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PAPER 79-21

PORTABLE DRILLING EQUIPMENT FOR SHALLOW PERMAFROST SAMPLING

J.J. VEILLETTE
F. M. NIXON

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

1980

ERRATUM

Table 6, page 28

Type Hughes 500D should read:

Type	Sling load (lb)	Passengers	Block speed (mph)	Endurance (hours) 20 minute reserve	Engine Type	Fuel Type	Fuel Consumption (gallons/h)	Length (ft)
Hughes 500D	2000	4	160	2:80	Turbine	JP4	26	30.5

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PORTABLE DRILLING EQUIPMENT FOR SHALLOW PERMAFROST SAMPLING

Abstract

This paper is intended primarily for investigators concerned with shallow (10 m or less) drilling and sampling in frozen soils, and emphasis is on man-portable coring equipment. A description and performance evaluation of the hand-held frost table probe, modified Hoffer probe, standard and modified CRREL core barrels, and motorized equipment for split tube drive sampling, power augering, diamond drilling, water-jet drilling, and trenching are presented. The evaluation criteria include portability, purpose of the investigation program, ground temperature, and texture of the materials.

The compressive strength of frozen soils varies with ground temperature, texture, and water (ice) content. A minimum ground temperature of -5°C is proposed as the practical limit for application of the drive sampling technique in any soil except those with a high clay fraction; a rough latitudinal limit coincident with the -5°C ground isotherm can be used when considering the application of this method in summer. Probing for accurate determination of active layer thickness, while valid for most soils, is not a reliable method in clay-rich soils.

Hand-held power augers equipped with CRREL core barrels are used successfully at any ground temperature below 0°C to core sand, silt, clay, ice, and peat. The operation of power augers, however, is affected by the rotational speed of the coring tool. Field testing indicates that machines of low boring spindle speed (50 rpm) and high torque (350 ft•lb) give consistently satisfactory results.

A light-weight diamond drill, the Winkie GW-15, permits coring of frozen ground consisting of weathered bedrock, sand, silt, and clay in uncased boreholes to depths of 10 m, using a fuel oil drilling fluid cooled naturally below 0°C. Double tube swivel-type core barrels with face discharge diamond coring bits, rotated at speeds of 1500 rpm or more at feed (downward pressure) values of 90 kg, produce excellent cores. Using fresh water as drilling fluid, cores may be obtained in summer in sand, silt, and clay but with significant reduction in core quality. Cores obtained using water in low temperature permafrost in the Arctic Islands are of better quality than those obtained in "warmer" permafrost of upper Mackenzie Valley.

Diamond-drilling rod, core barrel, and bit size specifications conforming to CDDA (Canadian Diamond Drilling Association) standards are summarized and presented in tabulated form. The limitations inherent in the recirculation of a drilling fluid are identified, and the V. Thompson drill water reclaimer and the hydrocyclone are proposed as alternate means warranting further research to achieve adequate sedimentation of cuttings.

Two all-hydraulic drilling machines, one mounted on an all-terrain vehicle – the ATV drill – and the other a two-component, helicopter-portable drill – the JKS 300, are described and evaluated. Performance data of the JKS 300 drill obtained in a wide variety of frozen materials and economical considerations led to the design of the ATV drill, which consists of a 3.7 m mast supporting a hydraulically driven modified Winkie drill and mounted on an all-terrain Argo vehicle. It permits core production comparable to that obtained with heavier truck-mounted drills, if a depth limitation of 10 m is specified. A torque output of 500 ft•lb at the boring spindle is adequate for consistent coring using CRREL core barrels in frozen soils and is proposed as a guideline value for the designing of light-weight augering machines for frozen soils.

General information on fixed-wing and rotary aircraft available for arctic charter is presented. Special insulated core containers, plastic bags, and tin cans are used for the preservation and transportation of samples obtained for natural water (ice) content.

Résumé

Cet article s'adresse à ceux pour qui l'échantillonnage à faible profondeur (10 m) du pergélisol (dépôts meubles) à l'aide d'outillage portatif présente un intérêt particulier. La facilité de transport, les objectifs du programme d'échantillonnage, la témperature et granulométrie du pergélisol servent de critères d'évaluation pour: la sonde manuelle ordinaire, la sonde Hoffer modifiée, les carottiers de type CRREL, standard et modifiés, de même que pour l'outillage motorisé pour l'échantillonnage par battage, à l'aide de tiges rubanées, par forage au diamant, pour le forage à l'aide de jet hydraulique et pour l'excavation de tranchées.

La teneur en eau (glace), granulométrie et température des sols gelés influencent leur résistance à la pénétration. Une température minimale du sol de -5°C est suggérée comme limite pratique de l'application de la technique par battage pour les sols gelés à l'exception de ceux contenant une importante fraction argileuse. L'isotherme de -5°C du pergélisol est proposée comme limite nordique pour l'application de la technique en été. La détermination précise de l'épaisseur de la couche active dans les sols argileux par l'enfoncement d'une tige jusqu'au refus donne parfois des résultats erronés.

La prise de carottes dans les sables, silts, argiles, glace et tourbe à l'aide de tarières motorisées portatives et munies de carottiers de type CRREL se fait facilement à toute température du sol inférieure à 0°C. Par contre le rendement d'un carottier est sérieusement affecté par sa vitesse rotative. Les essais de terrain indiquent que de basses vitesses rotatives au porte-foret (50 tpm) et une haute force de torsion (350 pi•lb) produisent les meilleurs résultats.

Une foreuse au diamant de faible poids, la Winkie GW-15, utilisant de l'huile à chauffage refroidie naturellement en dessous de 0°C comme liquide de circulation, permet la prise de carottes de matériaux gelés tels le till, la roche altérée, les sables, silts et argiles, dans des trous non tubés jusqu'à des profondeurs de 10 m. L'utilisation de carottiers à double parois (tube intérieur stationnaire), avec des couronnes perforées, à une pression de 90 kg et tournant à 1500 tpm ou plus produisent des carottes de haute qualité. La prise de carottes pendant l'été, avec de l'eau douce comme liquide de circulation réussit dans les sables, silts et argiles, avec toutefois une diminution de la qualité des carottes. Les résultats sont en général meilleurs dans les îles de l'archipel arctique que dans, par exemple, le pergélisol à plus haute température de la haute vallée du Mackenzie.

Une synthèse des dimensions conformes au normes établies par la CDDA (Canadian Diamond Drilling Association) est présentée sous forme de tableau. Les problèmes associés à la recirculation d'un liquide de forage sont reconnus et afin d'obtenir une sédimentation plus efficace des débris de forage le "drill water reclaimer" de V. Thompson et l'hydrocyclone devraient faire l'objet de recherches plus poussées.

Deux foreuses à fonctionnement hydraulique, l'une montée sur un véhicule tout-terrain, la foreuse ATV, l'autre consistant de deux partis distinctes, adaptées au déplacement par hélicoptère, la JKS 300, sont décrites et évaluées. Des études de rendement de la JKS 300 dans divers types de pergélisol de même que des contraintes d'ordre économique ont conduit à la réalisation de la foreuse ATV. A part le véhicule Argo, la machine comprend, un mât de 3.7 m qui supporte une foreuse Winkie GW-15, modifiée pour accepter un moteur hydraulique. Pour la prise de carottes à des profondeurs de 10 m ou moins la foreuse ATV se compare favorablement en terms de rapidité à de plus lourdes foreuses montées sur camion. Une force de torsion de 500 pi•lb au porte-foret est suffisante pour l'utilisation de carottiers de type CRREL. Cette valeur est suggérée pour le bénifice de ceux intéressés à innover dans la domaine de tarières motorisées légères pour le pergélisol.

Des renseignements d'ordre général sont présentés sur les avions et hélicoptères disponibles dans le nord Canadien, de même que sur l'utilisation de contenants spéciaux isolés pour préserver des carottes de pergélisol, de sacs de plastiques et boîtes de conserve pour la préservation d'échantillons pour déterminer la teneur en eau (glace).

INTRODUCTION

In recent years, an increasing number of earth scientists, environmentalists, and soils engineers, who occasionally require shallow subsurface data from areas underlain by permafrost, have engaged in studies in the Canadian Arctic and sub-Arctic. Requests for information on portable drilling equipment and field procedures are received each year by field officers of Terrain Sciences Division of the Geological Survey of Canada who have drilling experience in northern terrain. Although abundant literature is available on drilling methods and equipment for nonpermafrost terrain with procedure guidelines well established over numerous years of experience, information on permafrost coring is scant. The objectives of this report are: (1) to summarize the results and field experience accumulated by scientists with Terrain Sciences Division by presenting a description and evaluation of various drilling equipment and methods, and (2) to inform users with no field experience how to select the method best suited to their particular needs.

Experience has indicated that many uninitiated users have unrealistic expectations of the performance of light-weight, portable drilling equipment. The information presented here is by no means exhaustive, but constitutes a representative sample of the methods and techniques in use for the shallow drilling and coring of frozen ground.

Most requests for information on portable equipment include one or more of the following provisos: equipment must be light weight; the area under investigation has difficult access and is remote from service centres; light aircraft (helicopter or fixed-wing) are the sole means of transport; drilling budget is small; and cores are required. Those making the requests commonly show a lack of familiarity with drilling and coring equipment in general and of logistical aspects such as helicopter and fixed-wing payloads, cabin dimensions, and range. They often have unrealistic expectations in terms of core recovery, core size, and maximum depth attainable. Usually no experienced personnel are available to operate or supervise drilling operations, and users have little or no knowledge of local ground conditions, such as soil texture and availability of water.

These limitations initially applied to the drilling and coring components of extensive terrain inventory programs recently carried out by Terrain Sciences Division in the Western Arctic (Mackenzie Valley), Arctic Islands, and District of Keewatin. Because of the large areas covered by these surveys, subsurface investigation had to rely on aircraft-portable, light-weight drilling equipment. This constraint led to experimentation with various portable drilling machines and coring tools in several types of permafrost terrain. Drilling projects were carried out at locations west and north of Hudson Bay between 56° and 81°N.

Because shallow drilling is conducted in the upper permafrost zone, which is affected by seasonal temperature fluctuations, an understanding of the characteristics of this zone is necessary in order to assess correctly the performance of drilling and coring equipment.

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THE UPPER PERMAFROST ZONE

Permafrost is present if the mean annual ground temperature is less than 0°C at least one year (Fig. 1). It is strictly a temperature condition, and as such the definition applies to all earth materials including bedrock. In this report "permafrost" refers to frozen unconsolidated deposits, unless specified otherwise, and "shallow drilling" refers to vertical boreholes to 10 m or less depth. This 10 m layer of ground is the portion of permafrost where seasonal ground temperature fluctuations are largest. In general, seasonal temperature fluctuations penetrate to depths of 20 m or less (Judge, 1973). At the depth at which the amplitude of seasonal fluctuations becomes zero, the ground temperature corresponds roughly to the mean annual surface temperature; from there the temperature increases more or less regularly downward.

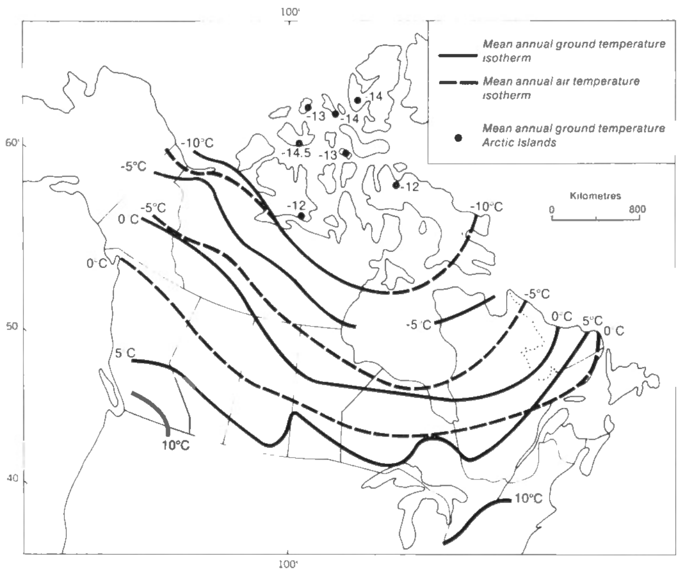


Figure 1. Map of mean annual air and ground temperatures in Canada (after Judge, 1973). Permafrost extends northward from the 0°C ground isotherm.

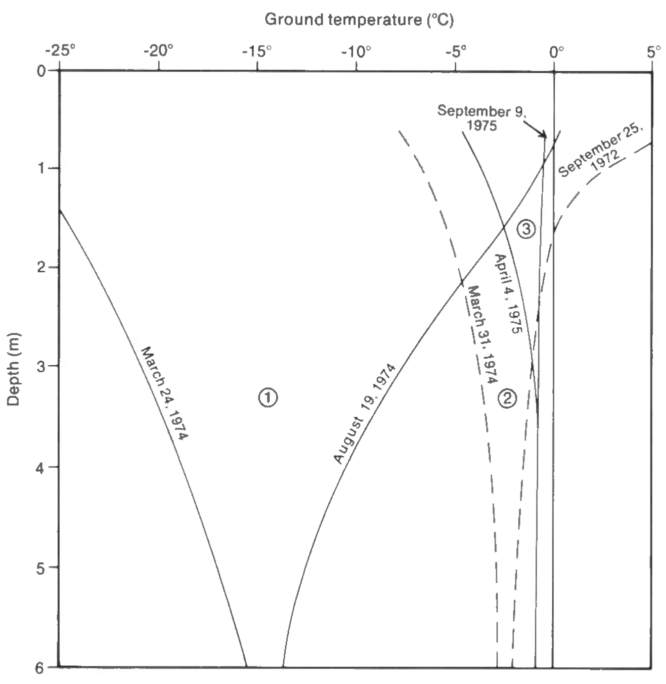


Figure 2. Graph showing annual range of ground temperatures to a depth of 6 m for: (1) central Banks Island (73°N), (2) Norman Wells, Northwest Territories (65°22'N), and (3) Thompson, Manitoba (55°47'N).

A general decrease in ground temperature occurs with increasing latitude (Fig. 1). In Canada the mean annual ground temperature is slightly higher than the mean annual air temperature, especially for mid-latitude regions. Factors such as snow cover, topography, wind exposure, ground cover, and ground moisture account for local variations in ground temperatures and the magnitude of the difference. Snow cover thickness, depth, and duration are considered the most important factors governing the difference between mean annual air and ground temperatures (Judge, 1973).

The amplitude of the seasonal ground temperature variation at a given depth in near surface permafrost is greater for higher latitudes. Figure 2 shows three ground temperature envelopes, each covering a one-year span for three different latitudinal zones. Envelope 1 is from central Banks Island (73°N), where measurements were recorded in 1974. The low temperature boundary was obtained from measurements recorded on March 24, in a seismic shothole; the high temperature boundary was obtained on August 19, from a different borehole in the same area.

Envelope 2, from the Norman Wells area (65°22'N), Mackenzie River valley, is based on monthly measurements from September 1972 to March 1973 (Isaacs, 1974). The low temperature boundary was recorded in late March 1973 and the high temperature boundary, in late September 1972. Development of a thick active layer (1.5 m), is illustrated by the portion of the late summer temperature profile that is above 0°C.

Envelope 3, from the Thompson, Manitoba area (55°47'N), is based on weekly ground temperature measurements (Harold B. Dahl, National Research Council, pers. comm.) from October 1974 to November 1975 and shows the narrowest range of temperatures for all depths. The low temperature boundary was recorded on April 4, 1975 and the high temperature boundary, on September 9, 1975.

While local environmental factors, such as proximity of large water bodies, may affect the shape of a ground temperature envelope, there is a general correlation between latitude, mean annual surface and ground temperatures, and amplitude of temperature variations for a given subsurface level. These relationships are of importance in assessing the performance of drilling and coring equipment. The upper permafrost zone cannot be considered (even for drilling purposes) to be a mass with constant physical and thermal properties, but rather as a mass whose physical and thermal properties vary both seasonally and latitudinally, and also with depth.

Frozen Soil as a Drilling Material

The indurated character of frozen soil containing particles bonded by ice offers the possibility of using drilling techniques and equipment normally reserved for solid bedrock. The degree of induration of material is dependent on the interrelations of ground temperature, texture, and quantity of unfrozen moisture. Soils artificially reduced to low temperatures (below -25°C) have a strength comparable to that of nonfissured soft rock (Hvorslev and Goode, 1963). The following properties of frozen ground govern the performance of coring and drilling tools:

1. The short-term strength and adhesion between embedded stones and the matrix increases with decreasing temperature.
2. For fine grained soils, the freezing point is depressed by pore and capillary water.

3. Unfrozen water decreases soil strength, which facilitates drive sampling but causes breaking and thawing of cores when drilling with a fluid.

4. A low degree of saturation with ice (a soil in which only part of the pore space is filled by ice) decreases the strength of frozen soil.

Results of laboratory experiments on frozen soils with different textures show the relationship between compressive strength and soil temperature (Fig. 3). All soils indicate a marked increase in compressive strength with decreasing temperature, the increase being greatest for granular materials. Assuming that these values apply in the field, frozen silts at -1°C near the southern limit of permafrost (0°C isotherm, Fig. 1) have a compressive strength around 300 psi (pressure and torque units are expressed in the British system of measures throughout the text), whereas similar silts in the Arctic Islands at -15°C have a compressive strength of 1500 psi – a five-fold increase. There is also a seasonal variation in compressive strength. Both variables must be considered in planning a shallow depth drilling program.

Some of the water retained in fine grained soils remains unfrozen considerably below 0°C. Figure 4 indicates that the amount of unfrozen moisture for a given temperature is related to soil particle size. It follows that soils with appreciable quantities of unfrozen moisture (fat clays) have the lowest compressive strength.

Although all drilling methods are temperature dependent, the two methods most affected by ground temperature are drive sampling and diamond drilling. For drive sampling, which consists basically of forcing a coring tube into the ground with repeated blows from a drop-hammer, low ground temperatures and silty, sandy, or gravelly soils constitute the most adverse conditions (Fig. 3).

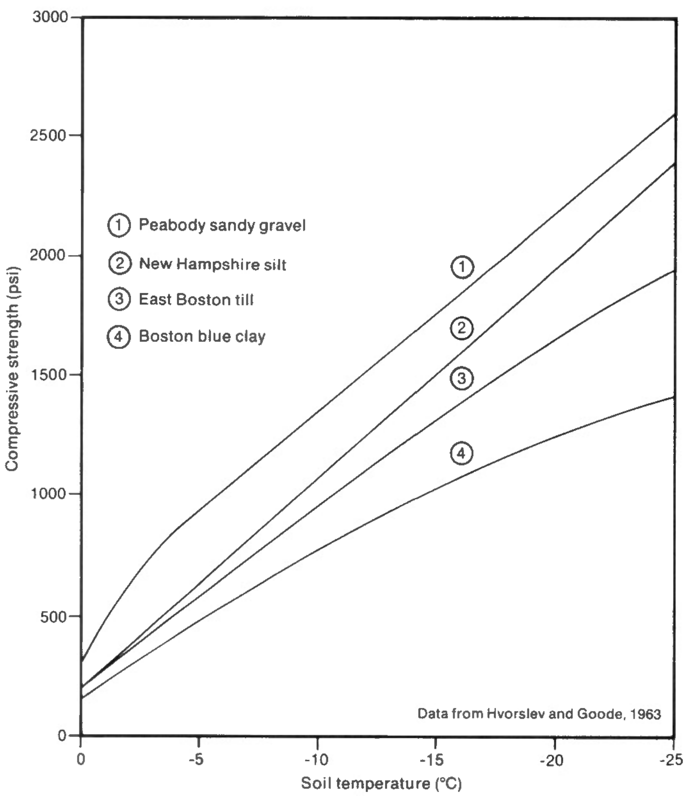


Figure 3. *Graph showing strength-temperature relations for frozen soils of different texture.*

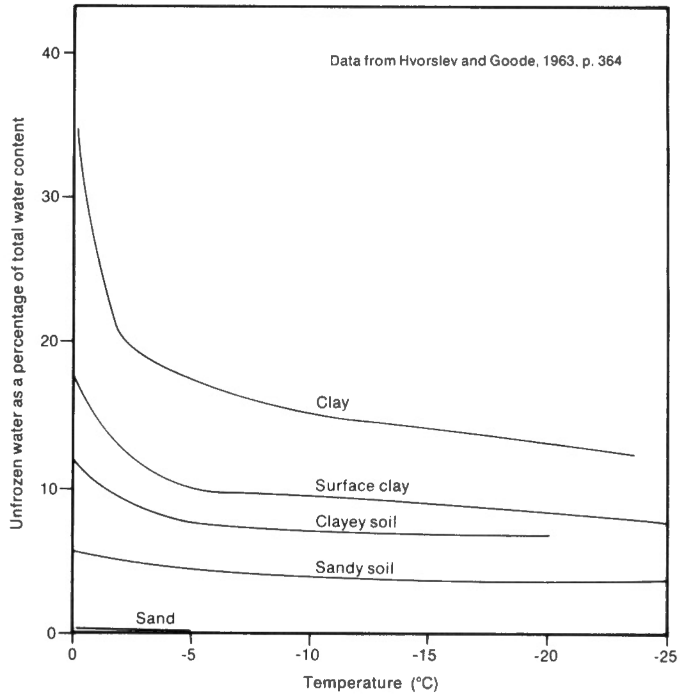


Figure 4. *Plot of unfrozen water content of frozen soils vs. temperature.*

For best results drive sampling should be confined to the summer when soil temperature is highest (and compressive strength lowest) and to areas south of the -5°C ground isotherm. Optimum conditions for diamond drilling are different. Because this method requires circulation of a fluid inside the borehole and relies on the cutting action of a coring tool rotated at high speed, best results are obtained in low temperature permafrost containing little or no unfrozen moisture. Low temperature permafrost is characteristic of higher latitudes, but low temperatures will exist in the upper permafrost zone during the late winter – early spring period. Hard-frozen soils will not thaw as rapidly as those at temperatures only slightly below 0°C when drilled using a circulating drilling fluid.

DRILLING AND CORING METHODS AND EQUIPMENT

A variety of methods and equipment are used to investigate the upper permafrost zone. The selection of a method depends on the objectives of the project, logistics, costs, and the restrictions imposed by the material to be drilled. In some cases sampling can be done with hand-held probes or non-motorized augers.

Hand-held Probes and Samplers

Frost Table Probe

The frost table probe, which consists of a rigid metal rod sharpened to a point at one end and with a T-handle at the other end (Fig. 5), is used to measure the depth of the active layer in summer. It can penetrate thawed sands, silts, and clays to depths varying with the compaction of the materials, but not coarse gravels, stony tills, or frozen ground. The probe shown in Figure 5 has a square stem about 0.9 cm in diameter and is graduated in centimetres.

Accurate active layer depth measurements are possible only in materials where the 0°C ground isotherm coincides with the point of refusal of the probe. Ice-bonded sands, gravelly sands, sandy tills, ground ice, and ice-rich organic

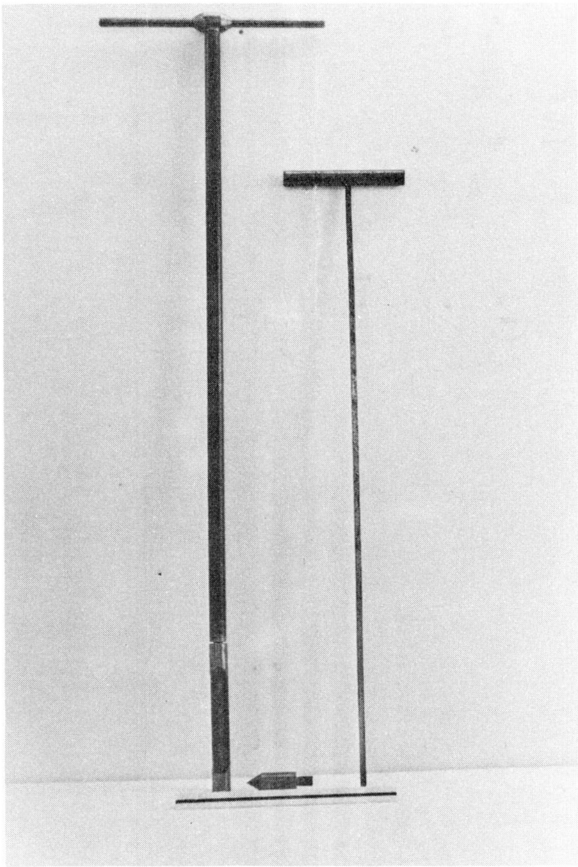


Figure 5. *Frost table probe (right and modified Hoffer probe (left); the removable point (between the two probes) is used with the modified Hoffer probe. (GSC 203205-F)*

deposits give a distinct refusal at the 0°C isotherm. Fine grained deposits, containing some unfrozen moisture, give a "gradual" refusal corresponding to ground temperature and the quantity of unfrozen moisture. As the rod can be pushed below the 0°C level in fine grained soils, the apparent active layer thickness is larger than the true value.

Mackay (1977a) demonstrated that probing may lead to errors of several hundred per cent in soils with a substantial clay fraction. Shallow pits in clays commonly can be excavated with an ordinary shovel to a few centimetres below the 0°C isotherm. The presence of ice lenses and a greater stiffness to the material are often the only indicators that the pit floor is below the frost table. Consequently, accurate active layer thickness in fine grained soils should be determined by temperature measurements. Steel probes with temperature sensors at their tips are available commercially or can be assembled in a laboratory (Pichette and Pilon, 1978).

Modified Hoffer Probe

This sampler probe is probably the lightest and most portable piece of coring equipment available for frozen material. The basic components include a bit, extensions, and a removable T-handle (Fig. 5). The cutting edge and core holder, formed of a single piece of steel, constitute the bit. The standard Hoffer probe, with a smooth cutting edge at the bit, is used mostly by pedologists in nonpermafrost areas. In the early 1960's, R.J.E. Brown (pers. comm., 1977) adapted the probe to permafrost investigation by replacing the smooth cutting edge with a serrated edge, hardened steel bit. A sample is obtained by driving the bit manually with repeated short blows into permafrost. A small core (2.5 cm diameter for the bit shown in Fig. 5) gradually is forced into the bit and can be removed from an opening down one side of the bit after it has been brought to the surface. Although core breakage is high, the size of the sample is sufficient to provide the investigator with a reliable estimate of the ground-ice content and texture of the material.

Adding 1 m extensions permits coring to greater depths. R.W. Klassen (pers. comm., 1974) used the probe to penetrate frozen peat bogs and underlying glaciolacustrine clays in northern Manitoba. S.C. Zoltai (pers. comm., 1974) used it for extensive sampling of peats to depths of 3 to 4 m along Mackenzie Valley. Frozen fine grained soils slightly below 0°C have significant unfrozen water, which explains the success of these two investigators. Brown (1965) commented earlier on the influence of ground temperature and soil texture on ease of penetration of the probe in permafrost of northern Manitoba and Saskatchewan.

Trials with the probe on Somerset Island, Northwest Territories (74°N) during summer 1975 showed that in this colder permafrost the rate of penetration in frozen peat is too slow to be practical. For best results, use of the probe should be restricted to fine grained soils and peat during the summer period when compressive strength of the near surface soil is least and to areas south of the -5°C ground isotherm (Fig. 1). Deposits with a high clay fraction (large amount of unfrozen moisture) may allow successful use of the probe north of the -5°C ground isotherm.

Standard and Modified CRREL Ice-coring Augers

The standard CRREL auger has proven valuable in coring snow, ice, and fine grained organic and mineral soils in various cold regions throughout the world. Designed by the United States Army Corps of Engineers as a hand-driven coring tool, modified versions of the core barrel have been used on small and large rotary drills of various types, including diamond drills.

The standard USA-CRREL (Cold Regions Research Engineering Laboratory) ice-coring auger, now produced by Geotest Instrument Corporation, consists of a stainless steel core barrel, 11.3 cm O.D. (outside diameter) and 92 cm in length (Fig. 6), which gives a 7.6 cm diameter core. The hollow barrel has a welded double-helix flight configuration, with a 20 cm pitch. A stainless steel cutting shoe with removable cutting inserts fastens to the bottom of the barrel. A removable head couples the barrel to the extensions and permits removal of the core through the top of the barrel. The T-handle couples directly to the head when starting a hole, and to 1 m aluminum extensions fitted with stainless steel pin-type couplings at greater depths. The cutting inserts are fastened to the shoes with screws and can be made of steel or tungsten carbide.

Most CRREL augers in current use by Terrain Sciences Division are of shorter length or smaller diameter than the standard USA-CRREL barrel. Figure 7 shows coring augers that produce cores of 3.8 cm, 5.1 cm, and 7.6 cm diameter. All core barrels, heads, and shoes are made of mild steel and may be built in machine shops. The cutting inserts consist of mild steel shanks with tungsten carbide tips.

Small diameter core barrels were designed for use with motorized power sources to provide faster penetration rates in low temperature permafrost and to reduce the peripheral speed at the cutting edge. For the same drill-spindle speed (the drill or boring spindle is the point of attachment of coring tools or extensions on the drill), the cutting edge of a small diameter core barrel obviously travels at a lower speed

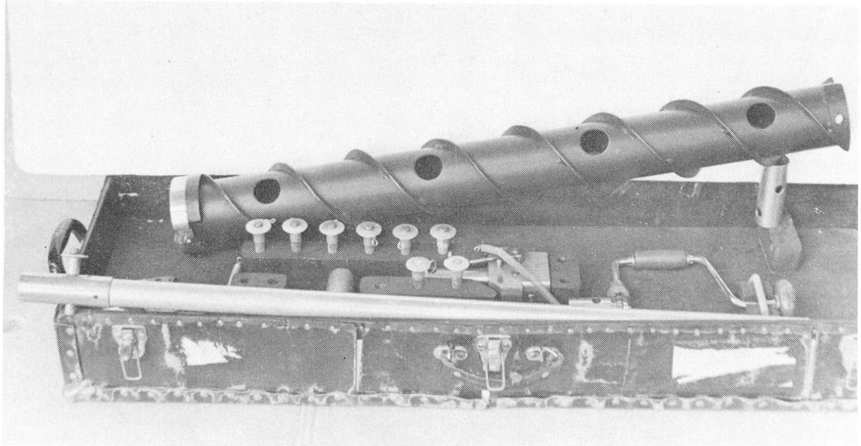


Figure 6

Standard USA-CRREL ice coring auger. (GSC 203205-G)

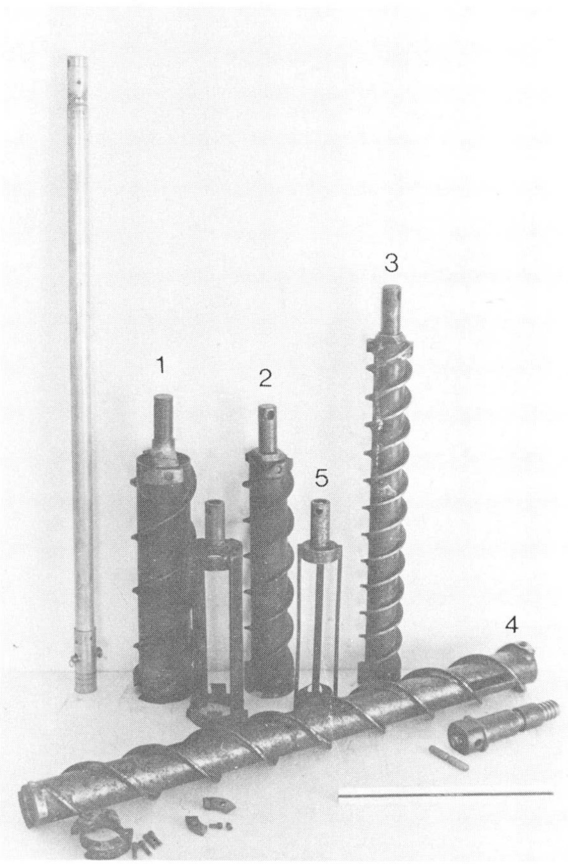


Figure 7. *Modified CRREL core barrels: (1) length 41 cm, core diameter 7.6 cm, (2) length 41 cm, core diameter 5.1 cm, (3) length 61 cm, core diameter 3.8 cm, (4) length 92 cm, core diameter 5.1 cm, deflectors in upper part of barrel, and (5) core catcher for 5.1 cm diameter cores. (GSC 203205-A)*

than that of a large diameter barrel. Lower speeds reduce frictional melting at the steel-permafrost contact and minimize the possibility of freezing the barrel in the borehole. A small diameter or shorter barrel also has less surface area in contact with the frozen ground, which reduces the chances of jamming. Drilling associated with most surficial materials mapping projects involves many shallow holes over a large area rather than a few deep holes. The time required for drilling a hole giving a 7.6 cm core is considerably longer than that for a hole of the same depth giving a 5.1 cm core, because the volume of frozen soil cut is about 36 per cent larger.

A major drawback of the CRREL barrel is the short length of core recoverable from a single trip down the borehole. All core barrels, whether standard or modified, are limited to a run (single trip down the borehole) of usually less than 50 per cent of their total length, and in most cases only 30 per cent. This is due, in part, to insufficient storage space for cuttings between the borehole walls and the barrel, which leads to packing of the cuttings between the flights or bridging of the cuttings above the barrel head and subsequent binding of the auger. Veillette (1975a) attempted to increase the length of the core run by equipping a 92 cm long, 5.1 cm diameter core barrel with steel deflectors in its upper part to divert excess cuttings inside the upper inside portion of the barrel (Fig. 7, no. 4); this modification increased the average core length recovered in one trip down the borehole for materials other than clayey soils.

A common problem when using CRREL augers is the difficulty of breaking the core from the bottom of the borehole. The core commonly remains solidly attached to the bottom after the auger has been withdrawn. This is particularly so when drilling with the large diameter core barrel (7.6 cm core). A core catcher, consisting of two metal rings held together by straight metal bars with the bottom ring holding spring steel blades fashioned in a basket-like core retainer (Fig. 7, no. 5) and attached to extensions, is lowered over the core. A quick movement sideways or a twisting motion is usually sufficient to break the core.

Field experience indicates that for high arctic areas, a core barrel producing a 5.1 cm core permits a reasonable compromise between speed of operation and core quality. It is felt that for the same depth, two holes with 5.1 cm diameter core closely spaced in a given deposit supply significantly more information on soil texture, ice distribution, and structure than a single hole giving a 7.6 cm core.

Drilling contractors successfully have adapted the CRREL auger to large rotary rigs, and core barrels producing cores 10 cm or more in diameter have been used. The development of rugged core barrels and tungsten carbide cutters, used with powerful rotary drills, now permits successful recovery of cores in moderately stony tills, gravelly sands, some gravels, or other soils previously considered nonaccessible to this type of tool. Little of the experimentation done by drilling contractors on such aspects as cutter geometry, barrel heads, and performance in various types of frozen soils has found its way into the literature.

Ground temperature also affects the penetration rate of CRREL augers, although it is not as significant a factor as in drive sampling. A rate of 46 cm/min at 96 rpm in clear glacier ice or lake ice at a temperature of -30°C, using sharp cutters and a vertical load consisting of only the auger weight has been reported by Geotest Instrument Corporation (1973). Blake (pers. comm., 1977), however, reported that two to three days were necessary to core 5 m of frozen peat in the Arctic Islands using a core barrel (7.6 cm core) rotated by hand. We cored a 7 m hole in ice-rich glaciolacustrine varved clays in northern Manitoba using a modified CRREL auger (3.8 cm diameter core) rotated by hand in about 8 hours; ground temperature at this site was slightly below 0°C.

Unfrozen soils or soils containing a significant amount of unfrozen water, as a rule, are difficult or impossible to core using a CRREL auger. Frozen clays at a temperature between -1° and 0°C (large amount of unfrozen water) will liquefy rapidly if coring is attempted with a CRREL barrel rotated at excessive speeds (200 to 300 rpm) using a power auger.

Man-portable Core Drills Used Without a Circulating Fluid

The drills described in this section vary in their degree of portability and do not require the circulation of a drilling fluid in the hole (dryhole method). For power augers, comparisons are presented between different drills from the same general category in an effort to isolate the most desirable power source characteristics necessary for permafrost coring.

Drive Sampling

Drive sampling in frozen ground requires the same equipment and procedures used for drive sampling in soils outside the permafrost zone. The technique consists of driving a tube sampler into the ground using a drop-hammer. The equipment is essentially the same as that required for the application of the Standard Penetration Test.

The Acker portable drive sampling drill (Fig. 8) has been used extensively for sampling programs. It consists of a sectional aluminum tripod derrick, complete with tie bolt, bail sheave, and 2 cm diameter hoisting rope. A 11.5 cm O.D. cathead, driven by a roller chain and powered by a four-cycle, 5 h.p. Briggs and Stratton engine, raises the 63.5 kg drop-hammer, which is confined between two jar collars and slides along an A-size, 92 cm steel rod.

Tube samplers are the usual coring tools used with the drill; these range in size from 5.1 to 11.5 cm O.D. and may be of solid or split tube type. The split tube sampler consists of a barrel that opens in two halves to expose the entire sample (Fig. 9). With the 63.5 kg drop-hammer, the 5.1 cm O.D. split tube, accommodating either 46 or 61 cm of 3.5 cm core, and conforming to Standard Penetration Test requirements, commonly is used in permafrost. Where prolonged pounding (slow penetration) is expected or drop-hammers heavier than 63.5 kg are used, the Lynac sampler, which incorporates a thickened head section, is preferred. Core retainers usually are not necessary when coring frozen soils.

Split tube sampling has been used extensively during summer in Mackenzie Valley, mainly south of the -5°C ground isotherm (Fig. 1). At the relatively warm temperatures prevailing in permafrost in Mackenzie Valley during summer (Fig. 2), the compressive strength of the most common surficial materials (clay, silty clay, clayey till) is only moderately higher than that of nonfrozen soils (Fig. 3), mainly because of significant amounts of unfrozen moisture. Conditions, therefore, are excellent for the drive sampling

Figure 8. *Acker portable drive sampling drill. (1) Tripod, (2) engine and cathead, (3) the 63.5 kg drop-hammer. (GSC 203506)*

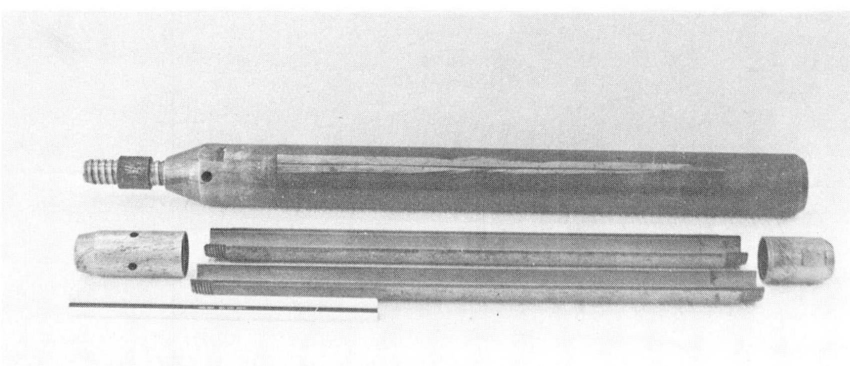


Figure 9

Split tube drive samplers: 7.6 cm outside diameter, closed (top) and 5.1 cm outside diameter, open (bottom). (GSC 203205)

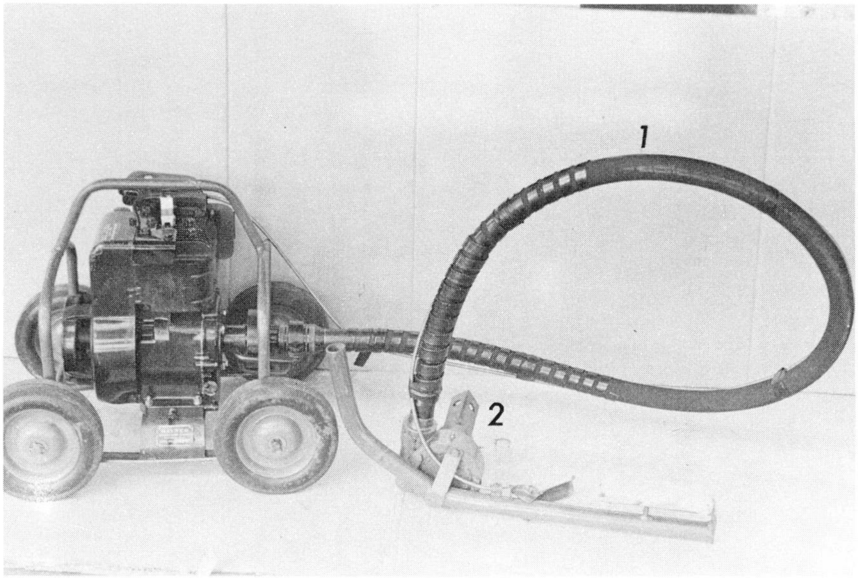


Figure 10

Haynes earth drill, model 500. (1) Flexible shaft drive, (2) reduction unit. (GSC 203205-K)

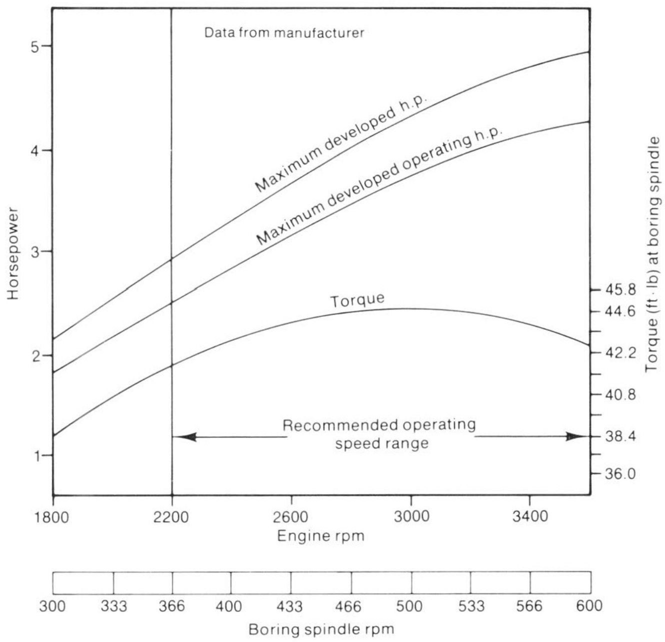


Figure 11. *Performance chart, Haynes drill, model 500.*

method and explain the popularity of the method (Isaacs and Code, 1972; Hughes et al., 1973; Rutter et al., 1973; Heginbottom, 1974). Drive sampling in silty sands or sands at -5°C or lower, however, is very slow and causes excessive wear of equipment. Drive sampling using a 5.1 cm O.D. split tube and a drop-hammer mounted on a helicopter portable rotary drill in February 1972 in the Fort McPherson, Northwest Territories area (67°N) was not successful in the near surface zone due to very slow penetration and to the highly fractured core resulting from prolonged hammering. While sampling ice-rich organic silts and sands in the same area in early June 1972, 40 to 100 blows per 30 cm of penetration were required in the upper 2 m of permafrost, but fewer were required below that depth. ASTM (American Society for Testing and Materials) specifications define refusal (Standard Penetration Test) as a penetration of less than 30 cm for 100 blows of a 63.5 kg hammer falling freely from a height of 76 cm.

Unfortunately, not enough data correlating blow counts with material type and ground temperature are available to establish a practical northern limit for the application of the method. Considering the slow penetration rates in the upper permafrost zone in winter, the -5°C ground isotherm (Fig. 1) is proposed as the northern limit for a reasonable application of the technique in all materials except clays.

The tripod, engine, drop-hammer, drill rods, coring tools, and hand tools necessary to drill a 9 m hole weigh about 260 kg, with the heaviest single piece being the 63.5 kg hammer. The equipment is awkward to carry and not well suited to back packing; however, it is man-portable over short distances. For helicopter moves, the equipment may be tied to the helicopter racks (skid mounted helicopter) or placed in a sling.

Split tube permafrost cores are usually of good quality, and recovery is often close to 100%. The cores, although slightly disturbed due to the considerable thickness of the sampler walls, permit a detailed stratigraphic description of the material, including ground ice. Core samples from a split barrel may be used for index engineering tests such as liquid and plastic Atterberg limits, grain size distribution, and natural water content.

Hand-held Power Augers

Power augers are popular among scientists involved in shallow permafrost coring. The equipment is man-portable over a variety of terrain conditions and consists of few separate parts. In general, power augers used to rotate the standard CRREL ice auger or modified CRREL barrels can be used in any frozen soil except extremely gravelly or stony ones. When using continuous flight augering rods with an overburden bit, power augers can be used in both frozen and unfrozen sediments.

Unfortunately, all power augers using the CRREL barrel or modified CRREL barrels are subject to a common problem – binding of the barrel in the hole when excess cuttings are packed solidly between the helical flights. This shortcoming is inherent to the barrel design, but in this respect, some power augers perform better than others. Three models of power augers (Haynes earth drill, General Equipment digger model 51, and Stihl 4308 auger) that have been used extensively in conjunction with CRREL barrels are described and compared below, with the objective of pointing out the desirable characteristics for a light-weight power auger in permafrost coring.

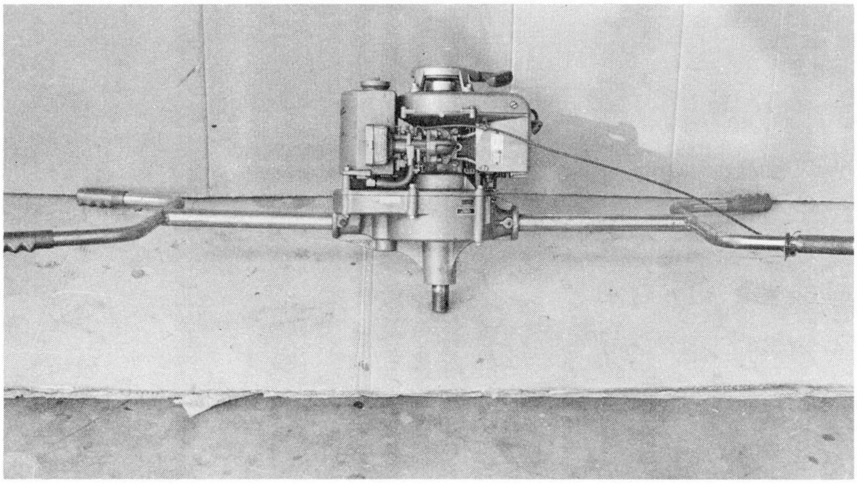


Figure 12

General Equipment digger, model 51. (GSC 203205-I)

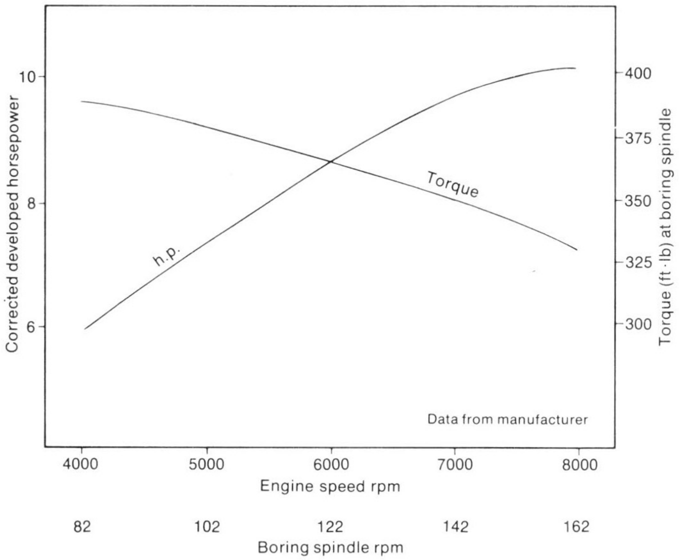


Figure 13. *Performance chart, General Equipment digger, model 51; reduction from engine shaft to boring spindle is 49:1.*

The Haynes earth drill consists of a Briggs and Stratton, wheel-mounted, four-cycle engine which delivers power to the boring spindle through a flexible shaft-drive (Fig. 10). A reduction unit reduces spindle speed to one-sixth the speed of the engine shaft. Model 500 (5 h.p.) and model 700 (7 h.p.) were used in the field. The drill has been used extensively in central and lower Mackenzie Valley and in the Arctic Islands in recent years to core ice, frozen sand, silt, clay, and peat. One man is sufficient for its operation.

The power curve for Haynes model 500 (Fig. 11) shows that maximum torque is reached at engine speeds of between 2800 and 3200 rpm, corresponding to reduced boring spindle speed of 466 to 533 rpm. Speeds of less than 300 rpm will develop little torque and will cause the centrifugal clutch to slip if an obstacle is encountered in the borehole.

A two cycle, 9 h.p. gas engine, with a reduction of 49:1 from engine shaft to boring spindle, constitutes the power unit of the General Equipment digger, model 51. The power head rests directly on the extensions providing additional downward pressure (Fig. 12). Two men are necessary for effective operation. The drill has been used in Mackenzie Valley and the Arctic Islands.

Figure 13 shows the power characteristics of the drill. With a boring spindle speed range of approximately 80 to 150 rpm, the peripheral speed of the coring tools is greatly reduced compared to the Haynes drill. Torque is in the 325 to 400 ft•lb range and is considerably higher than that developed by the Haynes drill.

The Stihl 4308 auger is mounted in the same manner as the General Equipment digger, that is, with the engine directly above the reduction unit and the entire power assembly resting on the extensions while in drilling position (Fig. 14). Power is provided by a two-cycle, 3.4 h.p. gas engine. This two-man drill has been used extensively in permafrost north of the -10°C ground isotherm (Fig. 1).

The drill is rated by the manufacturer at 354 ft•lb of torque for a maximum boring spindle speed of 50 rpm. Its principal characteristic is a high (150:1) engine to boring spindle reduction ratio which permits the development of torque similar to the General Equipment digger, model 51, despite a much lower horsepower output.

Figure 15 illustrates the peripheral speed generated at the outer cutting edge of three different sizes of modified CRREL core barrels, rotated by three different power augers. For example, a point located on the outside of a CRREL barrel shoe, 11.5 cm in diameter and rotated at 500 rpm, will travel at 179.5 m/min.

The Haynes drill generates the highest speeds at the borehole wall/core barrel interface. The performance of this power auger is related closely to its low torque/high boring spindle speed characteristic. In relatively warm permafrost (-5°C or higher) and at penetration rates of 30 cm/min or less, coring with an 11.5 cm O.D. barrel at spindle speeds of 360 rpm or higher will generate frictional heat at the core barrel/borehole wall contact resulting in the creation of a thin film of water on the cuttings held between the helical flights. Immobilization of the core barrel results in almost instantaneous freezing of the barrel to the walls. Ice-rich varved clays at slightly below 0°C (high unfrozen water content) in the vicinity of Thompson, Manitoba could not be cored successfully with the Haynes drill using an 8.9 cm O.D. barrel. The high rotational speeds liquefied the clays, rendering further coring impractical. At the same location, H. Baker, National Research Council (pers. comm., 1976) reported successful coring of the clays using a power auger with much lower boring spindle speeds. The development of "mud rings" (clay adhering to the core barrel surface) at the base of the barrel is common when coring clayey soils with the Haynes drill.

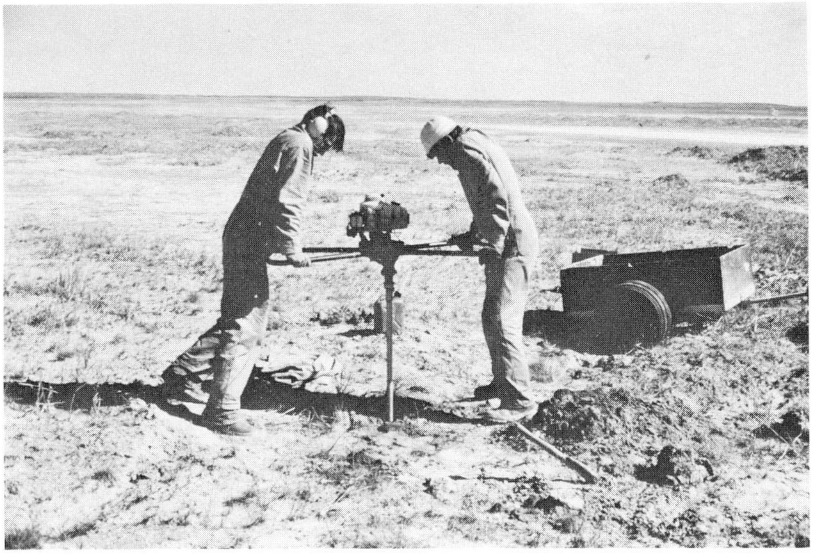


Figure 14

Stihl 4308 two-man auger used with a CRREL core barrel. (GSC 202921-H)

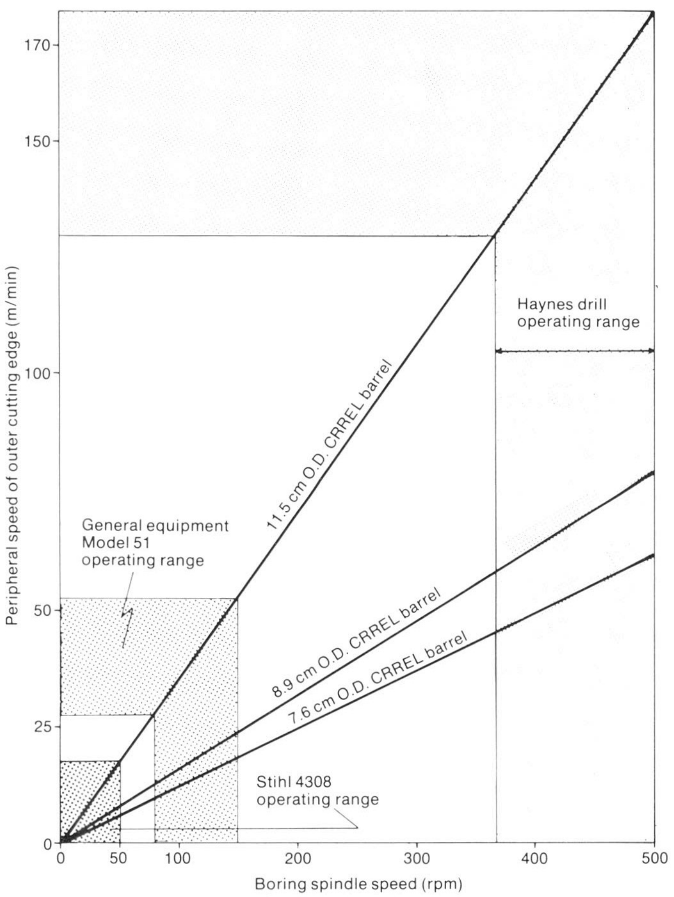


***Figure 15**. Boring-spindle speed vs. peripheral speed of outer cutting edge for modified CRREL barrels of 11.5, 8.9, and 7.6 cm O.D. used with three different power augers.*

The use of small diameter barrels (8.9 and 7.6 cm O.D.) minimizes these problems (Fig. 15), but the Haynes drill still produces much higher peripheral speed than those of the other two power augers. In the event of accidental jamming of cuttings near the base of the barrel, such high speed leaves little time for the drill operator to realize the situation and to withdraw the tool from the hole.

The Haynes drill is not easily man-portable and is the heaviest of the three power augers described here. Although the flexible drive is cumbersome, it can be carried in the rear compartment of most turbine helicopters.

Despite a substantial reduction in boring spindle speed and a large increase in transmission output torque, the General Equipment digger, when used with CRREL core barrels, is still susceptible to problems of binding the coring tool down the borehole. The auger is lighter and more compact than the Haynes drill and can be carried conveniently in a back pack or transported inside a helicopter.

The effect of very low boring spindle speed is only fully appreciated with field testing. Boring spindle speed of 50 rpm or less, such as produced by the Stihl 4308 drill, reduces the peripheral speed of the core barrel at the borehole wall/core barrel interface and improves the upward movement of cuttings. Although the problem of jamming the barrel in the hole is not eliminated completely, the slower boring spindle speed improves control of drilling. If a mud ring develops around the base of the barrel or if excessive amounts of cuttings pack in the helical flights, the labouring sound of the engine will indicate imminent jamming and warns the operator to raise the equipment before seizure occurs. This occurs with any power auger, but because of the higher spindle speed of the Haynes drill and the General Equipment digger, the time between the first labouring sound and the jamming of the barrel is often too short to permit the operator to take action to prevent seizure.

Low rotational speed slightly reduces the rate of penetration; however, this can be offset by keeping the cutters sharp, as even slight dulling will reduce the rate of penetration. Coring 3 m of quartz sand with a low ice content will dull fresh cutters to such a degree that the subsequent 3 m will take twice as long. An abundant supply of cutters should be taken to the field. Carbide cutters can be sharpened by a "greenstone" wheel on a generator powered bench grinder.

Table 1

Observed depth of penetration of a modified CRREL core barrel (5.1 cm core) for one run in a variety of frozen materials

Material	Penetration (% of core barrel length)	Natural water (ice) content (% by dry weight)	Ground temperature (°C)
Clean ice	60	–	<-10°
	40	–	>-10°
Sand, well bonded pore ice only	40-50	20-25	Any
Soils with 75% or more ice by volume	50	–	<-10°
	30	–	>-10°
Silt	40	25-30	<-10°
	30	25-30	>-10°
Clay	25	30-40	<-10°
	20 or less	30-40	>-10°

Note: Penetration values apply only to a core barrel held in vertical position; horizontal and inclined core barrel positions usually permit longer runs.

Weighing only 21 kg, the Stihl 4308 drill can be carried in a back pack or transported inside a helicopter. A locking ring chuck eliminates the need for a pin-type attachment between the boring spindle and the extensions of core barrel and permits quicker handling of extensions.

For successful coring in permafrost using CRREL core barrels, a man-portable power auger should have two important characteristics: 1) low boring spindle speed (50 rpm suggested) and 2) sufficient torque (350 ft•lb suggested). Power augers with maximum boring spindle speed between 50 and 80 rpm were not tested but also may be satisfactory.

These characteristics are of special interest to the buyer of a light-weight, man-portable power auger, as they allow optimum use of a small engine of relatively low horsepower. A high reduction ratio from the engine shaft to the boring spindle will produce high torque and low spindle speed. The Stihl 4308 drill ideally combines these characteristics.

As previously discussed, the CRREL barrel geometry is such that cuttings cannot be stored adequately between the helical flights if the full length of the core barrel is rotated into the ground. As a rule, 25 to 50% of the core barrel length can be advanced in the ground for each run using hand-held power augers. The same limitation applies to large rotary drills using the CRREL barrel, although advances in excess of half the length are possible in some frozen soils due to the greater torque and downward pressure produced by large rotary drills.

Table 1, based mainly on field performance data obtained with the Stihl 4308 drill, relates length of barrel advance for one run to moisture (ice) content, type of material, and ground temperature. These values are offered only as a guide, as length of run depends on many other variables, including operator experience. The -10°C ground isotherm is an arbitrary limit based on equipment performance at locations north of it. Generally clean, very cold ice is cored easily and permits long runs. Brittle cold ice breaks into chips which do not adhere together; warm ice, upon rotation in the core barrel flights, packs into a snow-like mass which causes bridging on the barrel head and may induce binding. Sand containing only pore ice is cored easily at any temperature. For ice with appreciable amounts of included soil, ease of penetration varies according to the texture of the inclusions, being poorer for clayey ice than for sandy ice. Cold silts of low ice content permit runs somewhat similar to those in sandy deposits. Cuttings from warm silts pack in the flights and cause blocking or bridging. Clay shows the poorest results as the unfrozen water favours the formation of mud rings at all temperatures, but more commonly in warmer permafrost.

For engineering projects where specifications call for continuous cores to shallow depths (5 m or less) and extensive borehole coverage in sand, silt, or clay, or exploratory testholes in gravels (chip samples), the use of low boring spindle speed, light-weight power augers adapted to rotate modified CRREL core barrels and continuous flight augers of small diameter should be considered. In remote locations where positioning costs of heavier drilling equipment commonly represent a substantial amount of the total project cost, it may prove economical to use one or more light-weight power augers in lieu of a larger drill.

For rapid drilling, without coring, continuous flight augers 6.5 cm diameter, using a 7.6 cm overburden drag bit, were used successfully with the Stihl 4308 drill in frozen glaciofluvial sands and gravels of northern District of Keewatin. Depths of 6 m were attained in about 30 minutes. Coring with a modified CRREL barrel had proved unsuccessful and augering was the only other method of exploring the gravels. Drilling was possible despite the well bonded nature, and the low temperature of the materials.

Man-portable Core Drills Used With a Circulating Fluid

Two light-weight diamond drills were used in permafrost – the GW-4 Winkie and the GW-15 Winkie. These drills require a fluid circulating through the drill rods to remove cuttings at the bit face to cool the bit. Specifications and some field results obtained with the GW-15 Winkie drill will be presented after an introduction to the equipment and methods required for diamond drilling.

Diamond Drilling Equipment

Of all the techniques used in the drilling and coring of frozen ground, diamond drilling requires the most elaborate equipment. Furthermore, the quality of the resulting core is highly dependent on the skill and experience of the operator. Because diamond drilling is used extensively for mineral exploration where moves between drill sites are less frequent than those of most soil sampling projects, the equipment is generally poorly suited to frequent displacements. The requirement of an adequate supply of drilling fluid at, or transported to, the drill site reduces mobility and may add considerably to logistical costs. Despite these limitations, when penetration or coring of frozen materials, such as coarse gravels, very stony tills, weathered or competent bedrock, or continuous coring to great depths is specified, diamond drilling is recommended.

Table 2

Outside diameter dimensions for drill rods and weight per 10 foot rod length with coupling for the W series rods

Letter designation	Rod O.D. (inches)	Weight of 10 foot rod with coupling (lb)
EW	1 – 3/8	30
AW	1 – 23/32	38
BW	2 – 1/8	50
NW	2 – 5/8	55
HW	3 – 1/2	96

The suitability of the technique in securing undisturbed samples of frozen materials that are inaccessible to augering or driving equipment has been demonstrated by Hvorslev and Goode (1963), Lange (1963), and Isaacs and Code (1972). Several recent private drilling projects using fluid circulation systems with diamond drills or large rotary rigs were conducted with success in Mackenzie Valley area. Drilling projects carried out in 1975-1976 along the proposed Polar Gas Pipeline route on the west coast of Hudson Bay and in the Arctic Islands, in which difficult stony tills and weathered rubble were encountered, relied heavily on diamond drilling to obtain subsurface information.

Diamond drills are available in a wide variety of sizes and types, but are distinguished from other types of rotary earth drills by their high drill spindle speed. Large rotary drills seldom exceed spindle speed of a few hundred rpm, but diamond drills commonly operate in the 1000 to 2000 rpm range. Functions common to all rotary drills include a means of hoisting, pushing down (feed), rotating drill rods, and circulating a fluid to the bit face.

Drilling machines, although similar in function, are not standardized, but drill rods, casing, core barrels, and diamond bits are formalized into standard systems which permit interchange of equipment between manufacturers. Two major sets of standards are in worldwide use: the Metric standard, which predominates in Europe, and standards developed in English speaking countries. The Canadian standards described here result from efforts between CDDA (Canadian Diamond Drilling Association) and DCDMA (Diamond Core Drill Manufacturers Association) of the United States and BSI (British Standards Institution) of Great Britain.

In North America, drill rods with size designations E, A, B, N, and H although still in use, gradually are being replaced by the "W" series of slightly larger diameter (Table 2). The W series has the following advantages: reduced vibration, less danger of caving, more rapid return of sludge, increased water capacity through the drill string, and better equalization of water flow inside and outside the rods (Cumming, 1971).

The weight per 10 foot rod in Table 2 is for steel; special magnesium alloy (ZK60A)* drill rods and couplings (magnesium zirconium rods) are also available and are less than 25% the weight of steel. Comparing ZK60A alloy of typical yield strength 40 000 psi and specific gravity 1.79 with steel of yield strength 100 000 psi and specific gravity 7.9, the strength/weight ratios are:

$$\text{Steel} \quad \frac{100\,000}{7.9} = 12.65$$

$$\text{ZK60A} \quad \frac{40\,000}{1.79} = 22.4$$

Magnesium zirconium rods of AW and BW sizes were used in projects involving light-weight drilling and coring equipment and proved effective in saving freight costs and permitting faster and easier handling of rods.

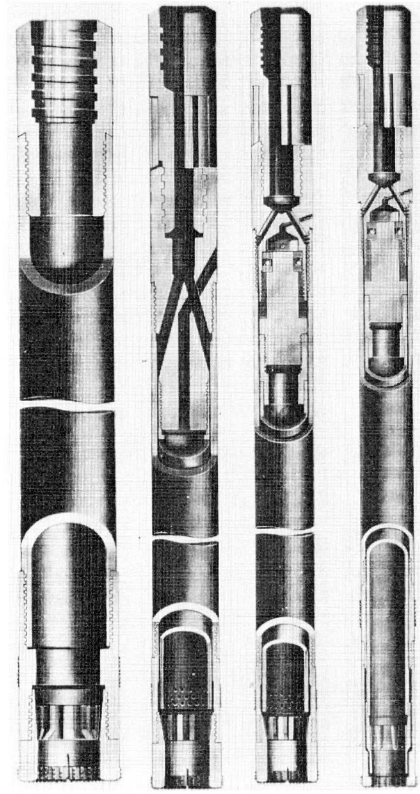


***Figure 16**. The four basic types of diamond drilling core barrels: from left to right, single tube, double tube rigid-type, double tube swivel-type, and double tube swivel-type M series (adapted from Acker, 1974). (GSC 202921-W)*

Core barrels are grouped into single tube, double tube rigid-type, and double tube swivel-type barrels (Fig. 16). Only the set core bits, set reaming shells, and core lifters for barrel designs are covered by standards (Table 3).

The single tube core barrel has an upper threaded end and a reaming shell to which a core lifter and bit are threaded (Fig. 16). The drilling fluid enters from the top and passes between the inside of the barrel and the sample, washing the entire length of the core. The primary use of this barrel is to core compact rock. It is used to drill holes in frozen ground when core recovery is secondary, as the fluid washes directly on the core and often destroys it completely. Occasionally, cores of frozen peat, only slightly disturbed, may be obtained with this tool.

* Data from Aerometal Products and Design Limited, Toronto, Ontario.

Table 3

Core barrel designs and bit dimensions conforming to DCDMA, CDDA, and BSI standards (A), and Boyles nonstandard WL wireline series (B)

A

CORE BARREL DESIGN				CORE BIT					
WF	WG*	WM	WT	O.D. set (inches)	I.D. set (inches)	Kerf width (inches)	Hole diameter (inches)	Core diameter (inches)	Core-to-hole ratio (area)
			RWT**	1.160	0.735	0.220	1-3/16	23/32	39.1%
	EWG	EWM		1.470	0.845	0.320	1-1/2	13/16	32.4%
			EWT	1.470	0.905	0.290	1-1/2	7/8	37.1%
	AWG	AWM		1.875	1.185	0.352	1-15/16	1-3/16	39.3%
			AWT	1.875	1.281	0.304	1-15/16	1-9/32	45.9%
	BWG	BWM		2.345	1.655	0.352	2-3/8	1-5/8	49.1%
			BWT	2.345	1.750	0.305	2-3/8	1-3/4	55.0%
	NWG	NWM		2.965	2.155	0.412	3	2-1/8	52.2%
			NWT	2.965	2.313	0.333	3	2-5/16	60.2%
HWF	HWG			3.890	3.000	0.453	3-15/16	3	59.0%
			HWT		3.187	0.360	3-15/16	3-3/16	66.5%
PWF				4.725	3.627	0.560	4-3/4	3-5/8	58.4%
SWF				5.725	4.439	0.654	5-3/4	3-7/16	59.7%
VWF				6.840	5.505	0.682	6-7/8	5-1/2	64.2%
ZWF				7.840	6.505	0.682	7-7/8	6-1/2	68.3%

*Formerly X series
**Formerly XRT
Adapted from Canadian Standards Association (1972)

B

Core barrel design WL	O.D. set (inches)	I.D. set (inches)	Hole diameter (inches)	Core diameter (inches)	Core-to-hole ratio (area)
AWL	1.875	1.062	1-15/16	1-1/16	30.2%
BWL	2.345	1.433	2-3/8	1-7/16	33.7%
NWL	2.965	1.875	3	1-7/8	39.1%
HWL	3.762	2.500	3-51/64	2-1/2	43.4%

The double tube rigid-type core barrel consists of an inner and outer tube which are attached to the barrel head and rotate with it. The drilling fluid passes between the inner and outer tubes to the bit, exposing only a short section of core to the washing action of the drilling water (Fig. 16). The barrel is designed for use in hard to medium hard, compact to slightly fractured bedrock. The core touches the rapidly rotating walls of the inner tube and thus is exposed to wear and erosion. This barrel is not recommended for coring of frozen ground.

The double tube swivel-type core barrel also consists of an inner and outer tube, but swivel bearings allow the inner tube to remain stationary while the outer tube rotates. As the core slips inside the inner tube, it is protected from the drilling fluid and the wrenching and eroding action of a rotating tube (Fig. 16). The inner tube in the M series may be adjusted so that its lower end rests only slightly above the inside of the bit crown, exposing a small portion of the core to the drilling fluid.

This type of barrel is used to core friable shattered bedrock, and in frozen ground it outperforms the designs previously described and has been used successfully with light-weight drills to core a variety of soils. When used in conjunction with face discharge bits, part of the drilling fluid is diverted through holes in the bit crown, thus reducing the amount of fluid in contact with the core and reducing core damage.

The triple tube swivel-type core barrels are essentially double tube swivel-type core barrels in which a third tube is inserted to give additional protection to the sample. Such barrels often are used in friable coal beds. The innermost tube commonly consists of plastic tubing split lengthwise to permit removal of a core in the same way that a split tube core is removed.

The triple tube barrel is not believed to outperform significantly the double tube M series barrel in frozen ground, because the main difference is the increased thickness provided by two inner tubes. In some cases, this thicker protective envelope may minimize core damage, especially when drilling with water above 0°C. Erosive action of the drilling fluid, however, occurs mainly at the bit face and in the gap between the bottom of the inner tube and the inside of the bit and often is as serious in the triple tube barrel as in the double tube type. Isaacs and Code (1972) claim 90 to 95% core recovery using NX size swivel-type triple tube barrels and water as a drilling fluid with a GW-15 Winkie drill in permafrost.

Core barrel designs (Table 3) refer to specific characteristics common to a group. The WF design is available only in large sizes commencing at HWF. The main features are a double swivel-type design, unattached core lifter case, and face discharge bits. It is commonly used with mud fluids.

The WG design has a medium width kerf (the annular groove cut by a coring bit) bit and comprises the double tube rigid design (formerly X series). Sizes EWG and NWG can be converted from rigid to swivel-type by replacing the barrel heads with those of the WM design.

The WM design is also a medium kerf bit design and cuts the same size core as the WG. It features a double tube swivel-type design and internal fluid discharge close to the bit face. Barrel head dimensions are the same as on the WG design. They are not available in sizes larger than NWM.

The WT design has a narrow kerf and larger core design. Basically of double tube rigid-type, it can also be converted to double tube swivel-type in the larger sizes.

Wireline core barrels constitute the last important group of coring tools not yet covered by standards (Table 3). A wireline barrel is basically a double tube swivel-type barrel in which the inner tube containing the core can be brought to the surface through large diameter drill rods while the outer tube remains in the hole. The wireline technique introduced some thirty years ago is now used widely in diamond drilling and often has proved successful in situations where conventional barrels have failed.

Advantages of the wireline technique in permafrost drilling are numerous. The large diameter drill rods, slightly smaller than the coring bit, act as casing by preventing accumulation of debris on the barrel head. When drilling at air temperatures above 0°C, the coring tools are left in the borehole at all times and are cooler, and thus closer to ground temperature, than they would be if brought to the surface often. Finally, the technique saves considerable time in rod handling during deep coring.

On the other hand, the core-to-hole ratio (Table 3) is lower than for conventional barrels, and when large cores are specified, heavy drills must be used to handle the wireline coring tools, adding to the overall operational costs. Small drills and light-weight portable drills are not suited to the use of wireline equipment. In recent years numerous cases of successful coring of permafrost using the wireline technique with large drilling machines have been reported from the Canadian Arctic.

Both coring and noncoring diamond bits are available in a variety of configurations and diamond settings adapted to rock conditions, but little research has been done for use in frozen ground. Hvorslev and Goode (1963) experimented with both carbide inserts and diamond bits in various soil-ice mixtures, but the optimum designs for frozen soils have not yet been determined.

As diamond bits are used mainly for coring frozen tills or gravels and soils containing materials that are difficult to penetrate by any other means, it is not always possible to select a bit that will be suited to the heterogeneous texture and hardness of such deposits. In bedrock drilling practice, the rule-of-thumb calls for a few cutting stones per carat (unit employed in weighing gem stones; most countries have adopted 200 mg or metric carat) for soft rocks, with the number of stones per carat reaching a maximum for hard rocks. Due to the possible variability of hardness of unconsolidated coarse textured deposits in a single hole, bits usually are selected based on an intermediate size of stones, 25 to 40 per carat. A high density of cutting stones (100 per carat) results in a slow drilling rate in sticky soft material.

Although the density and arrangement of cutting stones are important, the configuration of the bit, relating to the passage of the drilling fluid at the bit face, is of special importance in permafrost work. Restricted waterways at the bit will cause excessive fluid pressure on the core which results in thawing and damage. Therefore, bits with a configuration that diverts some of the incoming fluid away from the core are most popular, and the face-discharge coring bit (Fig. 17) generally is specified. Minor modifications to standard face-discharge bits, such as enlargement of waterways and enlargement of the holes through the crown of the bit, in some cases have increased core quality. The effectiveness of the holes through the bit crown in diverting fluid away from the core often is reduced due to clogging by fine material, which has to be removed frequently. Enlarged waterways are probably more effective. Table 3 shows bit dimensions relative to barrel design.

Noncoring bits used primarily in blast hole drilling are of little concern to investigators interested in obtaining detailed subsurface information on frozen soils. Their use, however, provides a rapid means of drilling holes in stony material for the purpose of installing borehole instrumentation. Figure 17 shows two types of non-coring bits.

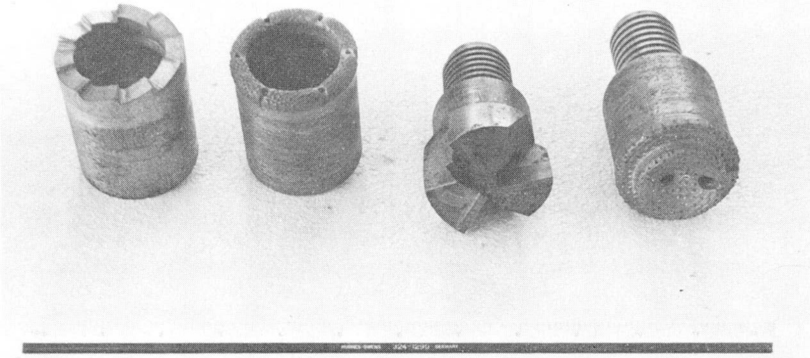


Figure 17

Bits used with the GW-15 Winkie drill in frozen soils: from left to right, coring carbide bit, face-discharge diamond bit, non-coring three-wing drag bit, and non-coring concave diamond bit. (GSC 203205-D)

Drilling Fluids and Pumps

Water is the most common fluid circulated in diamond drills, although the use of muds, developed largely for oil drilling, is gaining popularity where difficult overburden conditions are encountered (Gray, 1970, 1971). Drilling muds seal highly fractured rock or permeable unconsolidated material, facilitate the positioning of casing, and increase core recovery. Common drilling fluids used in permafrost are: fresh water; calcium chloride and sodium chloride brines in varying strengths cooled below 0°C; and fuel oil cooled below 0°C. All drilling fluids serve the dual purpose of removing cuttings and cooling the bit.

Coring permafrost, even at relatively shallow depths, using fresh water in uncased boreholes causes problems, mainly due to thawing of permafrost by the fluid. This method is not recommended if continuous, high quality cores are desired. It is, however, the simplest and least expensive method to apply, and under certain conditions will provide cores of sufficient quality for estimates of ice contents and for soil index engineering tests. A considerable amount of drilling using portable diamond drills and water as drilling fluid was carried out in the summers of 1972-76 in the Arctic between 61°N and 81°N.

Solutions of sodium chloride (common salt) and calcium chloride are the usual brine drilling fluids. Hvorslev and Good (1963) preferred sodium chloride to calcium chloride because the former absorbs heat when dissolved, whereas the latter produces heat during solution and is more corrosive.

Ordinary Arctic Grade fuel oil also may be used in coring frozen ground. Lange (1963) and Isaacs and Code (1972) completed some holes using fuel oil cooled by a mechanical refrigerating unit during summer. For drilling at low air temperatures, fuel oil can be used without refrigeration (Hughes et al., 1974).

Special water-base muds with potassium chloride and polymers were used successfully to core frozen soils (Northern Engineering Services Ltd., Calgary, pers. comm., 1975). Such muds normally are used with large rotary drills and pumps and require a double-wall core barrel with a large annular space. These constraints prevent their use with standard coring tools and light-weight drills.

The recovery of both physically and thermally undisturbed cores in a variety of frozen material using drilling fluids with a freezing point depressed below 0°C has been demonstrated by several workers and drilling contractors in recent years. The main limitation for summer operations is the cost of elaborate mechanical refrigerating units required to cool the drilling fluid below 0°C (Isaacs and Code, 1972; EBA Consultants Ltd., Edmonton, pers. comm., 1976). The fluid also can be cooled by dumping ice and snow or dry ice in the slush tank. Hvorslev and Goode (1963) describe simple cooling units equipped with an ice or snow filled chamber. Drilling projects of Terrain Sciences Division involving portable drilling equipment relied mainly on fresh water in summer and fuel oil in winter as circulating drilling fluids.

The simplest drilling fluid circulation equipment, that is, general purpose pumps and small slush tanks, has been used with light-weight diamond drills. Three categories of pumps were tested in the field: gear, progressing cavity, and centrifugal; the latter was found to outperform the other types.

The centrifugal pump is popular for various domestic and industrial applications. Flow results from the action of a rotating impeller, and the pump will not stall if circulation is blocked. Its high volume/low velocity characteristics and internal clearances make it better suited to the coring of frozen ground. The model shown in Figure 18, used with both

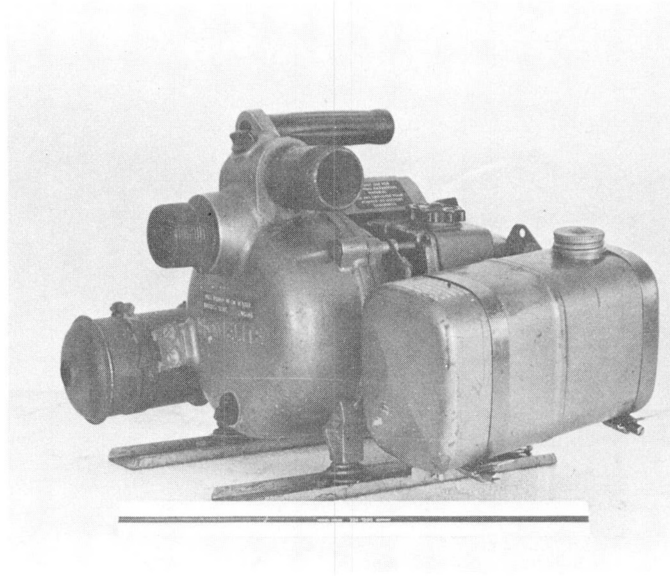


Figure 18. *Compact XL Homelite centrifugal pump used with the GW-15 Winkie drill. (GSC 203205-C)*

fresh water and fuel oil, with a capacity of 182 L/min and 60 psi pressure, definitely outperforms the other types of pump.

The progressing cavity pump is widely used with small diamond drills circulating water for coring hard rock. The pump drive is connected to the output shaft of a small gas engine by a flexible coupling (Fig. 19). The basic components of the pumping mechanism consist of a helical stainless steel rotor enclosed in a synthetic rubber stator. The spinning of the rotor creates "progressing cavities" which carry the drilling fluid and its material load towards the discharge port. The pump is self-priming and easily maintained.

The progressing cavity pump proved unsatisfactory for coring frozen soils with water. Drilling in sandy, abrasive soil results in rapid wear of the stator due to the large quantity of sludge (fine cuttings produced by the drill bit) generated by hole enlargement, necessitating frequent replacement. Its low volume/high pressure characteristic also accelerates erosion at the bit face, resulting in frequent core damage. The model used in the field, with a capacity of about 27 L/min and a pressure of 125 psi, performed poorly in coring frozen sand with fresh water; excellent results were obtained coring frozen sand and other materials using fuel oil cooled below 0°C.

The gear pump, whose performance is equivalent to the progressing cavity pump, was used to a lesser extent.

Experimentation With the GW-15 Winkie Drill in Frozen Soils

The GW-15 Winkie drill has been used primarily by geologists and prospectors for shallow (50 m), mineral exploration drilling. It consists of a 10 h.p., two-cycle, air-cooled gasoline engine with the drive shaft mounted vertically in a transmission assembly containing the clutch, gear box, and water swivel (Fig. 20). Power is transmitted from the engine shaft to the reducing gears through a centrifugal clutch. A two-speed transmission and a removable reduction unit (for augering) produce the full range of spindle speeds and torque shown in Table 4. A press supports the drill and permits application of downward pressure and lifting by a hand-wheel (Fig. 20). A base

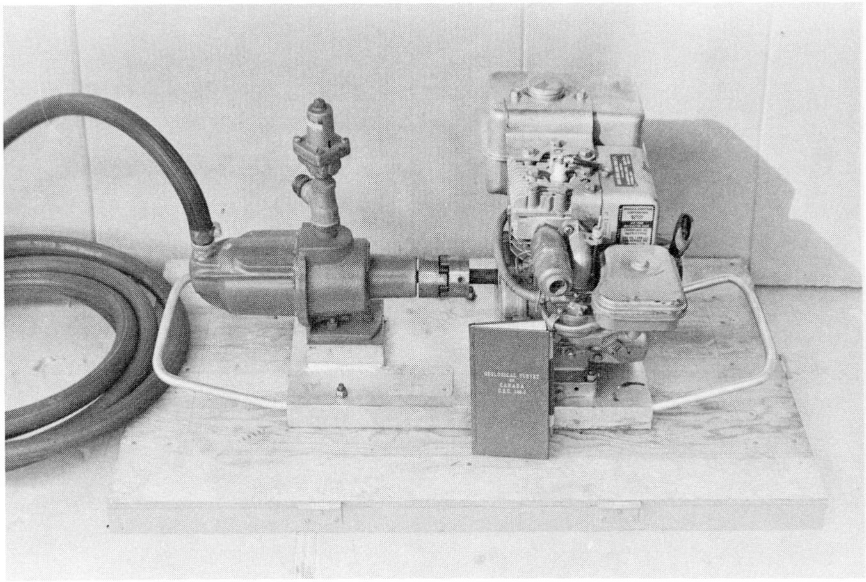


Figure 19

Robbins and Meyer progressing cavity pump. (GSC 203205-O)

Figure 20

GW-15 Winkie drill mounted on a base and positioned at a drill site: (1) drill, (2) adjustable back stays with sling, (3) base, (4) lifting wheel, and (5) press guides. (GSC 316-5)

consisting of a wooden or metal sledge and telescoping back stays, locked in place with bolts, may be added to allow removal of the drill head from above the hole while handling rods. The sledge also may act as a base for the pump. This arrangement is a self-contained unit, weighing approximately 125 kg and well suited for helicopter transport in sling loads.

Following summer field trials in permafrost with the GW-15 Winkie drill (Isaacs and Code, 1972), which showed the difficulty of handling heavy coring equipment with the drill, Hughes et al. (1974) conducted further experimental testing during winter 1972-73 to assess the potential of the drill for shallow (10 m) permafrost coring. As most frozen ground coring for engineering purposes is done with large diameter (N-size or larger) equipment, the reliability of small diameter core barrels (A and B sizes) used with chilled fuel oil had to be assessed before departure for the field. An artificial "permafrost" pit, 2.4 m deep, 1.2 m wide and 2.4 m long, divided in sections containing ice, ice-rich gravels, sands, and moderately stony "till", was prepared in Calgary in early winter 1972-73 to test drilling equipment and procedures.

Standard core barrels of 1.5 m length were considered undesirable due to the high risk of core damage resulting from a continuous run of that length and the additional physical effort involved in handling long barrels. For the trials, barrels were shortened to accommodate 90 cm of core, and AWM, BWM, and NWM double tube swivel-type core barrels were tested. The bits used were of the face-discharge type, and reaming shells were left blank. A-size magnesium zirconium drilling rods in lengths of 92 cm and 1.52 m were used rather than steel rods. A small sheet metal slush tank weighing 12.7 kg with an 11.5 cm O.D. collar extending 18 cm below the bottom of the tank was built. Holes were started to 20 to 25 cm depth using an 11.5 cm O.D. modified CRREL barrel. The collar of the tank fitted tightly with the borehole wall, thus preventing loss of fluid at the surface. A Robbins and Meyer progressing cavity pump was used to circulate the chilled fuel oil (Fig. 19).

The results obtained at this experimental site were helpful in selecting suitable accessory drilling equipment for frozen ground coring. BWM double tube swivel-type core

Table 4

Range of boring-spindle speed and torque for the GW-15 Winkie drill

				with reduction unit (6.5:1)	
Engine rpm	Torque ft•lb	Spindle rpm	Torque ft•lb	Spindle rpm	Torque ft•lb
High speed: Reduction from engine to drill spindle (3:1)					
8000 to 4000	Average 6	2667 to 1333	Average 18	410 to 205	Average 110
Low speed: Reduction from engine to drill spindle (7:1)					
9000 to 3500	Average 6	1286 to 500	Average 42	198 to 77	Average 270

barrels and bits (2-3/8 inch diameter hole, 1 5/8 inch diameter core) were preferred to the smaller A-size equipment, which had higher core breakage, and to the larger N-size equipment, which was more difficult for the drill to handle. The main result was that cores of coarse material, such as sandy gravel, well bonded with ice, could be obtained with little disturbance, despite the relatively small diameter of the core. This experimental work led the way for a drilling program in early spring 1973.

Drilling With Fuel Oil Cooled Below 0°
A Field Example and Evaluation

From mid-March to late April 1973 drilling was carried out within a radius of 40 km of Old Crow village, northwestern Yukon Territory and in the Bathing Lake area, 100 km south of Inuvik, Northwest Territories. The objective in the Old Crow area was to investigate the thickness, texture, ice content, and engineering properties of the unglaciated deposits covering long pediment slopes. Attempts at coring, using a Haynes power auger with CRREL barrels, in summer 1972 (Hughes et al., 1974) had met with refusal at 1 to 2 m. In the Bathing Lake area hummocky moraines of clayey stony till, considered too difficult for augering, were selected for diamond drilling, with the same objectives as in the Old Crow area.

From mid-March to early April air temperature at Old Crow ranged from about -40° to -10°C. Temperatures of -30°C or lower adversely affected the motorized equipment (drill and pump). Weekly ground temperature readings taken later in a borehole (drilled April 3, 1973) at Old Crow provide an estimate of the ground temperature at the time of drilling (Fig. 21). As drilling was conducted in late winter, ground temperatures were probably even lower than those shown by the January 25th profile in Figure 21. In the Bathing Lake area ambient temperatures were considerably milder than at Old Crow, especially in late April; air temperatures around 0°C were recorded often during early afternoon on sunny days. The ambient temperatures were sufficiently low at all times to keep the drilling fluid, Arctic Grade fuel oil, below 0°C.

Drill sites, previously selected on aerial photographs, were visited and where necessary were cleared of trees to permit landing. A Hughes 500C helicopter was used because of its small main rotor diameter (8 m); at sites with dense tree cover, cleared areas 10 x 25 m were sufficient for the helicopter to manoeuvre with a light sling load. An area roughly 4 x 4 m then was cleared of snow to receive the

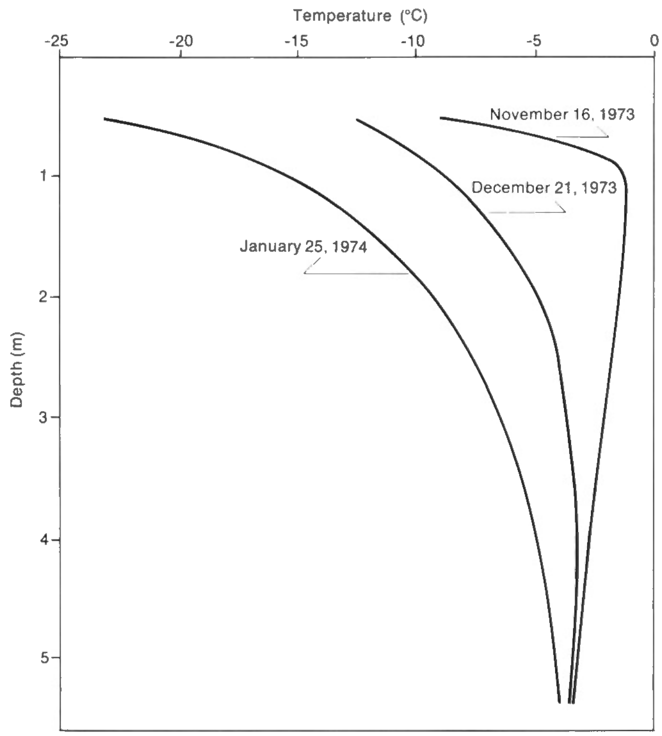


Figure 21. *Ground temperature profile, Old Crow, Yukon.*

GW-15 Winkie drill and accessory equipment. The two main sling loads consisted of the drill itself and a tool box and work bench combination used for extruding cores (Fig. 22) and for minor field repairs. The drilling fluid was kept in 45 L kegs and was carried inside the aircraft. Two core barrels were used interchangeably during drilling, with one man extruding core from one barrel and logging, while the other two drilled with the second barrel.

Little core description was done in the field. After extraction, cores were placed in air-tight plastic sleeves, labelled, and brought to base camp every day. All cores were described in detail for ice structure, ice distribution, and lithology. Representative samples for engineering index tests were selected, and a close range, colour photographic record of all cores (1000 slides) was kept. At Old Crow, a storage

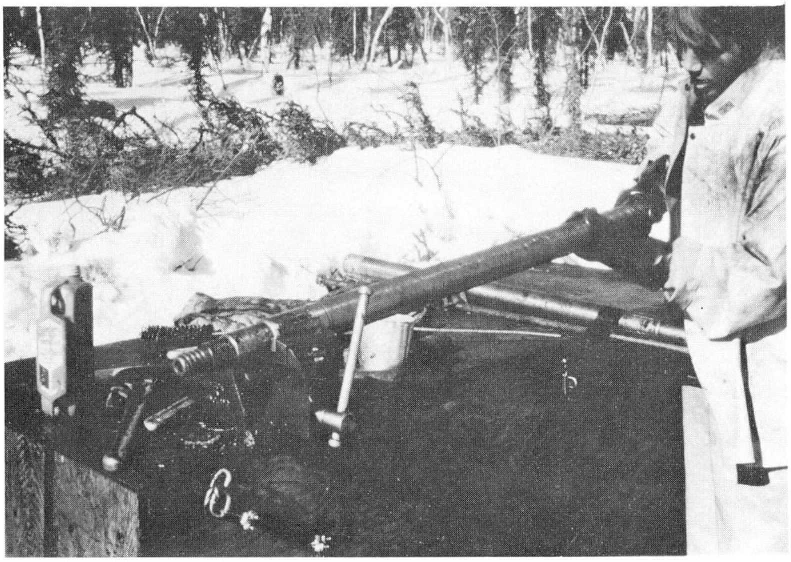


Figure 22. Extruding core on helicopter-portable tool box and work bench combination. (GSC 202921-K)

area kept slightly below 0°C was used for core description. For the second phase of the program, Bathing Lake area, core description was done at the Inuvik Research Laboratory.

A total of 35 shallow holes were drilled in the Old Crow and Bathing Lake areas in deposits in which attempts at augering had failed. Coring was performed in a variety of coarse textured frozen material including weathered granites, carbonates, and conglomerates; glacial sediments such as clayey silty till containing clasts of sandstone, shale, limestone, and quartzite; and glaciofluvial sand and gravel. Core recovery was high (85%), and core damage was limited mainly to minor thawing of ground ice on the outside of the core samples. The following observations and conclusions resulted from the project:

- using fuel oil cooled considerably below 0°C, diamond drill permafrost cores as small as 1 5/8 inch diameter can be secured with a high recovery rate to depths of 10 m in uncased holes. Typical cores obtained in weathered granite and quartzite, stony clayey till, and sand and gravel are shown in Figure 23.
- A diamond drill weighing less than 75 kg is satisfactory for securing core samples to 10 m depth.
- About 65 to 90 L of fuel oil, including the oil circulating in a small volume slush tank, is sufficient to drill a 6 to 7 m B-size hole. Most of the fuel oil can be recovered after completion of the hole; most holes were drilled with a total loss of less than 20 L.
- Loss of circulation occurred on three occasions 1 to 2 m below the surface of stony, well drained morainic ridge crests, and drilling had to be stopped. These were the only examples of "dry permafrost" encountered, and casing would have been necessary before circulating the fluid.
- A high drill spindle speed in excess of 1500 rpm, with moderate downward pressure, produces satisfactory penetration rates in sandy and silty till deposits. In lag gravel and in weathered bedrock consisting of large clasts in a matrix of sand and silt, better results were obtained by using the maximum downward pressure attainable while maintaining maximum drill spindle speed.
  - Drilling massive "cold" clear ice with diamond bits is very slow (5 to 10 cm/min). Where substantial massive ice concentrations are suspected, diamond bits set with few coarse stones (5 to 10 per carat or less) or with carbide inserts are preferable.
  - Tiny ice chips circulating in the fuel oil at air temperatures of -20°C or lower accumulated at points of restricted flow in the circulation system and blocked circulation completely, necessitating the withdrawal of the coring tools from the hole for cleaning. The chips and fuel oil formed a sludge which commonly blocked circulation in the barrel head just above the waterways. This usually occurred after an interruption of circulation, which allowed the ice chips to settle in the barrel head. The problem was minimized by adding small amounts of methyl hydrate to the drilling fluid and by shielding the foot valve of the suction hose with layers of mosquito screening.
  - Fuel oil will cause swelling of the rubber shut-off valve in the head of core barrels to the point where circulation is blocked; at air temperatures above -20°C the problem did not occur. The situation can be corrected by removing the outer 3 to 5 mm of the washer-type valve with a pocket knife.
- Excellent undisturbed cores were obtained consistently in most material at fluid temperatures of -25°C or less.
- Core thawing was frequent at fluid temperatures above -5°C except in well bonded sands. Clayey silty till cores were most susceptible to damage at depths of more than 3 m. Assuming ground temperature at 3 m to be about -6°C (Fig. 21), clay and clayey soils (Fig. 4) could have as much as 16% unfrozen water content which probably explains the difficulty in obtaining good cores in this material. One hole drilled in clay in the Bathing Lake area had to be abandoned at 4 m due to gradual thawing of its walls, which resulted in a thick fuel oil and clay mixture which the pump could not handle. Figure 24 shows cores of till exhibiting partial thawing.
- Core breakage was high and unbroken sections of 30 cm or more were rare, except in sandy, ice-bonded, pebble free deposits of low segregated ice content. Breakage was reduced with increasing core diameter.

Although B-size (1 5/8 inch) core is sufficient to provide adequate stratigraphic information and samples for index engineering tests, the core is too small for most other engineering tests. NWM (core diameter 2 1/8 inches) short barrels, powered by the GW-15 Winkie drill, were used on a subsequent project in stony tills of the Eskimo Point area, west of Hudson Bay. The larger size of these barrels generally does not permit the application of sufficient bit pressure for effective coring. Large increases in pressure frequently result in stalling of the barrel due to clutch slippage.

Drilling With Fresh Water in Summer

A decision to use a light-weight diamond drill with water as drilling fluid in permafrost must take into consideration serious inherent limitations. Chances of successfully coring tills with moderate to high stone contents, gravelly soils, or any deposits containing large rock clasts are extremely low. The -10°C ground isotherm is proposed as the southern limit for consistent successful diamond coring of ice, sand, silt and clay, using fresh water.

The GW-15 Winkie drill, with basically the same accessory equipment as that described for winter drilling, was used during summer at various locations in the Arctic Islands, and the GW-4 Winkie drill in lower Mackenzie Valley. The GW-4 Winkie drill has the same components as the GW-15, except for a high and low speed transmission. It is strictly a hand-held drill and is not mounted on a frame. Commercial production of this model is discontinued.

For helicopter-supported projects, the equipment is moved in slings between drill sites. If water is not readily available at the drill site, a bucket consisting of a 205 L barrel with the top removed and attached to a sling is used to scoop water from nearby ponds, lakes, or rivers. When drilling without helicopter support, equipment can be moved on the ground by all-terrain vehicles or, for short moves (a few hundred metres), by a two to three-man crew.

In summer, drilling must penetrate the active layer. As in winter drilling, casing is not used due to the frequent moves (up to 4 per day) between holes. Anchoring the drill with metal pins through the active layer is not practical; if it is necessary to stabilize the drill base, a piece of plywood loaded with loose soil is laid across the sledge. A narrow trench is dug to the frost table on which the slush tank rests.

No matter how carefully these preparations are made, it is only a matter of time before the top of the borehole thaws and is enlarged. If penetration is rapid, 1 to 2 m of frozen ground can be drilled before seepage between the tank collar and the borehole walls takes place. After the top of the hole has become enlarged, the slush tank is of little use; but the inside of the trench, even in sandy soils, by then often is lined with the fine sludge from the borehole which acts as a sealant. Generally one barrel of water is sufficient to drill a 6 m hole.

Thawing of the borehole top and excessive enlargement can be reduced considerably by casing to 1 to 2 m below the frost table in a dry hole and allowing the casing (e.g. plastic pipe) to freeze to the inside of the hole. Drilling below the casing using water circulating inside the casing pipe, however, rapidly loosens the pipe and return water is forced between the hole walls and casing, resulting in an increasing loss of water with depth.

Low ground temperatures (-10°C or less) and using circulating water only slightly above the freezing point (0° to 3°C) greatly improve core recovery. Those conditions are characteristic of the Arctic Islands and northern mainland. Field results lead to the following observations:

- undisturbed core recovery in gravelly soils is poor at all latitudes.
- Penetration rates of 30 cm/min or more produce good cores.
- Drilling in ice-bonded silts and sandy silts containing small segregated ice lenses commonly results in high quality cores and high core recovery.
- Poorly ice-bonded medium and coarse sand or ice-rich sand will be washed readily by water and result in less than 50% recovery or even total loss. Sand cored at a high rate of penetration occasionally will produce excellent cores (Fig. 25).
- Massive, clean, "cold" ice can be cored using fresh water but more slowly than sand, silt, or clay. Slow drilling (5 to 10 cm/min) may result in partial thawing of the core (Fig. 25).
- Core recovery is generally high in clay, but frequently the ice is etched to below core surface; cores with large quantities of segregated ice show maximum disturbance.

Given the uncertainty of coring results using a light-weight diamond drill and fresh water compared with dry coring with the CRREL barrel or drilling with a liquid chilled below 0°C, one may raise the question of the usefulness of the method. The selection of this method can only be assessed in terms of the program objectives. Users disenchanted with a particular technique often compare the performance of one piece of equipment to another without considering the respective merits and limitations of each piece of equipment and the conditions surrounding its application. Diamond drilling with water usually will not produce cores in gravelly or rubbly permafrost but will permit location of coarse grained layers and will indicate their thickness which is not always possible with a hand-held power auger or a drive sampling tool. Light-weight diamond drills have provided holes for instrumentation in difficult soils, installation of bench marks, and proving bedrock. The coring of gravelly and stony frozen soils remains problematic, regardless of the type and size of equipment used.

Man-portable Noncoring Equipment and Methods

Water-jet Drilling

Water jetting at pressures of 100 to 150 psi is a proven method of preparing vertical exposures for stratigraphic investigation. The basic technique consists of washing away the thawed material to expose the underlying permanently frozen soil, and in some cases to cut into permafrost.

Jetting has been used to dislodge drilling and coring tools which have become stuck in a borehole and subsequently have frozen in the drilling water. A string of drill rods is assembled and a water swivel is attached at the top. Water is pumped through the rods, which are lowered down the hole, to the top of the core barrel. Usually a few minutes of washing enlarges the borehole so that the tool can be freed.

Using 2.54 cm I.D. steel pipe and a Wajax Mark 26 centrifugal pump generating 150 psi, Judge et al. (1976) penetrated 20 m of frozen sand and silt in 55 minutes at Tuktoyaktuk, Northwest Territories, and installed a thermistor cable for temperature measurements. Mackay (1977b) reported drilling 23 m through a pingo using this technique.

Drilling by the water-jet method only requires a pump with sufficient pressure and a string of pipes. The major drawback is the requirement of a supply of water near the site. Where water supply is limited, recirculation of water via a slush tank or an excavation at the surface for sedimentation of sludge will reduce the water requirement. This method is strictly for drilling and cannot provide core or reliable sludge samples.

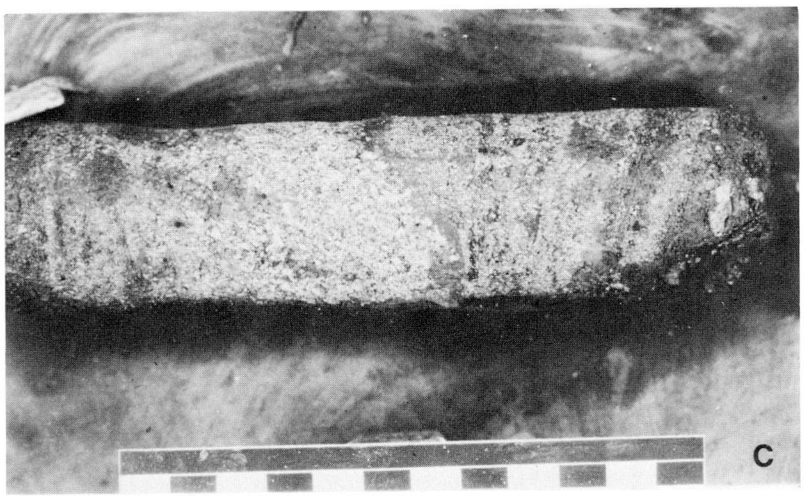
Dual-purpose Rotary Hammer

Electrically driven rotary hammers (Fig. 26), operating on a combination of electrical and pneumatic action, have been used for digging shallow trenches and pits in permafrost. A variety of tools can be attached to the drive-head, permitting cutting and even limited core drilling. Field procedure consists of digging a pit to the frost table and cutting into permafrost with chiselling tools in the same manner as road pavement is broken. The debris periodically is shovelled out before excavation can proceed. Carbide-insert core drill attachments allow retrieval of cores up to 11.5 cm diameter.

Excellent sections for soil and ground-ice description can be dug to a practical limit of 1 to 2 m below the frost table. The requirement of a generator limits portability. Rotary hammers are valuable complements to power augers because of their ability to excavate in coarse textured sediments.

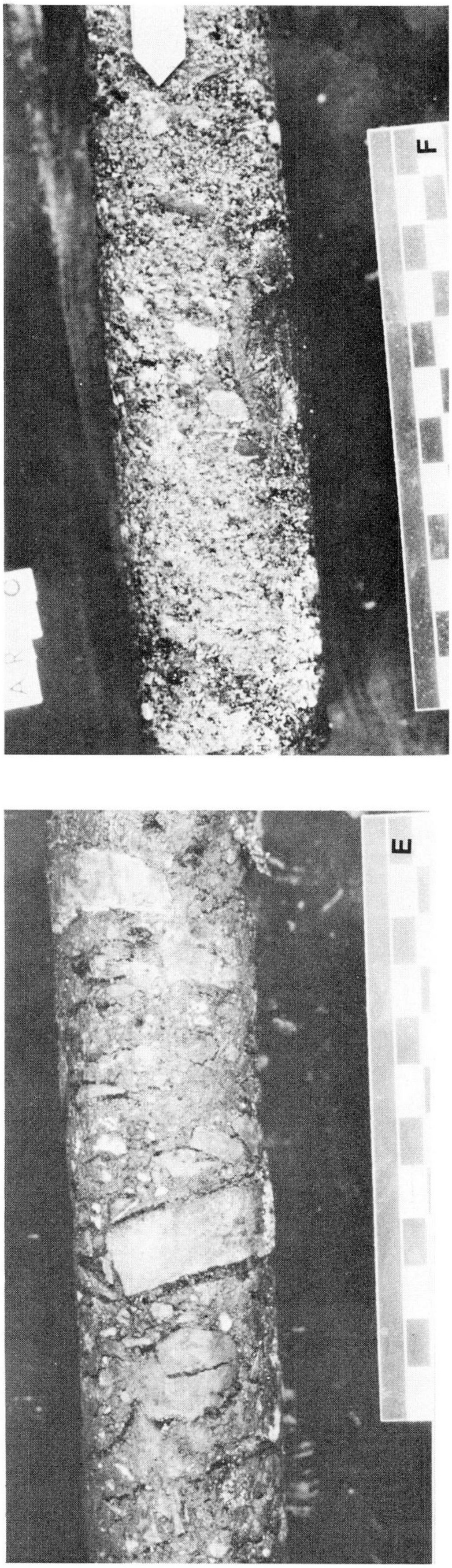
GSC 202921-S

GSC 202921-Q



GSC 202921-B

GSC 316-2



GSC 316-10

GSC 316-1

Figure 23. *Frozen cores (1 5/8 inch diameter) obtained using fuel oil at temperatures of -15°C or lower: deeply weathered granite (A,B) of low ice content; weathered quartzitic rocks (C) of low ice content; stony ice-rich clayey till (D) (dark spots and bands are ice); low ice-content clayey till (E); and gravelly sand (F) of low ice content. Scale is in centimetres.*

Drill/breaker Machines

These light-weight drilling machines, powered by small two-cycle gas engines, can be used to drill or drive by adapting the necessary drill chuck or breaker-shank housing to the output drill shaft. They commonly are used in permafrost to drive small diameter pipes for bench marks (P.A. Egginton, pers. comm., 1977) and to probe. Continuous sampling of a borehole is time consuming and must be limited to drive sampling of heavy wall tube samplers in a similar fashion to drive sampling with a split tube sampler. The Cobra model BBM47L and the Pionjar model BRH50 (Fig. 27) have been used to penetrate various types of permanently frozen materials. Drill/breaker machines are used for geochemical prospecting in nonpermafrost areas to penetrate several metres of fine textured deposits and to sample underlying tills. They can also be used for trenching.

Because of the small diameter of the coring tools used, drill/breaker machines are not adequate for subsurface work where good core samples are required. Although no reports of their performance in hard frozen soils (north of the -10°C isotherm) are available, it is likely that drive sampling with thick walled tubes in low temperature permafrost would be subject to the same limitations that apply to the split tube driving method and to the modified Hoffer probe.

HELICOPTER-PORTABLE AND ALL-TERRAIN VEHICLE DRILLS

Although the high mobility and light weight of the drills previously described make them of great value to terrain inventory studies of large areas, they are poorly suited for drilling closely spaced holes in a restricted area or for coring holes to depths exceeding 6 or 7 m. Two larger drilling machines were tested by Terrain Sciences Division in a search for a drill that was more efficient under such conditions. These, although "large" when compared with the man-portable equipment, are relatively small and light weight when compared with diamond drills and augers used in most engineering soil sampling programs in permafrost. Furthermore, both machines, the JKS 300 and the ATV-drill, are adapted for air transport by Twin Otter and medium sized helicopters.

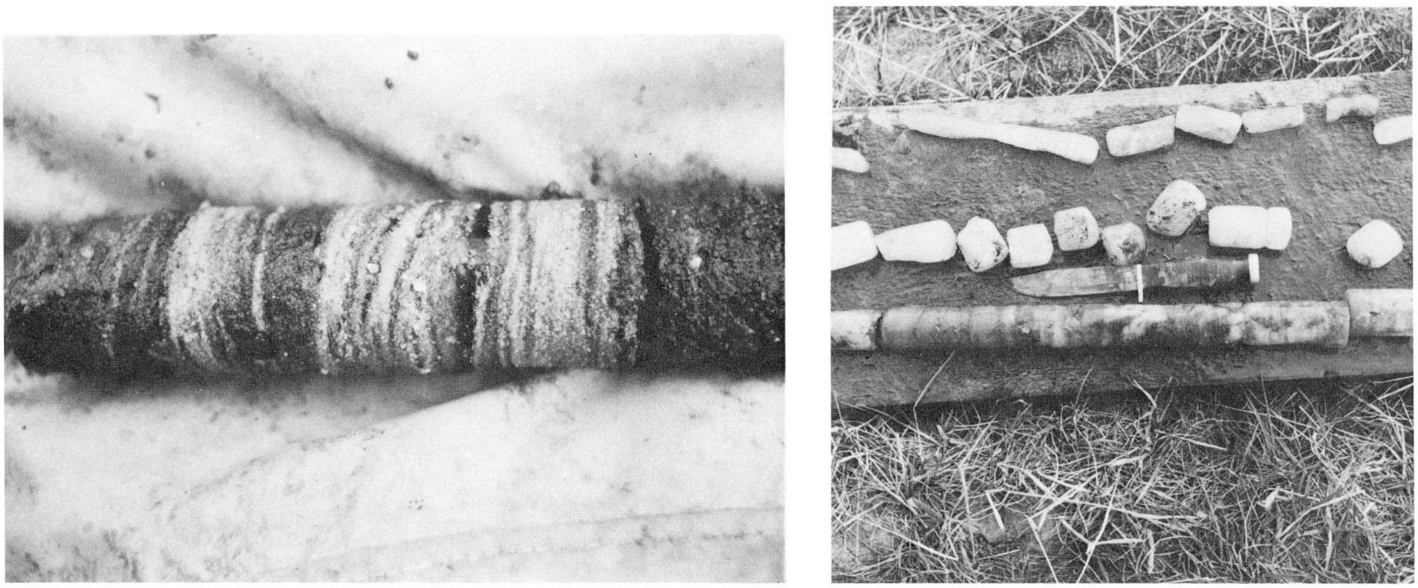
JKS 300 Drill

The JKS 300 is a hydraulic diamond drill which, through adaptations aimed mainly at facilitating transport by helicopter, was used for diamond drilling and augering in permafrost. It can be moved by helicopters capable of taking sling loads of about 400 kg and is well suited to moves with Twin Otter and single Otter fixed-wing aircraft (Veillette, 1975b). The assembled JKS 300 drill consists of two main components, independent from each other and constituting individual sling loads: the power pack and the drill frame and head (Fig. 28). The weight breakdown of the complete drill assembly without any accessory equipment is shown below.

Power Pack	Weight (kg)	Drill Frame and Head	Weight (kg)
No. 126 Volkswagen Industrial engine 44 BHP	128	Mast and hydraulic cylinder	114
Hydraulic pump and circuit with skid	176	Drill head	64
Total	304		178

Figure 24

Frozen core (1 5/8 inch diameter) of clayey silty till, containing few pebbles, obtained with fuel oil, showing partial thawing on its surface; dark bands perpendicular to core axis are ice veins. (GSC 202921-R)



GSC 202921-J GSC 170944

Figure 25. *Frozen cores (1 5/8 inch diameter) obtained in summer using fresh water as circulating fluid, Ellesmere Island, Northwest Territories: stratified sand (left), ice from an ice wedge (right). Note the greater amount of thawing for cores of pure ice (above knife) than for cores of ice with soil inclusions due to faster penetration rates in the latter. (Courtesy D.A. Hodgson)*

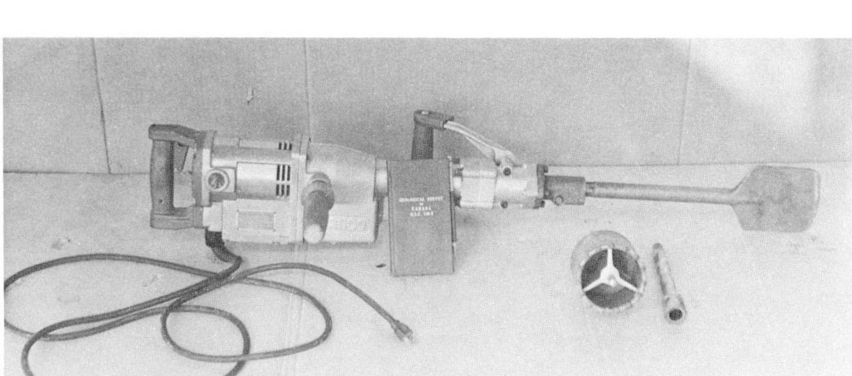
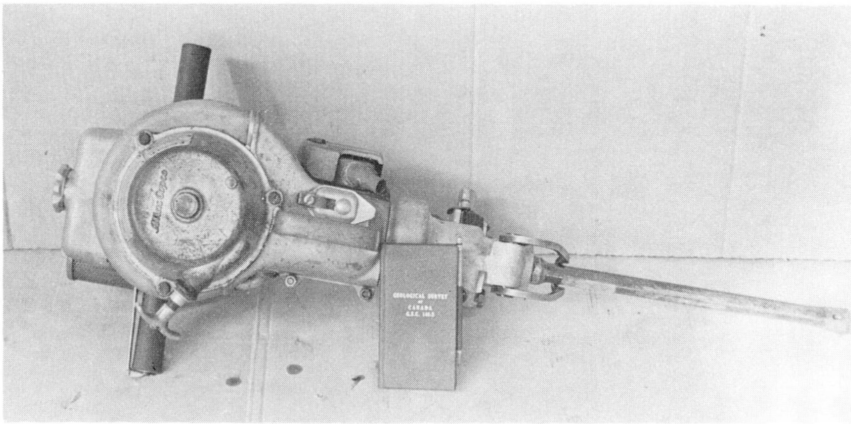
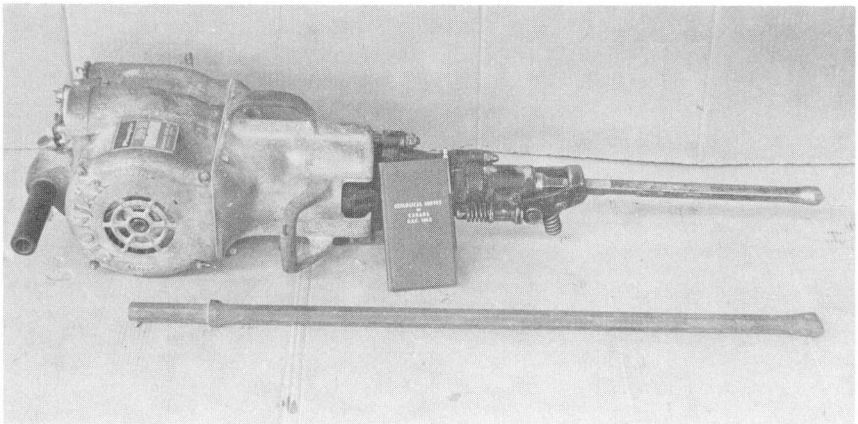


Figure 26

Dual-purpose Kango rotary hammer with chiseling bit (attached) and coring bit. (GSC 203205-M)



GSC 203205-J



GSC 203205-B

Figure 27

Drill/breaker machines: Cobra model BBM47L (top) and Pionjar model BRH50 (bottom).

***Figure 28**. JKS 300 drill in drilling position: power pack (left) and the drill frame and head (right) mounted on a platform for helicopter transportation. (GSC 202655-O)*

All drill functions are hydraulically driven, which permits close control of the operation. For augering purposes a hydraulic, light (18 kg), low-speed motor can be adapted to the drill head in a matter of minutes, giving the boring-spindle speed and high torque required. For diamond drilling a high-speed, 8 kg, motor can be substituted; for drive sampling a separate cat-head, also hydraulically driven, can be added. Although the JKS 300 is designed primarily for bedrock drilling, its capacity for low spindle speed makes it well suited to augering in hard-frozen soils using both CRREL coring augers and continuous open-flight augers. Its outstanding characteristic and the advantage it holds over the ATV drill is its lifting and pushing capacity as shown below.

Hydraulic system working pressure (psi)	Push (kg)	Pull (kg)
1500	4016	3128
2500	6682	4669

Rotational power (torque at the boring spindle using a 69:51 gear ratio and a low-speed, 74-370 rpm hydraulic motor) follows:

Hydraulic system working pressure (psi)	Torque (ft•lb)
2000	454
2500	568

Table 5

Torque at the boring spindle obtained from coring and augering in various types of permafrost, using a 8.9 cm O.D. modified CRREL core barrel or continuous flight augers with a 7.6 cm bit. Data obtained at boring-spindle speed in the 30 to 60 rpm range, with a bit load of 200 kg

Permafrost	Torque, using CRREL core barrel (ft•lb)	Torque, using continuous flight augers (ft•lb)
Friable sand	22	–
Ice	22	–
Silty ice	22-56	–
Clay and ice	22-75	–
Soft shale and ice	22-75	–
Sand and tiny ice lenses	22-66	–
Sand and ice inclusions	94-132	94
Soft shale	38-57	–
Soft sandstone	94	283
Gravel	–	56-132

Torque values are not much higher than those of the small portable augers discussed before; however, torque can be obtained at very low spindle speed compared to the small augers. Since rotation can be accomplished simultaneously with pushing or lifting, rotational power is usually sufficient for the use of continuous flight and CRREL coring augers to considerable depths. For higher torque at the boring spindle, a drill head with a gear ratio higher than 69:51 also could be used.

The drill first was used during summer 1974 for drilling and coring holes to 10 m or less in the Arctic Islands. Drilling many shallow holes necessitates frequent moves, and to permit short assembly and disassembly time the drill frame was mounted on a light-weight (89 kg) reinforced platform (1.06 x 2.13 m) of rectangular tubing designed to sustain loads up to 910 kg (see Fig. 28); the assembly is levelled using jack screws at each corner of the platform. Narrow rectangular plywood boxes secured to the sides of the platform were used as containers for drill rods and coring tools. The retracted mast and drill head, when lowered, was positioned between the two tool boxes. In this manner the drill can be prepared for a helicopter move in less than 30 minutes. The drilling platform and the power pack constitute separate sling loads; the two components are coupled by hydraulic hoses for drilling.

The JKS 300 drill has been used mainly for augering and continuous coring with CRREL coring augers. B-size magnesium zirconium drill rods using CRREL barrel heads modified to take diamond drilling rod threads were used for coring; standard 92 cm continuous flight augers of 6.7 cm diameter with different types of bits were used for augering. Continuous coring to a depth of 13 m with a modified CRREL auger giving 5.1 cm core was achieved. The lifting capacity of the JKS 300 drill can be used to advantage to withdraw the CRREL auger to the surface for the necessary frequent clearing of the flights or to retrieve core. Using a lifting iron tied with a chain to the drill cradle, the string of rods can be lifted in successive steps of 1.2 m (full stroke length) and then broken in 3 m or longer lengths for faster handling.

A limited amount of diamond drilling, using water as drilling fluid, with N-size coring bits and B-size noncoring bits was done for stratigraphic information. The results obtained do not differ significantly from those obtained with the GW-15 Winkie drill under similar conditions. Drilling with fluids chilled below 0°C was not attempted with the JKS 300 drill. Judging from the results obtained with the Winkie drill, however, it is likely that N- and H-size core barrels could be used effectively for coring to greater depths than with the Winkie drill. The JKS 300 drill is rated to a maximum depth of 300 m in bedrock using A-size wireline equipment.

The JKS 300 drill, although well suited to drilling situations requiring frequent moves, also can be used effectively for situations where depth of investigation takes priority over areal coverage requirements. It complements the ATV drill which is designed specifically for shallow, high density drilling.

Oil pressure gauges on the hydraulic system permit estimation of the pressure required for coring in a variety of frozen materials. Pressure values recorded in the field later were converted to torque values (ft•lb) to assess the rotational power necessary for effective drilling. These observations are valuable when considering the development of light-weight drills for permafrost and were of aid in designing the power characteristics of the ATV drill. Because light-weight drills and augers usually are limited to low torque values at the boring spindle compared to standard larger augers and drills, it is important to have an appreciation for the minimum and maximum torque values required in various materials using different coring or drilling tools.

Table 5, derived from drill performance data recorded in the Arctic Islands during summer 1974, demonstrates the most common torque values required for coring different materials.

The torque values shown apply to normal drilling conditions, that is, free of problems such as bridging of cuttings above the barrel head, excessive packing of cuttings between flights, etc. Such problems usually occur suddenly and require greater rotational power than that shown in Table 5 to avoid seizure of the tool in the hole. The JKS 300 drill, with a maximum torque of 568 ft•lb, shows a substantial reserve of rotational power for most frozen materials. The coring and drilling tools used to obtain

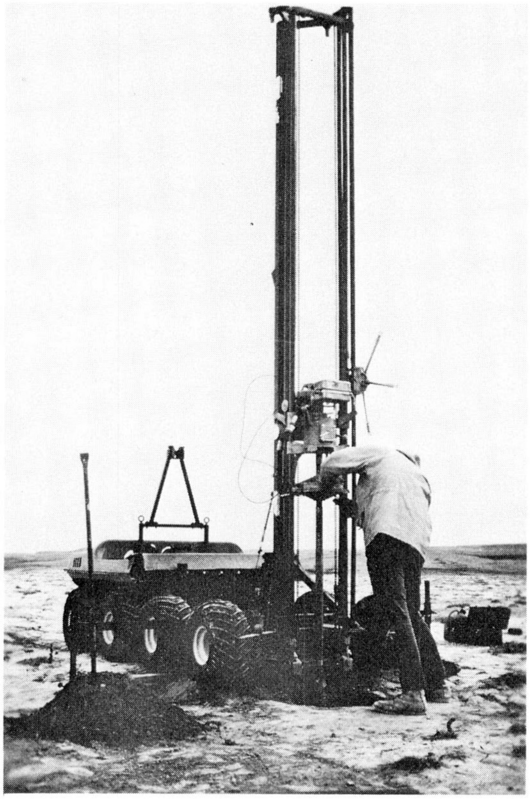


***Figure 29**. ATV-drill positioned at a drill site. (GSC 202655-Y)*

the torque figures are of relatively small diameter (8.9 cm O.D. maximum). Large diameter coring tools would require substantially more power and may not be consistently compatible with the drill.

The fact that the JKS 300 drill requires helicopter transport between sites imposes economic limitations on some drilling projects. A track-mounted carrier, capable of supporting drills the size of the JKS 300 and adapted to transportation by Twin Otter aircraft was developed (MacKenzie, 1976). The power source for the drill can be used to rotate the tracks, and hence a single power source is sufficient for both drilling and transportation. Such a carrier would reduce field costs substantially by decreasing the dependence on aircraft. Land use regulations governing the use of track-vehicles in arctic terrain, on the other hand, may prevent the use of the carrier in summer, although winter and spring drilling programs would benefit from this innovation.

ATV Drill

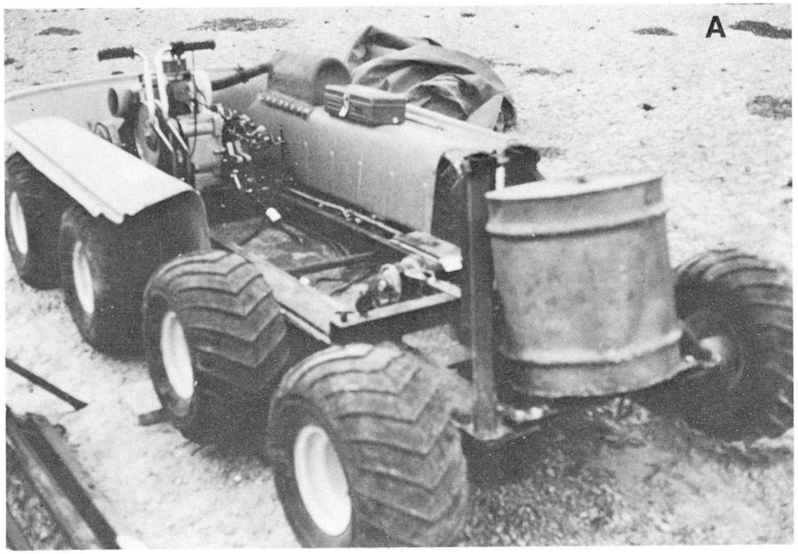
The ATV (all-terrain vehicle) drilling machine (Fig. 29) was developed (1) to reduce the dependence of drill crews on aircraft support for moves between sites and (2) to increase borehole production and so permit detailed subsurface investigation (Veillette and Nixon, 1975). Provided that a reasonable borehole coverage could be maintained, it was considered that a depth of 3 m was satisfactory for most surficial geology mapping programs and geotechnical reconnaissance studies in permafrost terrain. To meet these objectives, a mast-equipped, light-weight drill was adapted to an all-terrain vehicle. A prerequisite was that the ATV drill could be transported by Twin Otter aircraft or medium sized helicopter between major working areas. Three main components constitute the complete drilling machine: carrier, mast (frame), and drill.

An 8-wheel Argo all-terrain vehicle was modified for drill mounting to provide additional structural strength and stability in drilling position and to facilitate transport (Fig. 30). The standard one-piece plastic body, which permits the vehicle to float, is too large to fit through Twin Otter loading doors and had to be modified. Furthermore, removal of the rear half of the plastic body was necessary for drill mounting. Hence, the amphibious character of the vehicle was lost. Mounting points for the drill include a swivel pin and a lower lock pin supported by twin reinforced uprights at the rear of the vehicle and a raised cradle in front of the driver's seat to support the forward mast section during transport. The frame is strengthened with a steel plate welded between the members, and the wheel base is increased by 46 cm over the full length of the frame to lower the angle of the mast while in transit. A split drum electric winch serves to raise and lower the mast. Extended pads afford lateral support while in drilling position.

The mast allows more than 3 m of free travel for the drill head and consists of an extended Winkie GW-15 Unipress, reinforced by tying the two E-size guide rods to a rear tubular structural member with a triangular yoke at the top and bottom of the mast. The drill power unit rests in a cradle which slides on the rear mast tube and the two guide rod bushings. The incorporation of a drill mast has proven to be an important time saver in coring operations with CRREL core barrels. Assuming average drill runs of 15 cm, and a 30 cm thick active layer in which no coring is done, a minimum of 16 trips down the hole is necessary for continuous coring to a 3 m borehole depth (allowing a 30 cm run for the initial trip from the frost table). It was mentioned earlier that only short core runs are possible with this type of coring tool used in the vertical position and that the barrel must be retrieved frequently to dislodge cuttings held between the helical flights. When using hand-held power augers, retrieval must be done manually, resulting in fatigue to the operators. The mast permits easier withdrawal of the core barrel and eliminates rod breaking to a depth of 3 m. The other main advantages of the ATV drill are increased downward pressure on the auger cutting edge and reduced handling of drill rods.

The first version of the ATV drill was completed in 1975. The carrier was powered by a 29 h.p., forced air-cooled, twin-cylinder, two-cycle engine; two interchangeable power sources, the GW-15 Winkie and the Stihl 4308 were used for drilling. The mast originally was designed to take the Winkie drill but could accommodate the Stihl 4308 with special adapters. The drill head moved vertically along the mast with roller chains activated by a manually operated lifting wheel mounted on a rail along the right side of the mast (Fig. 30). Field testing of this early version of the ATV drill confirmed two important points related to the drilling and coring of frozen soils: (1) relatively low torque was required at the boring spindle and (2) adequate bit load significantly improved the drilling performance of low-power engines.

During 1977 the ATV-drill was subjected to major modifications aimed at facilitating field operations and at increasing the overall power of the drill. The manually operated lifting wheel, although effective, resulted in fatigue to the operators, especially when drilling holes deeper than 3 to 4 m. The use of small gas engines to rotate the drill limited boring spindle movement to only one direction. Two power sources, one for the drill and the other for the carrier, added to maintenance and breakdown time. Furthermore,



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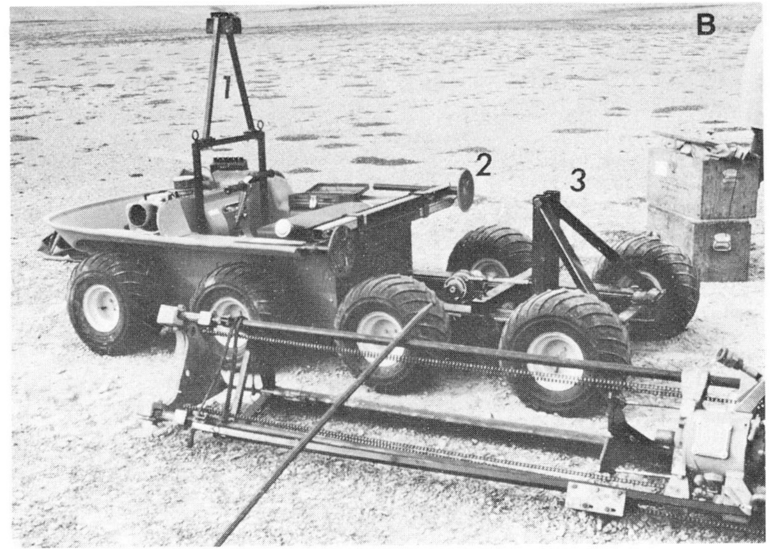
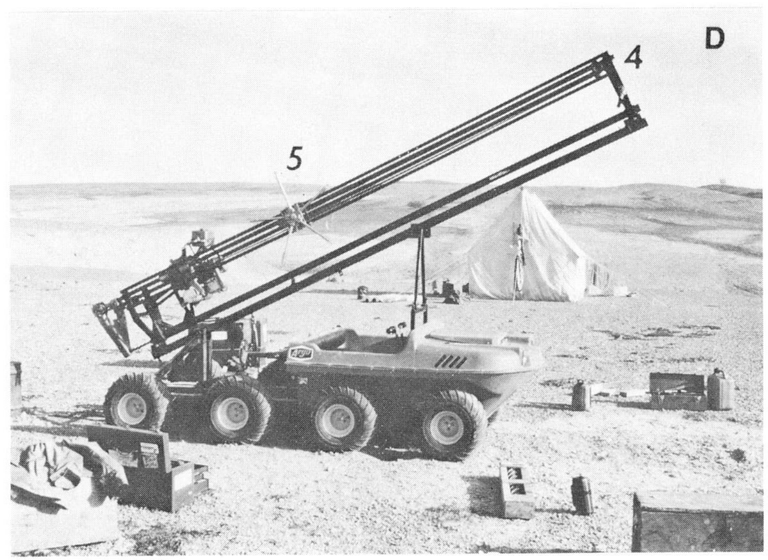


GSC 202921-F

GSC 202921 C



GSC 202921-M

Figure 30. *Assembly of the ATV-drill after transport in Twin Otter aircraft: (A) after adding lower half of shell, engine, and wheels to frame; (B) with raised cradle (1) driver's seat, extended lateral pads (2), and twin reinforced uprights (3); (C) with upper half of shell; and (D) complete with mast, triangular yoke (4), and lifting wheel (5).*

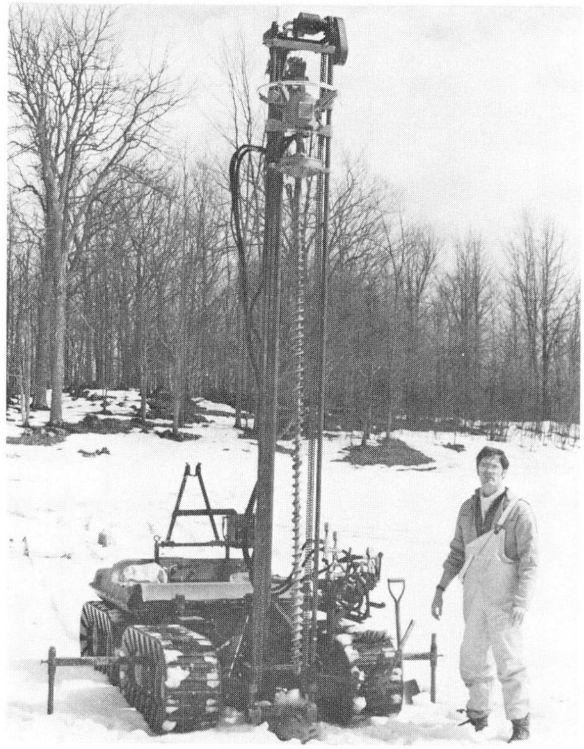
testing in unfrozen soils indicated that the drill could be useful for geotechnical investigation in fine textured soils, provided its rotational power could be increased and its operation facilitated. To eliminate some of these problems a hydraulic system was adapted to the drill so that all functions, clockwise and counter clockwise movements of the boring spindle and vertical movements of the drill head, could be controlled hydraulically (Fig. 31). For rotation, the GW-15 transmission was coupled to a hydraulic motor; for vertical movement of the drill head, a hydraulic motor was mounted on top of the mast, driving roller chains which permit the full use of the long mast. Roller chains and sprockets were increased in size to accommodate the additional power of the drill. A 16 h.p., air-cooled, four-cycle engine, which powers the vehicle as well as the hydraulic system of the drill, replaced the two-cycle engine of the first version. These modifications resulted in a minor increase in weight of the drill for a significant increase in rotational and lifting power. The drill has a downward pressure (feed) of approximately 1140 kg and a hoisting capacity of 910 to 1140 kg at 12 to 15 m/min. The range of boring spindle speed and torque follow:

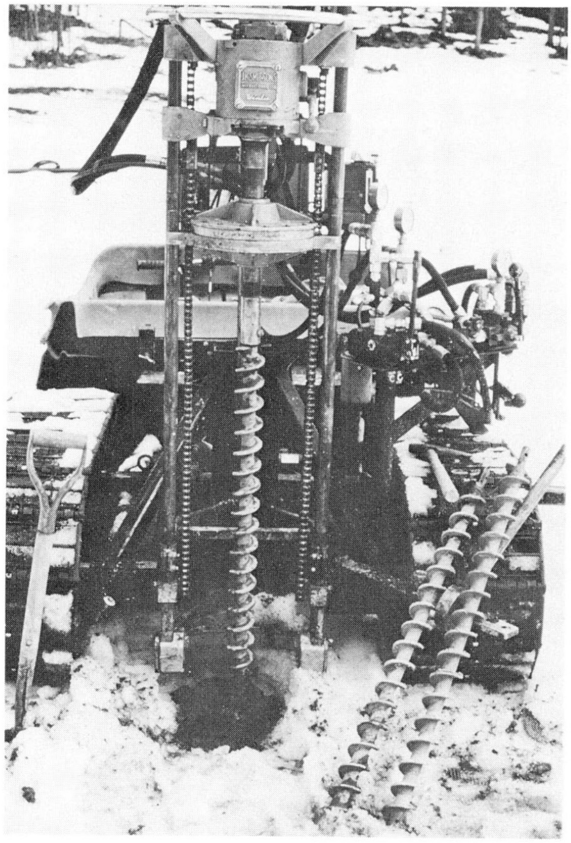
Boring spindle speed RPM	Torque (ft•lb)
1100	40
460	90
160	260
70	610
30	500-550

To date the drill has been tested in the Arctic Islands, upper Mackenzie Valley, at various locations in the Ottawa Valley area, and in the Lake Timiskaming area of northwestern Quebec. A detailed site study involving the coring of frozen peat and other types of fine grained frozen and unfrozen soils was carried out in the Fort Simpson area, Northwest Territories during spring 1977 (Nixon, 1978). Coring permafrost with modified CRREL barrels was performed on northern Somerset Island mainly in silts and clays during summer 1975, and limited diamond drilling and continuous flight augering was carried out in the vicinity of Resolute Bay, Cornwallis Island. P.B. Fransham (then with Terrain Sciences Division) drilled with 7.6 cm flight augers in marine clays and sands in Ottawa Valley during summer 1976 and reported successful sampling of clays to a depth of 20 m using 5.1 cm Shelby tubes. Most of this field work was conducted with the original version of the ATV drill. Recent tests in Ottawa Valley, Ontario and Lake Timiskaming, Quebec areas with the newly adapted hydraulic system clearly indicate the advantages of these modifications.

Overland stability of the vehicle was assessed over rugged arctic terrain, subarctic raised peat-taiga, and hummocky muskeg in Ottawa Valley. In the high arctic, slopes covered with rubbly deposits inclined at 16 to 18° and shallow river crossings did not cause any difficulty. With tracks installed, wet snow up to 50 cm deep and slopes to 20° did not cause any problems in the Fort Simpson area, Northwest Territories.

Transport by Twin Otter requires disassembly of the vehicle, but three men can load the mast and drill without breakdown. Disassembly time for the vehicle is about four hours for two men. Figure 30 illustrates the sequential assembly of the vehicle. Where road transport is possible, the ATV drill can be transported by truck or on a small tandem trailer towed by a light truck.





GSC 203407-E

Figure 31. *ATV-drill with adaptation of hydraulic system: (top) in drilling position showing hydraulic motor and reduction unit activating the roller chains at the top of the mast; (bottom) close view of drill and hydraulic controls on the right.*

Table 6

Helicopters available for arctic charter
Chart adapted and updated from data compiled by Herb Spear (Oilweek, 1972)

Type		Sling load (lb)	Passengers	Block speed (mph)	Endurance (hours) 20 minute reserve	Engine Type	Fuel Type	Fuel Consumption (gallons/h)	Length (ft)
Aerospatial Aerospatial	Alouette Gazelle	1300 1320	4	100 155	2:40 3:50	Turbine	Turbo	45 n/a	n/a 31
Bell	47G2	480*	2	70	2:20*	Reciprocating	av/gas 80/87 av/gas 100/130	13*	30
Bell Bell	G3B1 G3B2	850* 800*	2	80	2:40* 2:30	Reciprocating	av/gas 100/130	17* 16	38
Bell Bell	G4 G4A	800 550	2	80	2:30	Reciprocating	av/gas 80/87 av/gas 80/87 av/gas 100/130	16	n/a
Bell	47J2	700	3	85	2:30	Reciprocating	av/gas 100/130	16	n/a
Bell Bell Bell Bell Bell Bell	204B 205A 206A 206B 206L 212	4100* 4200* 1116* 1200* 1879 4800	10 14 4 4 6 14	110 120 120 125 150 130	2:47* 2:20* 2:40* 2:42* 3:60 2:30	Turbine	JP4	68* 78* 21.5* 21.5* 28 80	44.7 42 29 29 42.8 n/a
Enstrom	F28C	750	2	100	2:40	Reciprocating	av/gas 100/130	12	29.3
Fairchild Hiller	1100	900	4	115	2:30	Turbine	JP4	19	30
Fairchild Fairchild	SL4 12E	950 900	3 2	70 80	2:00	Reciprocating	av/gas 100/130	18 16	29 28
Hughes	500	1000	4-6	135	2:40	Turbine	JP4	19	29
Hughes	500D	750	2	100	2:40	Reciprocating	av/gas 100/130	12	29.3
Sikorsky Sikorsky Sikorsky Sikorsky	55A 55T 58T 62	2600 2500 5300 2500	11 11 17 12	80 100 110 110	3:50 2:30 2:45 4:00	Turbine	JP4	42 35 85 70	46 46 46.6 46.6

*Where discrepencies in statements of performance by operators exist, figures were averaged.

PLANNING A DRILLING PROGRAM

Transportation

Considerably more planning is required for drilling activities conducted in remote arctic locations than in more accessible areas. Transportation in the Arctic is largely by small to medium sized aircraft. Hence, a knowledge of aircraft range, payload, sling load capacity (helicopter), and cabin dimensions is essential in planning a drilling program. Tables 6 and 7 summarize the main characteristics of the helicopters and fixed-wing aircraft commonly available for arctic charter. These data come from arctic operators and, as such, are considered more realistic than manufacturer's figures.

A factor related to air transportation is the seasonal variability of daylight. Figure 32 links duration of daylight for a given latitude with the time of year. Because Arctic twilight is prolonged, Figure 32 undervalues the amount of useful light in northern latitudes; however, it shows when there is sufficient light for a full working day. As most helicopters and some light fixed-wing aircraft are restricted to visual flying, this factor is most crucial in late winter and early fall when the length of daylight changes rapidly.

Ground transportation in winter can be by light snow vehicle for light-weight equipment and by a variety of tracked vehicles for heavier gear. Summer travelling is hindered by poorly drained ground and the presence of water bodies and is subject to land use regulations governing the size and type of vehicles. Small, wheel-mounted, all-terrain vehicles have been used with success in summer, particularly in the Arctic Islands. The Honda ATC 90 motorized tricycle (Fig. 33) has been used extensively by field personnel operating north of the tree line; it can tow a trailer with a 150 kg load.

Choosing Suitable Man-portable Equipment and a Drilling Method

The portable drilling and coring hardware and techniques described in this paper represent the basic equipment and methods in use for permafrost investigation to shallow depths. Drilling machines (the above-ground components) constantly are being improved, with new equipment coming on the market frequently; the light-weight drills described here are included only as examples. When choosing a power source to rotate drilling and coring tools in permafrost, one must first ascertain whether augering or diamond drilling speeds are required. For coring frozen, fine grained or sandy soils, for example, an auger power head, producing low boring-spindle speed and sufficient torque, is required. For diamond drilling in coarser materials, torque is less important than higher spindle speed.

Table 7

Some fixed-wing aircraft common in Northern Canada. Chart adapted and updated from data compiled by Herb Spear (Oilweek, 1972)

Type	Cruise Speed (mph)	Load Maximum (lb)	Maximum Range (miles)	Passengers	Fuel Consumption (gallons/h)	Fuel Type	Cabin dimensions					Landing requirements		Under-carriage
							Length (inches)	Width (inches)	Height (inches)	Volume (ft^3)	Area (ft^2)	Length of Runway (ft)	Ice Thickness (inches)	
DC-6	300	23 000	2400	70	320	100/130	816	105	93	4433	550	5000	45 Fresh	Wheels
C-46	180	15 000	1300	N/A	140	100/130	576	72	60	N/A	422	4000	37 Fresh	Wheels
F-27	290	10 000	1000	40	200	Turbine	362	82	80	1374	Var.	3500	32 Fresh	Wheels
DC-3	160	7300	1200	28	80	100/130	268	72	72	850	140	4000	24 Fresh	Wheels Skis
Twin Otter DHC-6	160	4000	700	19	75	Turbine	222	63	59	384	90	1000	24 Fresh	Wheels Skis Floats
Single Otter DHC-3	110	2300	600	10	26	80/87	192	60	60	345	(approx.) 75	1500	14 Fresh	Wheels Skis Floats
Beaver DHC-2	110	1200	470	6	21	80/87	108	48	51	125	31	1200	12 Fresh	Wheels Skis Floats
Cessna 185 Skywagon	153	830	858	5	13.4	100/130	-	-	-	-	-	1400	-	Wheels Skis Floats

Unlike power units, coring and drilling tools (the underground components) evolve slowly, and those described represent a reasonably comprehensive list of equipment in use.

It has been demonstrated that the performance of most drilling and coring tools is affected substantially by ground temperature, material texture, ice content, and degree of saturation by ice. Table 8 is presented to facilitate the selection of a specific piece of equipment when taking into consideration portability, purpose of investigation, and sampling requirements.

Any particular subsurface investigation may require more than one type of equipment. For example, a combination of diamond drilling and dry augering equipment may prove advantageous when dealing with cold (-10°C) permafrost showing lateral variations in texture.

Storage and Transportation of Samples

Engineering or glaciology studies may require the preservation of frozen cores for specific laboratory tests. Detailed procedures for transport and storage are described by Baker (1976). Although not a standard practice within Terrain Sciences Division, frozen cores have been transported south from the Arctic. At camps where adequate artificial refrigeration facilities were not available, cores were preserved in suitably capped boreholes. The procedure consists of casing the upper portion of a borehole well below the maximum seasonal depth of thaw with a plastic (PVC) pipe, placing the samples in a plastic sleeve inside the hole and capping it. It is important to have a tight seal between the pipe and wall of the hole in order to prevent water seepage from the active layer and refreezing at depth. A "refrigerator" of this type, consisting of several boreholes drilled side by side, can be made adjacent to a base camp. For shipping from the field to the south, regular commercial flights have been used with success. The cores, individually wrapped in Saran wrap, wax paper, and aluminum foil, are packed in domestic chest coolers (picnic type). The coolers remain outside cold storage usually for the length of the aircraft trip, and on arrival at their destination immediately are transferred back into cold storage. Cores could be kept frozen for at least 8 hours at air temperatures of 20°C or more without any observable damage (P.J. Kurfurst, pers. comm., 1977).

The method of storing samples in a borehole instead of in a mechanical refrigerator may not be practical if thermal disturbance is critical. Baker (1976) lists permissible temperature deviations for frozen samples subjected to tests concerned with compressive behaviour of frozen soils.

When much handling of cores at air temperatures well above 0°C is necessary, additional protection can be provided by using double-walled plastic pipes built according to the principle of commercial thermos bottles (Fig. 34). In addition to improved insulation, the core is better protected against breakage.

Table 8

Man-portable permafrost drilling equipment

Equipment	Weight	Dimensions	Power Source	Core Diameter
Frost table probe	N/A	Variable	Manual	N/A
Modified Hoffer probe	6.5 kg with three 1 m extensions	Longest part, 1 m	Manual	Bits of various sizes
CRREL ice coring auger and modified versions	18 kg including six 1 m extensions and accessory tools	Longest part is extension (1 m)	Manual; may be adapted to motorized equipment	Variable, 3.8-15 cm; standard model is 7.6 cm
Split tube portable drive sampler	260 kg complete with rods and accessory tools for a 9 m hole	Longest part is collapsable tripod (3 m)	Cathead powered by small 4-cycle engine	Varies with size of split tube used, commonly 3.5 and 7.6 cm
Haynes drill power auger, model 500	34 kg	60 x 60 x 45 cm	Gas engine 4-cycle, 5 h.p.	See CRREL auger
General Equipment power auger, model 51	24 kg	70 x 130 x 70 cm complete with handle	Gas engine 2-cycle, 9 h.p.	See CRREL auger
Stihl 4308 two-man auger	21 kg	130 x 65 x 40 cm complete with handle	Gas engine 2-cycle, 3.4 h.p.	See CRREL auger
Winkie GW-15 diamond drill	75 kg complete with Unipress	65 x 34 x 200 cm complete with Unipress; can be dismantled	Gas engine 2-cycle, 10 h.p.	Gives cores of A, B, and N sizes
Water jetting method (pump, pipes)	N/A	Varies with the pump used	Gas engine (pump)	N/A
Dual-purpose rotary hammer	About 65 kg including generator and tools	Drill box: 30 x 30 x 70 cm; generator: 45 x 45 x 60 cm	Gas engine 4-cycle (generator)	Up to 10 cm
Drill/breaker machines, Cobra BBM47L, Pionjar BRH50	25 kg – 30 kg without accessory equipment	Overall length 60 cm – 70 cm	Gas engine 2-cycle	Small diameter drive tube cores, usually less than 3 cm

Table 8 (cont'd.)

Transportation	Applications	Depth of Investigation	Ground Temperature Influence	Evaluation
Backpack	Measure depth to frost table	1-2 m	Will not penetrate sand slightly below 0°C	
Backpack	Measure depth to frost table, coring in frozen peat, clay, fine sand, and silt	Commonly 2-4 m	Most effective in clays and peat only slightly below 0°C	Lightest coring tool
Backpack	To core frozen sand, silt, clay, peat, and ice; ability to core coarser materials, gravelly sands, some tills of moderate pebble content increases with increasing size of power source	For manual operation, commonly less than 10 m in frozen soils, several tens of metres in glacier ice; using large rotary rigs, depths greater than 10 m in frozen soils are common	Well suited for coring hard, low temperature frozen soils. Rate of penetration decreases slightly with decreasing ground temperature. Generally not used to core nonfrozen soils	High quality undisturbed cores. Coring procedure is slow
Limited to short ground moves by 2-3 men; can be moved by helicopter as sling load or attached to heli-racks	To core frozen sand, silt, clay, ice, and peat, some gravelly sands, tills of low pebble and cobble content; to drive casing in wet areas	Maximum practical depth is 7-8 m or less when used with tripod and small 4-cycle engine tied to a tripod leg	Rate of penetration seriously reduced by decreasing temperature. Outperformed by power augers and other drills in low temperature permafrost (-5°C or less)	Good quality, slightly disturbed cores. Bulky and heavy, requires 3-man crew for effective operation
Backpack with difficulty; may be rolled on its wheels on smooth ground or carried inside helicopters	Power source to rotate CRREL barrels and continuous flight augers	Maximum practical depth in most frozen soils is 7-8 m or less, commonly 2-3 m	Best results in coring hard permafrost. Liquifies ice-rich clays at ground temperature only slightly below 0°C	High range of boring spindle speeds (366-600 rpm) in operating range is not compatible with consistent coring, with CRREL core barrels
Backpack or transported inside helicopter cabin	As above	As above	Slower penetration rate than Haynes drill, other conditions being equal	Improvement in torque performance and boring-spindle speed over the Haynes drill
As above	As above	Maximum practical depth is 7-8 m, commonly 3-5 m	Slow penetration in hard frozen ground; requires sharp cutters for best results	Distinct improvement over other power augers. Maximum boring-spindle speed of 50 rpm at a torque of 354 ft•lb, greatly facilitates coring. Also useful for augering with continuous flight augers
Restricted to short ground moves with all accessory equipment by 2 to 3 men; moved as sling load with helicopter	To penetrate and core frozen soils with appreciable amount of coarse materials; to core bedrock and rapidly drill holes	Maximum practical depth of continuous coring is 10 m; may be used to drill deeper holes	Best results are obtained in low temperature permafrost (-10°C or less)	Core quality is a function of ground temperature of the drilling fluid and rate of penetration. Requires more complex equipment than other methods described here. Must circulate a fluid in the borehole
Backpack or small aircraft.	To penetrate frozen ground for borehole instrumentation or other purposes	Depths in excess of 20 m have been reached	Slower penetration in low temperature permafrost	Provides a rapid and inexpensive way to drill a hole; no cores. Restricted to areas with good supply of water
Restricted to short ground moves; will fit easily in helicopter	Main use is shallow trenching and core sampling below the frost table	Maximum practical depth is 1-1.5 m below frost table	Low temperature permafrost harder to chisel and excavate	Provides excellent sections for soil (pedology) description. Time consuming and shallow depth limitation
Backpack	Mainly to drive stakes and moil points; chisel; trench. Was used to drive small diameter rods for bench marks to depths of 7 m in permafrost at temperatures of -2 to -3°C	Unknown. Clays in nonpermafrost areas can be penetrated to 20 m.	Subject to the same limitations as split tube driving. Probably not very effective in low temperature permafrost (-5°C or less)	Portable. Not suitable for most permafrost investigation, poor coring capability

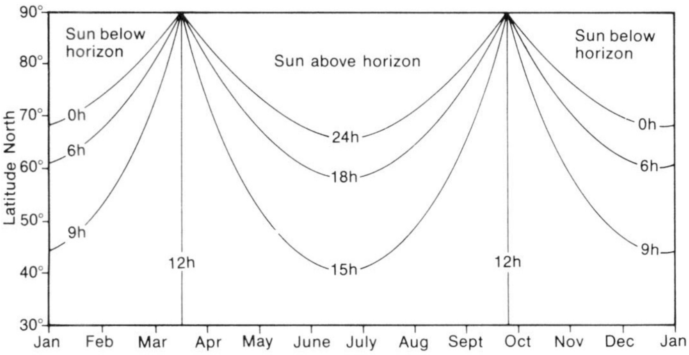


Figure 32. *Graph showing duration of daylight hours versus time of year for 30° to 90°N. (Meteorological Branch, 1970)*

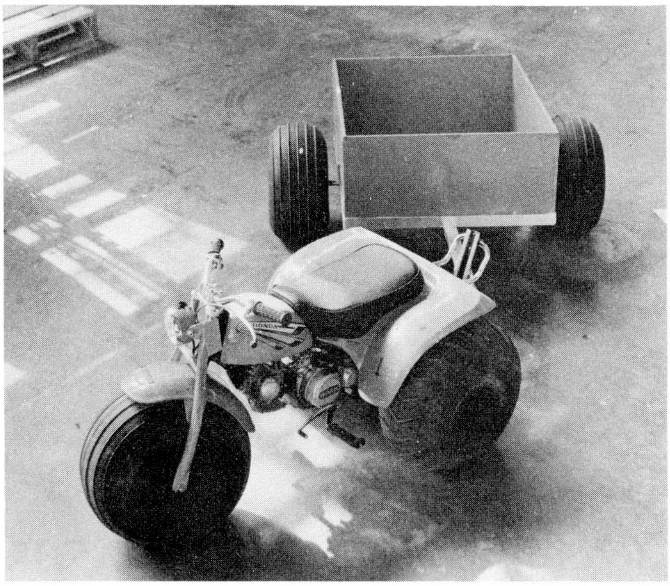


Figure 33. *Honda ATC 90 motorized tricycle and trailer. (GSC 203205-E)*

The most common use of permafrost samples is measuring field moisture content (ice content equivalent), for which cores need not be preserved in the frozen state. After adequate description, samples are brought back to the laboratory in sealed containers. Plastic bags can be sealed by a special clamp and the flame from a lighter or other heat source or, if an electric power source is available, an electric sealer can be used. Various types of strong, threaded-cap nylon containers are also available. Of all the methods tried, tin cans sealed in the field with a portable manual canning machine afford the most reliable means of preserving water content samples. The core or cuttings are placed in the can and the lid can be sealed in a few seconds. If properly sealed, the sample will be preserved for a long period of time without any loss of moisture. The can is labelled with a black marker pen, and the ink generally will not deteriorate unless exposed to moisture for prolonged periods. The full cans may be packed for long distance shipping in cardboard cartons securely wrapped with nylon tape or strapping material. Tin cans are well able to resist the rough handling on shipping routes between the field and southern locations. Although the can is not reusable, it can be used for oven drying and thus avoids an aditional transfer of material to a laboratory container. The laboratory time thus saved more than

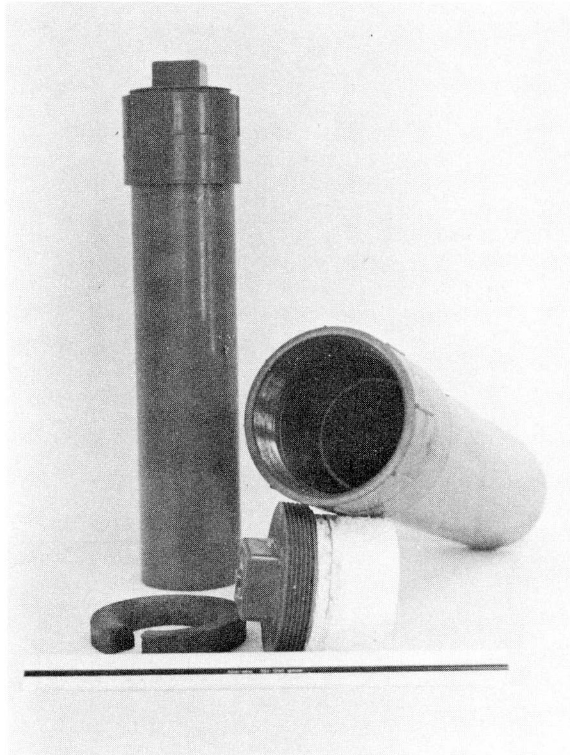


Figure 34. *Insulated individual plastic core containers. (GSC 203205-L)*

compensates for the cost of the cans. On the other hand, plastic bags, although very inexpensive by comparison often are damaged in transit giving rise to doubtful water content results.

RESEARCH NEEDS

Development of improved drilling and sampling equipment of minimum weight and maximum portability to obtain undisturbed cores for examination and testing was one of the research needs identified by Linell and Johnston (1973) for engineering design and construction in permafrost regions. Although some development of portable drilling machines and equipment has been made in recent years, conventional rotary and diamond drills, with minor adaptations for permafrost coring, are still used extensively, with the result that logistical costs are usually high.

The results presented in this paper demonstrate that successful augering with CRREL-type core barrels and continuous flight augers in frozen soils does not require high torque at the boring spindle (much less than augering in nonfrozen soils) under normal operating conditions. This situation should permit the design of relatively light-weight machines. On the other hand, low power at the boring spindle may result in occasional seizure of the tool (CRREL barrel) in the borehole. Because binding of a CRREL barrel can stall even the most powerful truck-mounted rotary drill, it seems reasonable to look for a solution other than a simple increase in rotational or pulling power. Accessory equipment that would permit heating the stuck core barrel electrically or dislodging it by means of a high pressure, fine jet of hot liquid with a freezing point well below 0°C should be examined.

For a detailed description of frozen soils and ground-ice quantity and structure, continuous coring is required. This procedure, whether in permafrost or in nonfrozen soils, is time consuming and expensive. Frozen cores have to be described immediately after extraction from the hole or kept in cold storage to prevent their destruction. When frozen cores are preserved for further testing in the laboratory, usually a few selected cores are chosen from a given borehole and the others are discarded after a brief description due to the difficulty and costs involved in preserving a large quantity of frozen cores. This situation marks the basic difference between permafrost cores and rock cores or soil tube samples which can be stored for indefinite periods of time and used for further description and testing. The development of adequate downhole descriptive techniques in permafrost, which would permit obtaining greater subsurface information from a testhole than presently possible, would permit a more rational approach to coring. Continuous flight augering or compressed-air drilling are rapid means of drilling in permafrost, but the cuttings obtained do not permit an accurate description of ground-ice structure and quantity. However, if such instruments as borehole cameras and periscopes were tested and proven to allow a detailed description of ice structure and distribution along the borehole walls, considerable information would be gained prior to coring which could be directed at the most interesting zones. Borehole geophysics (resistivity, SP, gamma-gamma, etc.), at the present stage of development, cannot provide the adequate description and estimate of ice content required for engineering purposes. The conditions in a permafrost hole, i.e., absence of water, smooth hole walls, and minimal danger of cave-in, appear ideal for the application of borehole cameras and periscopes. Considering the usual depth (3 to 15 m) of subsurface investigation in most engineering and surficial geology programs, the borehole cameras or periscopes required are relatively inexpensive and can be assembled in a laboratory.

For diamond drilling (or where a fluid is recirculated in the hole) the main gap in research, apart from lighter weight drilling machines, is in the drilling fluid circulation system. Means of achieving adequate sedimentation of cuttings, apart from the standard sedimentation tank, should be investigated. A reduction in the amount of drilling fluid required at the surface would facilitate the design of smaller, more portable fluid cooling units. The use of low- to medium-viscosity muds also would permit effective transport of cuttings from the bit up the hole, while reducing core erosion at the bit face.

Drilling permafrost with recirculated chilled fluids in summer necessitates the use of heavy cooling plants which can be moved only by large and high-cost helicopters. This, in part, is due to the large quantity of fluid required to permit adequate sedimentation of sludge and cuttings returned to the surface. Hvorslev and Goode (1963) found that a 567 L (150 U.S. gallon) slush tank was inadequate for both settling of the cuttings and cooling of fluid, and used instead a 1020 L (270 U.S. gallon) tank.

Two main sources of energy contribute to the increase of temperature of the fluid (Lange, 1963). Warm air surrounding surface pipes, slush tank, hoses, and other accessory equipment in contact with the fluid is the external source, and the refrigeration requirement may be reduced considerably by adequate insulation of these components. The internal source of energy is applied to the fluid stream by pumping; therefore, the refrigeration requirements, internal to the fluid stream, are equal to the power input of the pump.

Little can be done to reduce the energy supplied by the pump. On the other hand, alternative means of effectively removing cuttings from the fluid, using sedimentation equipment of smaller surface area than standard sludge tanks, should be examined. If successful, such equipment may permit the use of smaller and more economical cooling units.

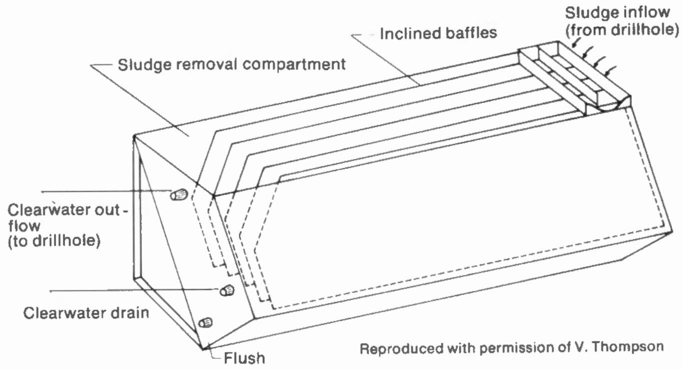


Figure 35. *The Thompson drill water reclaimer.*

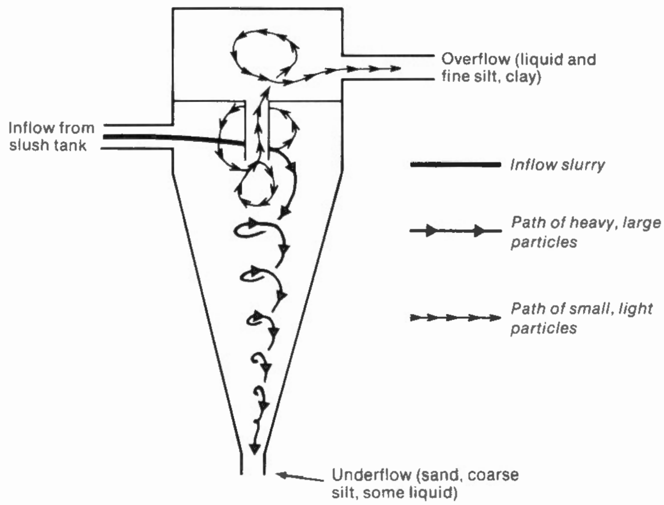


Figure 36. *Flow patterns that develop when clarifying a slurry with the hydrocyclone.*

The Thompson drill water reclaimer (Fig. 35) illustrates a method of saving the amount of drilling liquid required. This sludge tank operates on the principle that separation of solids is more effective when using a series of closely spaced, inclined baffles. Where water is scarce and in permafrost areas where brine or other antifreeze solutions are used, the tank gave good results in bedrock diamond drilling (V. Thompson, pers. comm., 1977). Laboratory testing of the unit was done in the Chemistry Division, National Research Council, Ottawa, using suspensions of calcium carbonate at various concentrations and feed rates. These tests confirm the ability of inclined baffles to remove solids more effectively than vertical baffles. It is not known if the slush tank has been used with refrigerated fluids to core frozen ground. The tanks come in various sizes and are much smaller than conventional ones. If used in conjunction with refrigeration equipment, they could considerably reduce the amount of fluid required and improve removal of cuttings.

Another approach to reducing the quantity of fluid and area needed for sedimentation of cuttings is to use centrifugal force. The use of hydrocyclones to accomplish this is common in industrial applications, and cyclones are used by the oil industry to remove solids in drilling fluids. The principle of the hydrocyclone as a clarifier is that a fluid entering a cylinder or open cone with sufficient pressure tangentially at the base of the cone forms a double vortex (Fig. 36). An outer vortex spirals towards the apex while the inner vortex, surrounding an air core, twists towards the base. If the fluid contains particles heavier than itself, centrifugal force carries the particles towards the wall of the cone and the apex in the outer vortex. Small, light particles are carried by the inner vortex towards the base along with most of the fluid. The hydrocyclone incorporates a controlled overflow outlet at the base of the cone through which the inner vortex escapes and an underflow outlet at the apex where a solid/liquid concentration leaves.

Application of this technology to problems with operational parameters similar to those of fluid drilling has been successful (Charsbury, 1954; Crayston et al., 1954). A model built in the laboratory gave encouraging results and allowed formulation of specifications required for a canvass of the industry to identify an appropriate commercial cyclone. A light (4 kg), small, and inexpensive unit was found and further laboratory testing proved that performance with water and fuel oil warranted field tests. During a spring drilling program using diamond coring equipment with fuel oil, the cyclone was integrated into the circulation system. The predictable problems of volume flux when circulation was blocked and ice particle clogging were identified. There has been no opportunity for further laboratory or field tests, but from the results obtained, the hydrocyclone shows potential as a desander/desilter when fluid volume is limited.

To date, little attention has been given to the abrasiveness of recirculated fluids when coring frozen soils. The oil drilling industry has shown that abrasiveness of drilling mud is reduced considerably when the sand fraction and the coarse silt fraction (>20 μm) are removed. In addition to temperature, abrasiveness of a fluid is thought to be an important factor affecting permafrost core quality.

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