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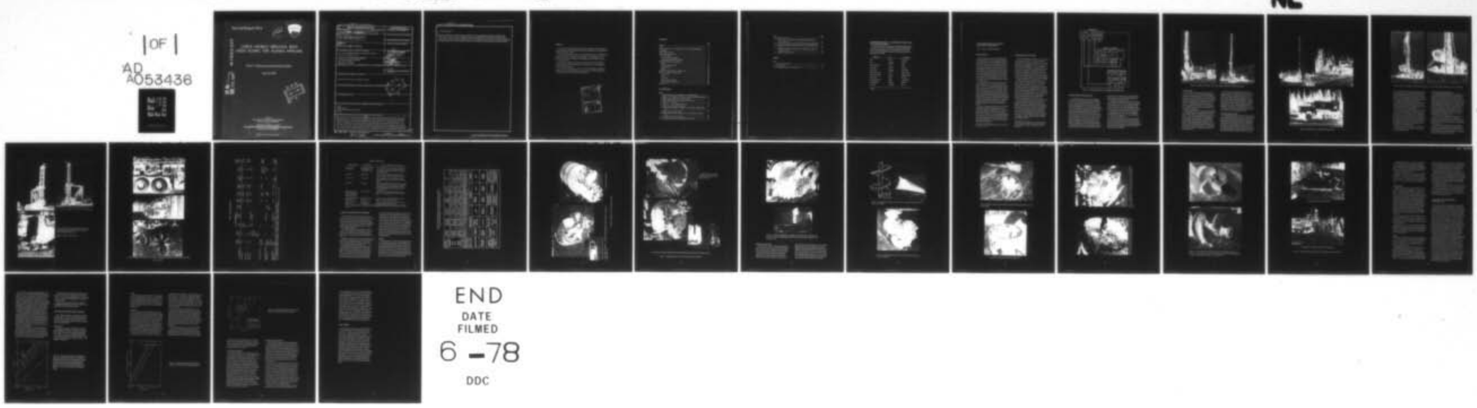

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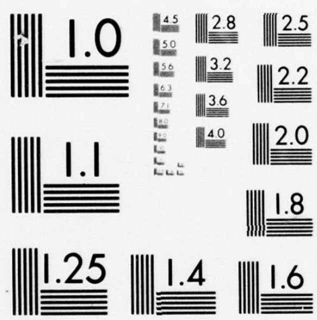

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LARGE MOBILE DRILLING RIGS USED ALONG THE ALASKA PIPELINE

Paul V. Sellmann and Malcolm Mellor

March 1978

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The requirement for installing more than 70,000 vertical support members along elevated sections of the Alaska Pipeline resulted in an extremely large drilling program. Several large drilling units, some specially designed, including rotary (auger), percussive, and combination rotary-percussive units, were selected for this job. This selection of equipment and techniques provided the potential to drill in all conceivable material types. An examination of these drills in the field, together with product literature, provided some insight into the characteristics of these drills compared with other commercially available drilling units. The pipeline drilling program provided a major impetus for design and development of new equipment in the area of large rotary-percussive, and → next page

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percussive drilling units. The pipeline drills in general showed sound design characteristics in weight, power, thrust, torque, and speed. Many of the auger boring heads could benefit from improvements in shape, angles, cutter position, and in consideration of "the center of the hole" problem. Need for work in this area was indicated by drilling rates, as well as by noticeable improvements in some augers following contractors' field modifications.

PREFACE

This report was prepared by Paul V. Sellmann, Geologist, Northern Engineering Research Branch, and Dr. Malcolm Mellor, Physical Scientist, of the Experimental Engineering Division, CRREL.

The work covered by this report was funded under DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions*; Task A2, *Soils and Foundations Technology in Cold Regions*; Work Unit 004, *Excavation in Frozen Ground.*

Special acknowledgment and thanks are expressed to the Alyeska Pipeline Service Company for permitting access to the pipeline route and extending their hospitality during the study.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

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ILLUSTRATIONS

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
foot	0.3048*	meter
foot-pound force	1.356	joule
pound force	4.448	newton
$foot^3$/min	0.02832	$meter^3$/min
pound force/inch	0.1751	newton/mm
pound force/$inch^2$	6.895	kilonewton/m^2
horsepower	0.7457	kilowatt
horsepower/$foot^2$	8.027	kilowatt/m^2
revolution/min	0.1047	radius/s
flow/min	0.01667	Herz

* Exact

LARGE MOBILE DRILLING RIGS USED ALONG THE ALASKA PIPELINE

Paul V. Sellmann and Malcolm Mellor

INTRODUCTION

Several types of large mobile drilling rigs were specially modified or newly designed to drill more than 70,000 holes for the Alaska Pipeline project. Holes were as great as 24 in. in diameter, and up to 65 ft deep. The holes were required to install the vertical support members (VSM's) that carry the Alaska Pipeline along elevated sections of the route. The natural variation in sediments and rock types encountered required holes to be placed in almost every conceivable ground condition. The drilling conditions were further complicated by the occurrence of permafrost of varying temperature, distribution and ice volume.

The drill rigs selected for this operation by the Alyeska Pipeline Service Company employ several different systems for penetrating the ground and removing cuttings (Jons 1975).* This variety in drill units endows contractors with the necessary versatility to match changing ground conditions, with no single rig providing a fully satisfactory solution to all drilling problems. The drilling equipment assembled for this project provides a unique display of the state of the art in development, operation, and capability of large, modern, mobile drilling rigs, as used for making large-diameter holes to relatively shallow depths.

As part of a CRREL program related to the study of pipeline construction equipment, distinctive features and operating characteristics of most of the units were examined, and some analysis and classification were undertaken. The information obtained in this report is based on personal field observations made from Fairbanks north to Prudhoe Bay, discussions with pipeline project personnel, and data from equipment manufacturers.

* Jons, John A. (1975) Drilling problems in frozen ground. *Pipeline and Gas Journal.*

BASIC DRILLING FUNCTIONS

Any practical drilling system has to make provision for *three basic functions:* (1) penetration of the ground material, (2) removal of surplus material from the hole, and (3) stabilization of the hole wall. *Penetration* can be achieved by: (1) direct mechanical action tools such as drag bits or diamond bits where the cutting or chipping tool moves parallel to the advancing hole bottom, or indentation tools such as roller bits or percussive bits where the tools move normal to the advancing face; and (2) thermal penetration (by melting, heat softening, or thermal spalling).

Material removal can be accomplished by: (1) direct lifting of cuttings or cores (either continuous screw transport by helical flights, or intermittent lifting of buckets, grabs, screws, or core barrels); (2) lifting of cuttings by fluid suspension (circulation of air, liquids or foams through stem and annulus); (3) lateral displacement of material into the hole wall (either by direct compressibility, or by infiltration of liquefied waste products); and (4) dissolving of cuttings or liquefied waste in the circulation fluid (applicable in such materials as ice and salts).

Hole wall stabilization, if needed, can be based on: (1) direct mechanical constraint by rigid casing (drilled-in or driven); (2) direct support by fluid pressure (high-density drilling mud or other suitable liquid); and (3) treatment of the hole wall material to improve its mechanical properties (specialized muds, cement grouting, ground freezing, molten rock). The basic drilling functions and ways of fulfilling them are shown diagrammatically in Figure 1, and additional details are given elsewhere (Mellor and Sellmann 1976).*

* Mellor, M. and P.V. Sellmann (1976) General considerations for drill system design. *Proceedings of the Ice-Core Drilling Symposium*, University of Nebraska, Lincoln, August 1974.

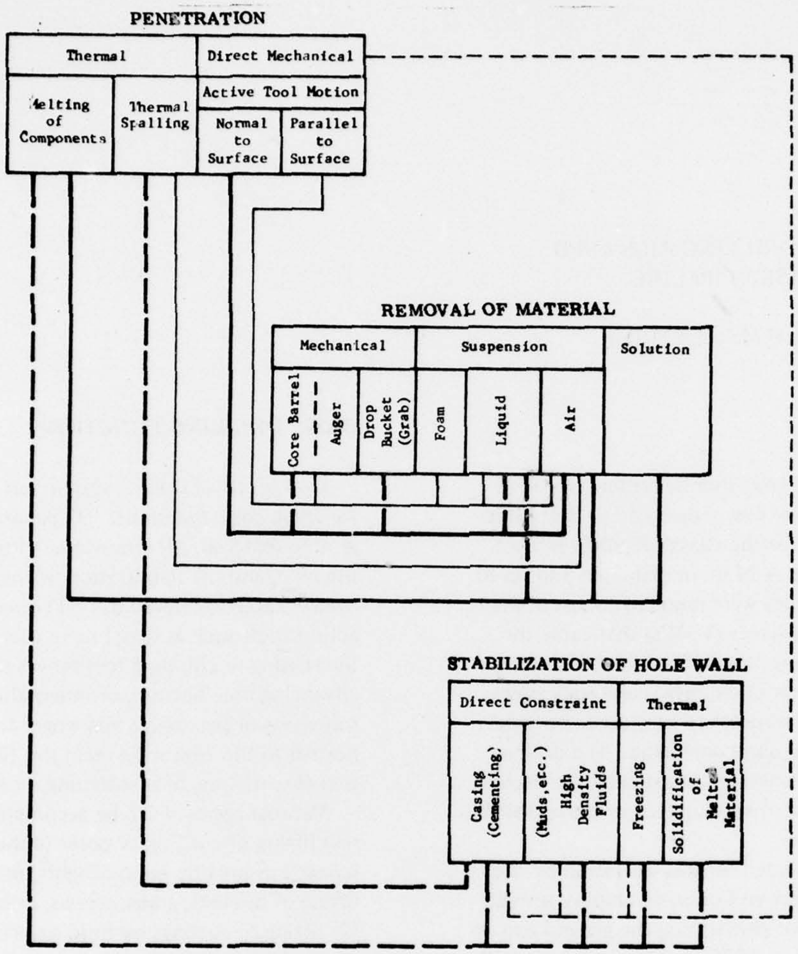


Figure 1. Basic drilling functions and suggested compatibility links.

ALASKA PIPELINE DRILLING RIGS

The VSM drill rigs used on the Alaska Pipeline project all achieve penetration by direct mechanical action. The rotary rigs all use drag bits or roller bits of some kind, while the percussion drills are fitted with either chisel-edge tools or bits with hemispheric studs. Commonly the rotary-percussive units use only the rotary capability for indexing of large down-the-hole hammers, although roller bits can be used on one of the units. Two of the rotary auger units also have the capability of using roller bits, since they are fitted with hollow kellys to allow circulation. The rotary units appear to be most commonly used as augers, employing short helical flight augers, with a variety of cutting bits. Cutting removal is handled in the conventional manner, by intermittently lifting material from the hole on the auger flight, which is then either spun or shoveled clear. The percussive, rotary-percussive, and rotary rigs using roller bits all employ air for cutting removal.

In well bonded permafrost, the hole walls do not require support. In unfrozen soils and in dry granular soils, the hole walls are prone to collapse, and the usual solution was to drive the VSM directly with a percussive rig or to case unstable sections of the hole.

Seven different drilling machines were selected for the pipeline project, and they can be grouped into three general categories; (1) rotary, (2) percussive, and (3) rotary-percussive.

The drills were distributed in the six construction sections along the pipeline apparently based on the drilling requirements, the number of units varying as the work schedule progressed. In some of the sections, the equipment records indicate that as many as 17 drilling units were assigned.

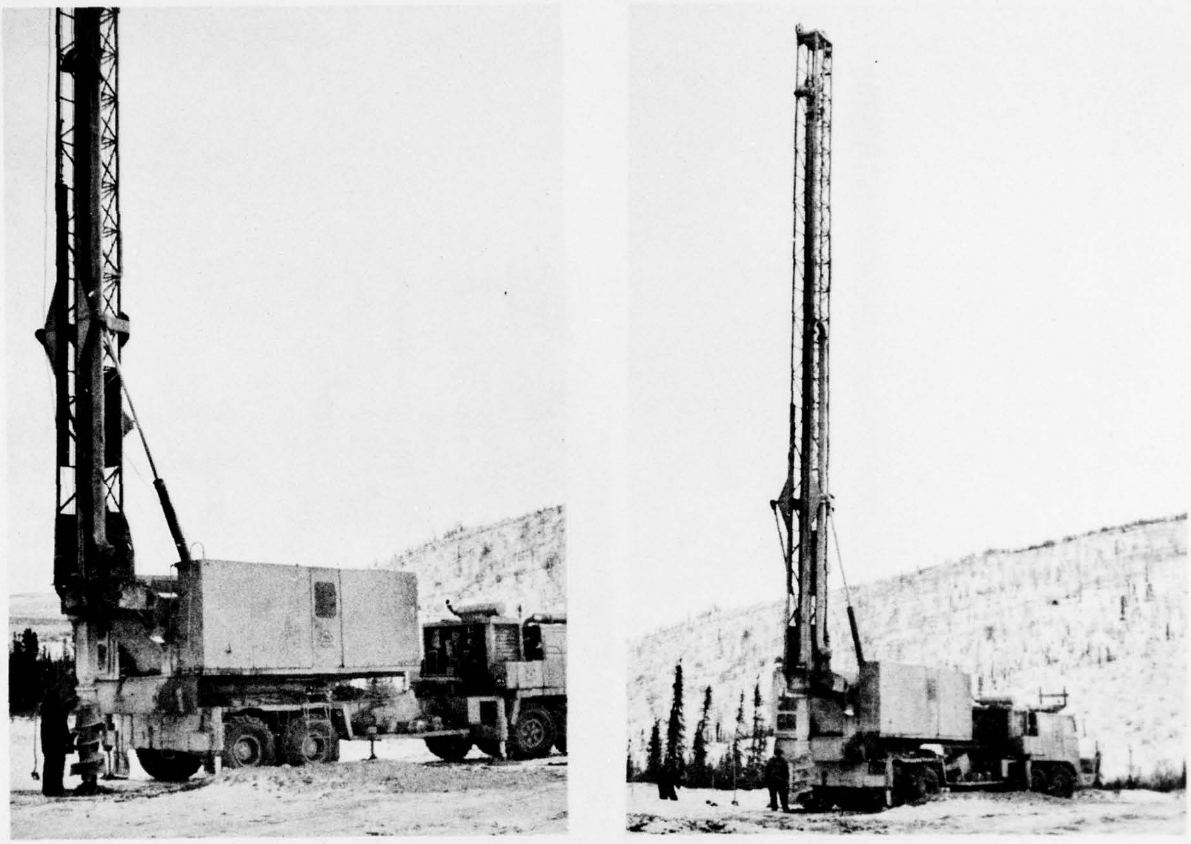


Figure 2. Hughes LLDH, largest of the rotary (auger) units with a 50-ft-depth capability.

Rotary machines

Three models of rotary (auger) rigs were used on the project. They were the most conventional and least modified of the drilling units. They are basically large augers of a type commonly used in construction. Common modifications and features of all the drilling equipment included extensive preparation for cold weather work (including heated operator cabs), enclosure of engine compartments, use of special alloys, heat treatment of some components, and provisions for equipment preheating.

The rigs purchased for the project were the Hughes *LLDH* digger (Fig. 2) and two Reed rigs, the *Taurus* (Fig. 3) and the *Texoma*. These rotary units were of different sizes with depth capabilities ranging from 35-50 ft based on kelly length. A crane-mounted Calweld auger, for which we have no data, was used in one of the southern construction sections. The Hughes *LLDH* and the Reed *Taurus* were fitted with hollow kellys to provide circulation for roller bits and for the Skidmore hammer discussed in a following section (see p. 13).

These drills are best suited for use in frozen soil and very weak or decomposed bedrock, with the most favorable conditions found in frozen clay, silt, and sand. Frozen gravel and some decomposed rocks increase bit wear and reduce penetration rates. The use of roller bits on these rigs can extend their capability into weak rock types. These rotary units are poorly suited for use in areas of unstable ground unless the instability is restricted to a very local zone that can be cased with a short section of casing. Other rotary rigs are covered in the rotary-percussive section.

Percussive drilling machines

The Becker drill was the only purely percussive drill used on the project (Fig. 4). One of its most important assets is that it is the rig best suited for use in areas of unstable ground, since the drill string was designed to include the VSM as the outer tube. The VSM ID permits the bit to pass through it, with the lower end of the VSM terminating immediately above the bit. This arrangement provides continuous casing as the drilling operation progresses, and allows the inner tubes and

Figure 3. Reed Taurus *on both track and wheel carriers.*

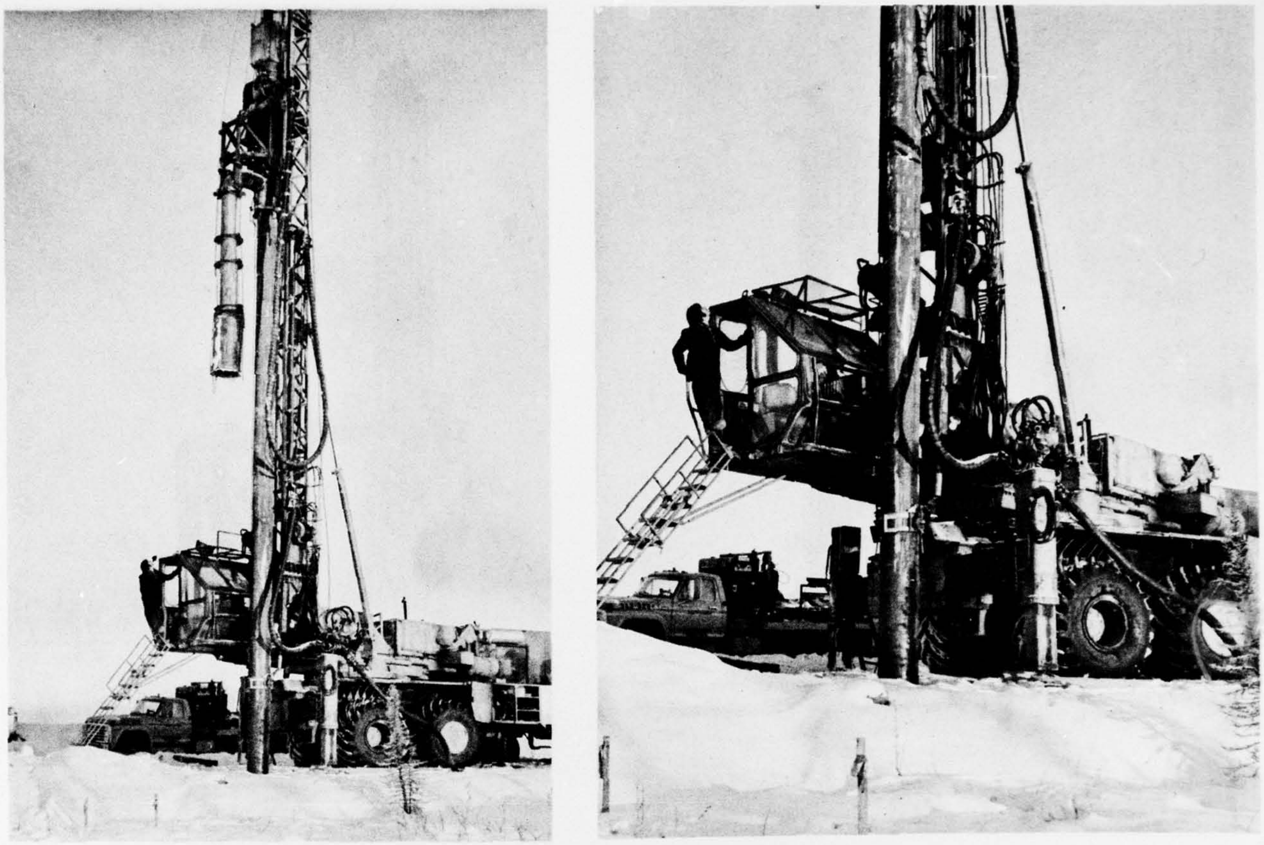


Figure 4. Becker 520 hammer drill with diesel hammer drive. A purely percussive drill with no rotary component.

bit to be removed, leaving the casing (VSM) installed. This drilling technique has the additional advantage that VSM installation is complete when the hole is drilled to its required depth. It eliminates VSM placement and slurry backfilling operations that are required with the other open hole drilling techniques.

The Becker drill operates well in a range of frozen and thawed materials, although it does not work in hard rock and performance is greatly limited in some frozen sediments, such as coarse gravel.

The drill string on the Becker drill consists of three tubes. The inner two tubes are a permanent part of the string, to which the large-diameter chopping bit is attached. As mentioned already, the outer tube is the VSM. The bit has an open center through which the cuttings pass into the inner tube. The cuttings are lifted up the inner tube by compressed air, which is discharged at the bit from the pathway between the inner and intermediate tubes.

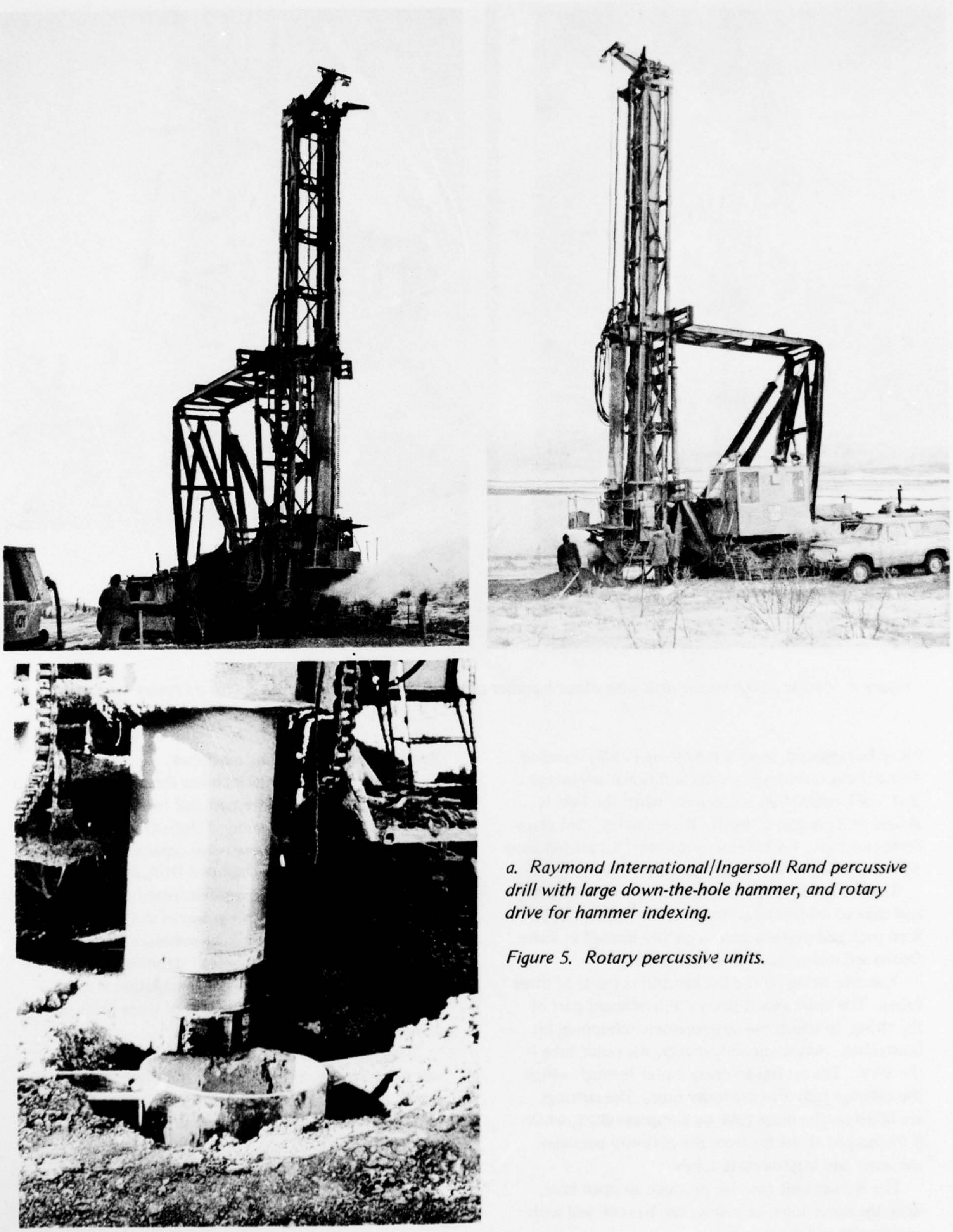
The Becker unit can also produce an open hole, since the outer tube, or casing, can be removed with a hydraulic jacking system.

Rotary-percussive drilling machines

This group of drill rigs includes three different units: the Parker, Raymond International Ingersoll Rand (Fig. 5a), and Alaska Diamond Drills (Fig. 5b), all of which have rotary and percussive capability. Only one of the units, the Alaska Diamond Drill, appeared to be rapidly adaptable to independent rotary drilling. One of the characteristics of this group of drills is that they are well suited for use in harder materials (frozen gravel and rock), where hole wall stability is usually not a major problem and casing installation is not a routine part of the operation. All of these drills use compressed air for cutting removal.

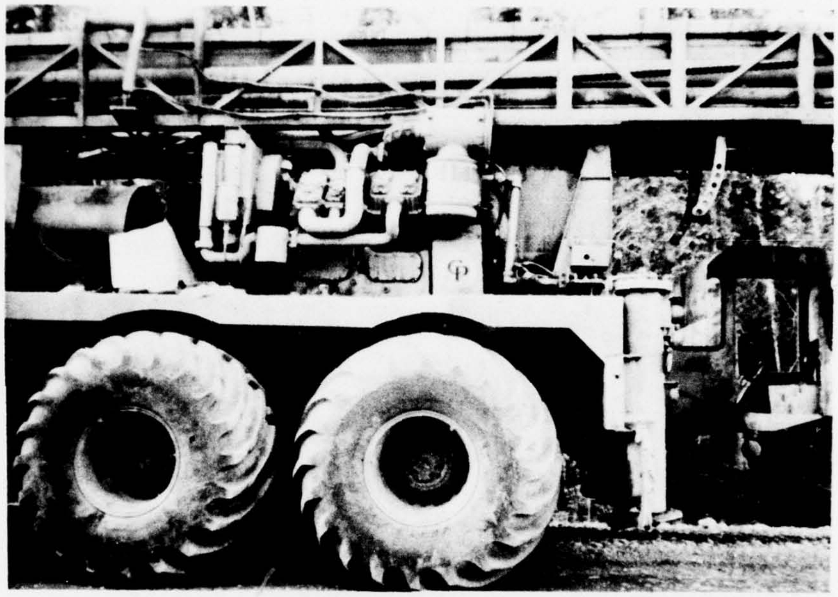
The Parker drill is a hybrid, with capability for a vibratory, rotary, and percussive component to be placed on the string. The operator can select the mode to be used. No first-hand information is available concerning this unit.

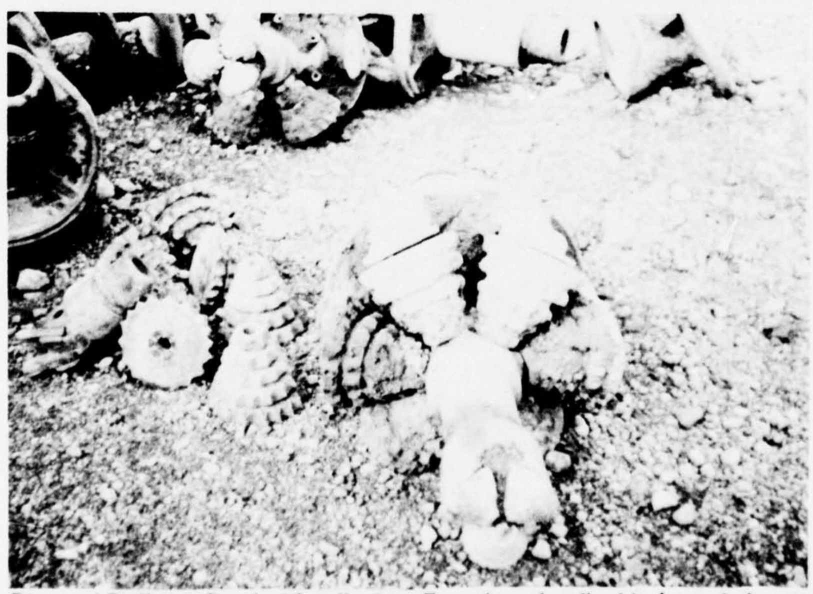
The Ingersoll Rand unit (Fig. 5a) is a percussive drill with a rotary component for indexing purposes. As mentioned, the Alaska Diamond Drill unit can be used for independent rotation drilling, or for percussive drilling with a large down-hole hammer.



a. Raymond International/Ingersoll Rand percussive drill with large down-the-hole hammer, and rotary drive for hammer indexing.

Figure 5. Rotary percussive units.





b. Alaska Diamond Drill unit fitted with roller bit. Forged tooth roller bit shown in lowest photograph.

Figure 5 (cont'd).

Table I. Drill rig specifications.

Drilling machine	Depth capability (ft)	Hole diameter (in.)	Total installed power: Rig (hp)	Total installed power: Circulation equip (air)	Head power (hp)	Head speed (rpm)	Rated torque (ft-lb)	Thrust capability (lb)	Blow frequency (blow/min)	Blow energy (ft-lbf)	Total weight, rig and carrier (lb)
Hughes *LLDH*	50	24	190 at 1800 rpm			12-104	100,000	60,000	NA	NA	114,300
Reed *Taurus*	45	24	184			25-281	84,000	51,000	NA	NA	78,000
Reed *Texoma*	35	24	125			33-497	36,200	56,548	NA	NA	44,000
Becker 520	50	16.75 OD with VSM. VSM is 18, 24 for open hole	117 for hyd, etc.	2×1,600 ft^3/min 345 hp (ea)	77	NA	NA	NA	85	30,000	
Alaska Diamond Drill	45-ft mast, 20-ft travel	24	220			0-50	21,000 at 50 rpm	(126,000)*	280	750 lb piston IR 24-in. diam hammer	80,000-90,000
Raymond International/ Ingersoll Rand	45 ft in 1 pass-max 60 with added string	24		2,000 ft^3/min	70 hammer only	0-100	9,000-12,000		675	3,400	
Parker Drilling Co. OIME VPR	40 ft in 1 pass	24	550	5,200 ft^3/min 125 psi		0-66	35,000	(117,000)†	V&P 0-1200	1,600	127,000 or more

* Thrust originally given as 40,000 lb, later given as 126,000 lb. Weight of rig given as 80,000 to 90,000 lb.

† Thrust originally given as 50,000 lb, later given as 117,000 lb. Weight of rig originally 127,000 lb, probably greater on tracked carrier.

Table II. Types of bits.

Drilling machine	*Cutting process*	*Bit types (diameter, cutter geometry)*
Hughes-TAP-50 *LLDH* digger	Rotary-primarily auger although mod. to include roller rock bits	24-in. bit diameters. Auger bits with a wide range of cutter geometry. Bits shown in Figures 6, 8, and 9. 24-in. Hughes roller cutter rock bits (various tooth configurations) (Fig. 13).
Reed *Taurus*	Rotary-auger	24-in. bit diameter. Several 1) Gopher-heavy-duty (Reed), 2) Pengo augers WPF and APF* (Fig. 6 and 7).
Reed *Texoma*	Rotary-auger	24-in. bit diameter. Several 1) Gopher-heavy-duty (Reed), 2) See Figure 7. (Pocket tool not commonly used).
Becker 520	Percussive	Bladed chopping bit-diameter. 16.75-in. OD with VSM. 24-in. for open hole. (Cutters aligned in a ring around outer edge-like a core bit. Surfaces between cutters slope toward the open bit center to aid in movement of cuttings (Fig. 10).
Alaska Diamond Drill (Power unit and compressor from Chicago Pneumatic-T-650)	Percussive rotary	Diameter - 24-in. 1) Ingersoll Rand-percussive bit (Fig. 12). 2) Reed percussive bit. 3) Their own rotary bit.
Raymond International/ Ingersoll Rand	Percussive rotary for index only	Diameter - 24-in. 1) Ingersoll Rand-percussive bit (Fig. 12). Carbide buttons on flat face.
Parker Drilling Co./ OIME-	VPR vibrator percussion rotary	Diameter - 24-in. Studded percussive bit with spiral setting and spiral airways. (Fig. 11).

* APF and WPF are the same except that APF has a removable head-commonly used with tungsten carbide teeth (Fig. 7).

TECHNICAL DESCRIPTION OF EQUIPMENT

The drills and some of their characteristics were covered in a general way in the previous section. This section covers the more detailed specifications and information on the rigs, bits, and circulation systems. These data are also used later to provide a comparison between these specialized drills and other commercially available drilling units.

The drill rigs and their specifications are listed in Table I. This information was obtained from a number of sources, which resulted in some conflicting information. In most cases manufacturers' data were used.

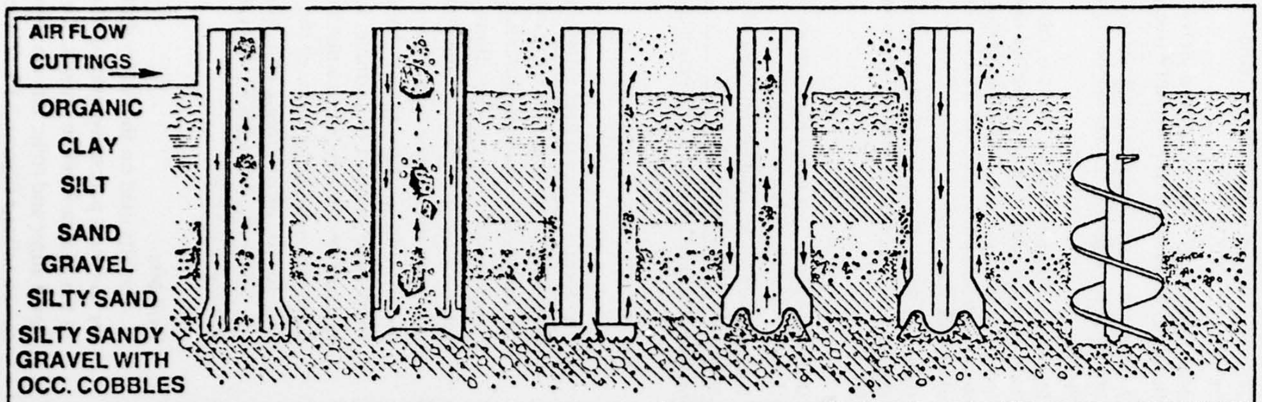
Additional information on the bit types and cutting and circulation schemes is given in Tables II and III. The bit types mentioned in Table II, and commonly used in the field, are shown in Figures 6-13.

The specifications listed in Table I were selected because they provide enough data to examine the potential performance characteristics of the equipment. For example, the information indicates that the rotary drills used as augers are similar, with differences related to their size and depth capability. The total installed power ranges from 125-190 hp. The torque ratings reflect differences in power and head speeds. In some cases the information can be confusing, since some manufacturers state values based on different considerations. The thrust data for some rigs are obviously maximum values that cannot be attained, since total rig and carrier weights are less than the available thrust. Some values also vary from those listed. For example, total weight of rig and carrier can vary, since a number of different carriers were used for some of the Reed units. The data for the other drilling units also help to illustrate the power requirements for the various parts of the drilling operation.

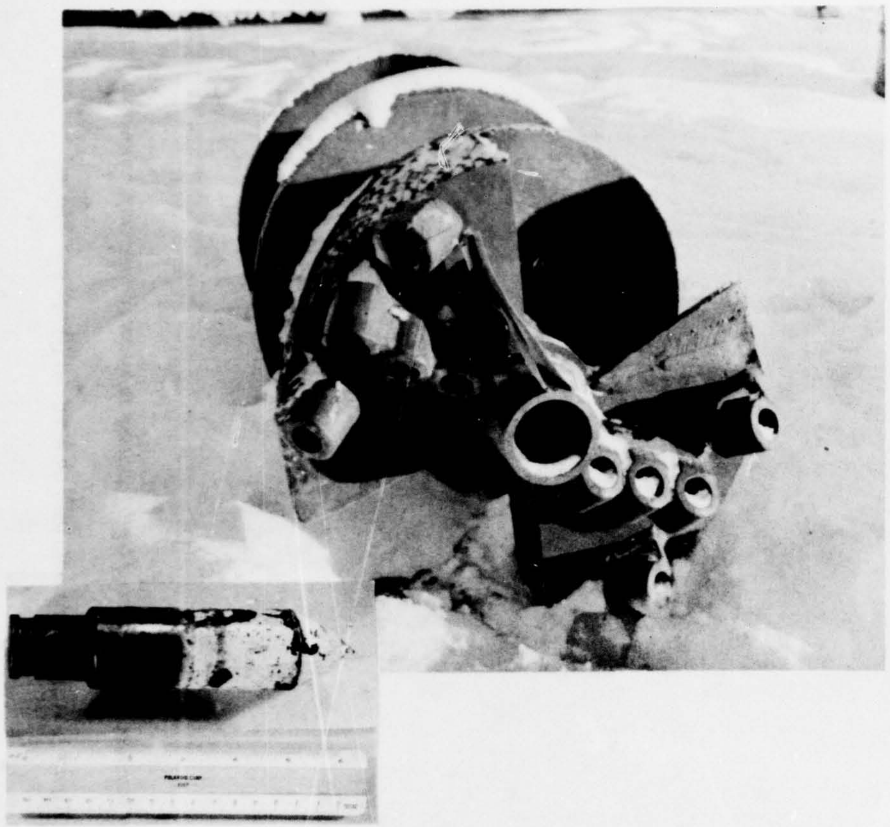
Drill bits

The bits used on the rotary drilling machines were for the most part conventional tools available prior to the Alaska Pipeline project. These fairly conventional auger and roller bits are shown in Table II and the associated Figures 6-13. The cutting tools that reflect the most recent design and development for the pipeline project are the chopping bits used on the percussive unit and the large-diameter percussive bits used on the Ingersoll Rand and Parker units.

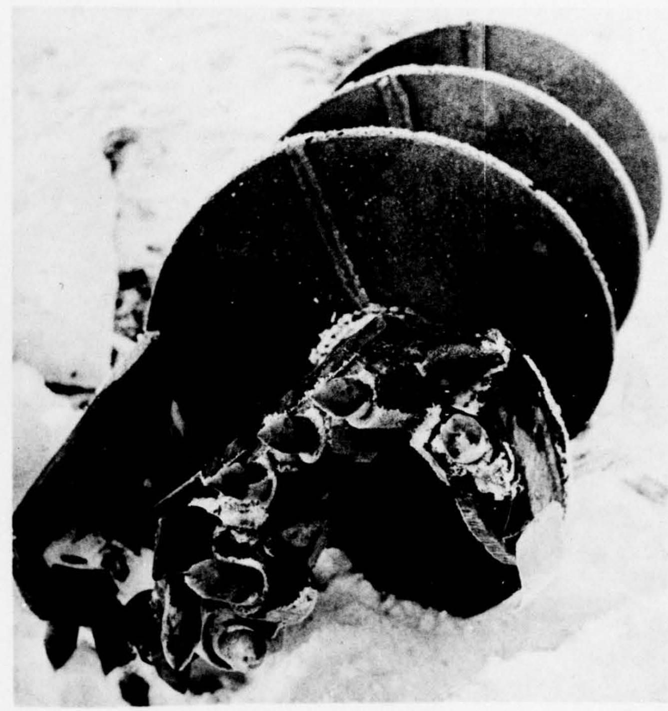
Table III. Drilling techniques in frozen ground (from Jons 1975).
(Copyright, *Pipeline and Gas Journal*; permission granted.)



DRILL TYPE	PERCUSSION			ROTARY		AUGER
CIRCULATION	Double Wall Reverse	Double Wall Reverse with Casing	Direct	Reverse (Vacuum)	Direct	None
DRILLING FORCES	Pulldown Percussion Rotation	Percussion	Rotation Percussion	Rotation Pulldown	Rotation Pulldown	Rotation Pulldown
MAJOR DRILLING PROBLEMS IN FROZEN SOILS	Some plugging in fine-grained "warm" frozen soils.	Slow in "warm" frozen clays. Slow in dense or very cold soils.	Hole erosion in coarse soils.	Freeze-back in fine-grained soils during winter. Plugging in silts and clays in summer drilling.	Hole erosion in coarse soils.	Slow with high auger wear in very cold or coarse soils. Some freeze-back in fine-grained soils in winter drilling.

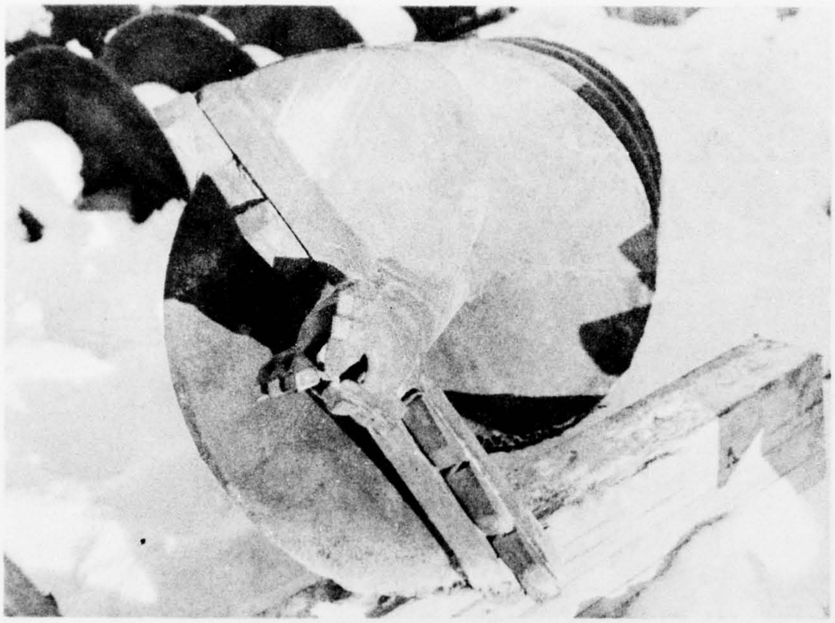


a. Auger used on Hughes rig. Tungsten carbide tipped bit shown in insert. Pilot similar to auger shown in b.

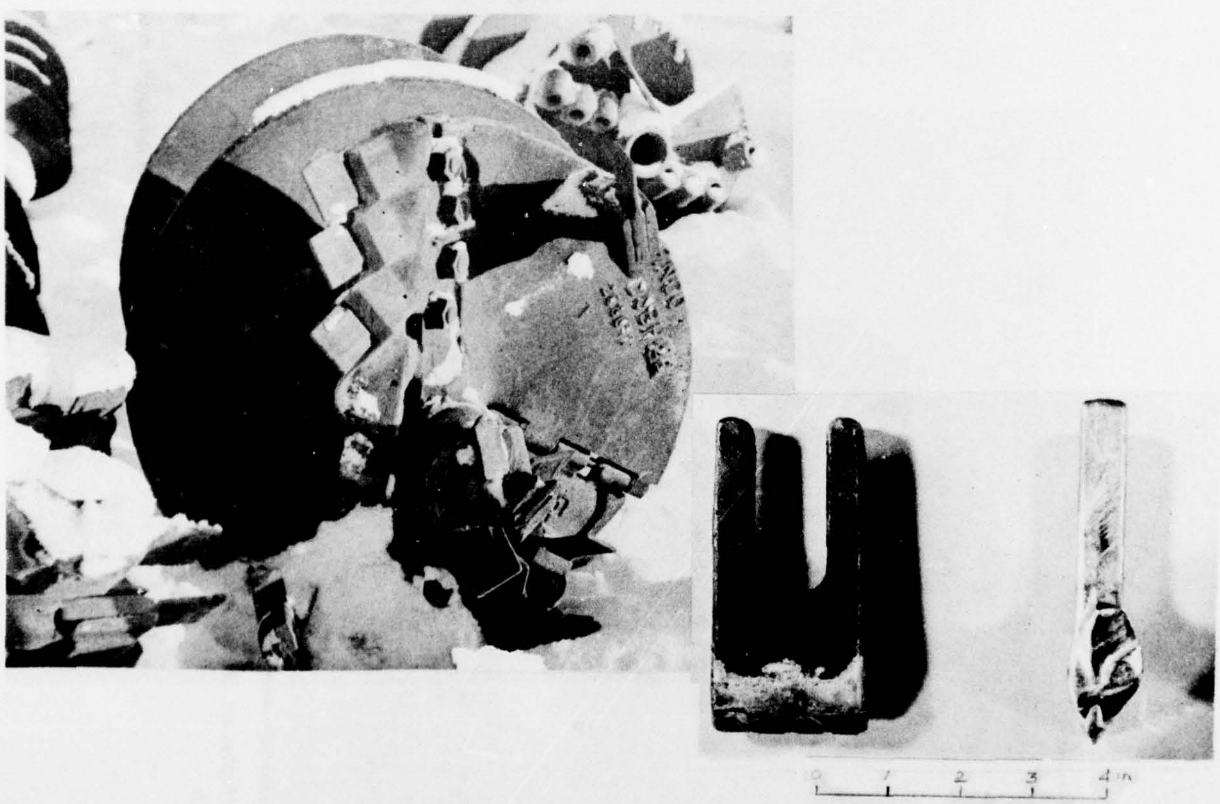


b. Auger used on Reed rigs.

Figure 6. Auger bit – bullet bit augers in general.



a. Gopher auger with tungsten carbide teeth; individual cutter shown in Figure 8.



b. Pengo auger standard with hard-faced teeth, optional tungsten carbide cutter shown in insert.

Figure 7. Augers commonly used on Reed rigs (Pengo and Gopher).

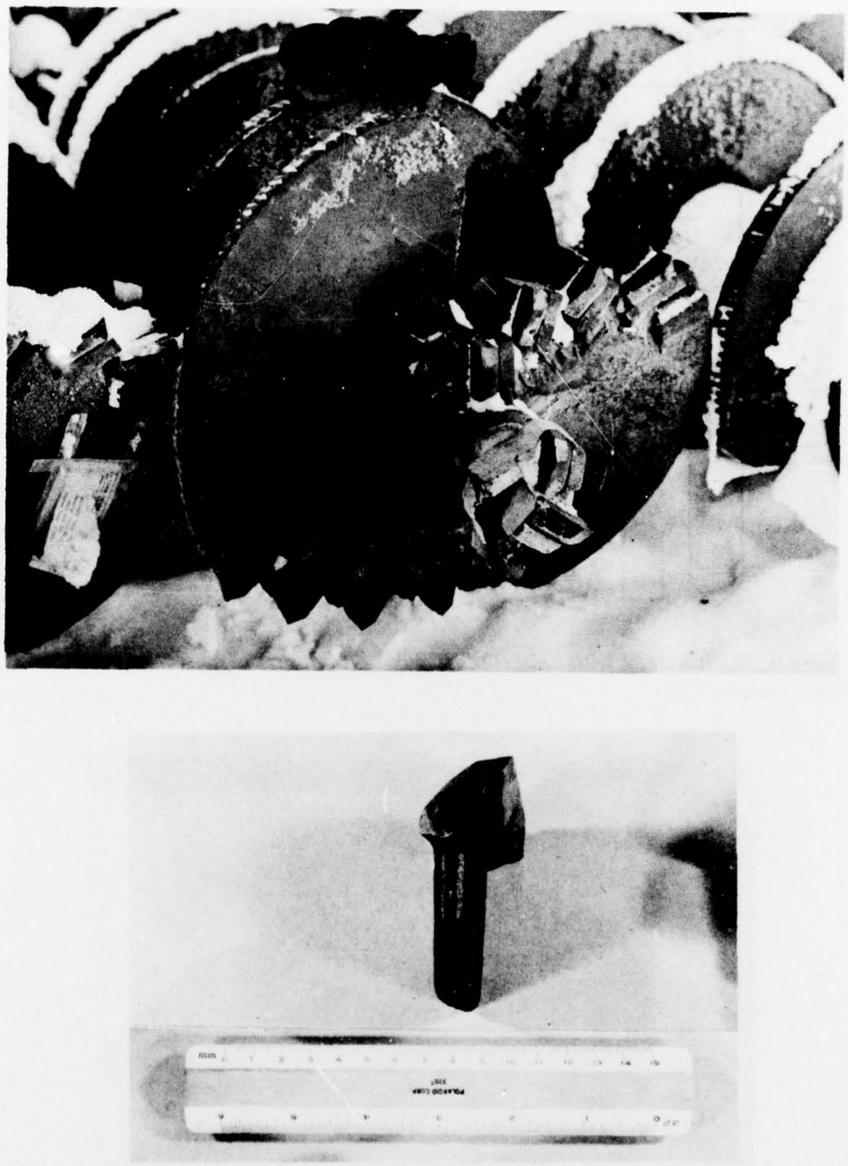


Figure 8. Double-start flight-auger for Hughes, with 10 tungsten carbide insert cutters (heavy-duty rock blade Gopher teeth). Pilot uses some cutters. Made by H and T Auger Co., Inc.

Skidmore hammer auger

The addition of a Mission down-the-hole hammer drill to the central stem of a 24-in.-diam heavy-duty auger resulted in this interesting tool. The modification was presumably intended to increase the operating range of the auger into harder and stronger materials such as frozen gravel and weak bedrock. This unit was not seen in operation; it is therefore speculated that the central hammer drill may improve auger performance, since it might avoid problems with pilot bits, and improve the potential to cut the difficult, central part of the hole. The central pilot hole can also provide a free face for material cut by adjacent auger drag bits to break to. Since the hammer drill requires only limited thrust for operation, it increases the thrust available to the drag bits.

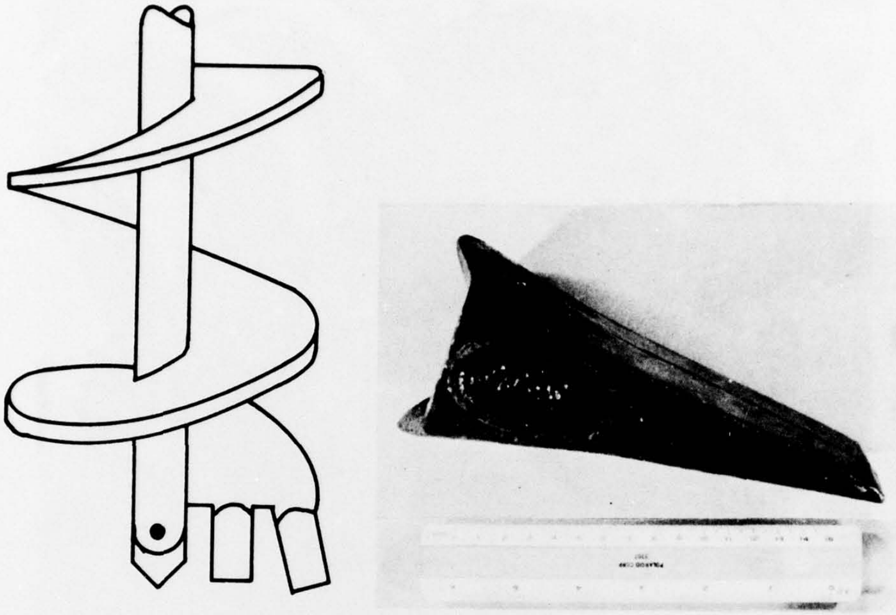
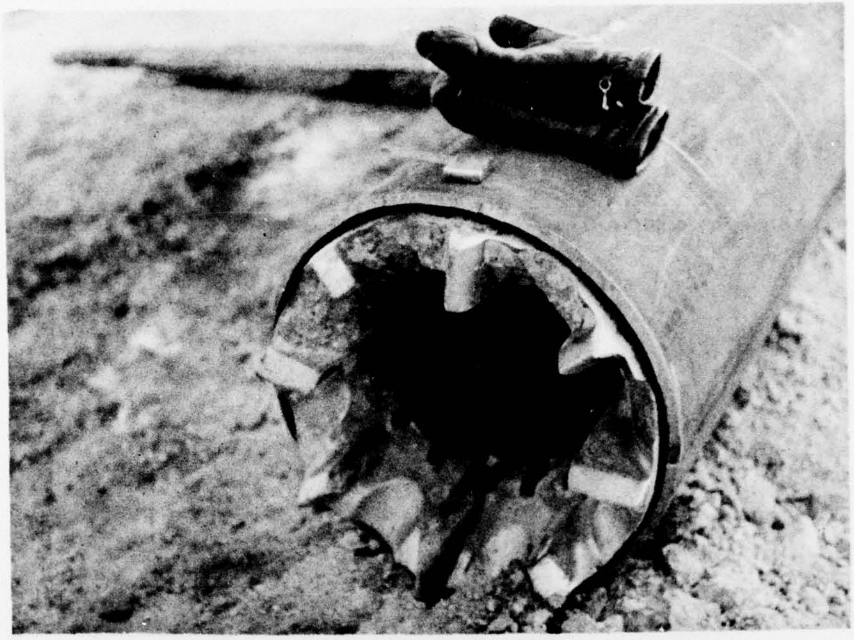


Figure 9. Hughes auger with Esco cutters. Pilot bit is a simple spear point on this model (single flight).

a.

Figure 10. Becker double-wall inner string with bit (a) and VSM over inner drill string (b).



b.

Figure 10 (cont'd). Becker double-wall inner string with bit (a) and VSM over inner drill string (b).

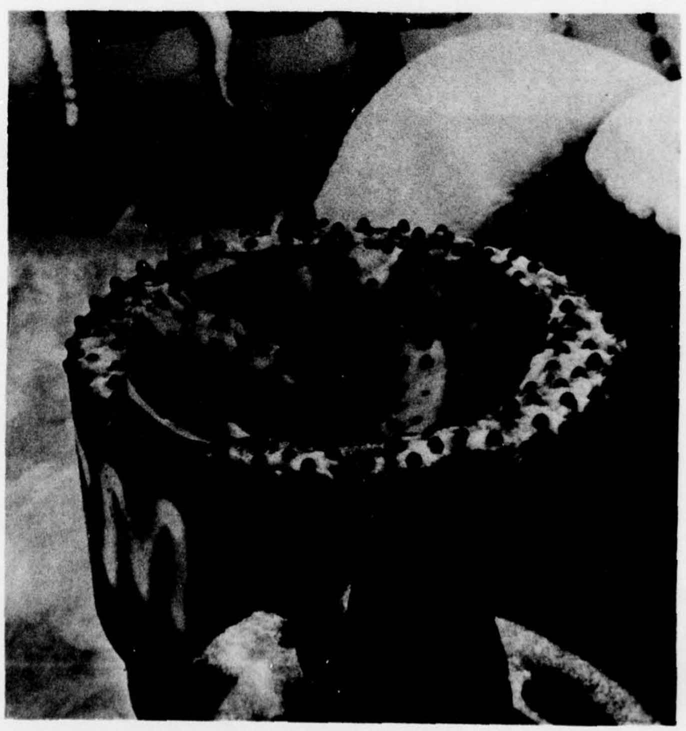


Figure 11. Percussive bit for use on Parker rig.

Figure 12. Large percussive bit used on Ingersoll Rand hammer. The face is dotted with hemispherical carbide inserts.

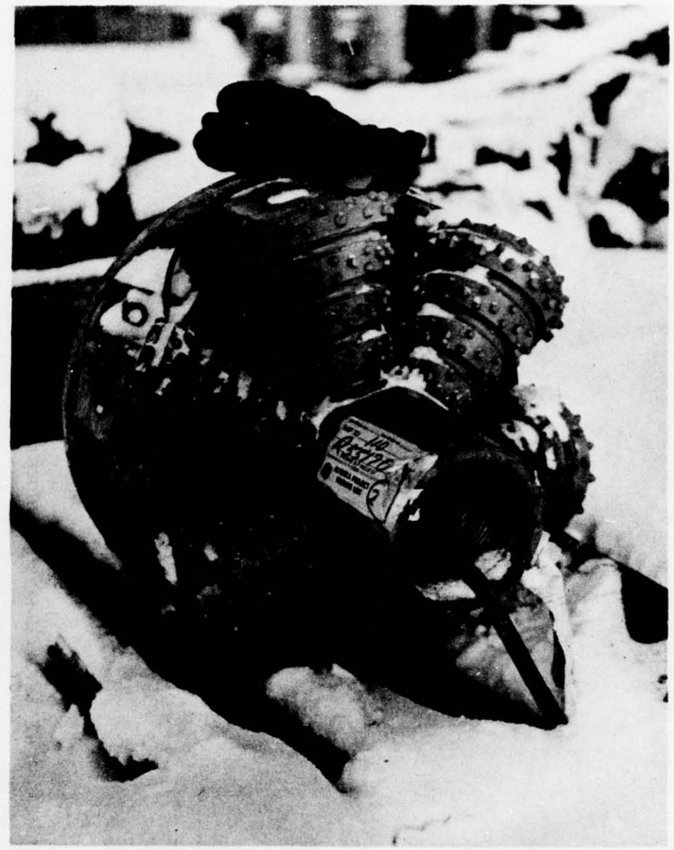


Figure 13. Hughes roller rock bit. Pilot not shown. (Also available with forged tooth rollers – in both long and short tooth configuration.)

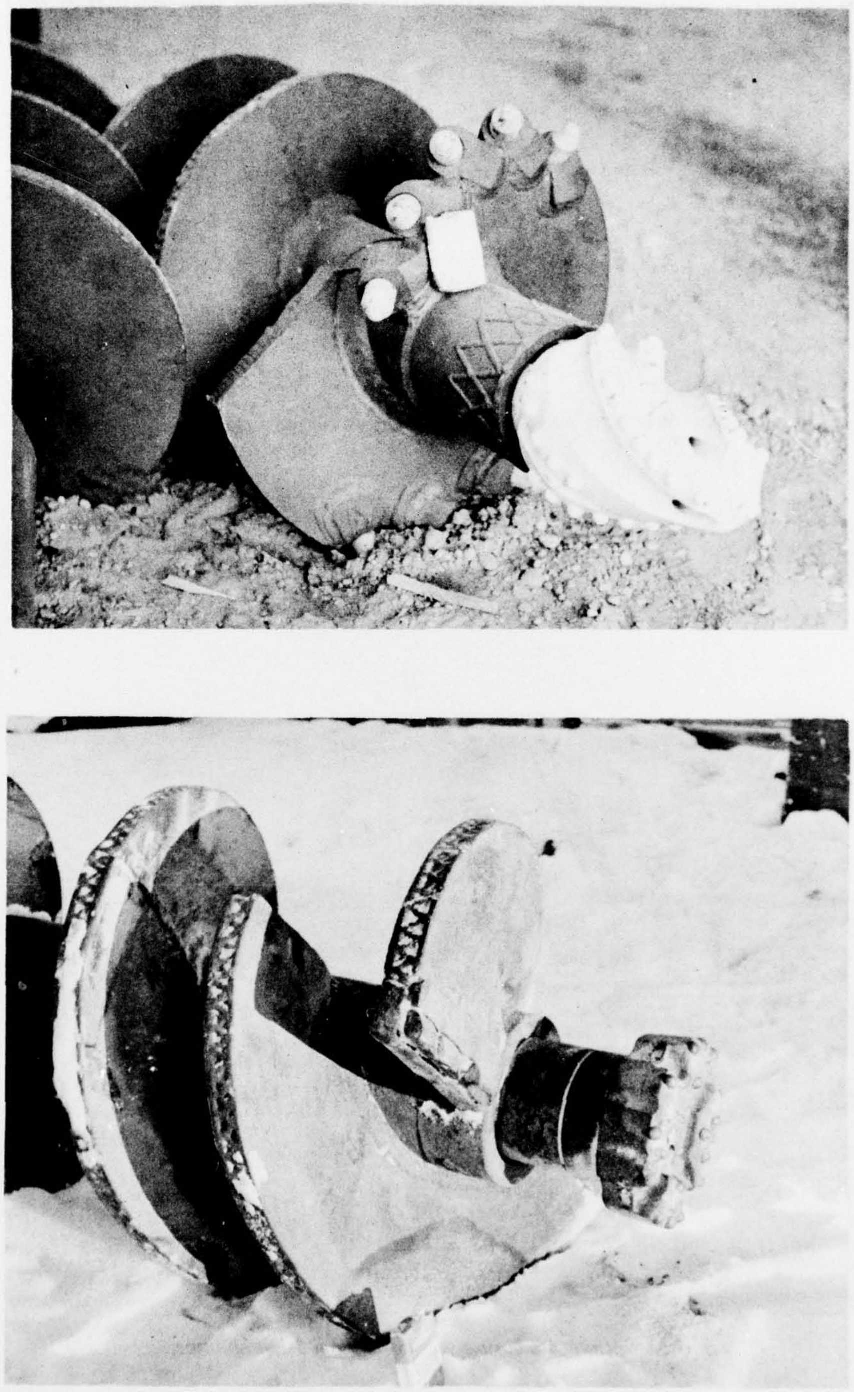


Figure 14. Auger modified to include a down-the-hole Skidmore hammer in its central core. The auger is apparently adaptable to the Reed Taurus and Hughes rigs. It requires an open kelly for airflow to run the hammer.

a. Casing section used with auger rigs.

b. Installation of a casing section using a T-bar spinner.

Figure 15. Casing used with auger rigs, and its installation using a T-bar spinner.

A disadvantage is that it requires an air supply, an air swivel, and a hollow-stem kelly (although some auger rigs already have these features). Cuttings are still transported on the auger flights, which eliminates the large air requirements that would be needed for transport of cuttings by air alone.

We did not see this unit in actual operation along the pipeline. The information presented is, in part, based on our impressions and on comments made by Reed personnel. The augers appear to be available for use on the Hughes auger and large Reed diggers (Fig. 14).

Cutting removal

The procedures used for cutting removal are complicated on some of the drilling units. If cutting removal is not directly mechanical as on the auger systems, it is accomplished by using compressed air. The air circulation systems varied greatly with the drilling techniques and equipment. Circulation included the conventional approach where air is pumped down the drill string and returned up the annulus between the hole wall and outside of the string carrying the cuttings. The Becker rig used a modified reverse circulation system, with air pumped down the hole in the annulus between the inner tube and the intermediate tube in the drill string. The air discharging at the bit face carries cuttings up the center of the inner tube.

The use of compressed air for circulation in holes of this large diameter require large air volumes. As a result, most of the systems using air circulation have large portions of the total drilling systems power used for compressing air.

Table III from Jons (1975) provides an excellent graphic illustration of some of the circulation systems employed in the pipeline drilling rigs. It also includes a summary of some of the problems associated with the various approaches.

Casing

One of the conditions that limited the application of most of the drills, with the exception of the Becker drill, was ground stability. The use of casing with any of the drills is time consuming and requires considerable additional effort.

The auger drills all could set casing at any time during the drilling operation. Most frequently the casing is required in the upper part of the hole to seal off the active layer, although it can be placed at depth to seal any unstable zone. Casing sections are usually short (not > 10 ft), since length is controlled by the clearance between the ground surface and the drill head. Continuous casing of greater lengths would require welding and cutting operations, which would not be compatible with this type of production operation. The casing is drilled in using a T-bar spinner attached to the kelly in place of the bit (Fig. 15).

It appeared that casing was not used with the rotary-percussive rigs. In early equipment trials, casing was set for one of the units using a diesel hammer. It might be anticipated that casing requirements for these drills would be less than those for drills such as the augers, since they are best suited for harder materials with fewer stability problems.

The Becker rig can be used in two ways. It can drill in a continuous casing that can be removed by jacking after the hole has been placed to maximum depth in areas of stable materials. It also can be used to place the VSM's directly. In many areas of unstable ground, the VSM's were placed directly.

UTILIZATION AND PERFORMANCE OF PIPELINE RIGS

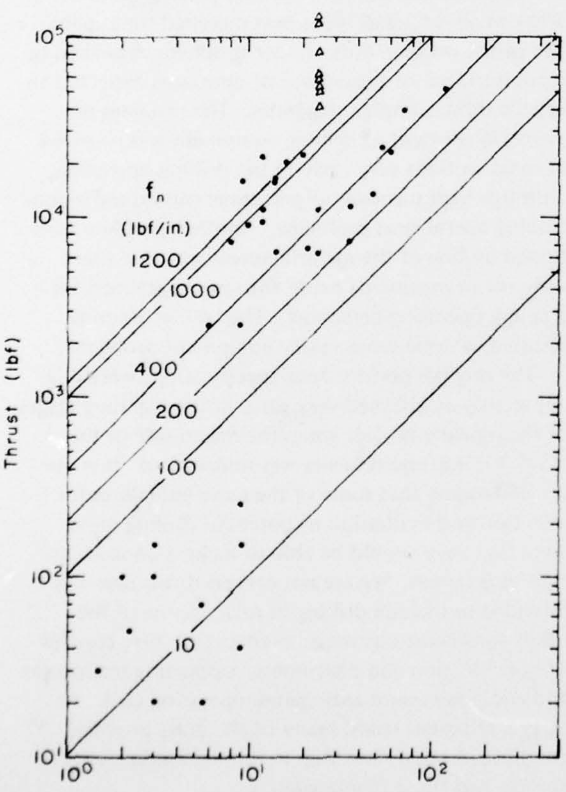
There were reports of some problems associated with performance of the drilling units. There are also explanations for some of the difficulties. Most of the early problems stemmed from not placing the drills in areas where material types best matched the capabilities of the drilling units. Other problems appear to be related to lack of experience of operators expected to handle these complex machines. The problem of proper placement of drilling equipment was resolved in most sections very early in the drilling operation, although high turnover of personnel caused some continuing operational problems. Another problem mentioned by one of the manufacturers was that there were no arrangements made with manufacturers for training operating personnel. The lack of training resulted in some unnecessary equipment problems.

The original performance specifications were apparently established very early in the planning stages of the pipeline project when the magnitude of the VSM drilling requirements was understood. It is our understanding that some of the early guidelines for selection and evaluation of potential drilling units were that they should be able to make a 24-in.-diam hole at 2 ft/min. We are not certain if this rate was intended to include drilling in rock. Some of the other considerations were: maneuverability, control of hole location and plumbness, supporting manpower and equipment, and anticipated operating cost. At early equipment trials, many of the units provided good penetration rates that in some material types approached the 2-ft/min goal.

The information obtained along the pipeline indicated that rates varied greatly depending on ground conditions. The rotary rigs (augers) working in frozen fine-grained material could obtain rates near the design goal, while rates did drop off with augers in the frozen gravels. Examination of daily production logs showed noticeable variations from day to day, with production ranging from 2 to 20 holes per shift. These values reflect operational problems such as the time required for mechanical breakdowns, cutter replacement, installation of casing, and varying drilling conditions.

No detailed information was obtained on how the auger bits performed. In at least two sections some modifications were made to the standard augers to increase their performance. The Hughes auger (Fig. 9) was changed in one section to have a balanced cutter arrangement, instead of cutters placed on just one wing. This was reported to increase performance and reduce wear on the flights.

Some of the new bits, such as the Ingersoll Rand percussive bit, are very expensive. It was reported that the bits cost $25,000 and that they would make about 1800 ft of hole, at a bit cost of around $14/ft. In one section costs for various bits used on the Alaska Diamond Drill unit ranged from $3.50-$6.00/ft.



The largest number of holes per shift, based on discussions in the field, was 27 holes, each 26 ft deep, in 10 hours. This was accomplished with one of the rotary units. A maximum of 17 holes/shift was reported for the Becker drill.

In general, the penetration rates for all types of equipment appeared to range from 0.4 to 24.0 in./min, depending on the materials encountered.

ANALYSIS OF MACHINE CHARACTERISTICS

Some attempt was made to compare the machines quantitatively. The intent was to compare the various types of machines used on the Alaska Pipeline with each other, and to compare them with similar machines that are in use elsewhere.

Vertical thrust

The rated vertical thrust of the rotary machines is plotted against head diameter in Figure 16, which also gives similar data for typical commercial auger drills over a wide size range. The plot shows immediately that the thrust capabilities of the pipeline rigs are well in excess of those for typical commercial augers – from 40,000 to 125,000 lbf.

Figure 16. Thrust of pipeline rigs (△) compared with many rotary drilling units of all sizes (·). Superimposed lines give thrust divided by diameter (f_n); these values give a measure of the normal component of cutting force where total cutter width equals bit diameter. Values can be adjusted by a factor in the range 0.4 to 1.2 in order to account for varying bit design.

Torque

The maximum rated torque of the rotary machines is plotted against diameter in Figure 17. The graph also gives comparable data for other auger drills, from very small hand-held tools to large shaft sinkers. As a group, the pipeline rigs have greater torque capabilities than typical commercial units – from 21,000 to 100,000 ft-lbf.

Tool forces

The vertical thrust and the available torque determine the maximum forces that can be applied to drag bit cutting tools, assuming that these tools are capable of carrying the forces without breaking. For low drilling rates, where the cutters are traveling along shallow helical paths, vertical thrust gives a measure of the normal component of tool force f_n, while torque gives a measure of the tangential component of tool force f_t. If it is assumed that all tools are loaded equally (as they should be when chipping to equal depths), f_n and f_t depend on the total width of all the cutting tools.

In Figures 16 and 17, lines have been drawn for various levels of f_n and f_t for the case where total tool width equals the hole diameter. This represents a case where the bit, or head, had two wings and no gaps between cutters. In other cases, an appropriate factor can be applied, since total cutter width may vary from about 0.4 to 1.2 times the hole diameter. For example, with only one wing and no gaps between tools, f_n and f_t would be double the values indicated by the lines in Figures 16 and 17.

The ratio of tool force components, f_n/f_t, is important because it gives the direction of the resultant cutting force and determines the necessary balance between thrust and torque. Rock cutting experiments show that f_n/f_t can be less than unity for sharp new tools, but with worn tools f_n/f_t increases and reaches values of 2 or more. Limit values of f_n/f_t for the pipeline rigs can be calculated as $f_n/f_t = VD/4T$, where V and D are maximum values of thrust and torque, respectively.

The resulting values of f_n/f_t are from 0.3 to about 2. The low values, which correspond to values for machines that derive from large-diameter soil augers, suggest that more thrust is needed to fully utilize the very high available torque when the machine is drilling

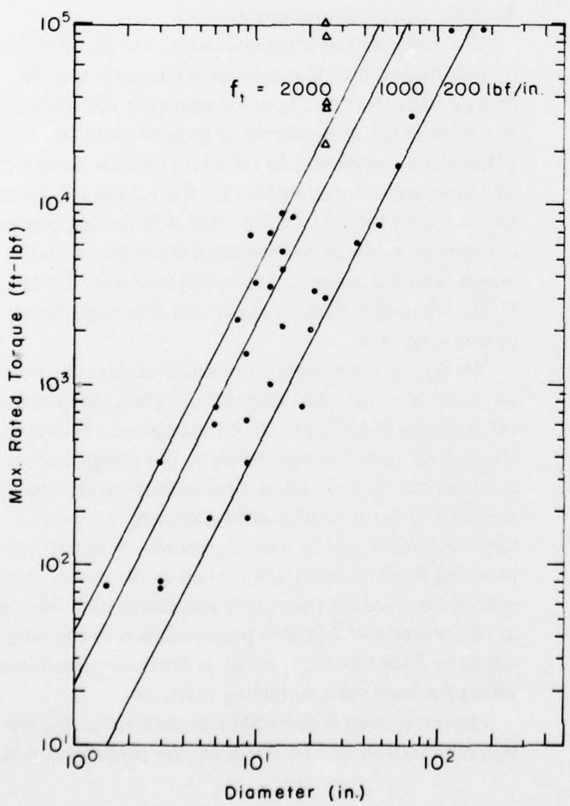


Figure 17. Comparison of maximum rated torque of pipeline rigs (△) with other commercial units (·).

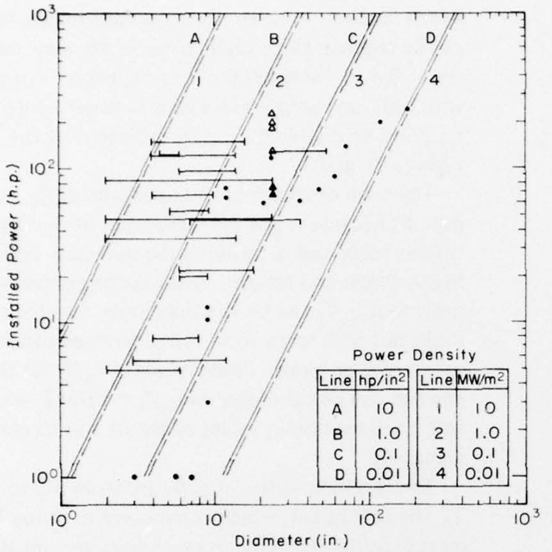


Figure 18. Installed power/diameter plot. Parallel lines indicate various levels of power density.

a 2-ft-diam hole in rock and permafrost. The high values, which correspond to rigs derived from roller rock bit machines, indicate a good balance between thrust and torque for rock drilling with drag bits (taking bit wear into account).

Power and power density

The power supplied to the boring head of a drill is sometimes hard to determine without detailed study of the particular machine; so in Figure 18 the installed power is plotted against head diameter. Lines have been drawn on the graph to indicate various levels of power density, i.e. power divided by hole area. The pipeline rotary rigs appear to have power densities in the range 40 to 70 hp/ft^2, while the pipeline percussive rigs have power densities of about 23 hp/ft^2 (based on head power only). These values are about as high as can reasonably be expected – higher than ordinary values for rotary and chain machines that cut rock, concrete, coal, etc. The plotted data for some of the ordinary commercial rigs seem to suggest much higher power densities, but this is largely an illusion derived from the idea that a powerful unit can apply all its power to the smallest bit that can be attached (10 hp/in.^{2} would destroy a rock-cutting drag bit very quickly).

Specific energy consumption

One scheme that is used to assess the performance of cutting and boring machines is based on specific energy consumption. Specific energy is the work done to cut or break unit volume of ground material. It is often more convenient to calculate specific energy by dividing power consumption by the volumetric excavation rate. In the case of the VSM drilling rigs, power consumption has to be estimated from the available power, and the volumetric excavation rate is $(\pi/4) D^2 R$, where D is hole diameter and R is short-term penetration rate.

We do not have good representative data for short-term drilling rates, and therefore, cannot make proper estimates of specific energy consumption. However, specific energies corresponding to the design goal of 2 ft/min can be calculated, noting that during the visit no piece of equipment reaching anywhere near this rate was ever found in frozen ground. If 90% of the installed power is arbitrarily taken as the power available at the head on the rotary machines, specific energy at full power and 2 ft/min penetration is in the range 4,000 to 7,000 lbf/in.^{2}, which is fairly comparable to values for hard rock tunneling machines.

However, even if the VSM rigs perform at the design penetration rate of 2 ft/min, the performance is not very impressive for frozen soil. Specific energy for cutting and boring is often related to the uniaxial compressive strength of the material that is being worked, and for any given machine or cutting process there is usually a rough linear correlation. With efficient operation of a drill or a tunnel borer, the ratio of specific energy to uniaxial compressive strength can be as low as 0.3 or so (the lower the number, the more efficient the operation). For operation of a drag bit tool under experimental conditions, the ratio can be 0.1 or lower. The strength of frozen soil is highly variable, but it is likely to be in the range 500 to 5,000 lbf/in.^{2} Thus the VSM drills are not very efficient even when penetrating at 2 ft/min, and when they are operating at the rates that were observed, they are remarkably inefficient in energetic terms.

CONCLUSIONS

The drilling and placement of VSM's in the harsh Alaskan environment is a tremendously impressive achievement. Nevertheless, the actual performance of the rotary drilling equipment did not seem particularly outstanding. The design penetration rate of 2 ft/min is quite modest when compared systematically with the capabilities of other rock cutting machines, but even so this rate did not seem to be attainable on a regular basis. The drilling machines themselves appear to have fairly sound design characteristics in terms of weight, power, thrust, torque and speed, although some improvements could be made if completely new machines were to be designed from scratch. The design of the drag bits and drag bit boring heads for the rotary machines (augers) leaves something to be desired. In particular, the shapes, angles and positions of cutters could be improved, and the "center of hole" problem could be handled better.