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GENERAL CONSIDERATIONS FOR DRILL SYSTEM DESIGN

Malcolm Mellor, et al

Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

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Drilling systems are discussed in general terms, component functions common to all systems are identified, and a simple classification is drawn up in order to outline relations between penetration, material removal, hole wall support, and ground conditions. Energy and power requirements for penetration of ice and frozen ground are analyzed for both mechanical and thermal processes. Power requirements for removal of material and for hoisting of drill strings are considered, and total power requirements for complete systems are assessed. Performance data for drilling systems working in ice and frozen ground are reviewed, and results are analyzed to obtain specific energy values. Specific energy data are assembled for drag-bit cutting, normal impact and indentation, liquid jet attack,

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and thermal penetration. Torque and axial force capabilities of typical rotary drilling systems are reviewed and analyzed. The overall intent is to provide data and quantitative guidance that can lead to systematic design procedures for drilling systems for cold regions.

PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Civil Engineer, of the Applied Research Branch, and Paul V. Sellmann, Geologist, of the Northern Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The report covers work done under Project 4A762719AT32, *Research for Engineer Applications of Nuclear and Non-nuclear Explosives in Theaters of Operations*; Task 03, *Explosive Effects in a Winter Environment*; Work Unit 002, *Cutting, Drilling and Breaking Frozen Materials.*

This report was reviewed technically by Dr. Ivor Hawkes and John H. Rand.

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NOTE ON UNITS

The primary units in this report are English units, since much of the relevant technology and much of the source material involve numbers that are rounded in this system. SI equivalents are given in parentheses as far as possible, and to cover those instances where dual units are not practicable, the following conversion factors are offered.

English unit	*Multiply by*	*To obtain SI unit*
in.	25.4	mm
ft	0.3048	m
ft/sec	0.3048	m/sec
ft/min	5.08	mm/sec
lbf	4.448	N
lbf/in.^{2}	6.895×10^3	N/m^2
in.-lbf/in.^{3}	6.895×10^3	J/m^3
ft-lbf	1.356	J
hp	0.7457	kW

GENERAL CONSIDERATIONS FOR DRILL SYSTEM DESIGN

by

Malcolm Mellor and Paul V. Sellmann

INTRODUCTION

Drilling involves an enormous range of highly specialized processes, products, and technologies, making it difficult to assimilate all the information required for solution of particular drilling problems. This difficulty is very pronounced in the case of problems that involve frozen ground and massive ice, since existing drilling systems are likely to require modification to meet the special ground conditions. It is therefore desirable to consider the basic elements of drilling systems that are often obscured by the technicalities and complications of practical products and processes.

In this short review, a scheme for classification and analysis of drilling systems is outlined as a preliminary step. The intention is to illustrate a broad systematic approach without attempting to cover each aspect of drilling in detail.

BASIC ELEMENTS OF DRILLING SYSTEMS

Virtually all practical drilling systems embrace three basic functions:

1. Penetration of the ground material
2. Removal of the surplus material
3. Stabilization of the hole wall.

Each of these factors can be dealt with in a variety of ways, leading to a very large number of potential combinations for complete systems. However, the number of available combinations is reduced somewhat by the need for compatibility between individual elements in a practical drilling system.

Figure 1 outlines the main elements of practical drilling systems and indicates some compatibility links between individual elements. It does not embrace novel experimental drilling concepts such as hypervelocity water jets or electromagnetic devices, although such things could be added to the scheme.

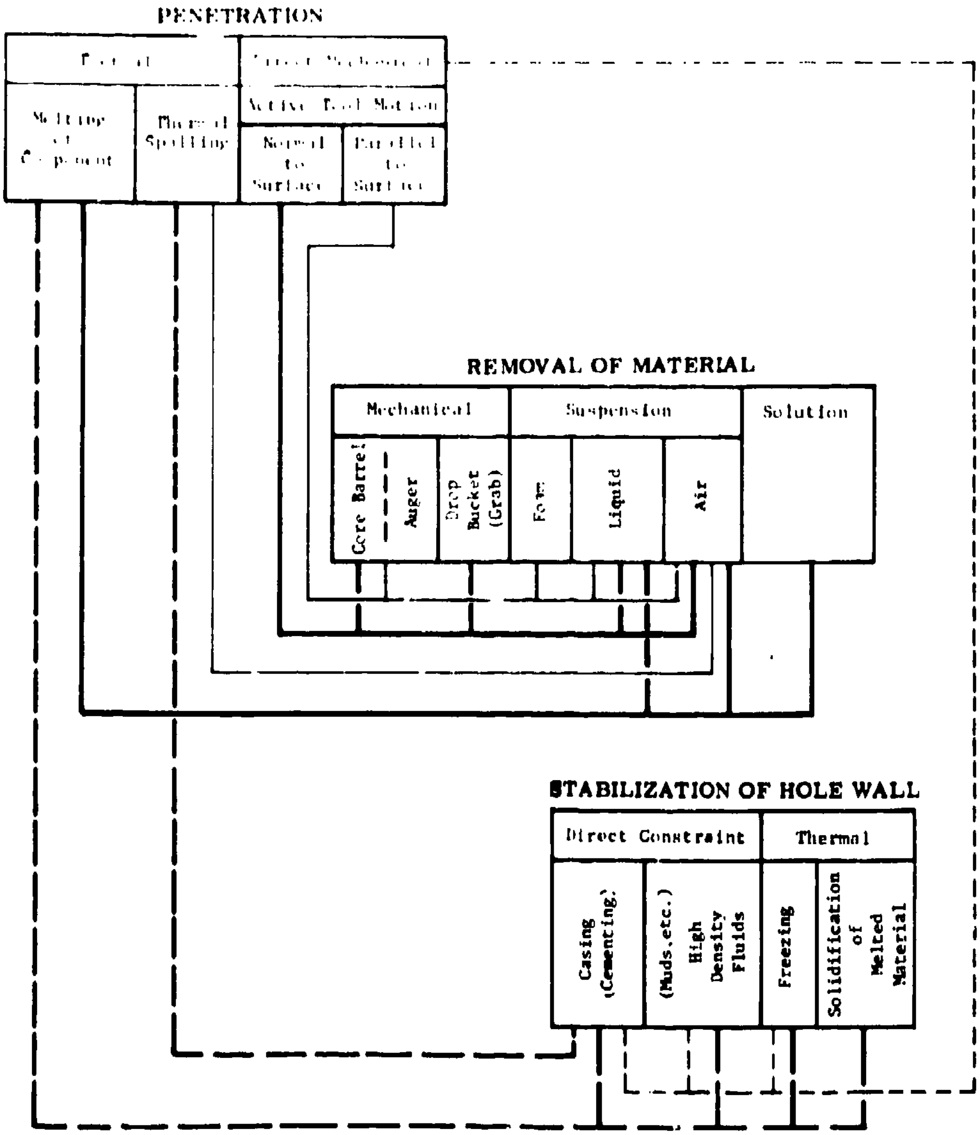


Figure 1. Elements of practical drilling systems and suggested compatibility links.

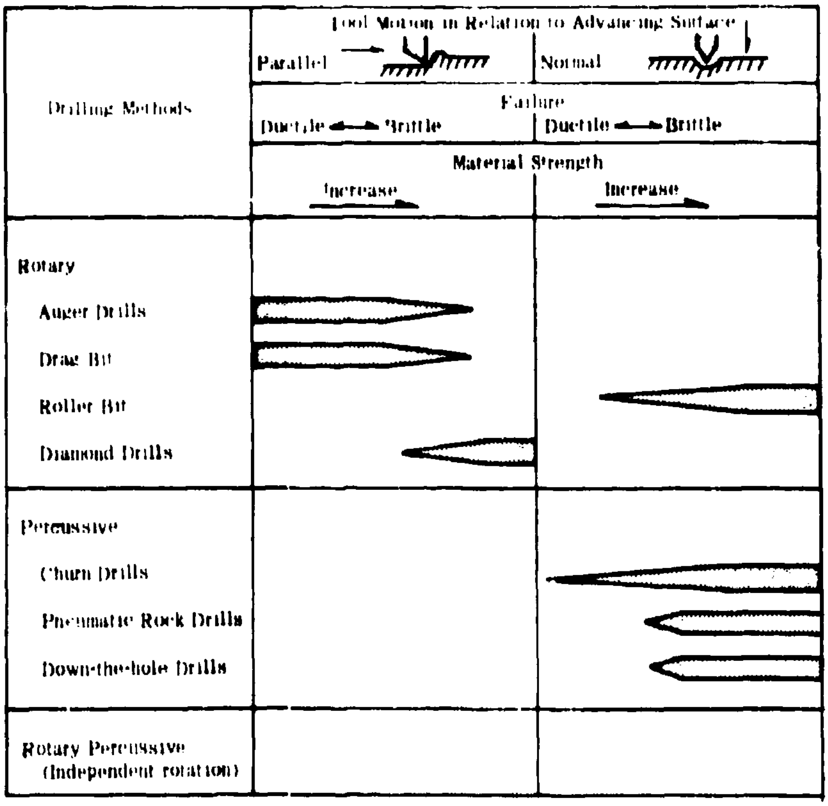


Figure 2. Range of applicability for various types of drilling methods in relation to tool motion and material properties.

Penetration

In most conventional drilling systems, penetration is accomplished by one of two methods: 1) direct mechanical attack, or 2) thermal attack.

Direct mechanical processes can be broadly subdivided according to the working motion of the bit or cutting tool relative to the advancing surface. Motion is usually either parallel or normal to the advancing surface. Percussive bits and roller bits are examples of tools in which the cutting or chipping element moves normal to the advancing surface during the active stroke. In these cases of normal motion, the resultant force on the active component is also very nearly normal to the advancing surface. Drag bits and diamond bits are examples of tools in which the cutting element moves parallel to the advancing surface. However, the resultant force on the cutter tip of the parallel motion tool is not parallel to the surface, since a substantial normal component of force is usually involved.

Many considerations enter into the selection of a mechanical process, but the choice is heavily dependent on the properties of the material to be cut, particularly the strength, ductility and abrasiveness. Figure 2 gives a rough indication of the range of applicability for various types of bits and drilling systems.

Thermal penetration methods usually depend upon either (i) complete or partial melting of one or more components of the ground material, or (ii) thermal spalling in suitable materials. Melting methods have been widely used in ice and frozen soils; representative devices include electrically-heated thermal corers and probes for ice, and steam point drills for ice and ice-rich mineral soils. Similar methods could be used in other materials with low melting point, e.g. sulphur. More novel melting devices are being studied experimentally for drilling and tunnel boring in hard rocks generally; these employ high temperature heating (up to about 2000°K) that is capable of melting and fusing silicates. Thermal spalling depends on development of large strains and high strain rates by rapid heating or cooling. The presence of strain discontinuities is also important. Certain types of rocks, known as "spallable rocks" (usually crystalline rocks with constituent minerals that may have widely differing expansion coefficients) are well suited to thermal spalling under the action of flame jets, plasma arcs, lasers, etc.

Jet penetration methods, which are still in the experimental stage of development, might be regarded as a special form of direct mechanical attack, although there may be some tenuous relations to thermal principles. Explosive shaped charges, in which interacting shock fronts form a jet and entrain metal particles, have long been used to punch shallow holes, but they have not been used for deep drilling (they have been considered for tunneling). Streams of free solid projectiles, which are basically similar in function to percussive tools, have been proposed for tunneling, but not for deep drilling. However, liquid jet drilling, using either a pure liquid or a liquid containing solid particles, is under active development. No jet drills have yet been built for use in ice or frozen ground, but basic experiments with jet pressures up to 100,000 lbf/in.^{2} (690 MN/m^2) have been carried out on ice and frozen soils, and rotating nozzle systems applicable to drilling have been developed.

Material removal

The material removal function is critically important to all drilling systems, and many varied and ingenious techniques have been developed. However, all material removal systems can be grouped into a few categories according to the process used. The following categories are suggested:

1. Direct lifting of cuttings or cores
2. Lifting of cuttings by fluid suspension (air, liquids, or foams)
3. Lateral displacement of material (especially in compressible soils)
4. Dissolving of cuttings.

Direct lifting can be accomplished by continuous screw transport using helical flights, by intermittent lifting of buckets, grabs or screws, and by intermittent lifting of core barrels. Continuous flight augers transport cuttings directly from the bit to the surface by screw action. Ideally, flow rate through the screw is equal to production rate at the bit, but in many ground conditions cuttings spill between the outside of the flight and the hole wall, so that the flight tends to recycle cuttings (this is one reason why bristle seals and flight casings have been developed). Continuous flighted systems find their main application in shallow drilling, usually not more than 100-ft depth. Intermittent lifting of cuttings after finite intervals of bit penetration can be accomplished with a variety of devices. Bucket augers load directly from the bit, as do the short sections of low pitch auger flight that accumulate cuttings until lifted clear. Flighted core barrels also load directly, both with core and with cuttings from the annulus between the core and the hole wall. There are also grabs, typically used with cable tool systems, that are lowered into the hole to extract cuttings after the bit has been removed.

Suspension transport is the most widely used and the most broadly applicable method for cutting removal at the present time. In a typical arrangement, fluid is fed continuously down the center of the drill rod or pipe, out past the bit, and back up the annulus between the drill stem and the hole wall. The fluid may be air, water (often with additives to increase density and viscosity), or other liquids (e.g. kerosene or diesel fuel for low temperature operations). The flow velocity (which is controlled by an air compressor or a fluid pump) must be sufficient to suspend and transport the cuttings. This type of system can be applied to almost every type of drilling system, from small hand-held percussive drills to deep oil-well rotary rigs. In a variant of the circulation pattern just described, fluid enters the hole down the annulus and returns up the drill stem, impelled by suction from the return end or by direct pumping into the annulus. When air or untreated water is used as the transport fluid, the discharged fluid with its load of waste products is often discarded, but when treated water or other expensive fluids are used, the discharge is passed through a settling system to remove cuttings and the fluid is then recirculated.

Lateral displacement of surplus material can be applied when rods or tubes are thrust into material that can be moved to accommodate the penetration, either by compaction, by plastic flow, or by absorption of liquefied waste products. Drive sampling, vibratory drilling, and pile driving in soils are examples of processes that require material to displace laterally. When a thermal drill or probe penetrates dense snow on glaciers and polar ice caps, the surplus meltwater can be absorbed and refrozen in the adjacent snow. A similar principle has been suggested for disposal of melted rock produced by thermal drills and tunnel borers, and it appears to be applicable in some rock types.

Solution. The change of solids to a liquid state can provide an attractive alternative to aid in transport or penetration of some materials, e.g. ice and salts. This is particularly true if the minerals require relatively small energy levels for a change of state. This could permit materials to be transported up the hole without the use of more cumbersome mechanical methods such as flight augers, and could also eliminate the requirement for pump circulation systems to be designed to handle solid particles.

Hole wall stabilization

It is essential to maintain stability of the hole wall while a drilling operation is in progress, and in many cases it is desirable to maintain stability after the completion of drilling. The primary objectives are to prevent wall failure and erosion of the wall by drilling fluids, and also to restrict lateral fluid movement into or out of the hole.

There are three general approaches to stabilization: 1) direct mechanical constraint with a rigid casing, 2) direct constraint with fluids, and 3) treatment of the hole wall material to improve its mechanical properties.

Direct constraint by mechanical means is usually provided by metal pipe placed in close contact with the hole wall. This type of casing can be placed either by driving it with pneumatic casing hammers or large drop hammers, or by drilling it in with a bit set on the bottom of the casing.

Casing can be placed after a hole is completed, or concurrently with a drilling operation. The approach used depends on the drilling equipment used, material properties, and objective of the drilling program. When casing is placed after hole completion, the conditions can vary from stable ground, which causes limited problems, to unstable ground where it is necessary to use high density fluids to maintain an open hole until the casing is placed.

Concurrent placing of casing with the drilling operation involves the progressive or simultaneous advancement of the casing and drill string. The choice of advancing the casing ahead of or behind the drill or sampling tool is controlled by ground conditions and the program objective.

Direct constraint by liquids is employed in many drilling situations when hole wall stability is a problem. A high density liquid or drilling mud is usually used as a drilling fluid, which loads the hole wall and prevents wall failure. In ice, this technique has been used in deep holes to retard closure of the hole by creep.

Treatment of the ground material usually involves the use of specialized muds, cementing techniques, or freezing. Specialized muds are often used to seal permeable rock types. In some cementing operations, cement grout is forced under pressure into the unstable or permeable soil or rock. The distance to which the ground can be grouted is determined largely by material properties. Freezing operations might be subdivided into active applications, in which previously unfrozen ground is frozen, and passive applications, in which frozen ground is maintained in the frozen state. In all passive applications, and in some active applications, thermal control is achieved most readily by circulating cold drilling fluid in a suspension transport system. In very cold weather, heat exchange between the drilling fluid and ambient surface air can be utilized, but in other circumstances it is necessary to refrigerate the drilling fluid. In some shaft-sinking applications that involve active freezing, freezing pipes may be driven in a ring around the shaft area to freeze the ground ahead of sinking operations. In order to maintain hole wall stability in frozen ground after drilling is completed, it may be necessary to insulate or refrigerate on a long-term basis, perhaps using special casing.

With the new rock melting drills, hole wall treatment is achieved by the melted rock material being displaced laterally into joints and pores of the adjacent material. Upon solidification a very dense and impermeable hole wall liner is formed.

BASIC ENERGY AND POWER REQUIREMENTS

In all drilling operations energy has to be supplied in order to penetrate the ground material and in order to remove surplus material. Energy is also required to lift and lower the drilling equipment in the hole. The rate at which energy has to be supplied determines the power requirements of the drilling system. In many practical drilling systems the inefficiencies and losses represent a significant addition to basic power requirements; nevertheless, it is important to analyze the basic requirements in order to determine how energy and power are distributed among the various elements of the drilling system.

Minimum energy and power requirements for cutting and chipping

In a mechanical drilling process a certain amount of energy is needed solely for cutting and chipping the material that is being penetrated. It is convenient to define this energy as the specific energy for cutting, i.e. the work done per unit volume of material cut. The absolute irreducible minimum value for this specific energy is given by the fracture surface energy of the material multiplied by the specific area (area per unit volume) of the cuttings (surface energy represents the energy change when material is cleaved so that some atoms or molecules change from the fully bounded condition of the bulk material to the partially bounded condition of surface material). It is fairly obvious that this minimum specific energy will vary with the size of cuttings, since specific surface area decreases as chip size increases. Taking surface energy as constant for a given material, and specific surface as inversely proportional to a linear dimension of the chip, minimum specific energy is therefore also inversely proportional to chip size; i.e. it is very large when the chips are fine but drops to very low values when the chips are very large.

When it comes to matters of practical determination, surface energy is a somewhat nebulous quantity and it is usual to simply define specific energy for a given cutting or breaking process, e.g. specific energy for indentation and shear cutting. Values are obtained for a given material by measuring the actual work performed by the cutting tool and dividing it by the resulting volume of material removed. For a given material and a given cutting process, specific energy varies with the size of cuttings, as already discussed, with the condition of the material (e.g. temperature, water content, porosity), with the geometry of the tool (shape, spacing and sequence of cutters), and with the rate of loading or straining (especially if there is a transition from ductile to brittle material response).

If a realistic estimate of specific energy can be made for a cutting process that is to be utilized by a drill, then minimum power requirements for operation of the bit can be calculated. If E_s is the specific energy for cutting, D is hole diameter and R is penetration (feed) rate, then the power required for actually cutting the material P_c is:

$$P_c = \frac{\pi}{4} D^2 R E_s. \tag{1}$$

If D is in inches, R is in inches per minute, and E_s is in in.-lbf/in.^{3} (or lbf/in.^{2}), then the required power is:

$$P_c = 1.98 \times 10^{-6} D^2 R E_s \qquad \text{hp} \tag{2a}$$

If D is in meters, R is in mm/sec, and E_s is in J/m^3 (or N/m^2), then the required power is:

$$P_c = 7.85 \times 10^{-4} D^2 R E_s \qquad \text{kW}. \tag{2b}$$

Frozen soil. There are two main sources for experimental values of E_s for frozen soils: Zelenin (1959, 1968) and Bailey (1967). Zelenin made a major study of the strength and cutting resistance of frozen soils, and for his cutting tests he used a large shearing or grooving apparatus and a drop-wedge for chipping the edge of block samples. His shearing tests were made with drag bits 0.4 to 7.9 in. (10 to 200 mm) wide, cutting at depths from 0.4 to 2.8 in. (10 to 70 mm) at a speed of approximately 1 in./sec (25 mm/sec). For sandy loam at temperatures in the range $-1°$ to $-3°$C, and at water contents of 18% to 34%, he obtained values of E_s mainly in the range 300 to 1800 lbf/in.^{2} (2 to 12 MN/m^2).* E_s decreased with

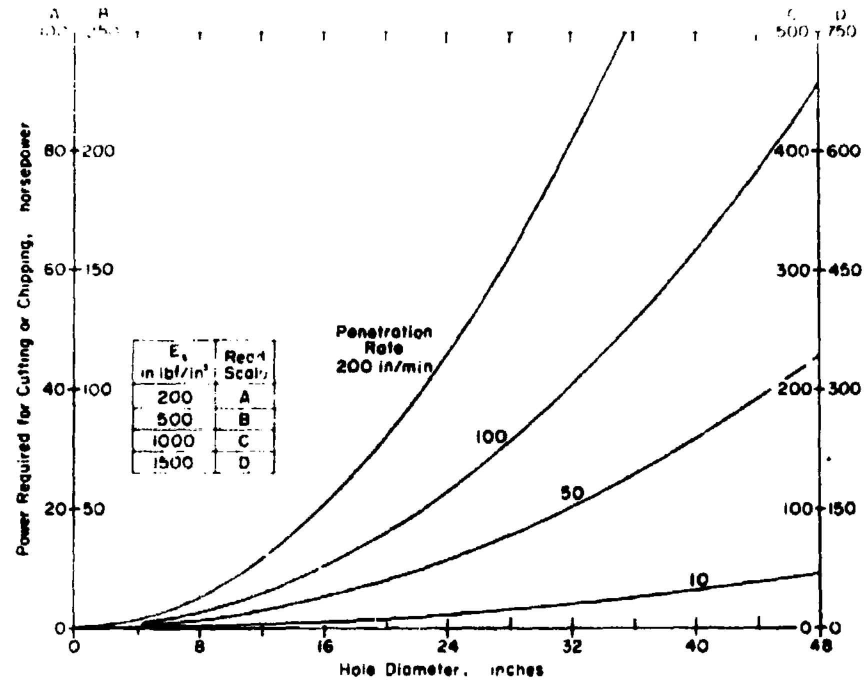
* Values of E_s were calculated by us from Zelenin's reported values for cutting force.

increasing width of cut, but did not change much with cut depth in the range studied. E_s was a maximum at a certain water content, which probably corresponded to the ice saturation value, and it increased significantly with decreasing temperature (by a factor of 4 as temperature dropped from −1° to −20°C). The drop-wedge, which turned out to have an optimum edge angle close to 30°, gave some extremely low values for E_s, down to about 50 lbf/in.^{2} (0.3 MN/m^2), but these probably resulted from unrealistically favorable situations, since other results ranged up to 1000 lbf/in.^{2} (7 MN/m^2). It was also found that with optimum interaction of multiple cutters, E_s could be lowered to 65% to 85% of the single cutter value.

Bailey made shearing experiments by turning cylinders of frozen soil in a lathe, using a variety of small cutting tools that took cuts from 0.02 to 0.2 in. (0.5 to 5 mm) deep. He tested sand, silt, and mixtures of sand and silt, mainly at −3° to −10°C, obtaining values of E_s in the range 400 to 2400 lbf/in.^{2} (2.8 to 16 MN/m^2). E_s decreased with increasing cut depth by 50% to 100% over the size range studied, and also decreased continuously as the tool rake was varied from −20° to +35°. There was a slight increase in E_s as temperature decreased and as dry unit weight increased. Bailey also made experiments in which wedges were indented normally into surfaces of frozen sand and frozen silt at various speeds and temperatures, and with varying wedge angle. Values of E_s varied from about 600 to 7000 lbf/in.^{2} (4 to 48 MN/m^2), but for sand they were typically in the range 600 to 2000 lbf/in.^{2} (4 to 14 MN/m^2) and for silt typically in the range 1000 to 2000 lbf/in.^{2} (7 to 14 MN/m^2). E_s increased as wedge angle increased from 30° to 90°, and tended to decrease when indentation craters were spaced closely enough for interference. For sand, there was not much evidence of significant influence by either temperature or striking velocity, but for silt E_s decreased as striking velocity increased from 4 to 75 ft/sec (1.2 to 23 m/sec) and as temperature decreased down to −30°C, as might be expected for material that exhibits some ductility.

To make order of magnitude calculations from eq 2, a value E_s = 1000 lbf/in.^{2} (6.9 MN/m^2) can probably be accepted for drag bit tools working on common frozen soils. A similar value might be taken for indentation cutting if the indentation tool works fast enough to induce brittle fracture, but if there is no brittle fracture (e.g., slow roller bit working on fine-grained soil at high temperature), the calculation, like the drilling operation, is futile. Taking E_s = 1000 lbf/in.^{2} and substituting in eq 2, $P_c \approx 0.002\, D^2 R$ hp. If D = 6 in. and R = 100 in./min, $P_c \approx 7.2$ hp; or if D = 10 in. and R = 60 in./min, $P_c \approx 12$ hp.

Ice. Shear cutting experiments were made on ice by Zelenin (1959), Bailey (1967) and Peng (1958). Zelenin took cuts 2 in. (50 mm) deep in ice at −1°C, and the specific energy ranged from about 280 lbf/in.^{2} (1.9 MN/m^2) for a cut 2 in. (50 mm) wide to about 700 lbf/in.^{2} (4.8 MN/m^2) for a cut 0.4 in. (10 mm) wide. Bailey took shallow cuts with a lathe at temperatures from −3° to −25°C, finding specific energy values in the range 70 to 700 lbf/in.^{2} (0.48 to 4.8 MN/m^2). Specific energy dropped by a factor of about 5 as cutting depth increased from 0.02 to 0.2 in. (0.5 to 5 mm), but it did not vary much with either temperature or cutting speed (in the range 1 to 10 ft/sec, or 0.3 to 3 m/sec). Variation of tool rake from −20° to +35° did not seem to have much effect on specific energy. Peng's work appeared rather confused, but from his results Bailey estimated that specific energy was about 200 lbf/in.^{2} (1.4 MN/m^2) at −2°C with cutting depth 0.125 to 0.25 in. (3.2 to 6.4 mm), tool width about 0.5 in. (13 mm), and cutting speed 1 to 4 ft/sec (0.3 to 1.2 m/sec). Bailey (1967) also made wedge indentation experiments on ice, finding specific energy



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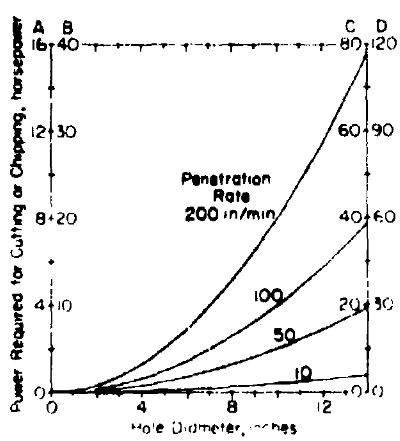


b.

Figure 3. Basic power requirements for cutting or chipping shown for a range of hole diameters, penetration rates, and specific energy levels.

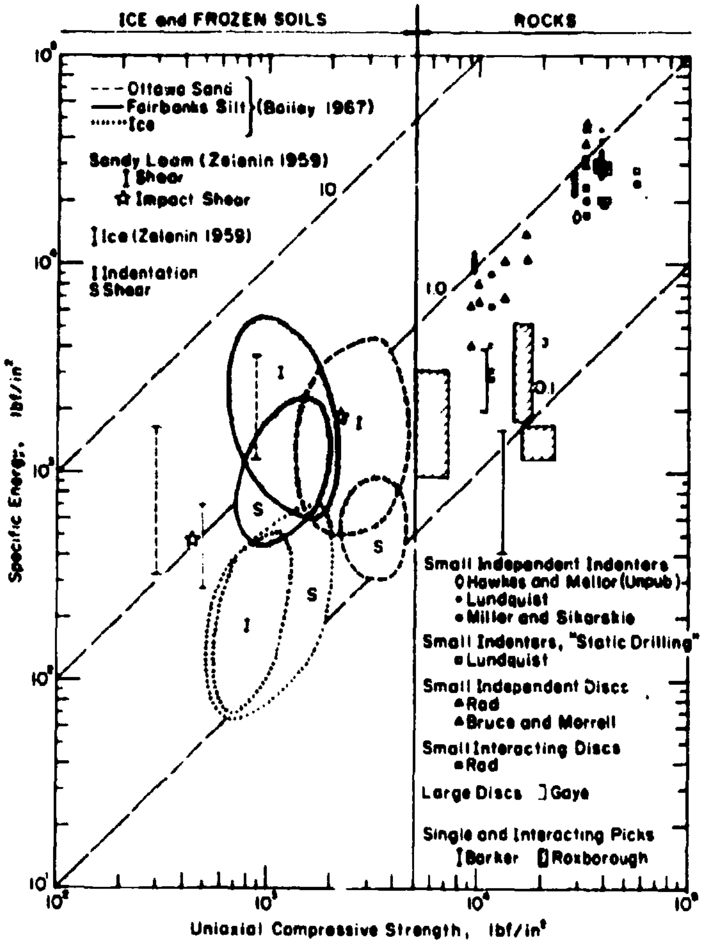


Figure 4. Specific energy consumption from cutting tests on rock, ice and frozen soil plotted against uniaxial compressive strength of the material.

values in the range 70 to 500 lbf/in.² (0.48 to 3.4 MN/m²) for temperatures in the range −3° to −30°C. There was no convincing evidence of much dependence on either temperature or entry velocity (in the range 3 to 40 ft/sec, or 0.9 to 12 m/sec), but specific energy increased as wedge angle increased from 30° to 90°. Lowest energy values were obtained with blows spaced closely enough for optimum interference.

In Figure 3 the basic power requirements for cutting or chipping are shown for a range of values of hole diameter, penetration rate, and specific energy. One rather striking feature of this plot is the very modest power requirement for boring small diameter holes at good rates in almost any kind of fine-grained frozen soil or ice. It might be noted that these power estimates assume that the full hole diameter is being cut. For coring, the required power should be lower by a factor of $[1 - (D_0/D_i)^2]$, where D_0 and D_i are outer and inner diameters of the coring head, respectively.

In laboratory tests on hard rocks, specific energy for indentation tools has been measured by Miller and Sikarskie (1968), Lundquist (1968), and Mellor and Hawkes (1972). Specific energy for indentation with disc cutters has been measured by Bruce and Morrell (1969) and by Rad (1970). The overall range of specific energy values covers more than an order of magnitude, and there is a linear correlation with the uniaxial compressive strength of the material tested (see Mellor 1972a). The ratio of specific energy to uniaxial compressive strength is mainly between 1.0 and 0.4 (Fig. 4). Basic power requirements for chipping rock with percussive bits or roller bits can be estimated by first estimating the probable limits of specific energy (between 100% and 40% of the uniaxial compressive strength), and then reading power from the appropriate scales of Figure 3, using multiplying factors of 10 or 100 if necessary (if specific energy for a certain rock is 20,000 lbf/in.^{2}, power can be read from the 200 lbf/in.^{2} scale and multiplied by 100).

Laboratory data on specific energy for drag bit cutting in hard rock are scarce, but Barker (1964) obtained extremely low values in experiments with large drag bits - specific energies down to 3% of the uniaxial compressive strength of the rock with optimum depth and spacing of cuts.

All available data for specific energy consumption in laboratory cutting tests have been compiled in Figure 4. Specific energy for cutting of rock, ice and frozen soils is plotted against uniaxial compressive strength on logarithmic scales and a linear correlation is suggested in accordance with findings in the field of rock mechanics. Most of the data lie in a band bounded by $0.1\ \sigma_c < E_s < 1.0\ \sigma_c$, where σ_c is uniaxial compressive strength.

Minimum energy and power requirements for penetration by melting

When a bit or probe penetrates a material by melting it completely, the material has to be heated to the melting point and latent heat of fusion for the melted fraction has to be supplied (an alternative for some rocks is to thrust the bit through softened, but not completely melted, material). In addition to the demand for sensible and latent heat, there is unavoidable but unproductive heat flow to the material surrounding the hole, and heat flow to the liquid fraction. This last item can become very serious if the drill is immersed in meltwater. Heat losses at the drill head are not easy to estimate in simple terms, especially for ice; a relatively simple analytical scheme for typical rocks has been developed by Murphy and Gido (1973), and a more complete but rather complicated analysis for ice has been made by Shreve (1962). However, for present purposes, which relate to general planning, a first estimate of the lower limit of power requirements can be obtained by assuming efficient heat transfer at the drill tip and ignoring unproductive heat losses to the surrounding material and to the melt.

For melting calculations on frozen materials, it will be assumed that all of the ice in the material to be removed is melted. Thus the minimum thermal power required for melting P_M can be expressed as

$$P_M = \frac{\pi}{4} D^2 R\, [m_i (S_i \Delta\theta + L_i) + m_s S_s \Delta\theta] \tag{3}$$

where m_i is mass of ice per unit volume of ground material, m_s is mass of mineral matter (soil grains) per unit volume of ground material, S_i and S_s are specific heats of ice and mineral matter respectively, L_i is latent heat of fusion for ice, and $\Delta\theta$ is the difference between initial ground temperature and the melting temperature. If the volume fraction of ice is denoted by ν_i, then

$$m_i = \rho_i \nu_i$$

and

$$m_s = \rho_s(1 - \nu_i)$$

where ρ_i is density of ice (0.917 g/cm³) and ρ_s is density of soil grains (≈ 2.7 g/cm³ for common soils).

Since sensible heat is likely to be small relative to latent heat for materials that have high ice content, a fixed value of $\Delta\theta$ can be taken for most calculations that deal with natural frozen ground or natural ice masses. For present purposes $\Delta\theta$ is taken as 5°C. Apparent specific heat of ice at −5°C can be taken as 0.5 cal/g·°C, and latent heat of fusion for phase change at 0°C can be taken as 79.7 cal/g. Specific heat for soil grains can be taken as 0.2 cal/g.

For solid ice, $\nu_i = 1.0$, and hence

$$P_M = 0.0908\, D^2 R \qquad \text{hp}$$

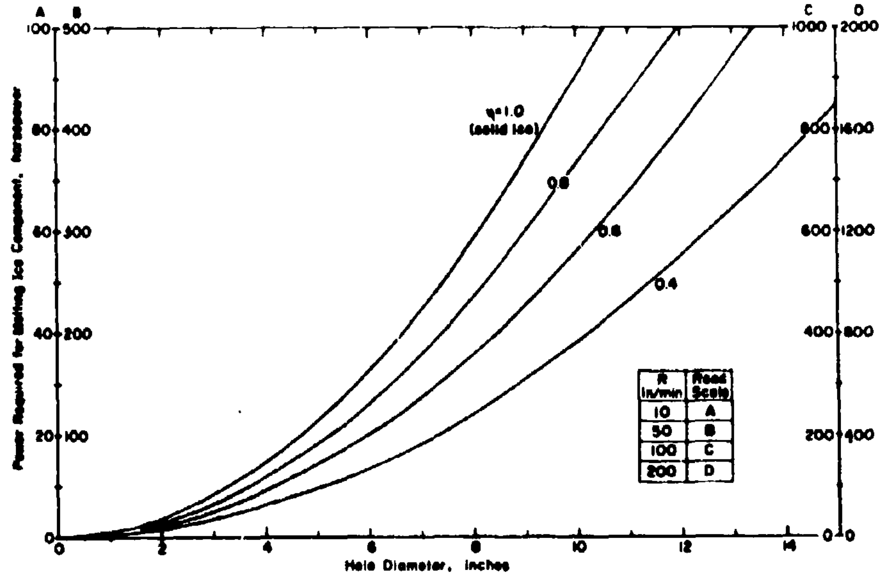
where D is in inches and R is in in./min. For ice-bearing soils, using the same units,

$$P_M = 1.204 \times 10^{-3}\, D^2 R\,(72.8\,\nu_i + 2.7) \qquad \text{hp.}$$

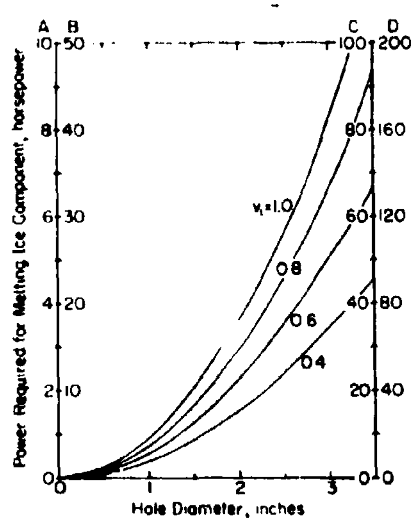
In Figure 5 the minimum power requirements for melting are plotted as a function of bit diameter for various penetration rates and ice contents. If this graph is compared with Figure 3, it can be seen straightaway that thermal drilling makes very much heavier power demands than direct mechanical drilling for the penetration process.

Equation 3 implies that penetration rate is directly proportional to power density, i.e. power divided by the working area of the boring head. However, there are practical limits to the power density that can be achieved with an electrical heater that has to have a reasonable working life (and also limits to the power density that can be usefully employed). Shreve and Sharp (1970) addressed this problem, and developed a hotpoint that had a working life better than 1000 hours at a power density of 1.2 MW/m². Similar efforts have been made in France, and power densities up to 3.25 MW/m² have been employed effectively (Gillet, personal communication). The "Subterrenes" under development at the Los Alamos Scientific Laboratory operate at high temperatures, but their power densities are in the same range as those of ice drills – existing models have worked in the range 0.3 to 2.5 MW/m² (Armstrong 1974), and requirements up to 5 MW/m² have been noted.

With an effective limit on power density, there is a limit to the attainable penetration speed with a thermal drill. Equation 3 can be rewritten for the limiting case in terms of maximum penetration rate R_{max} and maximum power density $(P/A)_{max}$:



a.



b.

Figure 5. Minimum power requirements for melt penetration of ice and frozen soils, shown as a function of hole diameter, penetration rate, and ice content.

$$R_{max} = \frac{(P/A)_{max}}{[m_i(S_i\Delta\theta + L_i) + m_s S_s \Delta\theta]} . \qquad (4)$$

In the case of solid ice at 5°C, the maximum penetration rate for a useful power density of 3 MW/m^2 is 9.5 mm/sec, or 1.87 ft/min. In other words, thermal drills of the type used so far do not appear to have the potential for development into very rapid ice drills (mechanical ice drills have achieved penetration rates an order of magnitude higher than the present limit for electrothermal drills).

Minimum power requirements for removal of material from open hole

The basic power demands for typical penetration processes (excluding losses and inefficiencies) are not much affected by hole depth but this is not the case for removal of cuttings, core or waste. The *minimum* amount of energy required to remove waste from an open hole of given depth is equal to the weight of material multiplied by the height of lift. If it is assumed that waste material is removed from the hole at the same rate at which it is produced by the penetration process, then the *minimum* power requirement for lifting material P_L is

$$P_L = \frac{\pi}{4} D^2 R \gamma_g h \qquad (5)$$

where γ_g is unit weight of the ground material in place, and h is the hole depth. With D in inches, R in in./min, γ_g in lbf/ft^3 and h in ft,

$$P_L = 1.376 \times 10^{-8} D^2 R \gamma_g h \qquad \text{hp.}$$

This relationship is shown graphically in Figure 6, and it can be seen that the basic power requirement for lifting cuttings is trivial for all but very deep holes and very large diameter holes.

Minimum power requirements for hoisting the drill string

When the drill string is being removed from the hole, either for core removal or at the end of the operation, it is usually desirable to hoist at an appreciable speed, and this can make a significant power demand. The *minimum* power requirement for hoisting P_H is determined by the submerged weight of the suspended string and the hoisting speed R_H:

$$P_H = whR_H \qquad (6)$$

where w is the submerged weight per unit length of the drill string and h is the length of the string. For a drill string that is immersed in a viscous fluid, there is an additional power requirement for overcoming fluid resistance, which increases with increasing hoisting rate.

For purposes of illustration, power requirements for hoisting in open hole will be considered. The weight per unit length of drill stem is a function of rod diameter. Weight per unit length would be proportional to diameter squared for geometrically similar rods or augers; this is approximately the case for drill pipe and casing, but continuous flight augers increase in unit weight at a lower rate because the flights become wide relative to the core rod as diameter increases. It will be assumed here that the weight of heavy drill

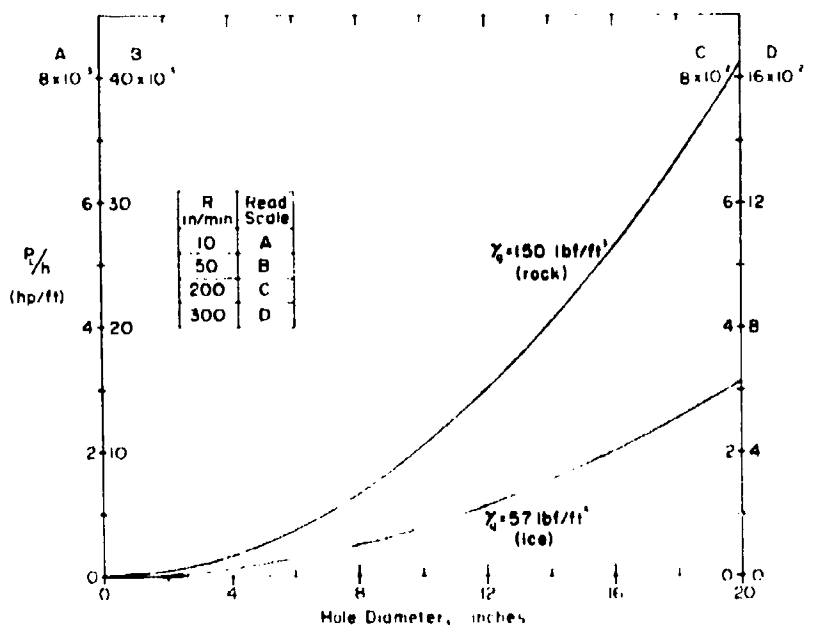


Figure 6. Basic power requirements for continuous lifting of cuttings shown as a function of hole diameter, penetration rate, hole depth, and material type.

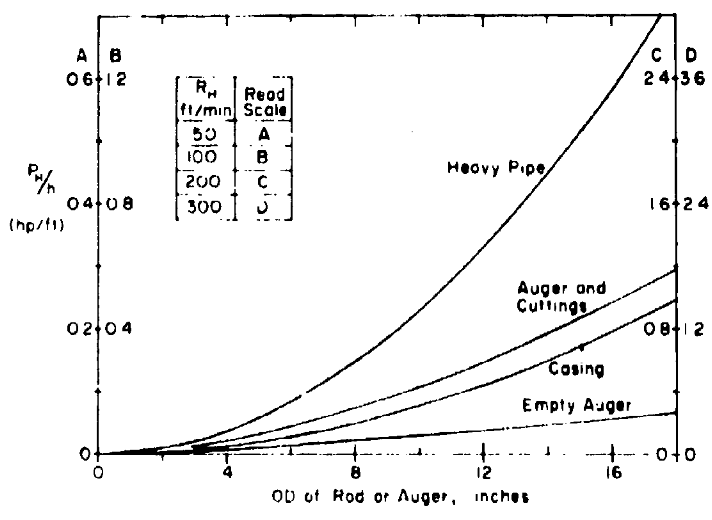


Figure 7. Minimum power requirements for hoisting drill pipes, casing and augers at various rates in a dry hole.

pipe in air is 1.5 D^2 lbf/ft, the weight of casing is 0.5 D^2 lbf/ft, and the weight of continuous flight auger is $D^{1.3}$ lbf/ft, where D is in inches and the relations are restricted to the common range of drill sizes. Figure 7 gives power requirements as a function of diameter and hoisting speed for pipe, casing, empty auger, and auger jammed full of cuttings. In many drilling systems this function requires the most power.

Assessing power requirements for complete drilling systems

The basic power requirements for a complete drilling system can be analyzed by going through a series of exercises similar to those just outlined. To these minimum estimates must be added the power needed to support the inefficiencies of practical processes and equipment.

Estimation of efficiencies and power losses is an important topic, since mechanical efficiency is often traded for convenience in practical operations. One way to arrive at estimates of power losses is to draw up energy budgets for actual working systems, comparing the overall input of work with the energy expended usefully.

In assessing the partitioning of power input for a drilling system, it has to be recognized that not all functions are performed concurrently, so that a single power source can sometimes be applied to two or more functions in sequence. For example, bit rotation and chip clearance can cease when rod is being hoisted.

MEASURED PENETRATION RATES FOR EXISTING DRILLING TOOLS

The following notes give examples of actual penetration rates for various types of existing equipment. Most of the information is taken from an unpublished report by Mellor et al. (1973), which illustrates many of the pieces of equipment that are referred to.

Ice

Drilling in ice presents no great problem if the equipment is properly designed and operated, but some projects have foundered because of inability to drill ice. Well designed drag bits are the simplest and probably the most efficient tools for cutting ice, as they require very little downthrust, modest torque, and no percussion. If the ice is perfectly clean and of zero salinity, drag bits do not require carbide tips or hardfacing, although some surface hardening is desirable. A slight amount of rock dust can create wear problems (Abel 1961), as can inclusions of precipitated salt crystals (Lange 1973a).

Small-diameter holes can be drilled with simple hand equipment at rates that are acceptable for some purposes. The 1.5-in. (38-mm)-diameter USA CRREL ice auger (essentially a ship auger with modified tip), rotated by a hand brace, can drill to 3 ft (1 m) at rates from 1.6 to 2.95 ft/min (8.1 to 15 mm/sec) (Kovacs 1970; Sellmann and Mellor 1974). With an electric or gasoline power-drive, the same tool can penetrate to 3 ft (1 m) at rates from 3.2 to 7.6 ft/min (16 to 39 mm/sec)(Kovacs 1970; Kovacs et al. 1973; Sellmann and Mellor 1974). Like any auger, this tool can be overdriven so that cuttings jam in the flight, and care must be exercised to match penetration rate with cutting clearance rate.

A simple 1.5-in. (38-mm)-diameter flight auger fitted with improved bits has drilled ice at rates up to 4.4 ft/min (22 mm/sec) when driven by a hand brace, and at rates up to 15.1 ft/min (77 mm/sec) when driven by electric hand drills (Sellmann and Mellor 1974). A 2.2-in. (56-mm)-diameter variant penetrated at rates up to 10.4 ft/min (53 mm/sec).

The USA CRREL 3-in. (76-mm) coring auger is sometimes used solely for drilling holes, producing hole of approximately 4.4-in. (112-mm) diameter. When turned by a hand brace, penetration rates of 0.8 to 1.2 ft/min (4 to 6 mm/sec) have been measured; when the same tool was turned with a T-handle, the rates dropped to 0.43 to 0.61 ft/min (2.2 to 3.1 mm/sec) (Kovacs 1970). With a gasoline drive, rates of 3.0 to 3.5 ft/min (15 to 18 mm/sec) have been measured as 2.4 to 4.0 ft/min (12 to 20 mm/sec) (Kovacs 1970) and 5.4 to 5.6 ft/min (27 to 28 mm/sec) (Kovacs et al. 1973).

A Russian hand-operated cutting ring device, used for coring or hole making, produces an annular hole 8.8-in. (224-mm) OD and 7.25-in. (184-mm) ID at the rate of 0.2 to 0.33 ft/min (1 to 1.7 mm/sec) (Cherepanov 1968-69). Drilling through 7-ft (2-m)-thick first-year sea ice takes 30 to 45 min (R. Ramseier, private communication).

A wide variety of commerical earth augers, or posthole diggers, have been adapted for drilling ice, especially for the use of ice fishermen. They commonly have diameters ranging from about 4 in. to 9 in. (0.1 to 0.23 m), and are normally intended for drilling to depths of only a few feet, although the writers have drilled to 16 ft (5 m) with 9-in. (0.23-m)-diameter hand-held gasoline-powered augers. Kovacs (1970) has driven an 8-in. (0.2-m)-diameter earth auger with various gasoline and electric drive units at a penetration rate of 1.2 ft/min (6.1 mm/sec). The writers have drilled numerous 9-in. (0.23-m)-diameter holes at somewhat higher rates (approximately 3 ft/min) with freshly sharpened ice augers, and ice fishermen have claimed rates approaching 5 ft/min (25 mm/sec) with 9-in. (0.23-m)-diameter augers, and 6 ft/min (30 mm/sec) with 7-in. (0.18-m)- diameter augers. In controlled tests, a 9-in. (0.23-m)-diameter auger penetrated at 5.3 to 7.5 ft/min (27 to 38 mm/sec), and a 5.5-in. (0.14-m)-diameter auger penetrated at 5.4 to 7.5 ft/min (27 to 38 mm/sec) (Kovacs et al. 1973).

Shothole drills developed for underground mining have been used to drill ice with a minimum of modification. Rausch (1958) drilled 1.75-in. (44-mm)-diameter shotholes in ice with pneumatic rotary-percussive mining drills, achieving penetration rates of 5 ft/min (25 mm/sec). Abel (1961) used percussive augers to drill 1.75-in. (44-mm)-diameter shotholes, obtaining overall penetration rates better than 5 ft/min (25 mm/sec) for 8-ft (2.4-m)-long holes. He also used a hand-held electric-powered auger to drill 2-in. (51-mm)-diameter holes at 5 ft/min (25 mm/sec). McAnerney (1968) used a hydraulically driven hand-held coal auger for boring 1.75-in. (44-mm)-diameter shotholes in frozen silt and ice, obtaining penetration rates up to 11.75 ft/min (60 mm/sec) in lenses of pure ice. Kovacs et al. (1973) drove 1.75-in. (44-mm)-diameter face augers and roof-bolt augers with electric drills, and achieved penetration rates up to 9.5 ft/min (48 mm/sec).

The writers have drilled with hand-held electrically-driven 3-in. (76-mm)-diameter augers to depths of 55 ft (17 m) using a variety of bits. With good bits, short-term penetration rates (4-ft increments) of 15 ft/min (76 mm/sec) were attainable. Controlled tests with similar tools gave penetration rates up to 14 ft/min (71 mm/sec) (Kovacs et al. 1973). Kovacs (1974) developed a light weight 3-in. (76-mm)-diameter auger that penetrates at up to 10.4 ft/min (53 mm/sec) with an electric drive unit. Similar rates of 3.4 to 13.9 ft/min (17 to 71 mm/sec) were reported for small-diameter auger drills in river and sea ice by Russian workers (Nikolaev and Trubina 1969).

From the foregoing performance records, it is clear that hand-held drive units are perfectly adequate for supplying the power, torque and thrust required for drilling holes up to 9-in. (0.23-m) diameter at fully acceptable rates in ice. However, frame-mounted units are required for hoisting and lowering when holes have to be drilled to considerable depth. The higher power that is usually available in a frame-mounted unit does not permit any significant increase in penetration rate over hand-held units, since cutting clearance sets a limit (an inept operator can twist off the auger stem if a highly powered unit is over-driven so that cuttings are jammed).

The U.S. Navy used a trailer-mounted drilling unit (approximately 5 tons) for experimental drilling in sea ice. Maximum penetration rate was 8 ft/min (41 mm/sec) with a 4.75-in. (0.12-m)-diameter tricone roller bit, and 1 ft/min (5 mm/sec) with a 14-in. (0.36-m)-OD (12-in. or 0.3-m-ID) coring bit (Hoffman and Moser 1967). Tests were also made with a 10-in. (0.25-m)-diameter auger, which penetrated at 6 ft/min (30 mm/sec) (Beard and Hoffman 1967).

For deep drilling in Greenland and Antarctica, USA CRREL has used an electro-mechanical coring drill. The drill bit had a maximum outside diameter of 6.13 in. (156 mm) and minimum inside diameter of 4.50 in. (114 mm). Penetration rates have been in the range of 0.12 to 0.66 ft/min (0.61 to 3.4 mm/sec) (Ueda and Garfield 1968a and b, 1969a).

A lightweight (500-lb or 230-kg) powered ice coring auger developed by the former Arctic Construction and Frost Effects Laboratory (ACFEL)* penetrated at 0.67 to 1.0 ft/min (3.4 to 5.1 mm/sec), taking 3-in. (76-mm)-diameter core and making a 4.75-in. (121-mm)-diameter hole (ACFEL 1954).

Thermal drills have also been used for boring holes in ice, although they are very inefficient in energetic terms compared with mechanical drills. Electrical hotpoint drills usually penetrate at rates not exceeding 60% to 80% of the theoretical rates calculated on the basis of melting with no heat loss. Theoretical penetration rates for lossless melting were given earlier, and some practical heat losses are discussed by Aamot (1967a, 1968). To give an idea of penetration rate, a 2-kW (2.7-hp) electric hotpoint can readily bore 2-in. (51-mm)-diameter hole at 0.33 ft/min (1.7 mm/sec). Shreve and Sharp (1970) achieved rates up to 0.49 ft/min (2.5 mm/sec) with 2.1 kW on a 2-in. (51-mm)-diameter hotpoint, while Stacey (1960) reached 0.63 ft/min (3.2 mm/sec) at 2.3 kW (3.1 hp) and 0.5 ft/min (2.5 mm/sec) at 1.8 kW (2.4 hp) for the same size bit. LaChapelle (1963) drilled at 0.30 to 0.33 ft/min (1.5 to 1.7 mm/sec) with 0.22 kW (0.3 hp) on a 0.71-in. (18-mm)-diameter hotpoint. The 3.625-in. (92-mm)-diameter Philberth probe penetrated at 0.16 ft/min (0.81 mm/sec) with 3.68-kW (4.9-hp) input in Greenland (Aamot 1967b).†

One of the authors has bored 0.73-in. (19-mm)-diameter holes to depths of 200 ft (61 m) at a rate of 0.27 ft/min (1.4 mm/sec) with a 0.25-kW (0.34-hp) electric hotpoint. Tobiasson (personal communication) has bored with a 0.5-kW (0.67-hp), 1.25-in. (32-mm)-diameter hotpoint at rates of 0.15 and 0.22 ft/min (0.76 to 1.1 mm/sec). On a larger scale, the 6.4-in. (0.16-m)-diameter USA CRREL thermal coring drill has penetrated at rates from 0.126 ft/min (0.64 mm/sec) in ice at 0°C to 0.104 ft/min (0.53 mm/sec) in ice at −28°C, the input power ranging from 3.5 to 4.0 kW (4.7 to 5.4 hp) (Ueda and Garfield 1969b). Russian electrothermal penetrators have drilled at 0.38 to 0.49 ft/min (1.9 to 2.5 mm/sec) with 1 to 2 kW (1.3 to 2.7 hp) on a tip diameter of 1.6 in. (40 mm) and at 0.38 to 0.55 ft/min (1.9 to 2.8 mm/sec) with 3 to 4 kW on a tip diameter of 3.1 in. (80 mm) (Korotkevich and Kudryashov (in press). Russian electrothermal corers have drilled at 0.16 to 0.25 ft/min

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* ACFEL was merged with the former Snow, Ice and Permafrost Research Establishment, U.S. Army Corps of Engineers, in 1961, to form USA CRREL.

† Philberth (in press) gives 0.11 ft/min (0.56 mm/sec) as the maximum rate of the 3.7-kW probe.

(0.83 to 1.25 mm/sec) with 1.5 to 2.2 kW (2 to 3 hp) on a wedge-profile annulus of 3.5-in. (88-mm) inside diameter and 4.4-in. (112-mm) outside diameter, and also at 0.08 to 0.11 ft/min (0.42 to 0.56 mm/sec) with 3.5 kW (4.7 hp) on a flat-base annulus of 5.1-in. (130-mm) inside diameter and 7-in. (178-mm) outside diameter (Korotkevich an Kudryashov in press). The French "bare-wire" thermal corer is reported to have achieved rates up to 0.33 ft/min (1.7 mm/sec) with about 4.1 kW (5.4 hp) on a head boring 5.5-in. (0.14-m)-diameter hole and taking 4-in. (0.1-m)-diameter core (Gillet in press).

Lightweight steam drills have been developed for boring in ice; a recent design (Hodge 1971) has bored 1-in. (25-mm)-diameter hole to 26-ft (7.9-m) depth at 1.8 ft/min (9.1 mm/sec), and 2-in. (51-mm)-diameter hole at 0.49 ft/min (2.5 mm/sec). In an earlier effort, Howorka (1965) drilled 0.8-in. (21-mm)-diameter hole to 26 ft (8 m) with a 0.1-in. (2.5-mm)-diameter steam nozzle at a rate of 0.87 ft/min (4.4 mm/sec).

Browning and Ordway (1963) used a flame jet to drill a 7.5-in. (0.19-m)-diameter hole in ice at 2.9 ft/min (15 mm/sec).

Frozen fine-grained soils

Drilling in frozen soil is often considered to be a difficult task equivalent to hard-rock drilling, but in fact holes up to 4.5-in. (0.11-m) diameter or more can be drilled in frozen fine-grained soils with hand-held units.

The writers have drilled 3-in. (76-mm)-diameter holes in frozen silts with continuous-flight, gasoline-powered augers at rates up to 7 ft/min (36 mm/sec), with penetration rates of 6.5 ft/min (33 mm/sec) readily attainable. They have also drilled 4.4-in. (0.11-m)-diameter hole with the USA CRREL 3-in. (76-mm) coring auger at short-term penetration rates of approximately 12 ft/min, or 61 mm/sec (appreciably faster than the same tool drilling in solid ice). McAnerney (1968) drilled 1.75-in. (44-mm)-diameter holes in frozen silt with a hydraulic, hand-held auger at rates ranging from 2.2 to 11.75 ft/min (11 to 60 mm/sec); the lowest rates were obtained in soil at temperatures close to the melting point, and the highest rates in cold soil (17°F, or −8.3°C) and in ice lenses.

In recent development work, 1.5-in. (38-mm)-diameter augers have been driven with a hand brace in frozen silt, achieving penetration rates up to 2.4 ft/min (12 mm/sec) (Sellmann and Mellor 1974). With electric drill drive units, the same hand augers penetrated frozen silt at rates up to 7.5 ft/min (38 mm/sec).

Heavy powered augers and rotary drilling systems are widely used for shothole drilling and for setting posts and piles. Lange (1964) gives some short-term penetration rates for mine shothole drills working in frozen sand. A 50-hp (37-kW) auger drilled 6-in. (0.15-m)-diameter shotholes up to 100 ft (30 m) long at 6.7 ft/min (34 mm/sec), while a 100-hp (74.6-kW) auger drilled 9-in. (0.23-m)-diameter holes up to 90 ft (27 m) deep at 4 ft/min (20 mm/sec). A 215-hp (160-kW) rotary rig with air circulation (Chicago Pneumatic 650) drilled 8.25-in. (0.21-m)-diameter holes at 6 to 7 ft/min (30 to 36 mm/sec) with drag bits. A Failing 43 rotary drill with air circulation drilled 6-in. (0.15-m)-diameter holes in frozen silt with bladed drag bits at 7 to 12 ft/min (36 to 61 mm/sec), with 9.25 ft/min (47 mm/sec) the most frequent rate (Mellor 1971). Large diameter augers, such as the Williams auger, do not normally have continuous flight, and cutting removal is cyclic. This results in low penetration rates overall; McCoy (1960) gives 14 to 16 ft/hr (4.3 to 4.9 m/hr) for 12-in. (0.3-m)-diameter holes and 12 ft/hr (3.7 m/hr) for 24-in. (0.61-m)-diameter holes in frozen peat, gravel and silt. Roller rock bits have sometimes been used for drilling frozen silts, but they are usually very ineffective.

Percussive rock drills are occasionally used for frozen fine-grained soils. McAnerney (1968) used a rotary-percussive air-leg rock drill with liquid circulation to bore 1.75-in. (44-mm)-diameter shotholes in frozen silt, and achieved penetration rates of 0.7 ft/min (3.6 mm/sec). A rotary-percussive rock drill with 3-in. (76-mm)-diameter bit and air circulation (Gardner Denver 123J) was used for shothole drilling in frozen ground during blasting trials by DuPont (Trans-Alaska Pipeline System 1969). Average penetration rate for a mixed silt/gravel section was 4.5 ft/min (23 mm/sec), with a maximum rate of 9 ft/min (46 mm/sec), and it was noted that drilling appeared to be faster in the gravel than in the silt.

Open-end pipe of 6-in. (0.15-m) outside diameter has been driven into frozen silt and sand at rates of 30 ft/min (152 mm/sec) with a high frequency vibratory unit (Huck 1969). A low frequency percussive tool (Ingersoll-Rand Hobgoblin) has been used to drive a 4-in. (0.1-m)-diameter solid steel rod into frozen silt at 2.3 ft/min (12 mm/sec) with a chisel point and 2.8 ft/min (14 mm/sec) with a moil point (Mellor 1972b).

McAnerney (1968) used a steam point to drill small diameter shotholes in frozen silt, achieving penetration rates as high as 4.5 ft/min (23 mm/sec), with an average rate of 3.3 ft/min (17 mm/sec). Browning and Ordway (1963) used a flame jet to drill frozen silt, obtaining penetration rates of 1.1 ft/min (5.6 mm/sec) for 6-in. (0.15-m)-diameter hole, 0.67 ft/min (3.4 mm/sec) for 7-in. (0.18-m)-diameter hole, and 0.375 ft/min (1.9 mm/sec) for 8-in. (0.2-m) diameter hole. Browning and Fitzgerald (1964) used a redesigned flame jet in frozen silt, and reached penetration rates of 1 ft/min (5.1 mm/sec) for 8- and 9-in. (0.2 and 0.23-m)-diameter hole, and up to 1.1 ft/min (5.6 mm/sec) for 7-in. (0.18-m)-diameter hole.

It is understood that in laboratory tests at the Los Alamos Scientific Laboratory very cold frozen silt (−73° and −143°C) was penetrated by a 3-in. (75-mm)-diameter high-temperature electrical hotpoint at rates up to 0.028 ft/min (0.14 mm/sec) with a power of 6.7 kW (9 hp) and a thrust of 1000 lbf (4.5 kN).

Frozen tills and gravels

When frozen ground contains pebbles and cobbles that are large relative to the cutting tools and the hole diameter, the nature of the drilling problem changes, since these pieces of hard rock have to be cut to permit penetration and removal of cuttings. Thus the drilling of frozen gravels and tills generally calls for rock drilling techniques and equipment.

Rotary drilling systems with roller bits and air circulation (Chicago Pneumatic T-650) have given penetration rates of 2.5 ft/min (13 mm/sec) for 8-in. (0.2-m)-diameter hole in frozen gravel (Mellor and Sellmann 1970). Lange (1968) tested a rotary drilling system (Failing 43) with liquid circulation in a till consisting of frozen clay with cobbles. Several types of drag bits and roller bits were tested for a range of rotational speed and bit loads. Penetration rate increased with increasing rotational speed and increasing bit load, with values ranging up to 2.5 to 3.5 ft/min (13 to 18 mm/sec). Some of the drag bits reached rates of 4 to 6 ft/min (20 to 30 mm/sec), but these rates could not be sustained. A rate of 1.5 ft/min (7.6 mm/sec) was a reasonable limit for efficient removal of cuttings.

Lange (1968) also tested augers in frozen till and obtained penetration rates up to 4.6 ft/min (23 mm/sec) with 6.25-in. (0.16-m)-diameter bits. However, the high penetration rates (3 to 4 ft/min, or 15 to 20 mm/sec) resulted in undue tooth breakage and excessive torque on the auger stem, and 1.5 ft/min (7.6 mm/sec) was considered to be the maximum rate for effective cutting clearance. Lange (1973b), using a Williams auger (4D-50, capacity, 36-in. hole to 50 ft) in frozen gravel, obtained an average penetration rate of 0.16 ft/min (0.81 mm/sec) in a 16-in. (0.41-m)-diameter hole 48 ft (15 m) deep. Similar rates were also obtained with a large rotary Failing 1500, drilling 16-in. (0.41-m)-diameter hole.

Abel (1960) used percussive rock drills for tunneling in frozen gravel. The penetration rate of airleg drills with 1.625-in. (41-mm)-diameter bits and frequency of 2000 blow/min (33 Hz) averaged 2.38 ft/min (12 mm/sec). Another drill with the same diameter bit and a frequency of 3000 blow/min (50 Hz) averaged 1.33 ft/min (6.8 mm/sec). Abel also tested 1.485-in. (38-mm)-diameter diamond drills, achieving penetration rates that averaged 0.375 ft/min (1.9 mm/sec) for both tapered blast hole bits and coring bits. Cooled diesel fuel was used as drilling fluid for the diamond drills.

Core barrels with outside diameter of 4.5 in. (0.11 m) have been driven into frozen gravel at rates of 6 ft/min (30 mm/sec) with a high frequency vibratory unit (Huck 1969). A low frequency percussive unit (Ingersoll-Rand Hobgoblin) has driven 4-in. (0.1-m)-diameter solid steel rod into frozen gravel at 0.31 ft/min (1.6 mm/sec) with a chisel point and approximately 0.25 ft/min (1.3 mm/sec) with a moil point (Mellor 1972b).

Browning and Fitzgerald (1964) drilled frozen gravel with a flame jet, producing 1-ft (0.3-m)-diameter hole at a penetration rate approaching 3 ft/min (15 mm/sec).

SPECIFIC ENERGY DATA FOR PENETRATION PROCESSES

Measured specific energy for drag-bit penetration

With an operating rotary drill it is awkward to find the process specific energy for cutting, as the total power input covers cutting clearance, hole-wall friction, and mechanical losses as well as the penetration process. However, some reasonably reliable values have been obtained for small drills by measuring power consumption with and without active penetration.

Ice. Kovacs et al. (1973) tested a variety of augers and auger bits in ice, obtaining values of overall specific energy for each drill and calculating values of process specific energy for the electrically driven drills. The best values of process specific energy, in the range 100 to 140 lbf/in.^{2} (0.7 to 1.0 MN/m^2), were obtained with two different designs of a 3.25-in. (83-mm)-diameter auger bit. Commercial coal bits of 1.75-in. (44-mm) diameter were much less efficient, turning in process specific energy values in the range 400 to 1500 lbf/in.^{2} (2.8 to 10 MN/m^2). The standard USA CRREL 3-in. (76-mm) coring auger had a process specific energy of 350 lbf/in.^{2} (2.4 MN/m^2), based on the volume of ice actually cut, and an effective value of 180 lbf/in.^{2} (1.2 MN/m^2), based on the total hole volume (including core). The standard USA CRREL 1.5-in. (38-mm)-diameter ship auger had specific energies in the range 340 to 880 lbf/in.^{2} (2.3 to 6.1 MN/m^2). For overall specific energy, the best values were turned in by two commercial gasoline-powered augers designed for ice fishermen. A 5.5-in. (0.14-m)-diameter auger with a 1-hp (0.75-kW) engine gave an overall value of 185 lbf/in.^{2} (1.3 MN/m^2), while a 9-in. (0.23-m)-diameter auger with a 3-hp (2.2-kW) engine gave typical values from 210 to 300 lbf/in.^{2} (1.4 to 2.1 MN/m^2). Best overall values for electrically driven units were around 300 lbf/in.^{2} (2 MN/m^2).

Sellmann and Mellor (1974) made tests in ice with 1.5 to 2.2-in. (38 to 56-mm)-diameter augers, and found best values of process specific energy around 300 lbf/in.^{2} (2.1 MN/m^2), with other values ranging up to 500 lbf/in.^{2} (3.5 MN/m^2) or so. Overall specific energy was in the range 500 to 1200 lbf/in.^{2} (3.4 to 8.3 MN/m^2).

Kovacs (1974) tested a 3-in. (76-mm)-diameter ice auger and obtained an extremely low value for process specific energy of 57 lbf/in.^{2} (0.39 MN/m^2) (better than the best values from laboratory experiments), with an overall specific energy of 240 lbf/in.^{2} (1.7 MN/m^2).

From the test results it seems that a process specific energy of 100 lbf/in.^{2} (0.7 MN/m^2) is not an unreasonable design goal, even for small drills that cannot enjoy the scale advantages of larger machines. To put this in perspective, a process specific energy of 100 lbf/in.^{2} (0.7 MN/m^2) for ice represents a dimensionless performance index (see Mellor 1972a) of about 0.1; i.e. the specific energy is about 10% of the uniaxial compressive strength of the material. For overall specific energy, 200 to 300 lbf/in.^{2} (1.4 to 2.1 MN/m^2) seems a reasonable design goal, with lower values more readily attainable on larger drills. In rock drilling research there is a rule of thumb that gives a dimensionless performance index of about 0.3 as the practically attainable lower limit for very efficient drills, and present indications are that this rule is not unreasonable for ice.

Frozen fine-grained soil. Sellmann and Mellor (1974) tested small electrically driven augers in frozen silt and obtained process specific energy values in the range 900 to 1600 lbf/in.^{2} (6.2 to 11.0 MN/m^2), with overall values in the range 1500 to 2300 lbf/in.^{2} (10 to 16 MN/m^2).

In undocumented field tests we obtained overall specific energy values down to 3300 lbf/in.^{2} (23 MN/m^2) for 3-in. (76-mm)-diameter gasoline-powered augers working in permafrost. We also obtained more favorable values boring 4.4-in. (0.11-m)-diameter hole in frozen silt with the USA CRREL 3-in. (76-mm) coring auger powered by a gasoline unit. Basing overall specific energy on the volume of material actually cut, values down to 1700 lbf/in.^{2} (12 MN/m^2) were obtained, while effective overall specific energy based on total hole volume dropped as low as 900 lbf/in.^{2} (6.2 MN/m^2).

In normal operation, large industrial drills tend to work less efficiently. For example, Lange (1964) observed a 50-hp (37-kW) auger drilling 6-in. (0.15-m) diameter hole with overall specific energy consumption of 8700 lbf/in.^{2} (60 MN/m^2), and a 100-hp (75-kW) auger drilling 9-in. (0.23-m) diameter hole with overall specific energy consumption of 13,000 lbf/in.^{2} (90 MN/m^2).

However, other types of very large rotary-cutting devices employing large drag bits have demonstrated much lower values of specific energy under frozen-silt field conditions. For example, large disc saws have cut with overall specific energy as low as 900 lbf/in.^{2} (6.2 MN/m^2) (Mellor 1975), a tunneling machine has had values down to 700 lbf/in.^{2} (4.8 MN/m^2), a large rotary trencher has given the spectacularly low value of 180 lbf/in.^{2} (1.2 MN/m^2), and a large miller/planer has given values of *process* specific energy down to 720 lbf/in.^{2} (5 MN/m^2) (Mellor 1972c).

There is obviously a lot of scope for design improvement in this material. In some cases attempts to combat abrasion and impact problems have led to poor tool geometry, but there are other factors involving both the kinematics and dynamics of the machines.

Measured specific energy for thermal penetration

The lower limit of specific energy consumption for thermal penetration of ice and ice-bonded soils is set by the latent heat, ambient temperature, ice content, etc., as already discussed. Putting this limiting value in the same units as are used for mechanical systems, the specific energy consumption for complete melting of solid ice from -5°C is 4.58 × 10^4 lbf/in.^{2} (316 MN/m^2). For frozen soils the corresponding value is approximately proportional to the volumetric ice content for soils that are close to saturation. In operating drilling systems the process specific energy consumption exceeds the theoretical value by an amount that is largely dependent on the power density, the penetration rate, and convective losses, while the overall specific energy consumption is dependent additionally on losses between the energy input source and the melting element. There may also be some question as to whether specific energy should be based on actual hole diameter or the drill diameter.

Electrical drills give the best idea of process specific energy for penetrating ice, since they are not subject to much line loss. Taking some of the penetration rates given in another section of this paper and neglecting bore enlargement, examples can be calculated. A 2-kW (2.7-hp) hotpoint boring 2-in. (51-mm)-diameter hole at 0.33 ft/min (1.7 mm/sec) gives a specific energy of 8.54 × 10^4 lbf/in.^{2} (589 MN/m^2), or a melting efficiency of 54%. The 3.625-in. (92-mm) diameter Philberth probe penetrating at 0.16 ft/min (0.81 mm/sec) with 3.68-kW (4.9-hp) input gives a specific energy of 9.86 × 10^4 lbf/in.^{2} (680 MN/m^2), or a melting efficiency of 46%. A 0.25-kW (0.34-hp) hotpoint of 0.73-in. (19-mm) diameter penetrating at 0.27 ft/min (1.4 mm/sec) gives a specific energy of 9.79 × 10^4 lbf/in.^{2} (675 MN/m^2), or a melting efficiency of 47%.

Shreve and Sharp (1970) obtained a melting efficiency of 75%, LaChapelle (1963) had a melting efficiency of 59%, and Stacey (1960) reached 86% to 88%, all with electrical hotpoints.

According to data on Russian electrothermal drills (Korotkevich and Kudryashov, in press), best values of useful specific energy for the small penetrator (1.6-in., or 40-mm, diameter) and the small corer (4.4/3.5 in., or 112/88 mm) working in 0°C ice were about 6 × 10^4 lbf/in.^{2} (400 MN/m^2) and 7 × 10^4 lbf/in.^{2} (500 MN/m^2) respectively. These values represent melting efficiencies of about 74% and 63% respectively. For the large corer working in ice at temperatures between -28° and -57°C, best values of specific energy were also about 7 × 10^4 lbf/in.^{2} (500 MN/m^2), which represents melting efficiencies in the range 75% to 86%. Results given for the large penetrator (3.1-in., or 80-mm, diameter) working in ice at -19° to -28°C are questionable, as they seem to imply melting efficiencies in excess of 100%. Best reported results for the French thermal corer working in Adelie Land (Gillet, in press) also seem on the optimistic side; 6-m/hr penetration with 4.05 kW (cutting 0.102-m core and 0.14-m hole) in ice at about -14°C implies a melting efficiency of 99%.

The efficiency of a steam drill is more difficult to work out, but Howorka (1965) gave some values for his equipment. About 50% of the input energy was lost between the burner and the boiler output (this has to be compared with the efficiency of an electrical generator). Of the energy put out by the boiler, 56% went into line loss, and 44% was available for drilling and compensating drilling losses.

At a more exotic level, some idea of process specific energy for melt penetration by a CO_2 laser can be gained from data given by Clark et al. (1973), who obtained specific energy consumptions for linear cutting of 6×10^4 lbf/in.^{2} (414 MN/m^2), or melting efficiency of 76%.

Measured specific energy for liquid jet penetration

Hypervelocity water jets have inherently high specific energy consumption, and they would therefore normally be used in such a way that some material is left uncut by the jet itself; i.e. the kerf-and-rib technique would probably be employed. However, for planning purposes it is useful to know the basic specific energy consumption for slot-cutting.

Experimental work on the cutting of ice with high pressure water jets has been summarized by Mellor (1974), and the most recent data have been reported by Harris et al. (1974). Reporting of specific energy has previously been avoided because of the complications raised by secondary melting of the test slots, and by surface spalling at very small penetrations. However, under low ambient temperatures and conditions of high traverse speed and relatively low flow rate (high pressure), it appears that initial slot width is about 2.5 times the nozzle diameter, as is generally the case for deep slotting in rocks. When this width is taken for calculation of specific energy, the calculated values are maximized. Some examples of upper limit values of process specific energy are given in Figure 8, and it can be seen that the values for low power nozzles are very high compared with values for any other cutting concept.

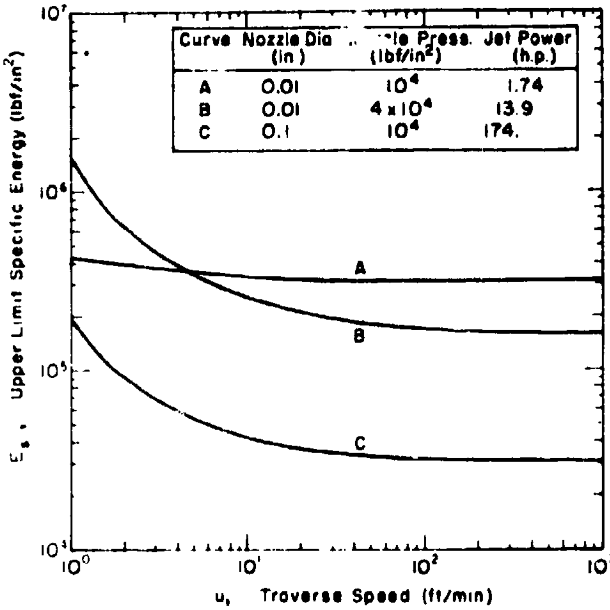

Figure 8. Examples of upper limit values for process specific energy in jet-cutting of ice.

The interesting feature about jets is that they permit development of tremendously high power densities. Power density (which for a given fluid and given nozzle design is proportional to nozzle pressure raised to the power 1.5) is 2.2×10^4 hp/in.^{2} (2.6×10^4 MW/m^2) for a pressure of 10^4 lbf/in.^{2} (69 MN/m^2), and 7×10^5 hp/in.^{2} (8.1×10^5 MW/m^2) for a nozzle pressure of 10^5 lbf/in.^{2} (690 MN/m^2).

Energetics of indentation and normal impact

Drills that work by normal indentation or normal impact include roller rock bits, which have a static force reaction, and percussive tools that rely largely on inertial forces. Because their special characteristics are well adapted to work in strong and brittle rocks, they have not found much application in ice or fine-grained frozen soils, although they are a natural choice for drilling frozen gravels. However, there has been some interest in drilling ice and frozen fine-grained soils with vibratory tools, which can be regarded as percussive drills working at high frequency and low amplitude.

Percussive drills cover a broad spectrum, but in practice there tends to be an inverse relation between frequency and blow amplitude, since the product of frequency and blow energy gives the output power, which ordinarily stays within a limited practical range. For convenience in rough classification, percussive devices can be grouped into: (i) low frequency machines such as piling or casing hammers (powered by steam, compressed air, or internal combustion); (ii) midfrequency machines such as percussive rock drills or impact breakers (powered by hydraulics, compressed air, or direct mechanical systems); and (iii) high frequency machines such as "sonic" drills and piledrivers (having primary excitation by rotating eccentric mass or electromagnetic driver, sometimes with hydraulic transfer medium). For machines with relatively high power output (say 18 hp), low frequency might be represented as of the order of 1 Hz with 10^4 ft-lbf (1.4×10^4 J) blow energy, midfrequency would be approaching 10 Hz with blow energy of 10^3 ft-lbf (1.4×10^3 J) or more, and high frequency would be 100 Hz or more with blow energy of 10^2 ft-lbf (1.4×10^2 J) or less.

The specific energy for indentation can vary greatly, being affected by "indexing" (spacing between individual indentations), depth of penetration (relative to indenter dimensions), and other factors. Laboratory data for low speed (3 to 40-ft/sec, or 1 to 12-m/sec) indentation (Fig. 4) give values of 70 to 500 lbf/in.^{2} (0.5 to 3.5 MN/m^2) for ice and 600 to 2000 lbf/in.^{2} (4 to 14 MN/m^2) for frozen fine-grained soils. Results obtained from impact of high-speed inert projectiles, ranging from bullets striking at up to 4000 ft/sec (1200 m/sec) to bombs striking at up to 1000 ft/sec (300 m/sec), indicate specific energy values in the range 350 to 3500 lbf/in.^{2} (2.4 to 24 MN/m^2) (Mellor 1972b). This somewhat indirect evidence tends to suggest that there is not much benefit to be gained by high speed indentation once the speed is high enough to induce a brittle response. Actual percussive drilling values for specific energy are not available, but rough estimates made from measured penetration rates in ice and frozen soil suggest that they are likely to be unfavorably high.

ROTARY DRILLING SYSTEMS

Torque and axial force in rotary systems

In a conventional rotary drilling system, the power used for penetration has to be transmitted as torque and thrust in the drill string, while in a rotary system with downhole drive the corresponding torque has to be resisted by reaction "skates" and the corresponding thrust has to be provided by the weight of the unit or resisted by thrust reaction pads. Thus, while the power requirement for penetration may be inconsequential from the standpoint of energy supply, limitation of specific energy may be important in reducing the torque and thrust demands in a lightweight drill system.

With drag bits that are sharp and aggressive (high relief angle, strong positive rake), axial thrust requirements are not high in ice and fine-grained frozen soils. From personal experience the writers have found that in ice the axial thrust divided by the total width of active cutters is typically in the range 10 to 25 lbf/in. (1.8 to 4.4 N/mm) when aggressive cutters are working well; values sometimes go up to about 45 lbf/in. (8 N/mm), and down to as low as 5 lbf/in. (0.9 N/mm). In frozen fine-grained soils the values do not seem to be much higher with freshly sharpened carbides, but they increase considerably as the cutters become blunted by abrasion. The low thrust requirements for ice are easily met, even in lightweight drills, and in some cases it may be necessary to "hold back" the drill, either by keeping the drill string in tension or by limiting cutter penetration (preferably by control of effective relief angle). The electromechanical downhole ice drills that utilize the cutting head of the original USA CRREL corer provide far more weight than is needed for the 1.3 in. (33 mm) of active cutting edge.

With small values of axial thrust, the product of axial thrust and penetration rate represents only a small amount of power; e.g. 70 lbf (311 N) thrust at a penetration rate of 10 ft/min (3.05 m/sec) represents about 0.02 hp (0.015 kW). Thus thrust power can often be neglected in relation to torque power, and torque can be expressed conveniently in terms of specific energy.

Since torque is power divided by angular frequency, and power can be expressed as specific energy multiplied by volumetric cutting rate, torque T can be written in terms of specific energy E_s, penetration rate R, hole diameter D, and revolutions per unit time N:

$$T = \frac{RD^2}{8N} E_s \,. \tag{7}$$

This is for plain drilling; for coring the torque is reduced by a factor $[1 - (D_o/D_i)^2]$, where D_o and D_i are outer and inner diameters of the coring head respectively.

From eq 7 it can be seen that torque is directly proportional to specific energy; some representative values are shown graphically in Figure 9. Torque can be reduced under some circumstances by increasing the rotational speed, but for a given power level there are limits to this effect, since chipping depth has to decrease as rotational speed increases and specific energy rises as a consequence.

Characteristics of commercial rotary drills

An important aspect of systematic design procedure involves analysis of existing equipment that has evolved through practical experience to satisfy industrial needs. The first goal is to organize readily available information on commercial units in such a way that some general rules of thumb can be developed. In order to illustrate the procedure, we have taken some data for drag-bit auger drills; similar procedures can be followed for other classes of rotary equipment. The auger drills and large diggers provide the most direct

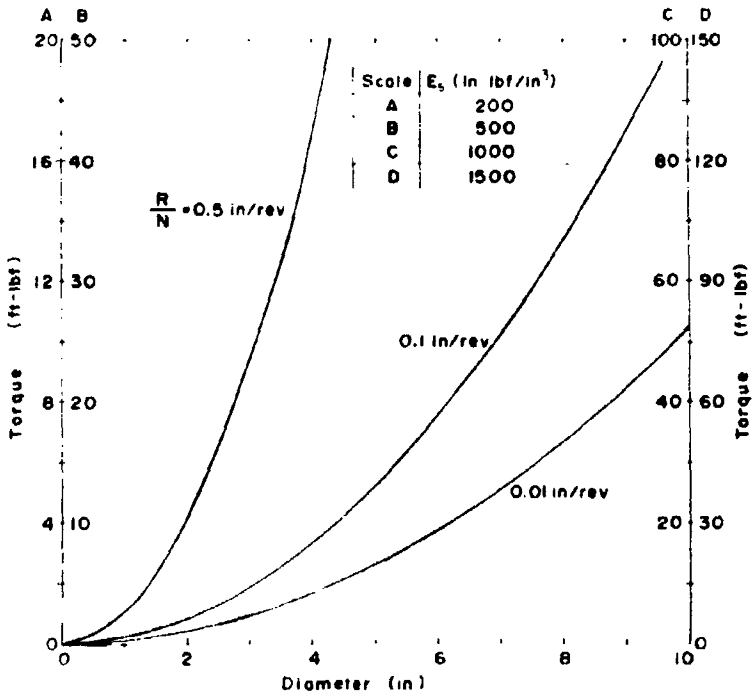

Figure 9. Required torque as a function of diameter, specific energy, penetration rate, and rotary speed.

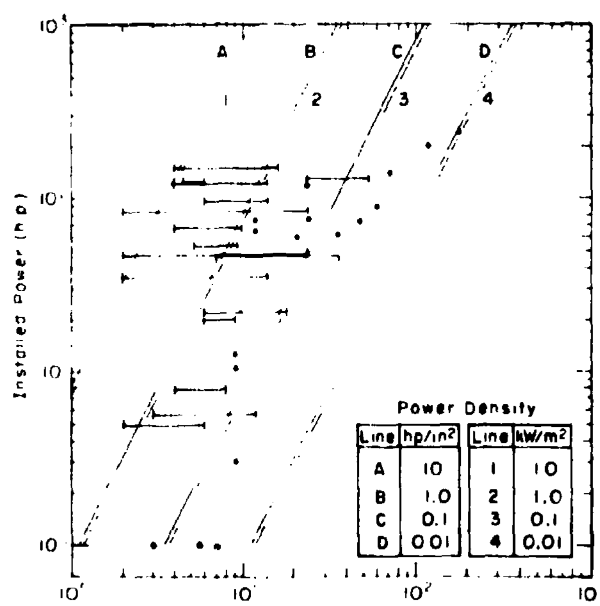

Figure 10. Installed power of existing rotary diggers and auger drills plotted against bit diameter. Lines representing a range of power density levels are superimposed.

information on power required for penetration of soil, ice, weak rock, and frozen ground, since there are no requirements for fluid or air circulation, and hoisting requirements are usually not as great as in other systems because of more limited penetration depth.

In Figure 10 the installed power of various augers has been plotted against bit diameter, using logarithmic scales to cover the wide size range. The assumption is that installed power is used largely for cutting and clearing in equipment of this type, so that there should be a significant dependence on diameter. From the simple mechanics of the operation, proportionality between power and the square of diameter is to be expected; i.e. any regression line drawn through the data of Figure 10 might be expected to have a slope of 2. Actually, the plotted data cannot be expected to define any unique relation, since commercial drills of this type have to cover a range of bit sizes with a single power unit, they have to operate in a variety of material types from soils to weak rock, and they have to accept different performance limitations in terms of penetration rate and depth capability. The diameter data for some of the drills were plotted to indicate the diameter range suggested by the manufacturer, while only the largest working diameters were plotted for some of the large diggers. We have therefore drawn a set of lines that represent different power density levels, and it can be seen that the pieces of equipment represented in the plot have power densities ranging from about 0.01 hp/in.^{2} (0.01 kW/m^2) to over 10 hp/in.^{2} (10 kW/m^2). Equipment at the low end of the power density range might include very large augers that penetrate slowly and do little continuous clearing (e.g. in sinking caisson shafts), or augers designed to work only to shallow depths in very weak material (e.g. fishermen's ice augers). The high end of the power density range tends to represent large or powerful machines operating with the smallest bits that can be fitted. An interesting feature of the plot is that relatively powerful augers operate at power densities of the order of 1 kW/m^2, whereas electrothermal drills for ice and rock operate at power densities of the order of 1 MW/m^2.

In Figure 11 rated thrust has been plotted against largest working bit diameter. If it is assumed that the total width of cutter edges on the bit is some simple multiple of the diameter (total width of cutter edge equals the diameter in the typical situation where the tools give 100% coverage of the face), then a linear relation between thrust and diameter is expected. In real life the total cutter width may vary from 0.4*D* to 1.2*D*. In Figure 11 we have drawn a set of lines that represent mean vertical thrust on unit width of the cutting tools, neglecting for present purposes the end effects of overbreak. The range is from about 200 lbf/in. (35 kN/m) to 1200 lbf/in. (210 kN/m) when total cutter width equals diameter. In laboratory cutting experiments on sedimentary rocks, the normal component of cutting force for unworn chisel-edge drag bits is typically about 200 to 300 lbf/in. (35 to 53 kN/m) for deep (but realistic) chipping. However, the normal component of cutting force increases with bit wear, in proportion to the area of the wear flat that develops on the relief face of the cutter.

In Figure 12 rated torque is plotted against largest working bit diameters. We make the assumption that developed torque reflects the tangential component of cutting force for uniformly loaded tools, and lines have been drawn to represent various force levels when total cutter width equals bit diameter (as in the previous figure total cutter width may vary from 0.4*D* to 1.2*D*). The range covered by the machine data is from approximately 100 lbf/in. (17.5 kN/m) to over 1000 lbf/in. (175 kN/m). In laboratory cutting experiments on sedimentary rocks, the tangential component of cutting force for unworn chisel-edge bits taking cuts between 1 and 10 mm deep typically lies in the range 100 lbf/in. (17.5 kN/m)

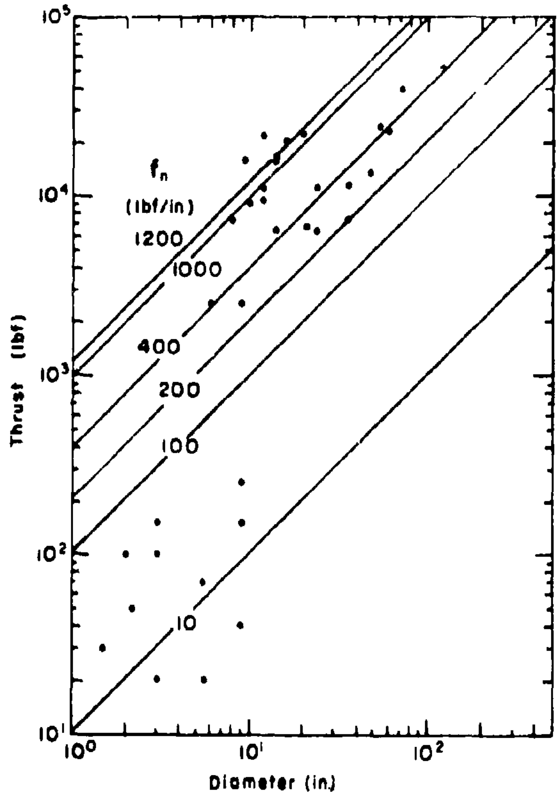

Figure 11. Maximum rated thrust plotted against maximum rated bit diameter for some existing auger drills and rotary diggers. Superimposed lines gives thrust divided by diameter; these values give a measure of the normal component of cutting force where total cutter width equals bit diameter. Values can be adjusted by a factor in the range 0.4 to 1.2 in order to account for varying bit design.

(for shallow cuts or for sharp tools with strong positive rake) to over 1000 lbf/in. (175 kN/m) (for tools taking deep cuts). The tangential force component tends to be less dependent on wear than the normal component, especially with negative-rake tools.

In Figure 13 rotational speed has been plotted against bit diameter, with the intention of defining the linear velocity of the peripheral tools, i.e. the maximum tool speed. However, some caution is called for in preparing and interpreting such a graph, since a drill that has a range of bit sizes and rotational speeds does not necessarily have the capability of effectively using the largest bits at the highest speeds because of torque or power limitations. For this reason, only rpm values that appeared most reasonable were plotted for the various diameters. In broad terms, the maximum potential tool speeds indicated by the graph are in the range 100 to 1000 ft/min (0.51 to 5.1 m/sec), which is the range normally considered

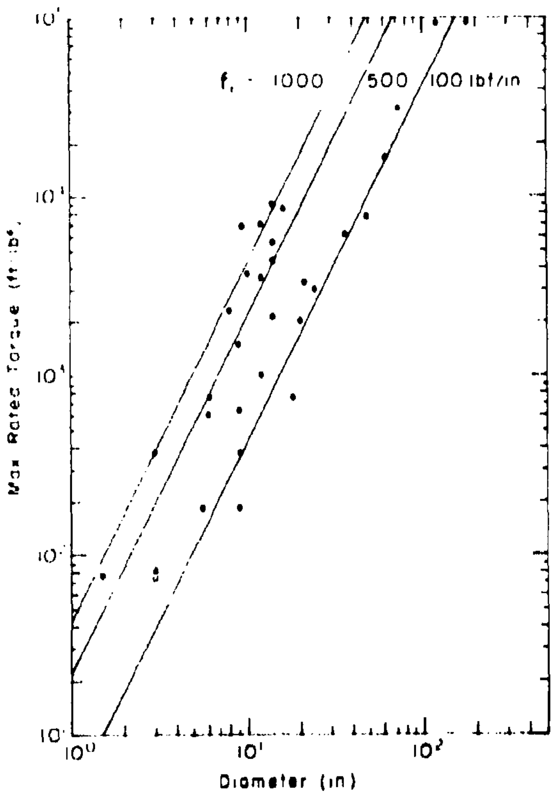

Figure 12. Maximum rated torque plotted against maximum rated bit diameter. Superimposed lines give the force of the torque divided by the diameter; these values give a measure of the tangential component of cutting force where total cutter width equals bit diameter. Values can be adjusted by a factor in the range 0.4 to 1.2 in order to account for varying bit design.

to be optimum in the design of drag-bit mining tools (wear becomes unacceptably high at greater speeds in abrasive rock.

CONCLUSION

While many drilling systems are bewilderingly complex at first sight, they provide only three simple basic functions: penetration, material removal from the hole, and hole stabilization. There are many ways of meeting each of these functional requirements, but because of the need for some degree of compatibility between each functional element of the system, the number of practical combinations is limited.

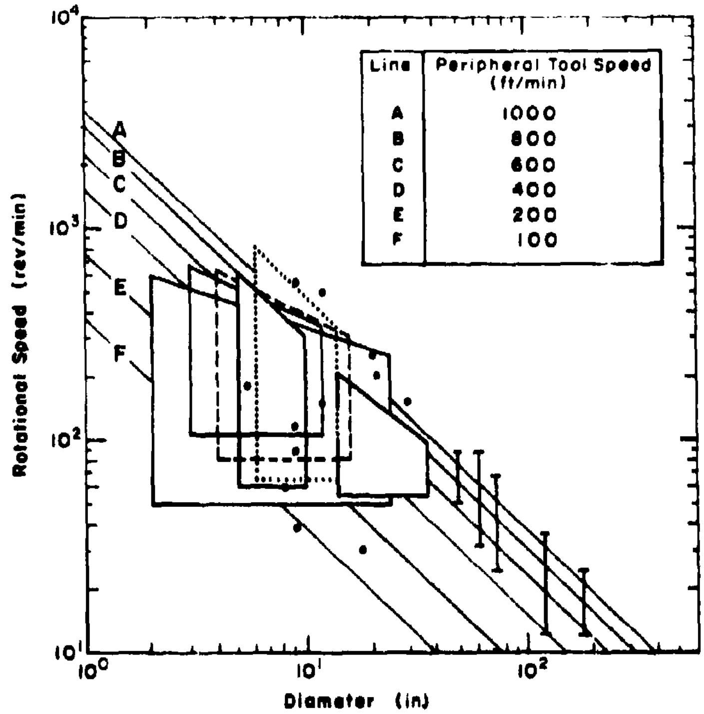

Figure 13. Rotary speed plotted against bit diameter. Superimposed lines represent various levels of peripheral tool speed.

The minimum power required to meet a given performance specification can be estimated for each functional element from simple physical considerations, provided that certain material properties for the ground material are known. These power estimates are useful for comparing concepts and assessing compatibility of the individual elements. They also provide a basis for estimating torque and axial force in rotary systems.

Field data for drilling devices operating in ice and frozen soils show wide discrepancies in performance, and suggest that many past operations have fallen far short of attainable energetic efficiency levels.

Some drilling concepts are inherently less efficient than competing concepts in energetic terms, but may still be attractive because they offer easy transmission of energy, possibly coupled with a potential for high power density at the drill tip. Practical limitations on power density can set a limit to potential penetration rate for some drilling concepts.

New drilling units for unusual ground conditions sometimes evolve unsystematically through successive empirical adaptations and modifications of components that are marginally suitable or weakly compatible. However, it now seems possible to reduce the dependence on empiricism in new development, since the data and methodology for an analytical approach are becoming available. This is particularly true in the case of rotary drilling, where current research into the kinematics, dynamics and energetics of rotary cutting is yielding systematic data on penetration and chip removal.

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