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ROTARY DRILLING AND CORING IN PERMAFROST. PART III. DEEP CORE DRILLING, CORE ANALYSIS AND BORE HOLE THERMOMETRY AT CAPE THOMPSON, ALASKA

G. Robert Lange, et al

Cold Regions Research and Engineering Laboratory

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CORPS OF ENGINEERS, U.S. ARMY
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13. ABSTRACT

Two holes were successfully drilled and cored to depths of 1000 ft and 1200 ft in the frozen mudstone of the Tiglukpuk formation at Cape Thompson, Alaska. Permafrost extends to a depth of approximately 1000 ft. The hole walls were successfully stabilized, even in zones of very weak rock, by the use of refrigerated diesel fuel as a drilling fluid, and frozen cores of good quality were taken with little difficulty. A thermistor cable was inserted in one of the holes and ground temperatures were measured to 1000 ft with a high order of accuracy and stability. Data required to predict accurate equilibrium temperatures were available one month following installation. The frozen cores were shipped to refrigerated laboratories where special methods of testing were developed for determination of some of their physical properties in the naturally frozen state. The total liquid content, as determined by oven drying, was found to be substantially greater than the water content as determined by Soxhlet extraction. It is inferred that water content determinations as normally carried out in the laboratory often do not indicate the original water content of the rock or soil samples obtained by core drilling with a liquid.

14. KEY WORDS

Cores
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PREFACE

This report was prepared by Mr. G. Robert Lange, Geologist, and Pvt. T.K. Smith, Northern Engineering Research Branch (Mr. William F. Quinn, Chief), Experimental Engineering Division (Mr. Kenneth A. Linell, Chief), U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

The drilling and coring reported here was carried out by the U.S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE) at Cape Thompson, Alaska, during the summer of 1960. The laboratory work was accomplished in the USA SIPRE laboratories at Wilmette, Illinois, during the following year.* USA SIPRE personnel returned to Cape Thompson during the summer of 1961 to retrieve the thermistor cable and accomplish some special drilling not covered in this report.

Mutual agreement between the U.S. Geological Survey, the U.S. Atomic Energy Commission and USA SIPRE resulted in letters and memoranda of understanding which authorized this liaison. The history of these is reported in greater detail below.

The senior author of this report, Mr. Lange, was project leader for USA SIPRE. Pvt. Smith, a geologist on active duty assigned to USA SIPRE, accomplished the laboratory work. Mr. W.K. Boyd, who was chief of the Applied Research Branch at the time, furnished overall supervision.

Except for the section on the USA SIPRE thermistor cable, this report has been published as a chapter in *The Environment of Cape Thompson Region, Alaska*, Willimovsky and Wolfe, Ed., U.S. Atomic Energy Commission, 1966.

The success of an exploration drilling program, particularly in remote locations, is strongly dependent upon the ingenuity and dedication of the drilling foremen and their crews. Much of the success of the drilling program reported here should be attributed to the following individuals: Messrs. Jack Tedrow (drilling foreman), Billy Harrington and Brooks Blair (drillers), Stanley Bennett, John Tompkins, Jr., Clay Vinson, Fred Hankinson and William Browne.

The senior author greatly appreciates the cooperation of Mr. Reuben Kachadoorian (who furnished a valuable critical review of this manuscript) and Dr. Arthur Lachenbruch of the USGS.

The assistance of Dr. Malcolm Mellor, Dr. Andrew Assur and Mr. James Smith, all of USA CRREL, with the analysis of the Soxhlet extraction data is also gratefully acknowledged. Technical review of the manuscript by Messrs. B. Lyle Hansen and Kenneth A. Linell (USA CRREL) was of considerable assistance to the authors.

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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.

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ROTARY DRILLING AND CORING IN PERMAFROST
Part III, Deep Core Drilling, Core Analysis and Bore Hole Thermometry at Cape Thompson, Alaska

by

G. Robert Lange and T.K. Smith

INTRODUCTION

Shortly after the explosion of atomic bombs at Hiroshima and Nagasaki, the Plowshare program was conceived and implemented by the U.S. Atomic Energy Commission to investigate peaceful uses for nuclear explosives. Project Chariot was a part of the Plowshare program. It was planned to detonate several nuclear explosives simultaneously beneath the surface of the shoreline near Cape Thompson, Alaska, to determine the feasibility of creating a harbor-like excavation on that remote and harborless coast (Fig. 1). An extensive study of the entire environment (meteorological, oceanographic, biological, geological, etc.) was made. The subsurface investigation reported here was a part of this broad environmental study.

Geologic and geophysical investigations preliminary to firing nuclear explosives at a considerable depth required that holes be drilled and/or cored to depths of approximately 1000 ft in rocks permanently frozen to about the same depth. Not only were samples desired for physical testing and lithologic description, but it was planned to make accurate measurements of the geothermal gradient (Lachenbruch 1965).

A competent drilling contractor was engaged to drill two holes during the summer of 1959. Using NC* continuous wireline coring equipment for most of the footage, he cored hole A (Fig. 2) to 598 ft and drilled and cored hole B to 1172 ft. The relatively warm water from Ogotoruk Creek was used as drilling fluid and no core was recovered in its original frozen condition. Further, the warm water thawed the ice which bonded fragments of the badly crushed rock comprising the Ogotoruk formation, causing the hole walls to cave. This in turn caused difficulties in inserting thermistor cables and damaged the cables after insertion. In addition, circulation of the warm water for drilling and the cementation of casing caused thermal disturbances which complicated the precise geothermometry program.

In 1954 USA SIPRE began conducting an investigation of methods of rotary drilling and coring in glacier ice and permafrost. The U.S. Army Engineer Waterways Experiment Station had been using chilled diesel fuel for coring in permafrost near Thule, Greenland (Hvorslev and Goode 1960). In 1958 experiments were initiated in permafrost with refrigerated drilling fluids. A refrigerator capable of cooling both diesel fuel and compressed air was used with a Failing Model 1500 drill rig to take cores of frozen silts and sands near Fairbanks during the summer of 1958. The following summer the same equipment was used in the same area to core frozen alluvial gravels. Some basic disadvantages of compressed air appeared during the 1958 trials, so that most of the work of the 1959 season was done with diesel fuel. This preliminary work demonstrated that the system offered

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* Approximately $3\frac{5}{8}$ in. hole × $2\frac{3}{4}$ in. core.

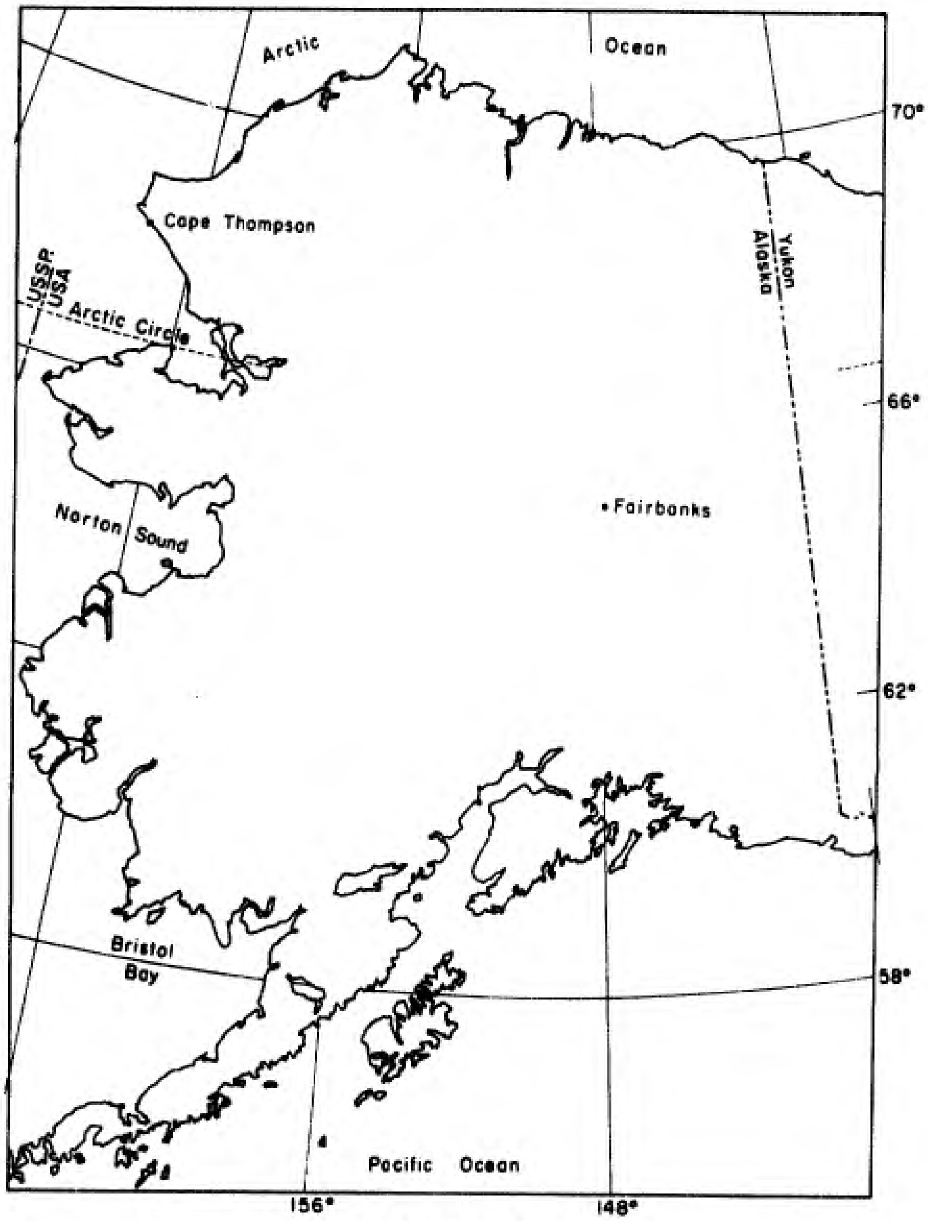

Figure 1. Map of Alaska.

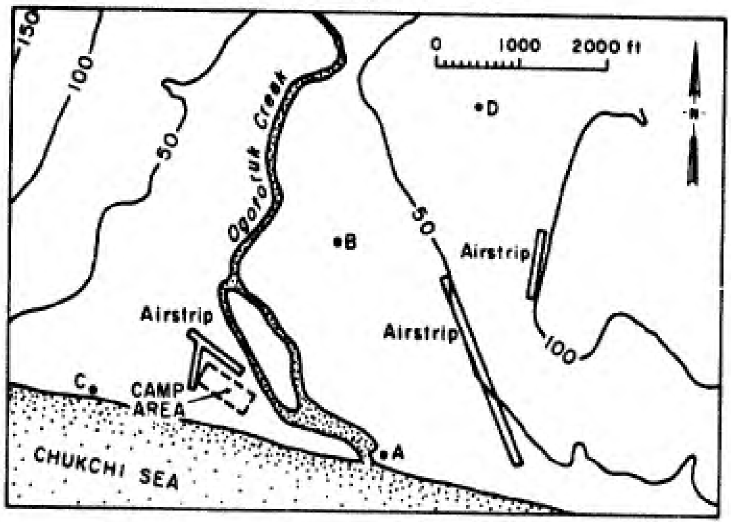

Figure 2. Site map showing location of holes A, B, C and D.

a method of obtaining thermally and mechanically undisturbed samples of any frozen earth material from any depth. However, the work had been of an experimental nature and had been confined to soils consolidated by ice and at relatively shallow depths. A deep hole in frozen rock was desirable as a good test of the operational capacity of the system.

Negotiations between *the U.S.* Geological Survey, the Atomic Energy Commission and USA SIPRE during the winter of 1959-60 resulted in an agreement between these organizations whereby USA SIPRE furnished drilling equipment and crew and the AEC, through its support contractor, Holmes and Narver, furnished camp and transportation support. USA SIPRE agreed to ship the frozen core to its refrigerated laboratory at Wilmette, Illinois, and share the core and laboratory investigations with the USGS.

In addition USA SIPRE wished to test thermistor cables and associated subsurface temperature measurement instruments. USA SIPRE and the USGS informally agreed to jointly calibrate a number of thermistors, and USA SIPRE inserted a thermistor cable in one hole (hole C) along with two cables prepared by the USGS. Data were exchanged by the two agencies in order to compare the two systems.

DRILLING AND CORING

Objectives

Two (possibly three) holes were required to depths of 1000-1200 ft in order to define the limits of the permafrost and to investigate the depth of influence of the projected blast. These holes were designated holes C and D (see Fig. 2). Continuous core would have been most desirable, but additional funds for continuous wireline coring equipment were not available, and it was considered feasible to drill open hole and core 10 ft of each 100 ft with the existing USA SIPRE core drilling equipment. Cores were to be taken in the original frozen condition and maintained in that state during shipment to the cold laboratory. Holes were to be kept open and free from caving walls so that the thermistor cables could be run in the holes without damage. It was also planned to develop special methods of testing applicable to frozen cores and a cold testing environment. USA SIPRE also desired to field test a bore hole thermistor cable and associated temperature measuring system.

Drilling plant design and operational plan

A hole diameter of $3\frac{7}{8}$ in. was chosen as compatible with readily available drilling and coring bit sizes and existing USA SIPRE equipment. A few feet of 4-in.-ID surface casing was set into bedrock. No casing was to be required during drilling since it was expected that the cold fluid would prevent the thawing of ice in the hole walls and resultant caving. NX ($3\frac{1}{2}$ in. OD) casing would be run in the hole upon completion of drilling in order to protect the thermistor cables. A most important requirement was that the existing pump and refrigerator should be capable of furnishing more than adequate up-hole velocity in this hole size.

Hughes and Reed type roller rock bits were used for the open hole drilling. Standard diamond coring bits to fit the $2\frac{3}{4} \times 3\frac{7}{8}$ DCDMA* double-tube, swivel-type core barrels were used. The bits were set with AA quality stones (10-14 per carat). Both internal and bottom discharge types were available and the core barrels were easily adapted to either type bit in the field. Duplicates of all drilling and coring bits and core barrels were available to insure completion of the work in case of failure or loss in the hole. Twenty feet of $3\frac{5}{8}$-in. drill collar was run just above the core barrel to improve the balance of the drilling string.

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* Diamond Core Drill Manufacturers Association.

The relatively new specification NW rods were used, as their 2⅝-in. OD used in the 3⅞-in. hole would provide an annulus sufficiently small to furnish more than adequate up-hole velocity. A larger hole size was considered in order to accommodate oilfield-type drill pipe with outside upset tool joints. Outside upset pipe joints are preferred because they allow much faster handling with elevators than the outside flush drill rod, which must be handled with a threaded hoisting plug. However, oilfield drill pipe with sufficiently small tool joints for adequate annular clearance was not available. A supply of 1400 ft of NW rod, in 20-ft lengths, allowed approximately 200 ft of replacement rods for wear, thread failure and possible losses.

The Failing Model 1500 SS drill rig is rated for 6-in. hole to 1500-ft depths and is mounted on a trailer with its own prime mover. An 80-hp gasoline engine drives the drill head with a 2⅞-in. × 28-ft splined kelly, and the double drum draw works is capable of a 15,000-lb pull including a sand reel with a capacity of 1600 ft of ⅜-in. wire line. The folding mast has a gross capacity of 40,000 lb, is 38 ft high, and has racking capacity for about 2000 ft of NW drill rod. It is also equipped with a power breakout table. A hydraulic crane scale served as a line scale for measuring the weight on the bit. A constant rate of feed, especially important for coring in homogeneous materials, is made available in the following way: the normally dead end of the main hoist line is stored on a truck winch which is driven by a small electric motor through a hydraulic transmission. Continuous speed ratios, from 1:1 to 100:1, can be obtained from the transmission. The line scale and constant rate feed device are shown in Figure 3. The entire rig was mounted on a semitrailer 8 ft wide by 24 ft long, equipped with triple axles and dual tires. Removable tracks that could be fitted over the tires and wrapped around all three axles and a dolly with tandem axles, similarly equipped with tracks, allowed mobility for tundra and beach. The rig is illustrated in Figure 4.

The skid-mounted pumping unit consisted of a 4½ × 5-in. duplex piston pump, with a capacity of 100 gal/min at 400 psi, driven by an 80-hp engine similar to the rig prime mover. A four-speed transmission provided pump speed control.

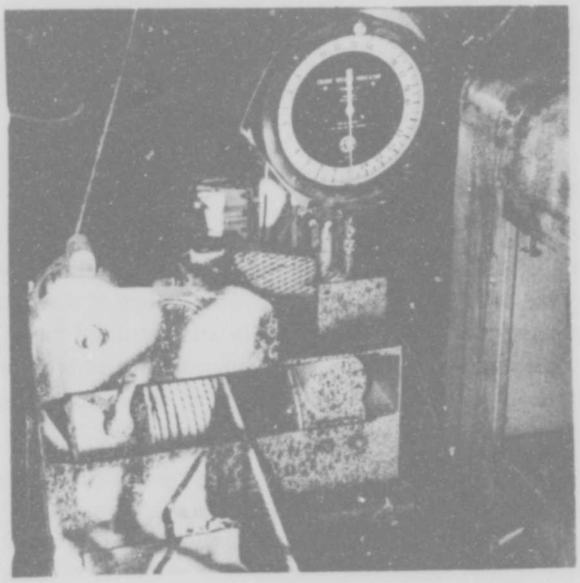

Figure 3. Constant rate feed device (lower left) and line scale (upper right).

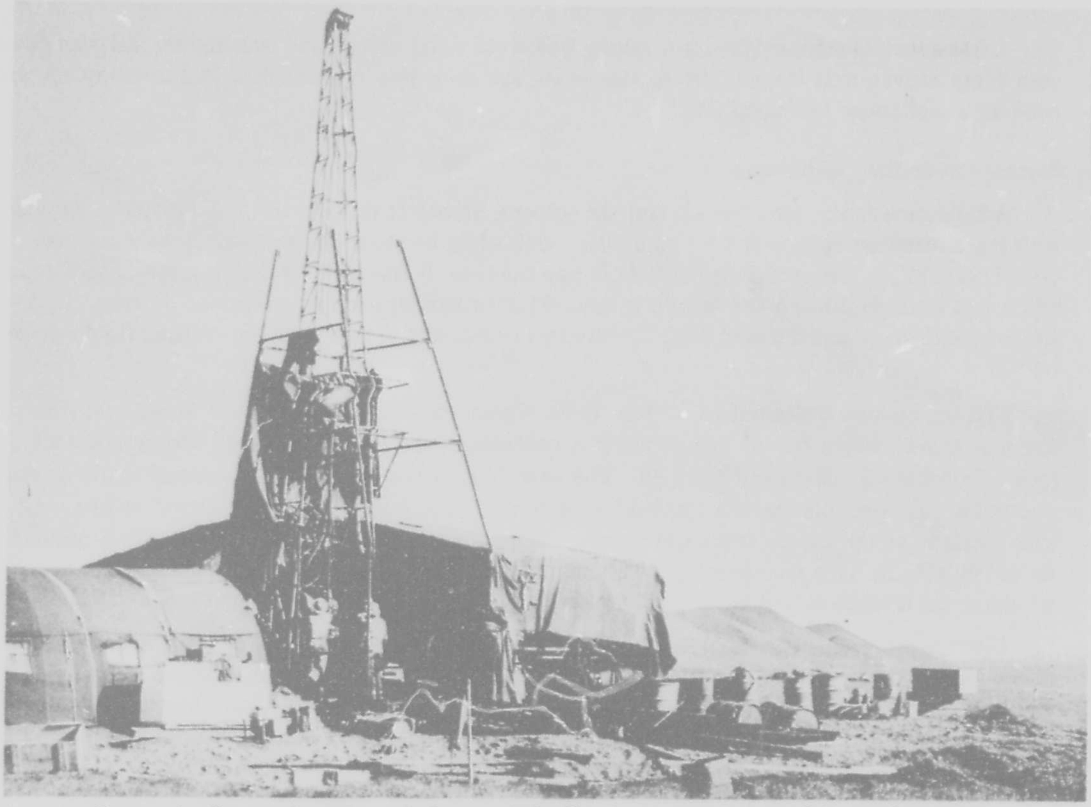

Figure 4. Rig enclosed by shelter on hole C. Jamesway hut used for tool storage and shop on the left.

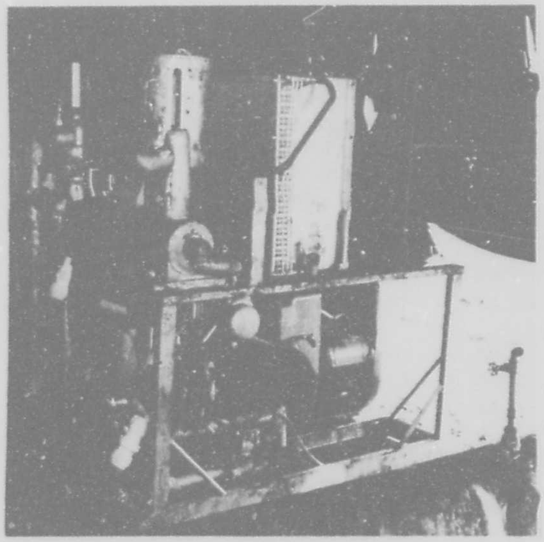

Figure 5. Portable drilling fluid refrigerator in place under rig shelter. Note brine inlet and outlet covered with frost at left.

The drilling fluid (diesel fuel) returning from the hole annulus passed through two steel settlement (i.e. "mud") *pits*. The pits, each 3.5 ft wide and 9 ft long, contained steel baffles. A small pump drove the recirculated diesel fuel from the pits through the tubes of a "shell and tube" heat exchanger. A flow of brine (ethylene glycol) circuiating in the insulated shell chilled the diesel fuel. The brine was cooled by a gasoline engine-driven Freon 12 compressor. At ambient temperatures up to +70°F this system could impose a temperature drop of 3°F on diesel fuel at a temperature of +18°F entering at a flow rate of 100 gpm. That is, it could remove 1060 BTU/min at this flow rate and temperature. After leaving the liquid chiller described above, the diesel fuel entered the main mud pump suction (at +15°F under design conditions) and was again pumped down the hole through the drill string. Figure 5 shows the refrigerator in the rig shelter.

Mechanical tools and equipment for maintenance and some repairs were provided, including gas welding and cutting equipment and a lightweight combination electric welder and generator.

A framework of lightweight steel tubing was made to fit around and over the rig and was covered with scrap canvas from the job site to shelter rig and crew from the weather. A Jamesway hut was used as a tool house and shop (Fig. 4).

Summary of drilling operations

A field supervisor, two drillers and six helpers arrived at the site on 30 June 1960. The barge with the drilling equipment arrived on 3 July. Unloading commenced immediately and was completed on 5 July. The gravel pad at hole D was ready on 6 July and the drill rig and associated equipment were positioned the following day. Rigging and piping was completed 14 July. Initiation of the drilling was delayed until 27 July by several difficulties with the drilling fluid refrigerator.

Drilling on hole D started on 27 July 1960. Continuous core of the 8 ft of frozen soil overburden was taken without casing and coring was continued 2 ft into the shattered frozen mudstone bedrock. This core is shown in Figure 6a. The first 16 ft of the hole was then reamed to 4¾ in. with a rock bit, and 4-in. casing was inserted to protect the collar of the hole. A strong casing seal was obtained as the casing froze to the rock. Thus normal cementing procedures, which release undesirable heat, were unnecessary. This surface casing served well without additional advance or cementing throughout the balance of the drilling.

Drilling proceeded at rates of up to 100 ft per shift (including the coring run), with two 12-hr shifts a day working 7 days a week. Coring runs were made with the 10-ft core barrel, generally at 100-ft intervals. A total of 87 ft of frozen rock and 8 ft of frozen soil core in generally good condition was taken. Table I summarizes the coring runs in hole D. The various grades of core condition (i.e. good, poor, etc.) are illustrated in Figure 6.

Table I. Project Chariot: Hole D coring summary.

Run no.	Date (1960)	Time	Depth* (ft)	Run (ft)	Recovery (ft)	Recovery (%)	Core condition and remarks
1	27 July	2250	1.2 - 5.8	4.6	4.6	100	Good – frozen soil
2	27	2345	5.8 - 10.4	4.6	4.6	100	Good – frozen soil
3	29	1020	100.0 - 107.2	7.2	7.2	100	Good – frozen mudstone – massive
4	30	0545	199.5 - 205.2	5.7	5.7	100	Good – frozen mudstone – massive
5	30	2200	296.0 - 300.0	4.0	4.0	100	Bottom 1.0 ft jammed in core catcher and thawed
6	30	2400	300.0 - 307.0	7.0	7.0	100	Good – all frozen
7	31	1300	400.2 - 408.9	8.7	0.0	0	Core lifter slipped – core drilled out to clean hole for next attempt
8	31	2000	412.8 - 418.5	6.3	3.7	58	Poor – gouge zone (?), barrel blocked
9	1 Aug	0540	500.0 - 502.8	2.8	1.0	36	Poor – core barrel blocked – 1 ft dropped and recovered in subsequent run
10	2	0030	502.8 - 510.3	7.5	7.0	92	Good
11	2	1400	601.4 - 605.5	4.1	4.1	100	Good – barrel blocked (?)
12	2	1940	605.5 - 612.8	7.3	6.9	94	Good but core fragile
13	3	1100	699.6 - 709.4	9.8	9.9	100	Good – 0.1-0.2 ft from previous run – rock bits losing gauge, core bits must be reamed into bottom
14	4	1030	801.6 - 811.4	9.8	9.8	100	Good
15	5	0445	899.9 - 906.8	6.9	6.9	100	Good – bit or barrel blocked – mud too thick (?)
16	6	2200	999.6 - 1002.3	2.4	2.4	100	Fair – good, barrel blocked
17	7	0330	1002.3 - 1010.3	8.0	8.0	100	Fair – good
18	7	1820	1099.2 - 1102.3	3.2	3.2	100	Good but barrel blocked
	8	1200	1200				Core barrel could not be inserted beyond 542 ft in attempt to core at 1200 ft, due to gauge loss in rock bits.
			Totals (rock and soil)	109.9	96.0	95 (avg)	

* Depths shown to top of casing – subtract 5.0 ft for depth from original ground surface.

Figure 6a. Core from hole D, 5.7-10.4 ft, showing the character of the surface of the bedrock at hole D. The interspaces between rock fragments are filled with frozen silt and ice. The run begins at 1.5 ft and the quality of the core is continuously good; the upper foot of core contains only silt and ice and the frequency of rock fragments increases with increasing depth. Strong vertical orientation of the rock fragments commences at about 4 ft.

Figure 6b. Core from hole C, 815-818.6 ft, showing poorest quality core. This condition was usually caused by core blocking in the core barrel due to the near vertical orientation and close spacing of the rock fractures.

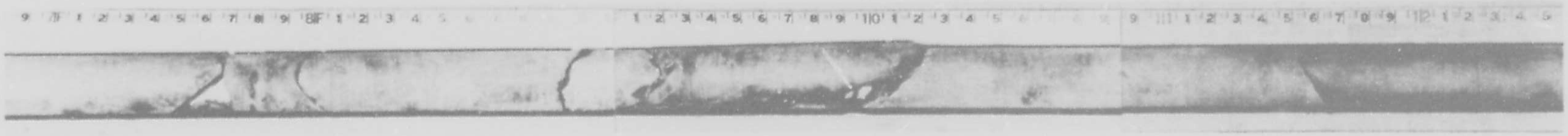

Figure 6c. Core from hole D, 996.9-1002.5 ft. Typically good quality core obtained from the more massive parts of the rock unit.

Figure 6d. Core from hole C, 196.7-202.3 ft. Typically good quality core obtained from the highly crushed zone. The darker streaks and shading are caused by diesel fuel which soaked into the core during drilling. A great deal of the diesel fuel was removed from the surface before these photographs were taken.

Hole D was completed at 1200 ft on 8 August; 1200 ft of NX casing was immediately run in the hole and two USGS thermistor strings were installed in the casing. The hole was left full of diesel fuel. The NX 3½-in.-OD casing string went easily into the hole, which had been drilled to a nominal 3⅞-in. with no evidence of caving of the hole walls.

Hole C was started on 16 August. Several unsuccessful attempts were made to core the unconsolidated (and unfrozen) beach gravels. The gravel may have originally been frozen and may have thawed during the preparations for drilling. The top of bedrock was encountered at 25 ft and 4-in. surface casing was set and frozen in the rock as in hole D. Drilling and coring operations were alternated in the same manner as in hole D. A total of 71 ft of frozen rock core was taken from 10-ft runs spaced at about 100-ft intervals. Hole size difficulties similar to those in hole D (see run 13, Table I) were encountered on the deeper coring runs. NX casing was run in the hole without difficulty. Table II summarizes coring runs made in hole C and hole C was completed at 892.8 ft T.D. on 30 August. Core condition is illustrated in Figure 6. One USA SIPRE and two USGS thermistor cables were inserted in the casing and the hole was left filled with fairly clean diesel fuel (Fig. 7).

Table II. Project Chariot: Hole C coring summary 1960.

Date	*Time*	*Depth* (ft)*	*Run (ft)*	*Recovery (ft)*	*Recovery (%)*	*Core condition and remarks*
16 Aug	1420	5.0 - 11.2	5.0	1.8	36	Poor – beach gravels – mostly thawed fluid lost to gravel
16	1530	11.2 - 13.2	2.0	0	0	Not frozen – Note: several more unsuccessful attempts were made to core thawed gravel and data are omitted
		(26.4-- top of bedrock)				
19	0900	27.9 - 30.2	2.3	0.9	39	Poor – badly shattered top of bedrock-– mudstone
19	1130	30.2 - 32.4	2.2	1.0	45	Poor – bit blocked
20	1700	112.0 - 114.6	2.6	2.6	100	Good but slight thawing as core blocked in inner tube
20	2230	114.6 - 120.0	5.4	5.4	100	Good
21	2245	199.9 - 208.6	8.7	8.6	99	Good
22	1200	300.7 - 308.9	8.2	7.3	89	Good
23	0245	412.8 - 416.4	3.6	3.6	100	Good – fair – actual recovery this run only 3.0; 0.6 picked up in next run
23	0600	416.4 - 421.4	5.0	5.0	100	Good – picked up 0.6 from previous run
26	0440	512.8 - 522.8	9.0	8.5	94	Good – had to ream core barrel down last 100 ft
26	1210	612.8 - 615.4	3.1	1.9	61	Poor – barrel blocked
27	0440	615.9 - 624.0	8.9	8.1	91	Ok (?)
28	0200	712.8 - 720.8	8.0	7.5	94	Good
28	1100	808.2 - 812.4	4.2	4.2	100	Poor to fair, bit blocked – 0.6 picked up next run
29	1200	820.0 - 822.7	2.7	2.7	100	Fair – bit blocked
30	0700	892.8 - 894.7	1.9	1.9	100	Poor – fair, bit blocked
		Totals (rock and soil)	82.8	71.0	86 (avg)	

* Depths shown to top of casing – subtract 5.0 ft for depth from original ground surface.

Figure 7. Inserting the three 1000-ft thermistor cables in hole C. The cables were laid out on the ground and "walked" in by six men.

Discussion of results

The core was recovered in the frozen state and the hole walls remained competent throughout the drilling of both holes, whereas drilling with warm water failed to accomplish this. This demonstrated the value of the refrigerated drilling fluid system for subsurface exploration in permafrost areas. Even for mineral exploration in the Arctic where physical properties of the core may not be important, refrigerated fluid could solve many troublesome and expensive caving problems. Since the fluid is circulated at close to the estimated ground temperature, the thermal disturbance due to drilling is greatly reduced. In programs where serious geothermometry is contemplated, chilled fluid offers the advantage of greatly reducing the time needed for temperatures to reach equilibrium (see page 13).

Selected samples of the core are shown in Figure 6. The core shown in Figure 6b was selected to generally represent the poorest core quality. Most of the core was of the quality shown in Figures 6c and 6d. Figure 6c is representative of the more massive zones and Figure 6d illustrates the appearance of the rock from the crushed zones. The photograph in Figure 6d was taken in a cold room at −10°C (as were all core photographs) and the rock appears to be fairly competent in the frozen state. However, when cores from the crushed zones were allowed to thaw, all cohesion between the small chips disappeared and the result was a completely incompetent pile of rock chips and powder. The competence of this rock unit, therefore, depends mostly upon the frozen condition of a very small amount of water in the rocks.

Figure 6a shows the lower portion of the core taken from the top of permafrost at 1.2 ft to a depth of 10.0 ft in hole D and illustrates the transition from the colluvial silts at the surface through frost-riven bedrock to sound bedrock.

The steel rock bits apparently suffered wear on the outer or gauge surfaces more rapidly than the diamond coring bits. This probably caused the troublesome reaming that was required when the diamond coring tools were inserted after the hole was advanced with the rock bits. The use of rock bits slightly larger than 3⅞ in. for the open hole drilling would have prevented this problem but would have required the use of 6-in. instead of 4-in. surface casing. The resulting enlargement of the annular uphole flow cross section was considered undesirable.

Approximately 6000 gal of diesel fuel was used in drilling the two holes because the very fine cuttings could not be separated out in the settling pits available. The fine grain size of the original sediment and breakdown of the original cementing agent of the rock by the diesel fuel are probably the principal causes of this. It is now felt that the filtrate loss (absorption of the oil by the rock) and consequent rock breakdown might have been reduced if greater quantities of Baragel (a viscosity additive) had been used in the diesel fuel. This might have resulted in larger chips which are more easily removed from the fluid system.

In coring any steeply dipping, highly fissile rocks, considerable difficulty is generally encountered as the core fractures at a high angle along the thin bedding planes in the core barrel, forming a cylindrical wedge that "blocks" the core barrel, causing the weight of the drill string to be transferred from the bit to the core. Premature "blocking" of the core before the end of the coring run occurred during many of the runs and often two or more round trips were required to obtain a reasonable amount of core from a single 100-ft interval. As "blocking" was expected because of the high dip, a chrome-plated inner tube was used in the core barrel to reduce the friction of the core on the inner tube as much as possible. No other solution to this problem is known at the present time.

SIPRE THERMISTOR – CABLE HOLE C

Introduction

The cable was constructed and calibrated and the bridge was designed and built under the supervision of the Measurement Systems Research Branch, Technical Services Division, USA SIPRE. Robertson, Raspet, Lillard and Schwartz (1966) initially described cable construction, circuit and bridge design and many other details of a subsurface temperature measurement system of a high order of accuracy and stability based upon the use of thermistors. The SIPRE cable in hole C was essentially similar to that described by Schwartz with the principal exception of the thermistor probes themselves. Small thermistors, hermetically sealed in glass, which are now generally available, were used in place of the larger, unsealed type described by Schwartz. Hansen (1963) describes the selection, aging and calibration of the thermistors used by USA SIPRE for geothermometry in the Antarctic; however, they were very similar to those used in the USA SIPRE cable. In that paper, he also described the special Wheatstone bridge* used for obtaining borehole temperatures in which 0.05°C is a significant absolute figure and 0.01°C is significant for gradient determinations. Lachenbruch et al. (1962) also describe thermistors, aging, calibration, cable construction and bridges currently in use by the USGS. The USGS system is derived from that described by Schwartz, except that they also use the small, new, sealed thermistors. A further exception to this is the USGS innovation consisting of enclosing the thermistor in pods sealed by threads and an O ring, allowing the thermistor to be retrieved for precise recalibration. The USGS bridge was used to collect the data presented below and it has the same accuracy as the SIPRE system described above (Lachenbruch 1962).

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* Designed at SIPRE independently of the simultaneous development of a similar system at the USGS.

Installation

The NX casing was cleaned on 1 September by circulating clean diesel fuel at temperatures between -5.0 and -10.0°C. *This* precaution minimized the possibility of cuttings settling back down the casing and jamming the cables in the casing.

The SIPRE cable was laid out on flat ground and taped to the USGS cables. The bundle of three cables was led over an improvised sheave and inserted in the casing.(Fig. 7). Just prior to installation a puncture was discovered in the sheath of the SIPRE cable at 955 ft; it was repaired in the field with Scotchcast, a catalytic insulating compound.

Results

The cable was read with the USGS bridge (ref. above) approximately 2½ hours after installation on 2 September 1960. During these observations null readings were difficult to obtain, apparently because of rapidly changing temperatures at the thermistor sites. The cable was also read by USGS personnel on 3 and 4 September. After USGS and SIPRE crews left the site at the end of the season the cables were read at intervals of approximately one month during the winter by William Lyons of Holmes and Narver. Monthly readings were continued until 13 July 1961 when the cable was removed from the hole and shipped to the laboratory for an ice bath check of each thermistor pod.

The resistance values read in the field were reduced to temperature by use of the computer generated table described by Hansen (1963). These data are given in Table III. Figure 8 shows these temperatures (θ_t) plotted against the time ($t - s$), in days, since the end of the thermal disturbance caused by the drilling, where t is the time from the arrival of the drill bit at the depth in question and s is the duration of the thermal disturbance at that depth. Thermistor 10 at a depth of 678 ft has always shown an open circuit which could have been cut when the cable was punctured just prior to installation. The balance of the data appear valid, well within the observational error except the reading of 7 May 1961 at the 175-ft depth. Since data taken on the same date from thermistors at depths above and below appear consistent, and data taken on previous and subsequent dates from that depth also appear consistent, this single reading is deemed questionable and is indicated by dashed lines in Figure 8.

Table III. Project Chariot: USA SIPRE thermistor readings (°C), hole C.

Cable installed 2 September 1960, removed from hole 15 July 1961 and shipped to laboratory.

			1960						*1961*					
Date drilled	*Therm. no.*	*Depth (ft)*	*2 Sep*	*3 Sep*	*4 Sep*	*2 Oct*	*7 Nov*	*11 Dec*	*18 Jan*	*26 Feb*	*2 Apr*	*7 May*	*5 June*	*13 July*
20 Aug	1	75	-4.78	-5.05	-5.07	-5.12	-5.15	-5.16	-5.12	-5.30	-5.38	-5.37	-5.30	-5.27
20	3	125	-4.50	-4.72	-4.72	-4.75	-4.73	-4.73	-4.74	-4.75	-4.75	-4.72	-4.72	-4.76
21	14	175	-4.32	-4.44	-4.42	-4.42	-4.45	-4.44	-4.45	-4.48	-4.41	-4.77	-4.50	-4.48
21	4	275	-3.77	-3.79	-3.76	-3.64	-3.64	-3.62	-3.63	-3.62	-3.63	-3.64	-3.65	-3.67
23	5	376	-3.20	-3.20	-3.18	-3.08	-3.07	-3.05	-3.05	-3.05	-3.04	-3.05	-3.07	-3.05
25	6	476	-2.76	-2.72	-2.68	-2.53	-2.51	-2.51	-2.51	-2.50	-2.50	-2.51	-2.51	-2.51
26	9	577	-2.20	-2.15	-2.11	-1.96	-1.94	-1.94	-1.94	-1.94	-1.93	-1.93	-1.94	-1.94
27	10	678	open circuit											
28	17	778	-1.26	-1.17	-1.10	-0.93	-0.90	-0.90	-0.90	-0.90	-0.89	-0.90	-0.90	-0.90
29	18	878	-0.63	-0.53	-0.47	-0.34	-0.33	-0.33	-0.33	-0.33	-0.33	-0.33	-0.33	-0.33
31	20	979	+0.06	+0.12	+0.15	+0.23	+0.23	+0.24	+0.23	+0.24	+0.24	+0.24	+0.24	+0.23

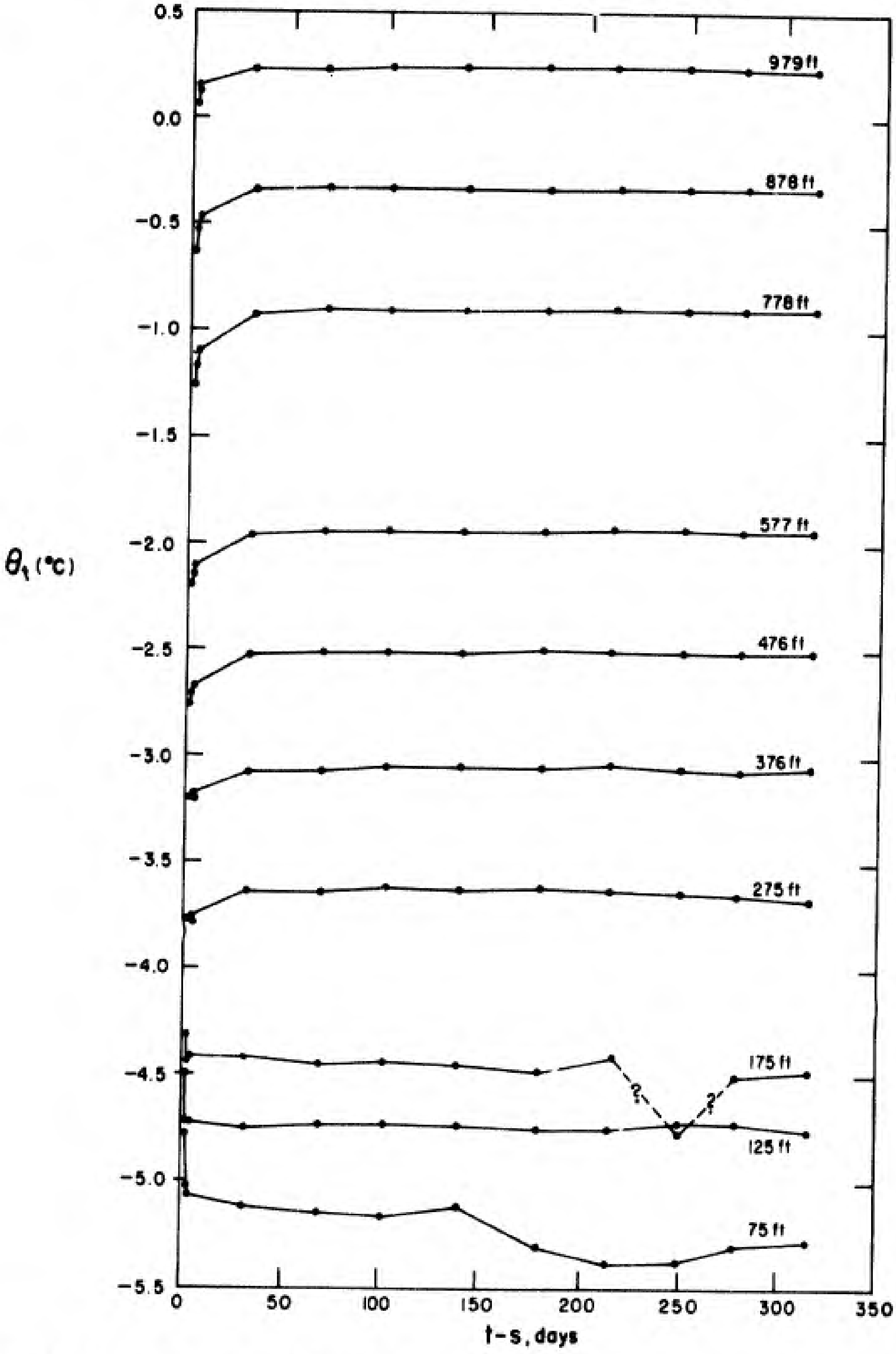

Figure 8. Cooling curves, USA SIPRE thermistors, hole C. Temperature, θ_t, vs time since cessation of thermal disturbance due to drilling, $t - s$.

Cooling of the borehole to equilibrium ground temperature

Previous temperature measurements in holes A and B gave a rough indication of the expected ground temperatures at depth. To minimize the thermal disturbance due to the circulation of the drilling fluid an attempt was made during the drilling of holes C and D to control the temperature of the circulating fluid to within a range approximately matching the expected subsurface temperatures at depth. Figure 8 indicates that during the drilling of hole C the effective borehole wall temperature was maintained in the neighborhood of -4.0°C. Because the temperature can only be controlled at one point in the circulation cycle, a single compromise temperature must be chosen which (hopefully) will split the expected subsurface temperature range. Thus, at depths where the undisturbed ground temperature is warmer than the selected drilling fluid temperature, the temperature of the borehole wall and fluid will increase with time as the equilibrium temperature is approached. The reverse will occur where the initial ground temperature is colder than the fluid. This effect is illustrated in Figure 8.

Inspection of the drilling records indicates that the drilling fluid was circulated at about 50 gal/min at temperatures that ranged between extremes of -3.0 and -9.0°C, and the mean effective temperature appears to be about -6.0°C. The difference between the temperature of the fluid flowing into the drill string and the temperature of the fluid returning at the annulus was generally observed to be 0.5 to 1°C.

Lachenbruch and Brewer (1959) discussed the dissipation of the thermal disturbance due to drilling in a borehole in considerable detail and from a theoretical and practical basis. Based upon earlier work by Bullard (1947), they use the following equation to predict the equilibrium temperature:

$$\theta_t - \theta_0 = \frac{q}{4\pi k} \ln \frac{t}{t-s} \qquad t > s$$

where:

θ_t = temperature at time t (°C)
θ_0 = equilibrium temperature, $t = \infty$ (°C)
q = rate of heat released (cal sec^{-1})
k = thermal conductivity of wall rock (cal $\text{sec}^{-1}\ \text{cm}^{-1}\ {}^\circ\text{C}^{-1}$)
t = time since bit reached depth under consideration (days)
s = duration of drilling disturbance at that depth (days).

However, for convenience of graphic analysis and where the time of the drilling disturbance is very short, let

$$\frac{q}{4\pi k} = -A, \text{ a constant at any one depth}$$

$$\theta_t - \theta_0 = A \ln \frac{t-s}{t}$$

Thus, to obtain θ_0, the log of $t - s/t$ is plotted against θ_t as shown in Figure 9. Equilibrium values obtained from this graphical analysis are given at the right hand side of Figure 9.

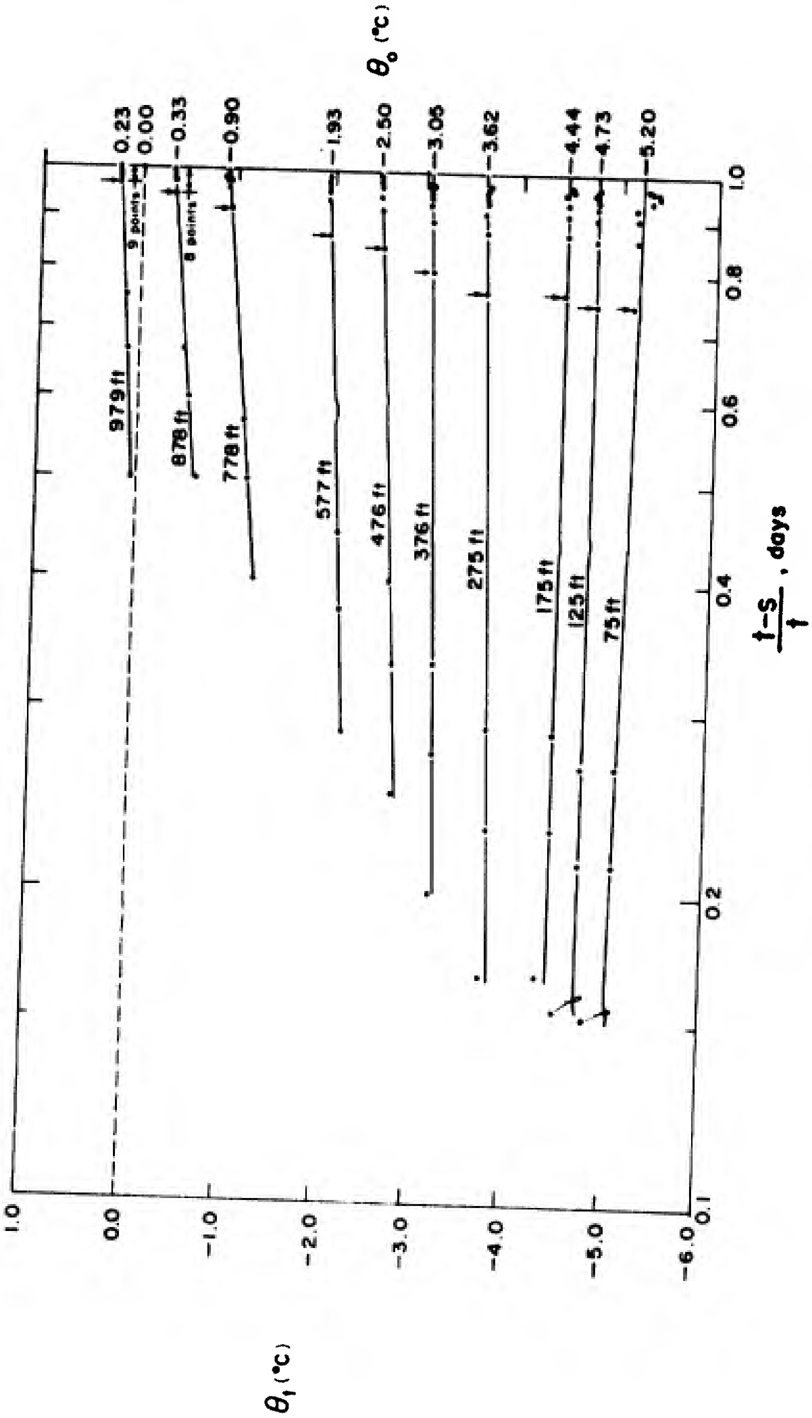

Figure 9. SIPRE thermistors, hole C, Project Chariot.

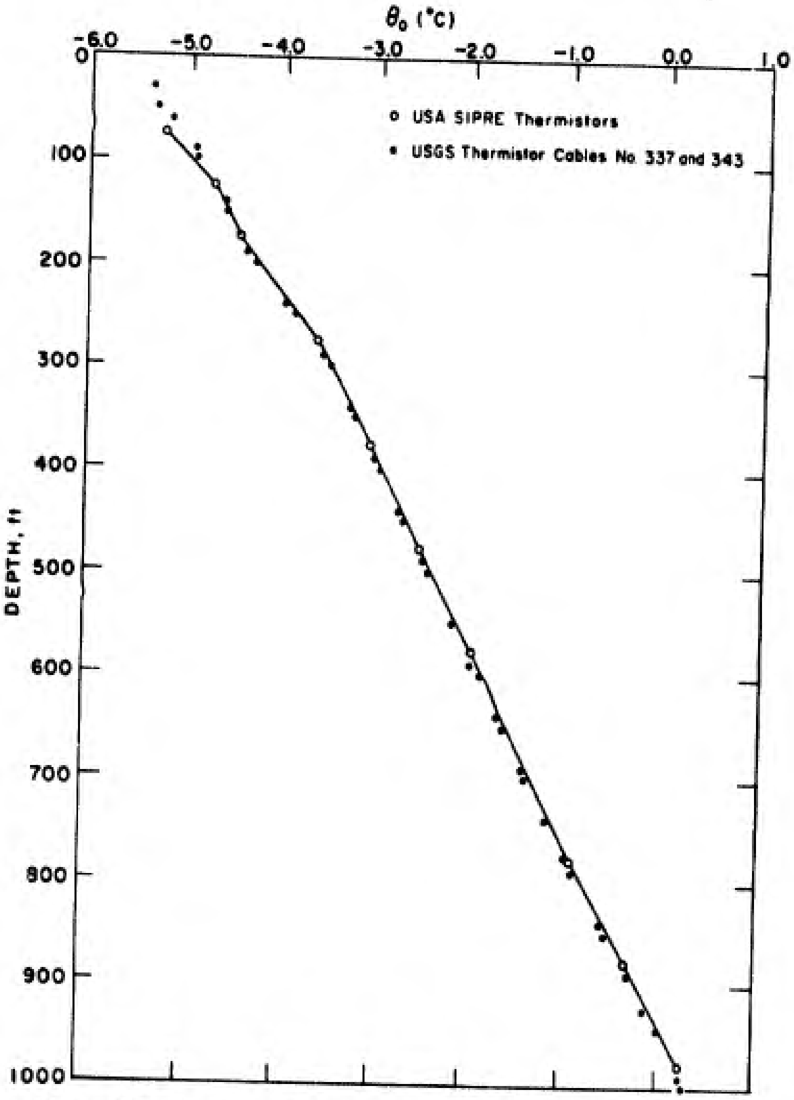

Figure 10. Equilibrium temperature, θ_0, vs depth, hole C.

Inspection of Figure 9 shows that accurate predictions of the equilibrium temperature could have been made at the time of the fourth reading on 2 October 1960, or about one month after installation of the cable. The points representing the readings of 2 October are indicated by small arrows in Figure 9.

The resulting equilibrium values are plotted against depth as open circles in Figure 10. Data from the 4 November 1960 readings of USGS cables 337 and 343 are shown on the same plot. This illustrates the high degree of accuracy and stability obtainable from the use of thermistors in a subsurface temperature measuring system.

CORE ANALYSIS

Introduction

Since the procurement of naturally frozen core and attempts to perform laboratory tests on samples in the frozen state appeared to be unique, an investigation of methods of testing the naturally frozen rock samples was initiated. It was assumed that, at a temperature of 0°C or lower, the sample contained the following five components:

	Weight		Volume		Density
Mineral grains	W_s		V_s		G_s
Free water (liquid)	W_w	W_ℓ	V_w	V_ℓ	$\gamma_w = 1.00$
Ice					$\gamma_i = 0.917$
Diesel fuel	W_f		V_f		$\gamma_f = .815$
Air (or other gas-filled voids)			V_v		
Total	W_t		V		G_t

Four components would exist in the same sample at temperatures above 0°C.

Accurate measurements of each of the five components would be of interest, especially if the percent of the total water frozen at various temperatures below the freezing point could be determined. However, quantitative differentiation between liquid water and ice is usually possible only by using calorimetric techniques that are beyond the scope of the present investigation.

During preliminary attempts to determine the liquid content (W_ℓ) by the standard method of drying to constant weight (W_s) and calculating the liquid content (normally water content) by $W_\ell = W_t - W_s/W_s$ (W_t = wet weight), it became evident that some part of W_ℓ was diesel fuel. A method of water extraction that would allow differentiation between water and diesel fuel was required.

A Soxhlet extraction apparatus was modified as shown in Figure 11. Toluene was used as the solvent since only negligible quantities of water are soluble in it; it has a low density (0.867 g/cm^3), and a boiling point (110.3°C) slightly higher than water. A sample of known weight (approximately 500-1000 g) is placed in the paper thimble in the sample chamber and the chamber is sealed. After boiling, toluene condensate returns from the condenser and flows down through the system in a liquid state. After the water trap is filled and rejects the remaining toluene condensate it collects in the sample chamber. When the chamber is filled to the height of the top of the siphon tube, the chamber is automatically siphoned empty. (The "zero" reading of the amount of water collected in the trap is made at the beginning of the first siphoning.) At this point, liquid water and its vapor are carried out of the sample along with the diesel fuel which is in solution in the toluene. The toluene in the lower flask is kept boiling continuously and the condensate that returns down through the system now contains water which is separated out by gravity in the water trap. The amount of water in the trap is read each time the chamber empties itself by siphoning.

Trial extractions were run on four samples before extraction of water from the 21 record samples was attempted. Two of these were "natural" samples, i.e. with the original water, and two were oven-dried to constant weight and "reconstituted" by adding an amount of water equal to the difference between the original weight and the dry weight. Data resulting from the extraction on trial sample 2 are given in Figure 12 (curve a). This sample was "reconstituted" by addition of 5.7 ml of water. The linear plot of the results suggests an exponential relationship. When ln y is plotted vs $1/x$ (Fig. 13), a good fit is obtained to $y = ae^{-b/x}$ in which y = the amount of water after any number of extractions x; e = the base of natural logarithms; a = the total amount of extractable water and b = the slope.

It became clear that large numbers of extractions could not be run on each sample if a significant number of samples were to be analyzed. A computer was used to predict the y intercept (where $x = \infty$) for increasing values of x, from $x = 4$ to $x = 27$. The resulting values of the y

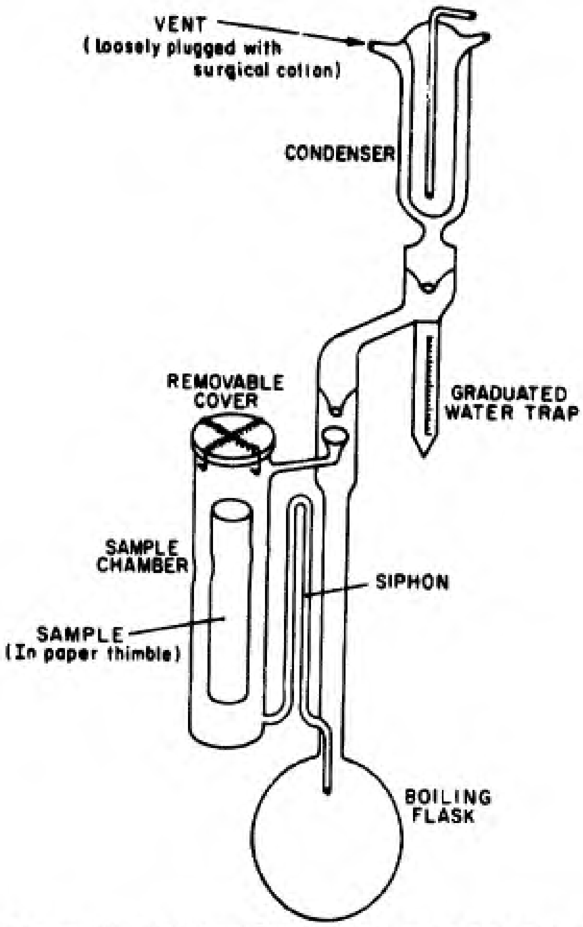

Figure 11. Modified Soxhlet extraction apparatus.

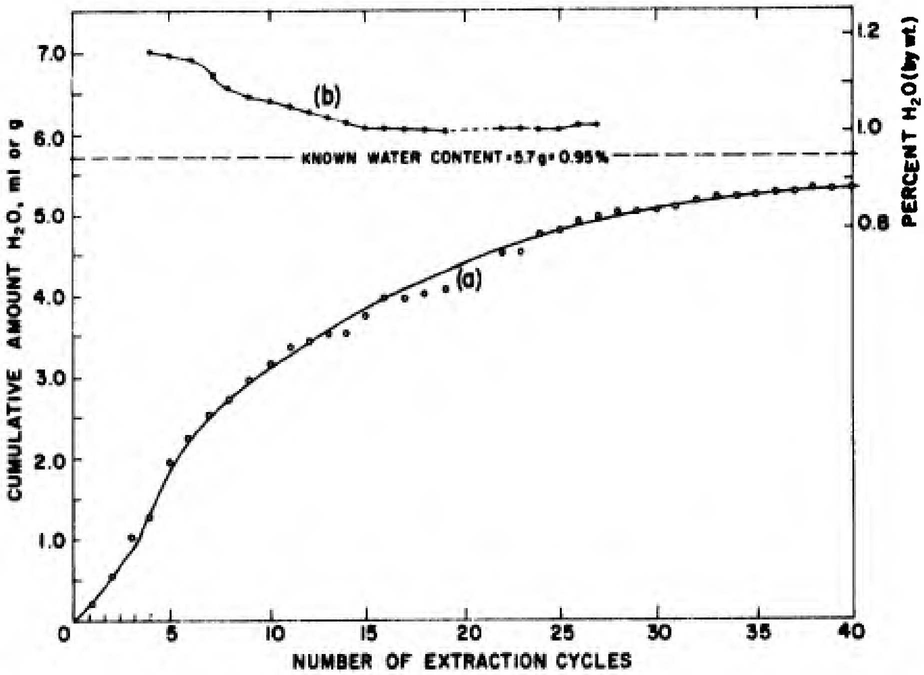

Figure 12. (a) Cumulative amount of water vs number of extraction cycles (5.7 ml of water added to oven-dry sample; weight, 600.2 g) (b) predicted values of (a) for increasing numbers of values of x and y.

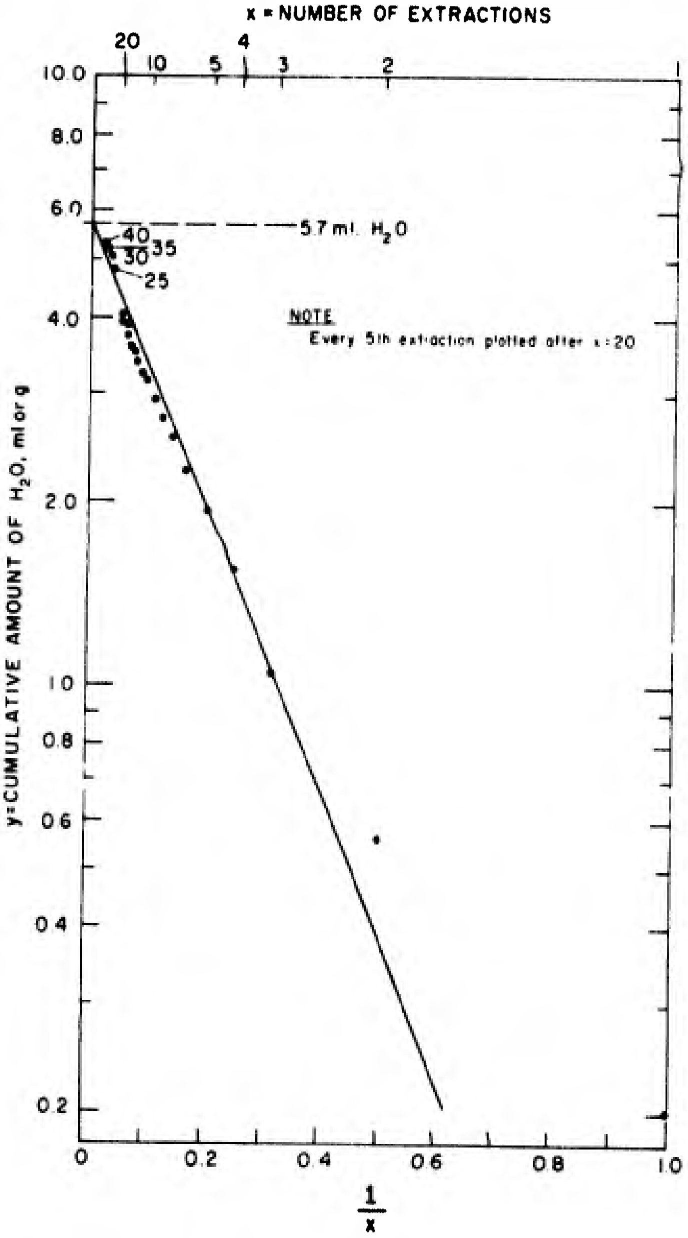

Figure 13. Second trial Soxhlet, ln g vs 1/x (5.7 ml of water added to dry sample).

intercept a are shown in Figure 12 (curve b) for the same sample as in curve a. The linearized form ln y vs $1/x$ was used to compute the intercept. It will be seen that after 15 extractions the total amount of extractable water was predicted to within 0.5% expressed in percent water content or approximately 5% of the total water content value. Similar analysis of the data from the remaining reconstituted trial sample and the two natural samples yielded essentially the same results. Semi-log and linear plots of data from the natural samples showed the same relationship between number of extractions and amount of water extracted as was derived for the samples containing known amounts of water. Computer analysis further showed that the value for the y intercept could be predicted after 20 extractions with almost the same accuracy as shown here for 40 cycles. In fitting the data for the first four trial samples to the relationship $y = ae^{-b/x}$, correlation coefficients were obtained ranging from 0.999 to 0.988, with highest frequency at approximately 0.997.

Procedure

Twenty-one samples were selected for analysis after a study of the core photographs. An attempt was made to distribute the samples selected through the entire range of the depths sampled and to insure that both the massive and crushed conditions of the rock unit were represented.

The selected samples were removed from storage at -20°C and kept in the -10°C room long enough to insure that the entire sample had become isothermal at -10°C. At this temperature, the bulk density was determined in the following manner. The sample was first weighed in air and then weighed submerged in iso-octane, which had been allowed to cool to approximately -10°C. Using temperature vs density data for iso-octane prepared by Anthony Gow of USA CRREL, the bulk density of the frozen sample G_t was calculated by:

$$G_t = \frac{W_t}{W_t - W_{It}} \times \gamma_{Io}$$

where:

W_t = wt in air at -10°C

W_{It} = wt immersed in iso-octane at -10°C

γ_{Io} = density of iso-octane at weighing temperature.

The samples were then removed from the coldroom and allowed to become isothermal at room temperature (approximately +20°C). The weight of the sample in air and the weight immersed in water were determined and the bulk density at room temperature G_t was calculated by:

$$G_t = \frac{W_t}{W_t - W_{It}} \times \gamma_w$$

where:

W_t = wt in air at +20°C

W_{It} = wt immersed in water at +20°C

γ_w = density of water at weighing temperature.

After immersion, samples were surface-dried and reweighed in air. No increase in weight was noted. Therefore, no water or iso-octane was absorbed by the rock sample during the immersion.

After determination of the bulk densities, the Soxhlet extraction process, described earlier, was carried out. Each sample was subjected to 19 cycles and the total amount of extractable water was predicted by graphic means on a semilog plot. This value is reported as V_w in the tabulated data (Table IV).

The samples were then oven-dried to constant weight (to obtain W_s) and the percent of total liquid (LC) was obtained by:

$$W_\ell = W_t - W_s \text{ and } LC = \frac{W_\ell}{W_s} \times 100$$

Table IV. Summary of core analysis data.

Depth of sample (ft)	W_t (g)	W_{It} (g)	γ_{Io} (g/cm³)	W_T (g)	W_{IT} (g)	W_s (g)	G_t (g/cm³)	G_T (g/cm³)	V_w (ml)	WC (%)	LC (%)	Description
a. Hole C												
116.6-112.0	963.4[illegible]	(-7°C) 709.25	0.714	961.37	604.31	949.40	2.706	2.690	7.48	0.8	1.5	Massive
196.5-196.9	830.61	(-7°C) 603.95	0.714	817.69	504.00	795.30	2.617	2.607	17.48	2.1	4.4	Crushed*
					Part of original sample							
198.6-198.9	968.70	(-7°C) 689.15	0.714	737.35	450.80	718.56	2.474	2.570	15.50	2.1	2.7	Crushed*
295.7-295.9	624.45	(-10°C) 445.45	0.71[illegible]	624.40	374.40	600.40	2.485	2.500	12.48	2.1	4.0	Crushed
296.9-297.3	545.[illegible]5	(-8°C) 403.40	0.71[illegible]	545.46	344.70	541.11	2.735	2.730	3.68	0.45	0.89	Massive
302.9-303.3	396.55	(-8°C) 293.40	0.7[illegible]	[illegible]96.75	252.50	393.40	2.745	2.710	2.98	0.76	0.80	Massive
409.4-409.6	869.75	(-8°C) 648.70	0.[illegible]	[illegible].80	548.40	865.10	2.805	2.710	3.08	0.36	0.54	Massive
511.2-511.5	704.00	(-7°C) 519.21	0.714	702.91	439.64	692.20	2.720	2.670	6.28	0.9	1.7	Massive
710.5-710.9	584.10	429.60*	0.714	582.85	365.00	574.30	2.700	2.680	4.90	0.85	1.7	Massive
					Part of original sample							
805.6-806.0	1070.66	(-7°C) 785.55	0.714	1046.00		1027.00	2.680		13.48	1.3		Crushed
817.0-817.4	743.36	(-7°C) 549.85	0.714	742.16	466.10	730.80	2.740	2.690	5.88	0.8	1.7	Crushed
b. Hole D												
101.9-102.2	1018.10	751.50	0.716	1016.96	645.95	1005.00	2.730	2.740	7.58	0.8	1.3	Massive
194.5-194.9	1157.90	843.30	0.716	1156.26	711.80	1127.49	2.630	2.600	27.48	2.4	2.7	Crushed
300.1-300.5	893.00	659.20	0.714	891.95	561.70	882.40	2.730	2.700	8.18	0.9	1.2	Massive
407.[illegible]-407.6	772.15	571.00	0.714	771.17	487.30	757.20	2.740	2.720	8.48	1.1	1.97	Massive
495.0-495.5	552.10	406.90	0.716	553.99	348.40	545.64	2.720	2.690	4.68	0.9	1.18	Massive
602.4-602.7	654.70	482.15	0.714	653.05	409.48	643.35	2.710	2.680	4.78	0.7	1.5	Massive
703.7-704.0	1226.50	906.90	0.714	1226.10	775.75	1217.60	2.740	2.720	7.58	0.6	0.7	Massive
806.1-806.4	954.50	702.50	0.716	953.85	603.85	946.60	2.710	2.730	6.28	0.7	0.78	Massive
997.7-998.0	883.65	652.15	0.714	883.05	558.88	874.50	2.730	2.720	5.58	0.6	1.0	Massive
1100.0-1100.2	469.30	345.80	0.714	469.05	295.00	466.70	2.710	2.690	1.08	0.2	0.55	Massive

* Part of sample lost after weighing in iso-octane.

W_t – wt in air @ -10°C

W_T – wt in H_2O @ +20°C

G_t – bulk density @ -10°C

W_{It} – wt in iso-octane @ -10°C

W_{IT} – wt in H_2O @ +20°C

G_T – bulk density @ +20°C

γ_{Io} – density of iso-octane @ weighing temp.

W_s – dry wt

V_w – vol. H_2O extracted by Soxhlet and calculation = W_w

WC – water content (Soxhlet)

LC – total liquid content (oven-dried)

Water content (WC) is then similarly obtained:

$$WC = \frac{W_w}{W_s} \times 100 \text{ (in percent)}$$

If the grain density G_s could be obtained then the porosity and the percent saturation could be calculated by:

$$n = 1 - \frac{G_t}{G_s} \times 100$$

and

$$S = \frac{V_w}{V_v} \times 100 \text{ (in percent)}$$

where:

n = % porosity
S = % saturation
V_w = vol. of H_2O ($\gamma_w = 1.0$)
V_v = vol. of voids
= $n \times V$
V = total vol. of sample
= $(W_t - W_{IT})/W_{Io}$

Therefore:

$$S = \frac{10^4 V_w \gamma_w}{n (W_t - W_{It})}$$

Unfortunately, grain density determination was attempted by a micro-technique, which did not yield acceptable accuracy when the results were applied to the much larger samples.

Results and discussion

Results of the analysis of 21 core samples are shown in Table IV. Water content values are quite low, ranging from 0.2% in a massive sample to 2.4% in a sample from a crushed specimen; however, it is possible that some small amounts of water may have been lost by sublimation during transportation and storage of the core.

Moisture contents determined by Kachadoorian* of the U.S. Geological Survey for the mudstone of the Ogoturuk formation within 10 ft of the surface at the Chariot site ranged from 3.1% in thawed mudstone to 12.5% in frozen mudstone. Data reported here, however, are for samples from depths of 100 to 1100 ft. The Alaska District Laboratory of the Corps of Engineers reported moisture contents ranging from 0.28% to 5.67% in thawed samples from holes A and B.†

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* Personal communication.

† Unpublished report by Materials Testing Laboratory, U.S. Army Engineer District, Alaska, October 1959.

The weights of the samples at room temperature (W_T) were generally slightly less than the weights of the frozen samples (W_t). If this decrease in weight was due to loss of water by evaporation, the water content values obtained from the Soxhlet method are slightly too low. However, since this loss in weight might have been caused at least in part by a loss of diesel fuel, water lost while "curing" the samples to room temperatures is not accounted for. Liquid contents determined by oven drying varied from less than 0.5% for the most massive sample to 4.4% for a sample from a crushed zone, indicating low liquid content even considering that the liquid content includes water and diesel fuel. During preliminary trials of the Soxhlet technique, the moisture content of a frozen massive sample was computed to be about 1.2%, which is within the range of values found for samples tested at room temperature.

All the samples from crushed zones exhibited a marked loss of strength when removed from the coldroom and allowed to thaw; some collapsed completely, demonstrating that ice, even when present in small quantities, strongly influences the competence of this rock.

A comparison of water content values obtained by the Soxhlet process with the total liquid content determined by oven-drying (Fig. 14) indicates that the samples absorbed a surprising amount of diesel fuel during the drilling operation. It is concluded that water contents determined by oven drying will include the drilling liquid added to the sample during coring or sampling and may be greater than the true water content. This evidence suggests that appreciable error can exist in water content determinations of rock cores and soil samples taken from holes in which water is used as a drilling fluid. The magnitude of the error is probably influenced by a combination of factors, such as the permeability of the sample, the release of intergranular pressure caused by the sampling procedure, and the geologic history of the rock or soil unit.

Bulk densities ranged from 2.47 g/cm^3 in a crushed or fractured sample to 2.80 g/cm^3 in a massive sample. The values reported are consistent with values found by the Alaska District Laboratory of the Corps of Engineers for thawed samples from holes A and B. There was little difference in the densities in the frozen state and at room temperature.

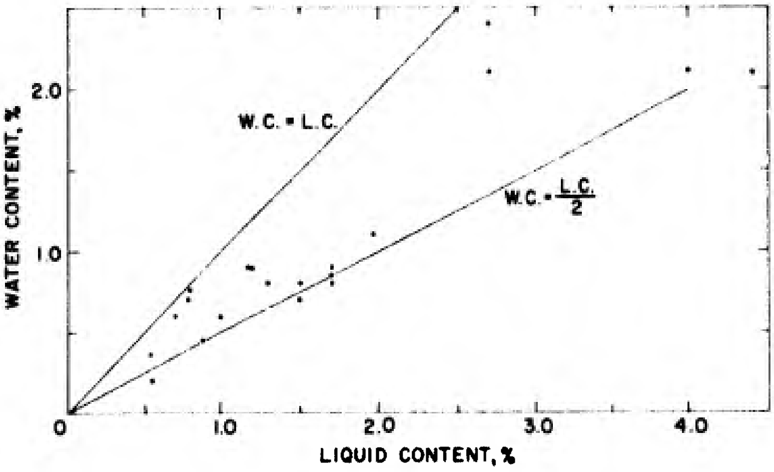

Figure 14. Liquid content vs water content for 21 record samples.

SUMMARY

Two holes were drilled and cored to 1000 and 1200 ft for Project Chariot at Cape Thompson, Alaska. The holes penetrated the mudstones of the Ogotoruk Formation, which were found to be permanently frozen to depths of 935 and 1170 ft. The use of refrigerated diesel fuel circulated at a temperature of approximately -5°C insured the recovery of cores in their naturally frozen state. Previous attempts to drill in these highly fractured rocks had been hampered by caving of the borehole walls when the warm drilling fluid melted the very small amounts of ice which constituted the principal bond of the rock fragments. The cold drilling fluid prevented the destruction of the ice bond and eliminated caving.

Thermistor cables inserted in the 4-in.-diam holes came to equilibrium in a relatively short time due to the small thermal disturbance of the cold fluid. Using an analysis suggested by Lachenbruch and Brewer (1959) it was shown that sufficient data to accurately predict the equilibrium temperature were available within one month of installation.

The samples were transported in their original frozen condition to refrigerated laboratories where special tests were devised to determine their physical properties in the frozen state. Bulk densities, water content and liquid contents were determined for 21 core samples. Bulk densities ranged from 2.47 to 2.80 g/cm^3, water contents from 0.2% to 2.4% and total liquid contents from 0.5% to 4.4%. The disparity between water and liquid content is attributed to the absorption of drilling fluid by the sample. It is suggested that rock and soil samples taken from bore holes drilled with a liquid may be subject to similar errors in water content determinations.

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