulties were encountered at depths around 350 feet. On four consecutive occasions holes were lost along with a total of 700 feet of drill rod at depths of 385 feet, 355 feet, 385 feet, and 300 feet respectively. For each of these runs the water temperature was never below, and was usually well above 140°F., showing that frost was not primarily, if at all, responsible for these delays.

Observations of rates of cooling already made in a shallower hole tended to support the opinion that frost was not to blame for the sudden and unpredictable loss of bore holes and equipment. Two other causes seemed probable, one that all the sludge was not being washed out of the hole, the other that the bit was mudding in natural sand deposits in the rock. Whatever the sources of trouble, it was manifested by an abrupt reduction in the amount of water passing through the rods, combined with a strong tendency for the rods to stick fast in the drill hole. In one instance the rods were recovered when these complications arose by applying the procedure described above; that is, the rods were rotated and raised by means of the swivel head until they were 3 or 4 feet off bottom. During the time the swivel head was being turned down the rods were held off bottom with the lifting bail and kept moving with pipe wrenches. After raising the string several feet, the hoisting equipment was used in the customary manner.

As a result of these additional complications three aspects of the operation were investigated to improve methods for removing all the sludge from the bore hole. First, the pressure at which water was forced through the rods was greatly increased; second, the bull-nosed bits, core barrel assembly, and rod couplings were inspected for constrictions; and finally, the casing used in starting the hole was wrapped with canvas and driven well into the rock to prevent sludge, which accumulated at the top of the hole, from seeping back down.

The pump used for circulating water down the drill rods was replaced by a three-stage centrifugal pump driven by an 80 h.p. engine. This machine could easily deliver 400 gallons of water each hour at pressures up to 300 lbs. per square inch. It did not register back pressures on the pumping mechanism, and thus did not indicate constrictions in the hole. When drilling at these pressures a flexible steel swivel hose was used in place of the standard rubber type which frequently burst under the additional strain.

Examination of bull-nosed bits, reaming shells, and core barrel back-end connections offered some opportunity for increasing the volume of water being circulated. The hole in the face of the bull-nosed bit was made larger and a second smaller hole was made in the wall of the bit near the cutting face. The water grooves in the bit were made considerably deeper and aligned with water grooves on the reaming shell. This system provided an alternative water passage if the face of the bit mudded, for then water could pass out the small hole in the side wall of the bit and keep hot water moving through the ground. Additional water grooves were cut in the reaming shells and the original groover was made deeper. The back-end connections for the core barrels were inspected for spurious materials which might prevent circulation but were otherwise unchanged.

The most important discovery arising from the inspection of the drilling apparatus was that few of the rod couplings were properly machined before leaving the manufacturer. The water passage in the standard E rod coupling measures 0·441 inches, inside diameter.

Those supplied in this case averaged only 0·370 inches. As there are 10 end couplings in each 100 feet of drill rod the reduced size of the water passage necessitates a considerable increase in water pressure to maintain a given rate of flow. The rod couplings were drilled out to have the correct inside diameter.

Efforts to set the casing firmly in the rock were only partly successful as the continual rod vibration soon worked the casing loose in the soft limestone. So long as the casing was tight, the return water appeared on surface, where it was passed through a sludge box enabling the solid material to be collected and removed from the top of the hole. However, when the casing worked loose an alternative path to surface was provided between the outside of the casing and the wall of the drill hole. Sludge collected at the top of the casing for it was filtered out as the water passed off through the gravel. Materials accumulating in this fashion might well seep back into the hole and cause complications at greater depths. A possible remedy for this is mentioned below.

Following these alterations another attempt was made to reach 500 feet. Water temperatures were closely watched and kept above 150°F. Checks on the rate of circulation revealed that, with water pressures kept at 200 lbs. per square inch, water was being circulated at close to 400 gallons an hour as compared with 150 gallons an hour for the previous shallow holes. Table IV relates water pressure, water temperature, and rate of circulation with depth for this hole. The increased circulation seemed to overcome all earlier difficulties and boring was continued to 450 feet, at which time a shortage of drill

TABLE IV

Depth of Bore Hole	Water Pressure	Rate of Circulation	Temp. of Water Entering Drill Rods	Temp. of Water Returning from Hole
feet	p.s.i.	g.p.h.	°F.	°F.
92	100	235	140	115
105	100	232	138	116
150	130	232	152	117
180	135	232	152	120
200	150	250	151	118
215	150	250	148	117
286	170	420	155	130
312	170	430	164	148
358	175	390	173	136
368	170	375	167	143
378	190	375	167	152
390	170	315	176	150
398	200	420	190	150
405	190	420	185	148
414	190	375	172	148
420	190	375	176	156
430	200	375	183	164
440	190	390	173	153
450	190	370	174	154

rods made it impossible to drill deeper. No complications were encountered and in all probability greater depths could have been reached. The temperature cable was installed at this depth and the operation was discontinued for the season on account of the shortage of equipment and because the time alloted for the operation was used up.

Analysis of the Summer's Difficulties

The second season's operations were reasonably successful. In anticipation of the fact that deeper holes would make increased demands on the pumping and water-heating equipment, the purchase of an additional coil heater and a new and stronger pump was recommended. It was also recommended that additional drilling personnel be hired to increase the efficiency of the 24-hour drilling program.

Summer of 1952

Description of the Summer's Work

A new coil heater and a pump capable of operating continuously at pressures of 300 to 400 lb. per square inch were acquired and shipped to Resolute Bay by air. Six men were hired to carry on the operation, working again under the direction of the writer.

The drill crew arrived at Resolute during the first week of July. When the machinery and water circulating systems were re-assembled as they were during the summer of 1951 (see Fig. 4) drilling was commenced, using the same methods which had proved so successful on the 450-foot hole. Two holes were lost due to frost at depths of 682 feet and 512 feet and thus a radical change in method was needed.

With each attempt at deep drilling high pressures were required to keep hot water moving through the drill hole. This is not unusual when drilling soft formations with E equipment, which allows only a small clearance for water passage. However, pressures up to 450 lb. per square inch were used over many shifts and this seemed excessive. In each instance the increase in pressure was accompanied by a decrease in the volume of water being circulated. It therefore seemed probable that the first step towards developing a successful technique might be to reduce this high pressure and to increase the volume of hot water being circulated through the drill hole.

Drilling began on the third hole with these ideas in view. When the pressure gauge on the circulating pump indicated 300 lb. per square inch the drill rods were pulled out of the hole. A pilot-reaming assembly was then sent down on the end of the E rods to ream the hole from a diameter of about $1\frac{1}{2}$ inches to $1\frac{7}{8}$ inches. The pilot-reaming assembly was made from a 24-inch AXT core barrel, complete with core bit and reaming shell, with a 3-foot length of E drill rod pinned inside the barrel and welded into the E-rod-to-AXT-barrel adapter. The short length of E rod preceding the AXT bit prevented the reaming assembly from wandering off the prepared hole. The results of reaming were immediately apparent. The pressure indicated at the circulating pump dropped from 300 lb. per square inch to about 150 lb. per square inch, while the volume of water being circulated was increased from 150 to 175 gallons per hour to around 300 to 350. This method was continued by drilling ahead 50 feet with a non-coring bit and then reaming the new ground with the AXT assembly.

Each section of hole was drilled twice when applying the reaming procedure, consequently the ground was exposed to the hot water for longer intervals before new and unheated ground was penetrated. Washing lasted from 1 to 2 hours before extracting the rods for reaming. Little time was devoted to washing the hole after the reaming bit reached bottom. At no time was ice encountered in the hole when re-lowering the rods, though circulation may have been discontinued for over an hour. So successful was the new method that core samples were taken over lengths from 5 to 10 feet at intervals of 50 feet, beginning at the 300-foot level and continuing down to 600 feet.

Just when fortune seemed to favour the completion of the third hole attempted in the 1952 season, the drill rods were seized by pieces of caving rock as they were being lowered to a depth of 660 feet. Attempts to free the rods by using the swivel head as a jack to raise and lower the rods, or by jarring them loose with the stand-pipe, were unsuccessful. A fourth hole was drilled to a depth of 740 feet using the reaming method. Then the threads on one of the drill rods stripped. The rods were hoisted to determine the reason for the sudden pressure drop indicated at the circulating pump. The decrease in pressure was, of course, associated with the rod fracture and 265 feet of drill rod remained in the hole. The season alloted to the project was over and the hole was abandoned.

Considerable time was spent attempting to fish rods from drill holes full of ice. It is interesting to note this change of outlook from previous years when holes and equipment were abandoned when rods were seized by the frost. However, the development of a successful drilling technique should include a satisfactory means of recovering equipment from the frozen ground. Late in the summer it became evident that rods and casing with left-hand threads were required to recover the right-hand equipment stuck in the drill holes.

At first it might seem that right-hand rods and adequate quantities of right-hand EX casing could be used to ream over the frozen E rods. As soon as the ice holding the rods was melted through the circulation of hot water, it should have been a simple matter to raise the string of rods. In practice, drilling with lengths of EX casing in excess of 50-75 feet is hazardous under the best of conditions as the casing is made from a thin wall tubing which spreads easily and bulges at the joints when subjected to strenuous usage. Occurrences of this kind must be avoided when drilling with hot water in frozen ground, as the expansion of the casing joints may cause a reduction in the volume of hot water being circulated through the hole, which in turn could mean the loss of the casing to frost.

However, 40- to 60-foot lengths of EX casing can be used successfully to thaw the top 4 or 5 drill rods. Drilling will not be required for more than the bottom 50 feet of the hole when the reaming procedure has been used. Left-hand rods with left-hand casing can, therefore, be employed to thaw, and turn off, from 1 to 6 of the top rods belonging to the frozen string. The cycle is repeated until the hole is clean and drilling can be recommenced.

Analysis of the Summer's Difficulties

The technique of reaming the hole to AXT size at regular intervals as drilling progressed allowed more water to be placed in contact with the formation and allowed it to be thawed more rapidly. This procedure apparently overcame the difficulties due to frost action, for the failure on the last two holes was due to equipment failure rather than to the freezing of the rods. The E equipment was proving to be too light for the difficult drilling being encountered.

It did not seem feasible to replace all the drilling equipment with the heavier A equipment, but still all the parties concerned were reluctant to abandon the project without a final effort.

Summer of 1953

Description of the Summer's Work

All the co-operating organizations were agreed that this would be the last season they would devote to the project. It was therefore decided that an effort would first be made to reopen the 740-foot hole and to fish out the drill pipe lost in it during the previous summer. If this were successful, a temperature-measuring element would be placed in the hole immediately, so that a limited objective could be accomplished. Only then would an attempt be made to drill to the 1,000 feet originally proposed. If the fishing operation were not successful, a hole would be drilled and a temperature element placed at any depth in excess of 600 feet at which difficulties threatened. Following this the 1,000-foot hole would be attempted if time permitted. Accordingly, equipment was assembled during the winter, and sent to Resolute in the spring airlift.

In preparation for the fishing operation a large amount of special fishing equipment was sent in, including AX flush-joint casing for washing over the drill pipe, a tapered rod tap, a tapered coupling tap, left-hand rod spears, outside or "bell" taps and bit and reaming shell taps. To prepare for the actual drilling, oversized diamond-set bits and reaming shells were ordered to bore holes of extra large diameter. It was hoped that the larger hole would relieve pump pressure. The dimensions of these oversize items as compared with their standard counterparts are shown in the following table:—

	Reaming Shell O.D. Inches	Bit O.D. Inches
Oversize diamond set Items........	1·550 ± ·005	1·535 ± ·005
Standard EXT diamond set Items..	1·485 ± ·005	1·460 ± ·005

The drilling party arrived by air on June 25. The party worked under the supervision of the writer.

When the drill and pumping and water-heating equipment was assembled and checked an attempt at the fishing operation was begun. A drill rod was cut off at an angle and used for washing out the 465 feet of ice above the rods frozen in the 740-foot hole. Washing progressed at the rate of 10 feet per hour to the top of the rods and was continued for 12 hours before attempting to lower the fishing tools. The fishing assembly consisted of 465 feet of left-hand rods terminated by a 10-foot length of left-hand casing with a left-hand rod tap threaded into the rod-to-casing adapter. After removing the rods used for washing, the left-hand equipment was lowered into the hole but was stopped by cave at 200 feet. When repeated drilling through the caved region failed to clear the hole the casing was replaced by a piece of ⅜-inch pipe, which was pinned to the leading end of the tapered rod tap. This small rod was no more successful in penetrating the cave than the casing. As quick setting cement had proved of little use and since there was insufficient casing to case the entire hole, fishing was abandoned in favor of drilling a new hole to 700 feet.

The drilling rig was moved 30 feet away in preparation for the drilling. The hole was collared with 7 feet of 2½-inch pipe seated on bedrock and 100 feet of AX casing. A device for drilling and reaming in one operation was made by coupling a 5-foot EXT core barrel in front of a 2-foot AXT barrel. The leading barrel was fitted with an EXT solid face bit and reaming shell, while the AXT barrel was fitted with an AXT core bit and AXT reaming shell. At depths greater than 500 feet, the EXT bit and reaming shell were replaced by the oversize diamond set items as an additional safety measure.

Drilling progressed smoothly to a depth of 687 feet. At this depth a marked increase was noted in the pressure required to circulate water through the hole, suggesting that the rods were not turning freely. The bit was run up and down through an 18-inch travel in an effort to free the rods and lower the water pressure. In the process of this operation a rod coupling was sheared, leaving 527 feet of "E" rod and the reaming bit in the hole. The fishing operation was started at once but after recovering 230 feet of rod, cave prevented successful continuation of the operation. There was no alternative but to start a new hole.

The second hole was drilled to 675 feet when similar trouble developed. After trying to reduce the water pressure by running the bit up and down in the hole, an attempt was made to hoist the rods, but they were jammed tight. The rods were turned back and 495 feet came free, leaving 180 feet of rod to fish. This time the hole was free from caving material and left-hand fishing tools were quickly brought on top of the rods. It required about one hour to wash a 10-foot length of casing over a frozen rod. The hole was then washed for an additional half-hour before seating the left-hand tap and backing off the top right-hand drill rod. When a rod coupling and drill rod were retrieved together, fishing progressed at the rate of 10 feet every two hours. On several occasions an extra trip was made to retrieve a rod coupling only. The necessity of making these extra trips might well have been avoided if each rod coupling had been pinned or welded to its respective rod. This procedure was repeated without mishap until the hole was 655 feet deep. At this time a 5-foot drill rod was used to carry a multi-element temperature cable down to 650 feet.

As the summer season was almost over and the possibility of drilling a 1,000-foot hole seemed remote, it was decided that the remaining time should be spent attempting to instal a temperature cable under the ocean. This was to be accomplished by drilling a 300-foot hole at an angle of 45° from a set-up 10 or 20 feet from the ocean. A standard EXT core barrel with oversize reaming shells and oversize solid face bits was used without the AXT barrel and with complete success. The clearance provided by the oversize bit and shell was adequate to permit the circulation of almost as much water as was previously used with the reaming assembly.

The hole was put down to 300 feet after 2 days drilling. When hoisting the rods a considerable quantity of cave was indicated over the lower two-thirds of the hole. These suspicions were confirmed when attempting to instal the temperature cable, which could not be worked down past 115 feet.

Analysis of the Summer's Difficulties

The pattern of difficulty in the 2 holes which were lost during the season was remarkably similar. In both cases pressure built up suddenly, and when an attempt was made to lift the rods they jammed in the hole and broke off. It is not clear how much of this difficulty was due to frost action and how much to the caving character of the formation. The temperature of the circulating water was probably close to freezing at the face of the bit so that a limit had about been reached for the use of hot water. It is difficult to be certain about this because the drill rods, which are being heated by the hot water flowing inside them, are in turn heating the water flowing back over their outer surfaces.

DISCUSSION AND CONCLUSIONS

In this section the difficulties encountered throughout the project are re-examined with a view to recommending a procedure which may help others contemplating similar work. These difficulties arise from the following basic problems:—

1. Frost action, with the consequent necessity of heating water.
2. Circulation difficulties.
3. Caving formations which mud the bit.
4. Failure of equipment.

Frost Action

This is the fundamental difficulty, and modifies all other problems. Aside from the difficulty of heating the water the use of hot water imposes a severe strain on the pumps, subjects the drillers to the danger of severe burns in the event of a hose failure, and prevents the efficient use of rod lubricants. This in turn results in excessive vibration of the rods with correspondingly excessive wear on equipment. Finally, the presence of the frost means that any small delays in the drilling operation, which are extremely difficult to avoid in practice, are likely to result in the freezing of the rods.

The heating system adopted at the beginning of the 1951 season, consisting of the commercial marine-type boiler plus a coil-heater operating in series, proved satisfactory, but was probably no more so than a series of 3 or 4 coil heaters would have been and was much more difficult to transport. When the coil heaters are designed so that they can be cleaned without dismantling the heater they give complete satisfaction. The duplicated pumping arrangement shown in Figure 4 proved satisfactory and is a necessity considering the difficulties which can result from even a brief failure of the pumping equipment.

The use of hot water in drilling as opposed to the use of chemicals in the drilling water (discussed later) works very well for the shallow holes. If water is circulated for some time prior to removing the rods the hole will remain ice-free long enough to allow minor repairs to the rig. This is borne out by an experiment conducted during the 1951 season. A hole was drilled to a depth of 115 feet with a bull-nosed bit in 9 hours, then washed with hot water for one hour. The rate of circulation was 150 gallons per hour, with water entering the rods at about 140°F. and coming back at about 130°F. At the end of this time a temperature element was lowered to the bottom of the hole and the temperatures shown in Table V were recorded. When the rods were returned to bottom, approximately one hour after circulation had stopped, 4 feet of ice had formed in the hole.

TABLE V

Depth of Thermometer in Drill Hole	Time Elapsed Since Circulation Stopped	Temperature in Drill Hole	Temperature in Undisturbed Ground
feet	minutes	°F.	°F.
115	10	60	8
	10¼	56	
	10½	54	
112	5½	67·8	8
	6	67·5	
	8	64·8	
	9½	62·5	
100	11½	58	8
	12	59	
	12½	58·5	
	13	58·2	
	14	57·3	
	15	56·8	
	16	55·7	
	17	55·0	
	18	54·2	
	19	53·4	
	20	52·7	
	21	51·9	
	22	51·3	
	23	50·6	
	24	50·0	
	25	49·2	
	26	48·8	
	27	48·1	
60	30	62·8	8
	31½	62·2	
	32	62·2	
40	33	63·1	10
20	34	65·0	13
	35	63·8	

The temperatures recorded at depths of 115 feet probably represent the trend of the thermometer towards an equilibrium temperature rather than an actual rate of cooling of the hole. Temperatures observed at 112 feet, five to ten minutes after circulation stopped will represent cooling, as will those recorded in the interval 11 to 30 minutes at 100 feet. It is evident that, if the water is circulated for a reasonable period after drilling has been stopped, there will be time to carry out minor repairs if the rods are raised several feet off bottom.

The use of hot water in drilling seems to reach a limit of applicability at about 600 or 700 feet, though the temperature of the water at the face of the bit could not be determined for the reason explained earlier. Conditions elsewhere, of course, may not be so severe as at Resolute Bay. The temperature of $-13°\cdot 5$C recorded at a depth of 50 feet is believed to be the lowest on record, and the temperature gradient obtained as indicated in a preliminary publication[1] suggested that the permafrost has a thickness in excess of 1,000 feet.

Until the middle of the final season it appeared that the use of hot water would provide a satisfactory solution for the frost problem, and for this reason no effort was made to use chemicals in the drilling water to lower its freezing point. Calcium chloride dissolved in the drilling water is being used in regions farther south with considerable success and there is no obvious reason why it might not be successful under more severe conditions. It does not crystalize out except at extremely high concentrations far above anything that would be required, nor does it stratify in a vertical column so that it would not freeze in the top of the hole. For ground temperatures observed at Resolute a concentration of about 1·8 pounds of calcium chloride to one gallon of water would be needed. In order to conserve chemicals, a closed water system with well-designed sludge boxes to remove the cuttings would be required, but this should not be difficult to construct.

Circulation Problems

Circulation problems, which were responsible for much of the difficulty encountered, derived largely from the use of the small E equipment. Difficulties were reduced considerably by reaming the hole to AXT size either after drilling or with a reamer above the bit, and by the use of over-size bits. These devices would have been largely unnecessary had the larger tools been used from the start.

Caving Problems

The mudding off of caving formations, a technique used in oil-well drilling, has only recently been adopted by Canadian diamond drillers. In this project, caving formations, combined with low temperatures provided the major difficulty at depths below 650 feet. Had it been possible to case these formations with AX, or even larger casing and to drill the remainder of the hole with E tools the project would have been simplified. However the original choice of E tools made this impossible.

Failure of Equipment

Most equipment problems arose from the use of hot water, which imposed a strain on the pumps and which, by dissolving the rod grease, resulted in excessive vibration. Actual failure of equipment would probably have been less serious had heavier A equipment been used.

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[1] A. Thomson and P. Bremner, *Nature, 170*, 705, 1952.

SUMMARY

Most of the difficulties met with were due to factors which might have been overcome by the use of larger equipment. Problems due solely to the permafrost were successfully overcome. The water heating and pumping arrangements devised were quite satisfactory. It is probable that for depths below 600 feet the use of chemicals in the drilling water would be necessary to overcome frost action.

The depths of the temperature measuring elements placed throughout the project are summarized in Table VI.

TABLE VI

Disposal of Temperature Elements, by Depth

Height	Depth	Element or Cable Number	Depth	Element or Cable Number
22 m.		1948–2	45 ft.	146
11 m.		1948–3	50 ft.	146, 147
2 m.		1948–4	50½ ft.	1950–4
	0	1948–9, 146, 1950–5, 147	55 ft.	146
	·10 m.	1948–10	60 ft.	146
	·20 m.	1948–12	65 ft.	146
	·42 m.*	1948–7	70 ft.	146
	·45 m.†	1948–11	80 ft.	146
	·85 m.*	1948–8	90 ft.	146
	1·0 m.†	1948–1	100 ft.	146, 147
	1·5 m.†	1948–13	150 ft.	147
	5 ft.	146, 1950–6	200 ft.	147
	10 ft.	146, 1950–1	250 ft.	147
	15 ft.	146	300 ft.	170, 147
	20 ft.	146	350 ft.	147
	21½ ft.	1950–2	400 ft.	147
	25 ft.	146	450 ft.	171, 147
	28 ft.	1950–3	500 ft.	147
	30 ft.	146	550 ft.	147
	35 ft.	146	600 ft.	147
	40 ft.	146	650 ft.	147

*In disturbed ground.
†In holes cased with garden hose.

ACKNOWLEDGMENTS

Acknowledgment is made to the United States Weather Bureau, Air Transport Command of Royal Canadian Air Force and Canadian Longyear Company for invaluable assistance, as well as to drill operators Victor Abel, Ambroise Menard, Harold Lafrange, John Duval, O'Brien Rivard, Lionel Anthier, Andre Sabourin, Paul Gauthier and Erle Kirkwood.