

INTRODUCTION TO DRILLING TECHNOLOGY

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ABSTRACT

Terrestrial drilling technology is reviewed. The general requirements for a drilling system are given and conventional drilling techniques (rotary drag-bit, rotary roller-bit, percussive, rotary-percussive) are described. Unconventional techniques for penetrating solids are outlined, including thermal drilling (spalling or melting), projectile penetration, high-pressure liquid jets, explosive jets, erosion by projectile streams, and chemical penetration. Special attention is given to drilling in ice and frozen soils; performance data are given, including values for penetration rate and specific energy consumption. The principles, theory and equipment relating to each drilling technique are indicated by means of diagrams.

INTRODUCTION

In many respects, terrestrial ice is an easy material to drill. It is quite weak, it is not abrasive, and it usually exists at a temperature close to its melting point. Ice-bonded soils are also fairly easy to drill as long as the grain size is many times smaller than the diameter of the drill. However, ductility in soils such as frozen clay can present some problems. Frozen coarse-grained soils such as ice-bonded gravel do not have particularly high bulk strength, but they are difficult to drill when the grain size of the rock particles approaches the diameter of the drill. Ice of very high porosity (usually called "snow," or "firn") is permeable and highly compressible; it can be penetrated easily.

Conventional drilling technology can be adapted for drilling in ice and ice-bonded soils, but it has been found desirable to aim for refinement as well as adaptation. Brute force is commonly employed in conventional drilling, but for research drilling in remote polar regions and high mountains, there is a need for small machines that are light in weight and highly efficient. In core drilling, the emphasis is on core quality.

For drilling small holes in ice, melting is a practical alternative to mechanical cutting, even though it is inefficient in energetic terms (the energy needed to melt unit mass of ice is sufficient to lift it against gravity to a height of 34 km). Some highly effective thermal devices have been developed for drilling and coring. There have also been many tests of wholly inappropriate thermal systems.

Over the years, a variety of unusual drilling requirements have been developed by the military, by industry, and by research groups. This has prompted studies of unconventional drilling techniques.

The intention here is to give a rapid review of drilling techniques, conventional and unconventional, that have been used or tested on Earth. The treatment is necessarily superficial, but there is an attempt to direct attention to the basic principles of each concept. Special emphasis is given to drilling techniques for ice and ice-bonded soils, and some useful numbers are given. In adapting drilling techniques for extraterrestrial tasks, consideration of the basic principles seems essential.

ESSENTIAL COMPONENTS OF DRILLING SYSTEMS

Drilling technology covers a wide range of practical tasks, with different industries having their own specializations and independent lines of development. An outsider tends to be overwhelmed by the enormous range of unfamiliar equipment, the apparent complexity of the varied operations, and the strange technical jargon. However, once the general principles have been grasped, it is easy enough to understand the details of drilling technology.

All drilling systems have two essential functions:

1. Penetration of the ground material.
2. Removal or displacement of material from the hole.

There is sometimes a third function:

3. Support of the hole wall.

When faced with a novel drilling task, the tendency is to concentrate on the first of these, the pene-

are likely to collapse if they are not supported artificially. When very deep holes are drilled on Earth, gravity body forces will eventually cause any kind of material to collapse when the stress exceeds the yield strength of the material. There are three general methods for stabilizing drill holes.

Direct mechanical restraint can be provided by setting a casing of metal pipe or plastic pipe in close contact with the hole wall. This casing is placed by driving it with some type of hammer, or by drilling it in with a special cutter set on the bottom of the casing. Setting of the casing can progress with the primary drilling operation, either advancing the casing ahead of the main bit or letting the casing follow the main drill. Alternatively, casing can be set after the drilling is finished, using temporary support by high-density fluid prior to setting of the casing.

Direct restraint by liquids is another way to prevent closure. During drilling, a high-density fluid, or "mud," is circulated as the drilling fluid, and it is left in the hole after drilling to balance the lithostatic pressure. For deep holes in ice, the fluid has to have a low freezing point, it has to be non-reactive, and the density has to match the *average* density of the ice column (since ice creeps, too much fluid pressure could enlarge the hole).

Treatment of the ground material is another possibility for supporting the hole. Common treatments include the use of specialized muds, chemical cementation (including pressure-grouting), and freezing. An unconventional possibility is fusion of the hole-wall material. For holes in ice or ice-bonded soils, the hole walls have to be kept cold, both during and after drilling. When a circulation system (air or liquid) is used in ice or frozen soil, the fluid has to be chilled, either by a heat exchanger or by a refrigeration system.

ICE AND ICE-BONDED SOILS

For drilling purposes, ice and ice-bonded soils can often be thought of as rocks. Ice is a unique monomineralic rock of low strength and low density; it occurs as the surface rock over large areas of the earth's surface. When water-saturated soils freeze they become sedimentary rocks that are cemented by ice. Frozen sand is a sort of weak sandstone, frozen silt is a siltstone, and frozen gravel is quite like weak concrete. In all cases the ice is the key ingredient for drilling purposes.

Ice is unusual in that it exists at very high homologous temperatures on Earth; it is easy to melt, though the latent heat of fusion is quite high. A most unusual characteristic is that the solid phase of ordinary ice Ih is less dense than the liquid phase.

One consequence of close proximity to the melting

point is an ability for ice to creep readily under sustained stress. At the strain rates developed in typical mechanical drilling, ice is quite brittle, but ductile behavior can occasionally cause problems, especially near the center of a drill hole and in very fine frozen soils, notably frozen clay.

Fine fragments of ice cut by a drill bit are surface-active. They adhere readily, to each other and to solid surfaces. A mass of fine ice grains is compressible, and sintering of the grains solidifies a static mass. Inadvertent melting, from frictional heat at the bit or from warm circulation fluid, can create serious problems in conveying cuttings out of the drill hole.

For most practical purposes in drilling, low-porosity ice is considered to be incompressible.

ROTARY DRILLING SYSTEMS

Rotary drilling is the dominant technique for making holes in solid materials. In rocks and soils, rotary drills are used to bore holes with a wide range of diameters, from less than 40 mm for shothole drills up to about 5 m for shaft-sinking rigs. If tunnel-boring machines are considered as drills, the diameter range extends up to about 10 m. In the manufacture of rock products and in research, rotary drills with sub-millimetre diameters may be used.

A rotary drill penetrates by applying thrust and torque to a drill bit, which does the actual cutting. When the diameter is very large, the cutting element is referred to as a boring head. Drill bits and boring heads generally depend on one of two basic principles:

- a. Cutting by a scraping action, where the cutter is a sort of chisel that moves parallel to the surface that is being cut.

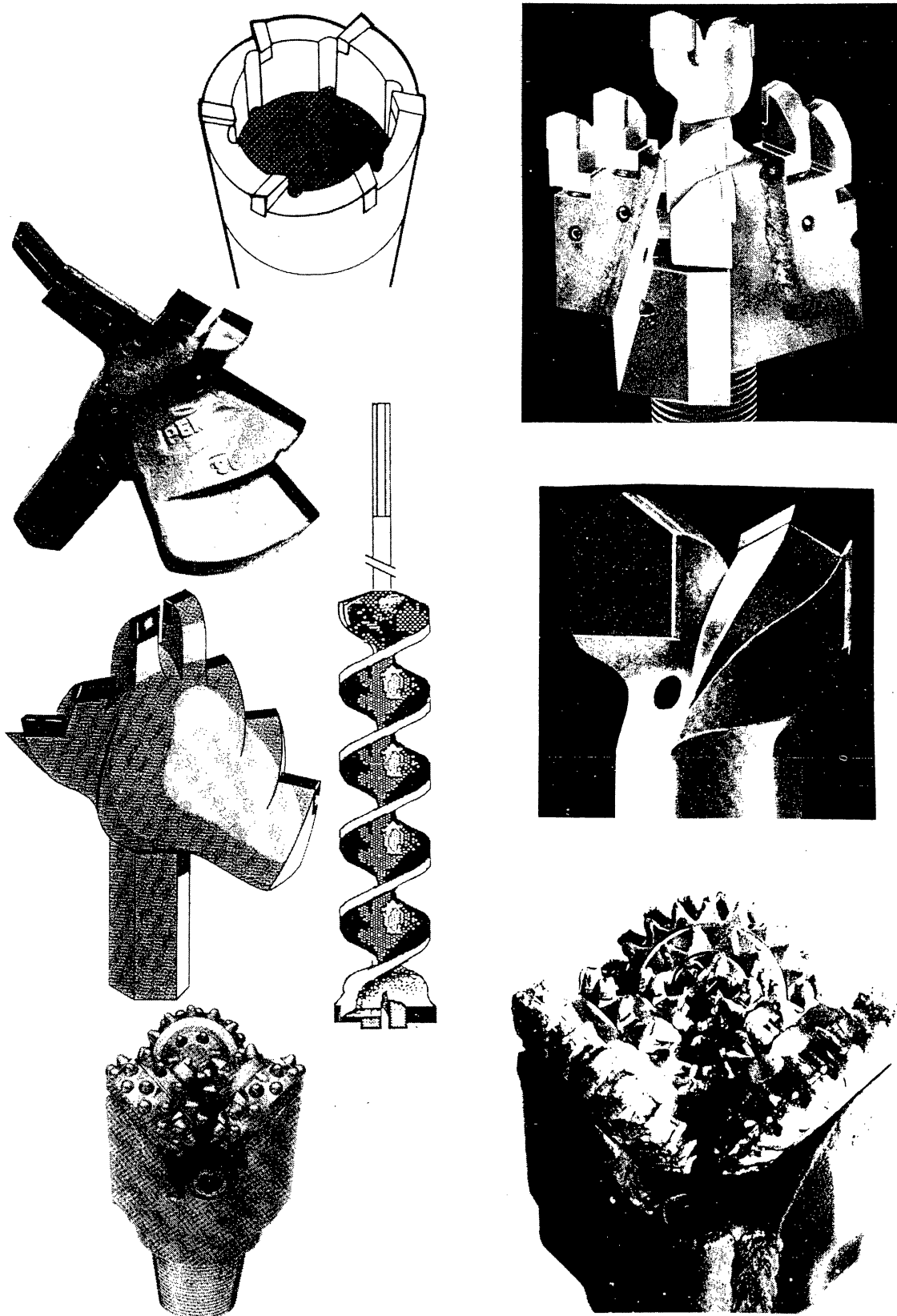


- b. Cutting by indentation, when hard projections on the bit are thrust repeatedly into the rock, normal to the surface that is being cut.



Type (a) bits are usually called drag bits. They work by scraping, shearing, planing or slicing the rock. Diamond bits are really primitive drag bits, with "whole-stone" diamonds or sintered diamond abrasives acting as very small cutters. Type (a) bits normally work in materials that are relatively weak and not highly abrasive, but diamond bits can be used in very hard rock.

Type (b) bits are called roller bits. They work by pressing free-rolling discs or cones against the rock, pitting it by brittle fracture and sometimes plucking at less brittle material. The rollers on the bit may have vee-edge discs or rings of indenters (chisel-edged, conical, or hemispheric). Type (b) bits are well-suited for work in hard rock.





The rotary drive system is usually external, i.e. at the top of the hole. Torque and rotation are transmitted from the rotary drive to the bit by a shaft, often a long string of coupled drill rods. The drill rod also serves as part of the transport system for removing cuttings, either by carrying a flow of compressed air or fluid, or by rotating a flight auger (screw conveyor). Drill rod is raised and lowered by a hoisting mechanism in a mast or tower. Torque reaction is usually provided by a heavy frame or carrier vehicle that relies on gravity for its stability. In a lightweight system, torque reaction can be provided by a long lever that is pegged into the ground.

The thrust system is also commonly external to the hole, often integrated with the system for raising and lowering the drill rod. In deep drilling, the weight of a long drill string can provide more than enough force on the bit, and it may be held in tension so as to regulate thrust to the proper value. Thrust reactions usually depend on gravity, positive downthrust reacting against the weight of the drill tower, turntable, drawworks, engine, carrier vehicle and suchlike. In raise boring, the drill string is in tension; it runs in a small-diameter pilot hole, pulling up a large boring head from an underground gallery.

There are also downhole rotary drilling units which follow the bit down the hole, providing torque and thrust from an internal drive system which is powered through an umbilical from the surface. Torque reaction and thrust reaction are provided by radial thrust against the hole wall. Tunnel-boring machines are very large downhole units. They can use both radial thrust and gravity for reaction against torque and axial thrust.

Rotation can be provided by hand (or other types of muscle power), by an internal combustion engine, by an electric motor, by a hydraulic motor, or by an air motor. Any of these things can drive either directly or through a mechanical transmission system (shafts, gears, chains, belts, rollers, flexdrive cables).

Thrust can be provided by muscle power, by gravitational deadweight of the rotary drive, by rack and pinion, by roller drive chains, by hydraulic actuators, or by gas actuators.

The primary power source can be muscle power, an internal combustion engine, electrical line power, electrical storage batteries, a tank of compressed gas, or water pressure. In principle, wind energy, solar energy, fuel cells, and nuclear sources could be used.

Intermediate drives between the primary power source and the final drives include mechanical transmissions, hydraulic pumps, air compressors and electric generators.

Cuttings are removed from the hole by a mechanical system or by fluid circulation. A continuous mechanical system depends on a continuous-flight auger in conventional drilling, and on screw or belt conveyors in tunneling. A cyclic mechanical system for

drilling uses such things as a bucket auger, a shallow-pitch short auger, or a core barrel (all have to be lifted to the surface for emptying). In tunneling, shuttle cars and trains are used. Fluid circulations systems carry cuttings out of the hole by suspension in a liquid, mud, or foam, or by turbulent suspension in a fast flow of compressed air. In a standard circulation system the fluid is forced down the inside of the drill pipe and it returns up the annulus between the drill string and the hole wall. Reverse circulation moves the fluid in the opposite direction, with return inside the drill pipe. Circulation is usually continuous, but it can be pulsed.

A rotary drill, or drilling rig, has to provide an optimum combination of torque, thrust and power for the bits it is intended to drive. It is usually rated for a maximum hole diameter.

Torque requirements are proportional to the square of bit diameter. For commercial augers that use drag bits to drill holes from 75 mm to 5 m in diameter, the maximum rated specific torque ranges from about 35 to 500 kN/m (i.e. kN-m/m²). The variation reflects differences between heavy-duty machines designed for hard ground and weak rock and lighter machines designed for soils. For commercial rotary drills that can use either roller bits or drag bits in the diameter range 75 mm to 250 mm, the maximum rated specific torque ranges from about 0.35 to 1.75 MN/m (MN-m/m²). Tunnel boring machines in the diameter range 2 to 10 m have maximum rated specific torque in the range 80 to 180 kN/m.

The thrust requirements for a rotary drill bit are often specified in the industry as force per unit diameter, but the maximum thrust capabilities of drill rigs correlate better with the square of maximum rated diameter. For augers and other mobile rotary drills (maximum rated bit diameters 75 mm to 2.5 m), the maximum specific thrust ranges from about 20 kPa to 7 MPa. Roller rock bits can accept loadings up to 5 MPa or more at low rotation speeds, but for fast rotation (>150 rev/min on large roller bits) the maximum acceptable pressures are from 0.5 to 2 MPa. On tunnel boring machines the maximum rated specific thrust is in the range 150 to 700 kPa.

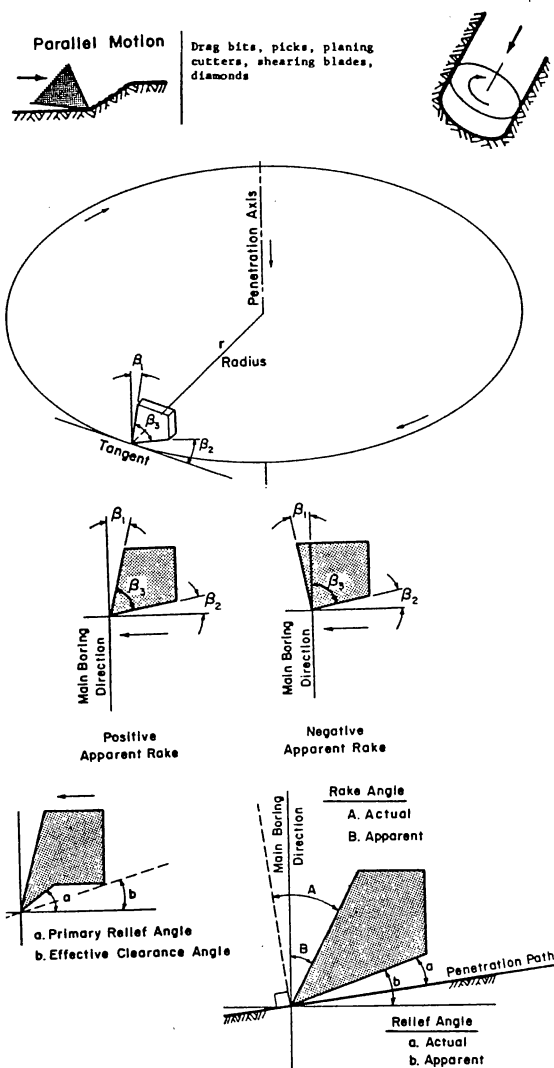
The rotation speed of a rotary drill can usually be regulated within fairly broad limits, but for drills overall there is an inverse relation between maximum rotation speed and maximum bit diameter. For auger drills that use drag bits, maximum rotation speed varies from about 20 rev/min for very large shaft-sinkers (3 to 4 m dia.) to about 500 rev/min for small rigs (250 mm dia. and less). Auger rotation is usually regulated so as to keep the maximum linear speed of the outermost cutters within the range 1 to 5 m/s. Roller bits are turned at speed from about 40 to 300 rev/min, keeping the maximum tangential velocity at the rim of the bit mostly within the range 0.5 to 3 m/s.

The installed power on a drill rig is usually much greater than the power needed to rotate the maximum size of bit at the maximum rated thrust and speed. The installed power has to provide for lifting drill pipe (sometimes from considerable depth at high rates) and also for clearing cuttings (by driving an auger or powering a pump or compressor).

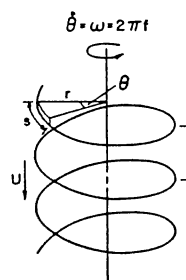
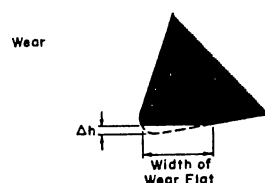
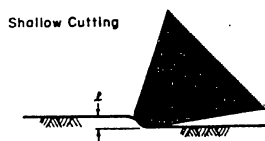
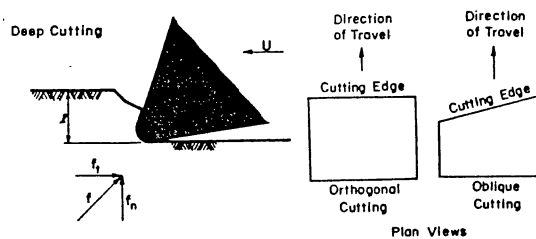
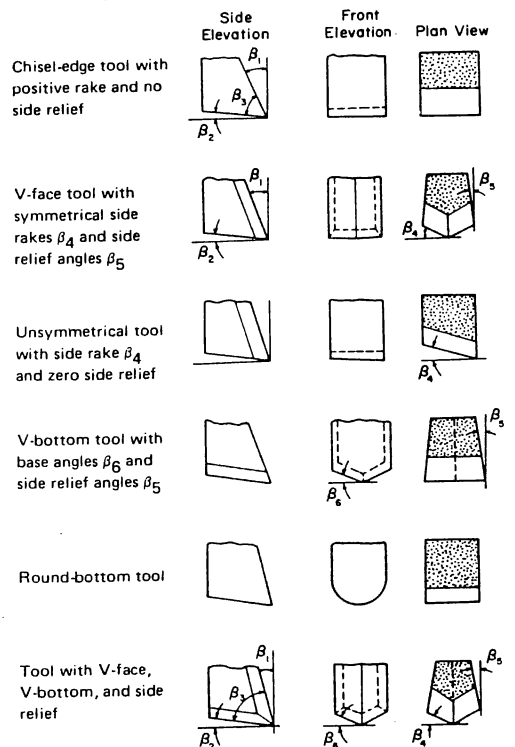
BITS FOR ROTARY DRILLING

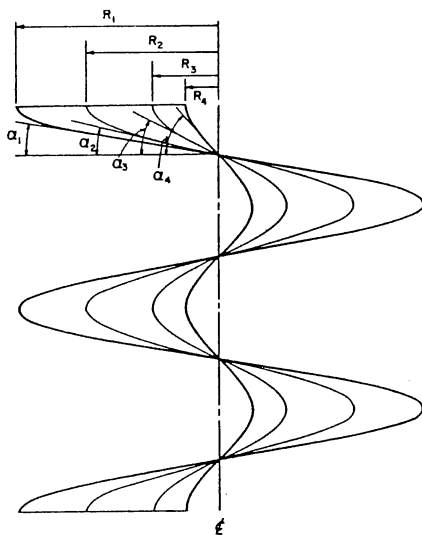
A. Parallel Motion Tools

The cutting edge moves parallel to the advancing work surface. The tool is forced into the work by axial thrust and is rotated across the face by torque. Tools include drag bits (chisel bits, finger bits, bullet bits), knife-edge bits (planing cutters, shearing blades), and diamond bits. In two-dimensional representation, tool is characterized by three angles: (1) rake angle, positive or negative (β_1), (2) relief, or clearance, angle (β_2), (3) included angle (β_3).



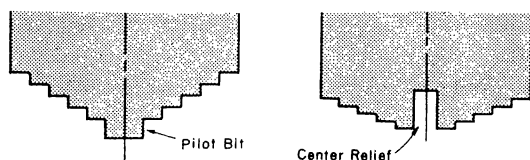
In three-dimensional representations, the geometry can take a variety of forms. The cutting motion may be approximately orthogonal, or oblique. Cutters should be as sharp as possible. They work best when cutting deep relative to the radius of the cutting edge. Wear increases the thrust requirements substantially.



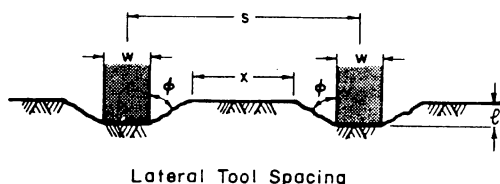


Each cutter advances along a helical path. The steepness of the helical path for each cutter is inversely proportional to the radius of that cutter.

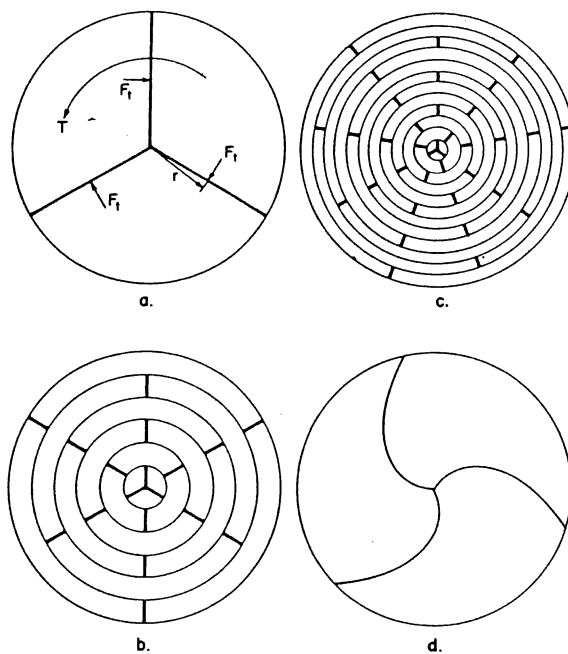
At the center of the bit the helical path is infinitely steep, so special provisions are needed. The bit can be designed to leave an uncut core which breaks off periodically and is discharged with the cuttings. Alternatively, there can be a miniature pilot bit. Poorly-designed bits rely on the friability of the ground material, or some other fortuitous process, to solve the center-of-hole problem.



The cutters on a bit may be continuous radial wings (straight or curved) or individual cutters with spaces between them, so that separate grooves (kerfs) are cut.



Adjacent kerfs have to meet or overlap so there is cutting across the full area of the face. Cutters should be arranged to give rotational symmetry, so that the drill is not vibrated by out-of-balance forces.

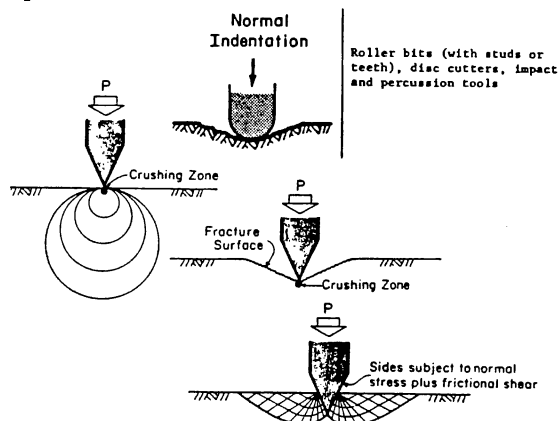


Example of balanced cutter arrays for 3 repetitions ($n = 3$, angular spacing $2\pi/3$).

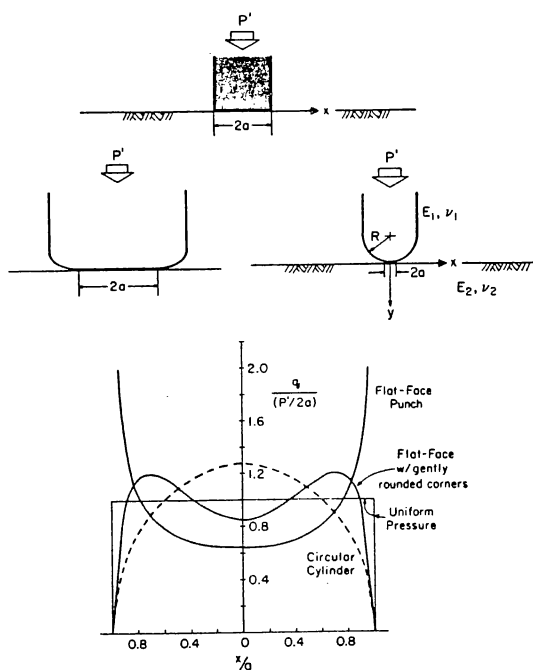
The specific energy for efficient drag bit cutting (E_s) correlates linearly with the uniaxial compressive strength of the rock (σ_c). The dimensionless index given by E_s / σ_c is typically in the range 0.05 to 0.5 (low numbers denote high efficiency). For ice, E_s ranges from 0.5 to 4 MJ/m³. For frozen silt, E_s is usually (but not invariably) higher, reaching values as high as 14 MJ/m³, even with efficient tools. For frozen sand, E_s is about 2 to 6 MJ/m³. Low values are obtained by using sharp, well-set cutters and operating the drill so that it produces large chips.

B. Indentation Tools

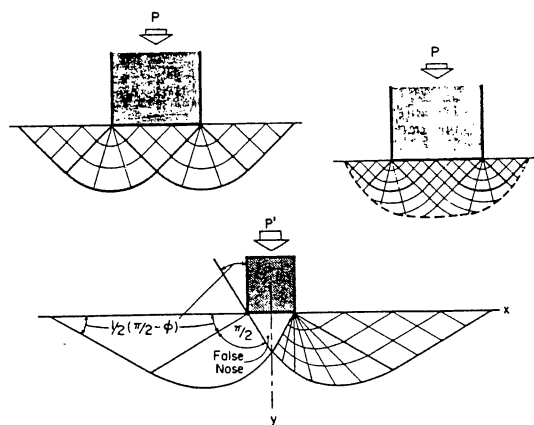
The cutting element thrusts into the work surface, forming a crater by normal indentation. The process is effective only in brittle material which cracks and spalls.



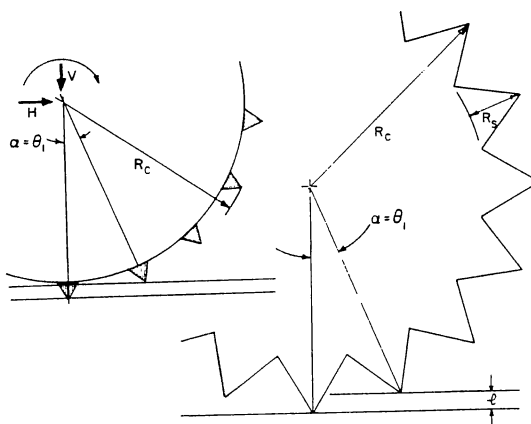
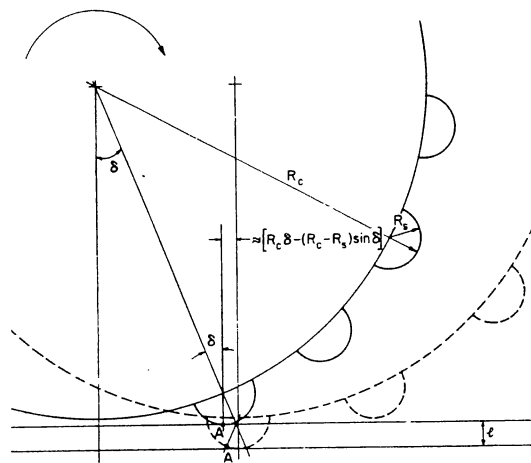
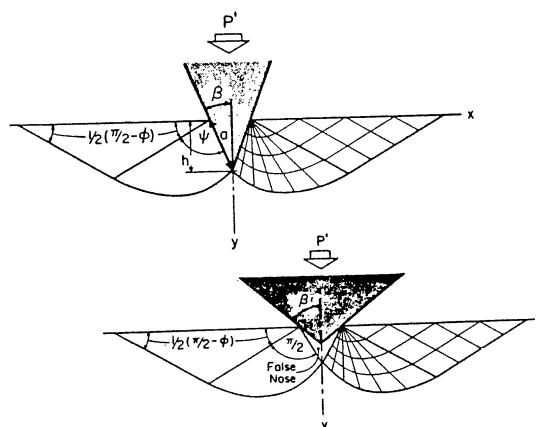
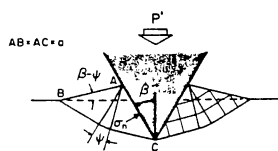
The initial elastic stress distribution varies with the shape of the indenter.



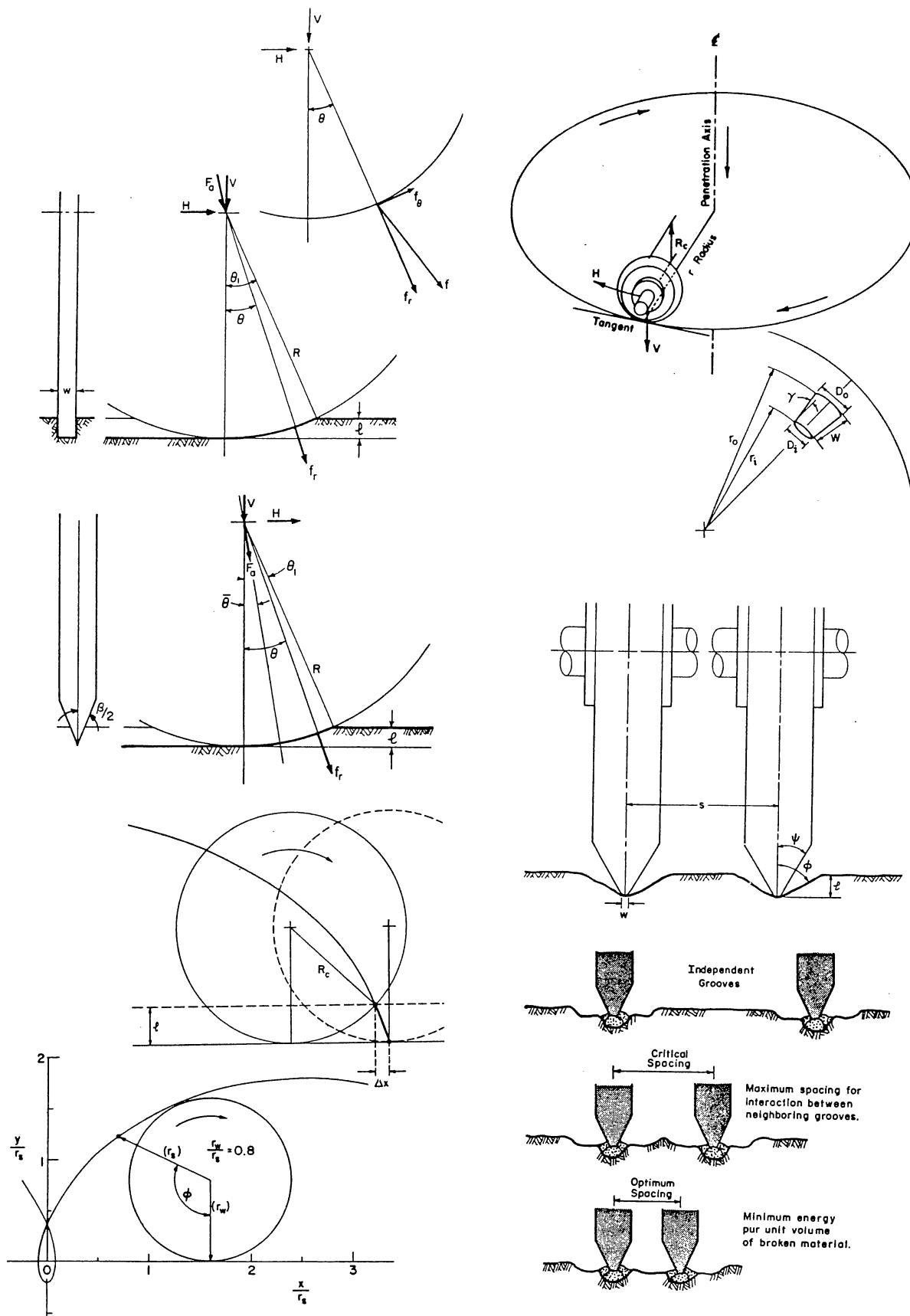
The penetration process and its dependence on indenter shape, material properties and interfacial friction can be explored by application of plasticity theory.



The indentation process is repeated by setting indenters around the perimeter of a roller, or by forcing the rim of a disc into the rock.

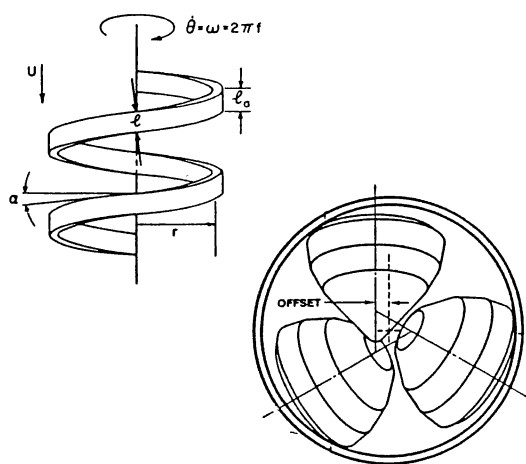


Each indenter, or each point on the rim of a disc, follows a cycloidal penetration path in typical operation. When studs or spikes penetrate to their full depth, they can pluck the material by following the path of a prolate cycloid. The cutting discs roll about an axis that is approximately normal to the penetration direction of the drill. They also travel in a circle around the penetration axis. Several discs, or several rings of indenters, can be combined into a single conical roller. On a typical drill bit, one conical cutter cov-



ers the entire radius of the bit. On a large boring head, numerous roller cones can be set out. Each disc, or ring of indenters, produces circular grooves on the working surface. The radial spacing between these grooves is optimized to give efficient operation of the bit.

Each point on a cutter actually follows a helical path as the drill penetrates. The *specific energy* for rock-cutting by indentation (E_s) has an overall linear correlation with the uniaxial compressive strength of the rock (σ_c). The dimensionless ratio E_s/σ_c typically ranges from about 0.25 to 1.5. Values of E_s for ice and fine-grained frozen soil are in the range 2 to 15 MJ/m³.

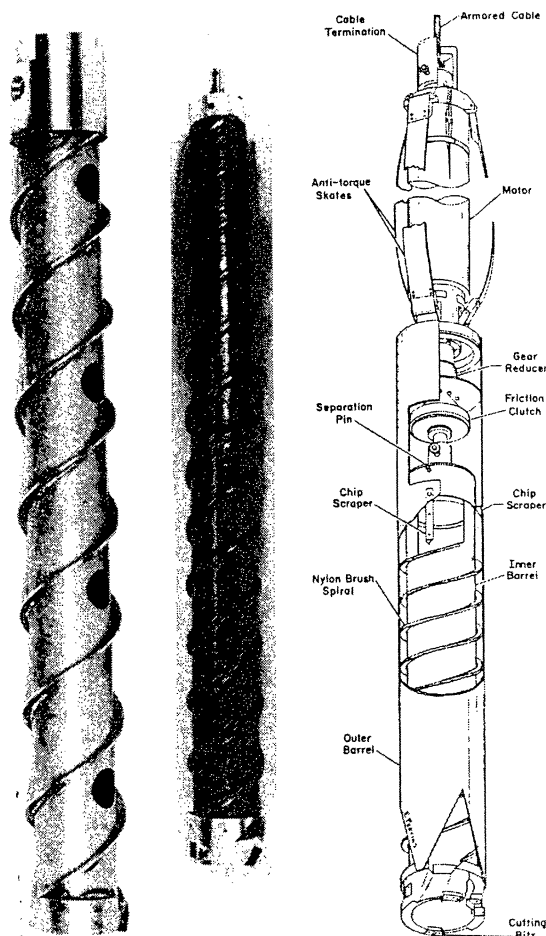


In the design and construction of commercial roller bits there are additional subtleties.

ROTARY DRILLING IN ICE AND FROZEN SOIL

For rotary drilling in ice and fine-grained frozen soils, drag bits (parallel motion) are the tools of choice. The individual cutters are usually chisel-edge tools, although conical cutters (bullet bits) can be used on large boring heads.

A cutter should be as sharp as possible, given the need for significant strength and wear resistance. In clean ice, very sharp steel tools can be used, with an included angle (β_3) of about 30° to 40° and a relief angle 5° to 10° steeper than the slope of the helical penetration path (say, $\beta_2 \approx 12^\circ$, $\beta_1 \approx +40^\circ$ to $+50^\circ$). The same tool design can be used for fine-grained soil, substituting tungsten carbide for steel in the cutting edge. With this kind of cutter, the normal component of cutting force can be expected to be about one-third of the tangential component when deep chips are being cut. With aggressive cutters of this kind, plus careful attention to the center-of-hole problem, the specific energy can be less than 1 MJ/m³ in ice and less than 10 MJ/m³ in frozen silt. When typical



unmodified commercial drill bits are used, specific energy values are an order of magnitude higher.

Using good augers in ice, we have achieved penetration rates up to 22 mm/s with hand-crank drills, up to 77 mm/s with hand-held electric drills, and up to 38 mm/s with hand-held gasoline drives. This covers a diameter range from 38 to 230 mm. With force-feed on drill rigs, higher rates are possible but not advisable, as the drill jams when the bit produces cuttings faster than the conveying system can transport them to the surface.

Using similar tools in frozen silt, we have achieved penetration rates up to 12 mm/s with a hand brace and up to 33 mm/s with hand-held gasoline drives. Shallow holes up to 356 mm diameter have been drilled with hand-held equipment. With a small drill rig, auger bits have penetrated ice-rich frozen silt at rates up to 46 mm/s.

By contrast, some very large drill rigs with badly-designed drag bits have been almost incapable of penetrating frozen silt. A common problem is that the bit forms a polished boss of uncut material at the center of the hole. Another problem is that the cutters become clogged with compacted fragments due to inadequate provision for clearing the cuttings.

Drag bits are not well suited for drilling small-diameter holes in coarse frozen gravel, but robust drag bits can be used for drilling large-diameter holes.

Roller bits can be used in ice and frozen silt, although they are not really appropriate, especially when ground temperature is near 0°C (ductility). Sea ice has been drilled at 41 mm/s with a 120 mm diameter roller bit.

Hand-held coring augers for ice and fine-grained frozen soil can give rapid penetration. Our old 76 mm I.D. steel core barrel could be driven at rates up to 28 mm/s. The current 110 mm I.D. fiberglass core barrel has been driven at rates up to 34 mm/s. The 76 mm corer (fitted with carbide cutters) has been driven in frozen silt at rates up to 61 mm/s, which is much faster than the same tool in ice.

When a core barrel is being used for sampling, especially in deep drilling, core quality is more important than penetration rate. Rotation rate and/or the angle of the helical penetration path are deliberately limited in order to assure good core quality.

PERCUSSIVE DRILLING

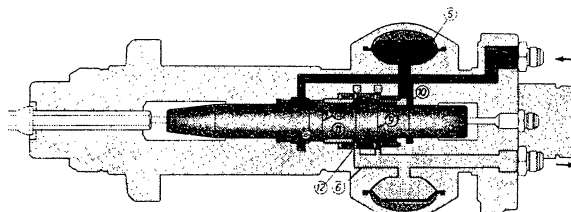
Percussive drilling depends on either: (a) the hammer and chisel principle or (b) the captive projectile principle. Of these, the first is by far the most common in modern equipment, as exemplified by percussive drills, jackhammers, impact breakers, downhole hammers, piledrivers and suchlike.

In a hammer drill, a steel hammer strikes a rod or an anvil and converts its kinetic energy to a stress pulse, which is then transmitted to the drill bit, either directly or via a long rod (the "drill steel"). The hammer can be swung by hand, dropped under gravity, driven directly by a gas-actuated piston (internal combustion, compressed gas, steam), or driven indirectly by using gas, liquid or a mechanism to cock a firing spring (gas or mechanical). Other possibilities include repetitive firing of chemical propellant,

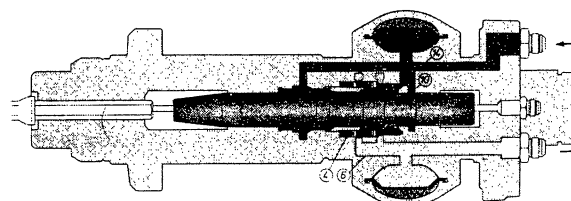
mechanical oscillation of a mass, or application of some electromagnetic driver.

Projectile impact is the essence of the old cable tools which repeatedly raise and drop a heavy weight, to which the bit is attached. Some impact breakers used for demolition have a short-throw captive projectile which is driven by air or fluid.

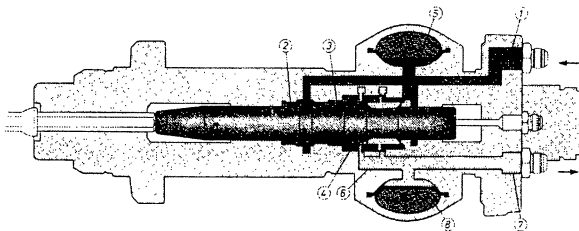
Percussive drills are used typically in hard, brittle rock which can be chipped into small fragments. Energy from the hammer is transmitted to the rock by the drill bit, which has either a number of hard, vee-edge chisels set radially, or an array of hard, hemispheric or conical studs. The bit is usually held in contact with the rock by a small bias force (< 70 N per mm of bit diameter). It receives repeated impacts from the hammer, rotating slightly between successive blows so as to move the indenters out of the



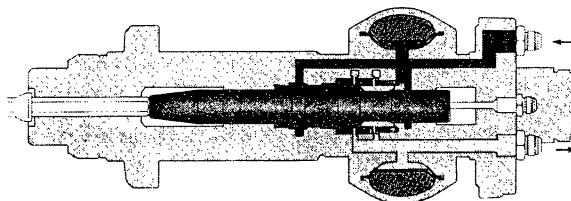
When the piston has travelled so far that edge (9) has covered ports (6), port (10) will have opened allowing pressure shock to escape and absorb in the accumulator (5). After this the edge (11) uncovers the ports (12) and the pressurized oil in the distributor chamber escapes to the return line. Before this, edge (13) prevents oil flow to the distributor chamber, and the pressure in the front part of the cylinder forces the piston backwards.



As the pressure in the distributor chamber is relieved, the high pressure prevailing against the rear face of the distributor (4) forces it forwards thus covering the escape ports (6). In this position the oil can flow to the rear part of the cylinder through a pressure port (14) between the distributor and the body. At the same time the oil can flow through port (10) to the cylinder.

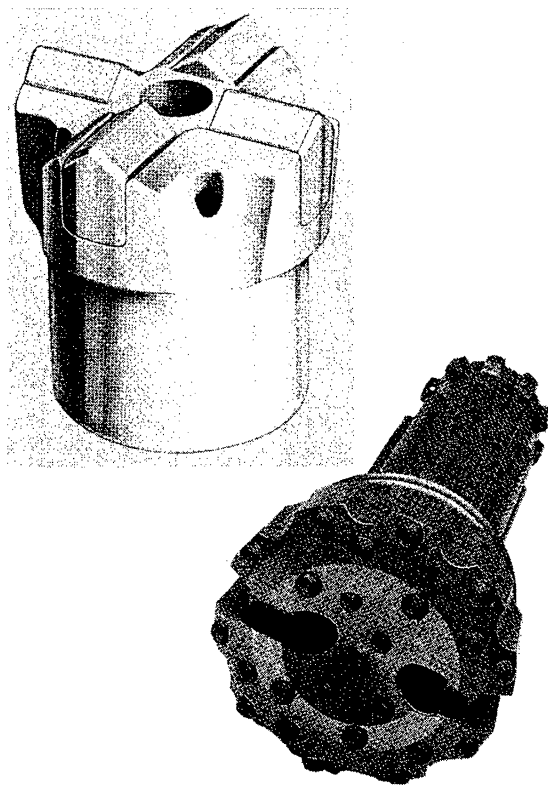


The piston is shown at the front end of its stroke. The hydraulic oil enters the drifter through the high pressure port (1) and flows into the front part of the cylinder (2) forcing the piston backwards and at the same time entering the distributor chamber (3) pushing the distributor (4) to the rear position. A part of the oil delivery enters the H.P. accumulator (5) compressing its nitrogen and thus accumulating energy. In this position the oil in the rear part of the cylinder escapes through port (6) to the return port (7). The L.P. accumulator (8) functions similarly to H.P. accumulator to prevent shock loads in the return hoses.



The piston moves forwards due to imbalance of forces prevailing in the rear and front parts of the cylinder. At the same time the H.P. accumulator is discharging oil to the H.P. line thus increasing oil flow to the cylinder. Shortly before the percussion point of the piston, edge (13) allows oil flow to the distributor chamber and imbalance of forces between distributor faces moves the distributor to the rear position closing the oil supply to the rear part of the cylinder. After the percussion point the return cycle of the piston begins as described above.

Tampella-Tamrock Hydraulic Drifters



craters they have just formed. This rotation, called indexing, can be produced by a rifle-bar mechanism (which gives a fixed angular displacement per blow) or by an independent rotary mechanism.

A percussive drill commonly has the hammer mechanism at the surface (this is called a "drifter," or for a small hand-held drill, a "sinker"). The impact from the hammer is transmitted to the bit as a strain wave through a robust elastic rod (the drill steel). Impact frequencies are in the range 20 to 60 Hz. For a given drill diameter (typically in the range 35–150 mm), operation becomes inefficient below a certain depth (of order 10 m), since blow energy is dissipated in the drill-rod couplings and in flexural vibrations of the column.

For deeper drilling by percussion methods, there are hammer drill units that attach directly to the bit and follow it down the hole (downhole hammers). These units are pneumatic, so that air for powering the drill is combined with the air circulation that clears chips and dust from the hole. Downhole hammers can drill large diameter holes (up to 1 m) to considerable depth. They are attached to rotary drill rigs and rotated slowly to provide the indexing.

Although percussive drilling is usually applied in brittle rock, percussive and vibratory equipment can be used to drive penetrators or sampling tubes into soft material that can be displaced radially. Pile-driving and drive-sampling are examples.

Percussive and vibratory devices work at widely differing frequencies, from less than 1 Hz for large pile-driving hammers to around 100 Hz for high-frequency vibratory tools. The blow energy for a single impact tends to be inversely related to frequency, ranging from 1 MJ or more for large pile drivers down to 30 J or less for small hand-held drills. The product of frequency and blow energy is the power delivered to the bit so that, for constant power, the frequency and blow energy are inversely proportional. The percussive power at the bit is about 40% of the input power for a good hydraulic drifter.

The specific energy of the drilling process decreases (i.e. efficiency increases) with increase of blow energy, largely because heavier impacts produce coarser chips (cf. comminution theory). However, because of limitations to the strength of drill steel and bits, typical percussive drifters cannot handle blow energies above about 0.5 kJ. Large-diameter downhole hammers can develop much higher blow energies, up to 5 kJ or more at frequencies around 10 Hz.

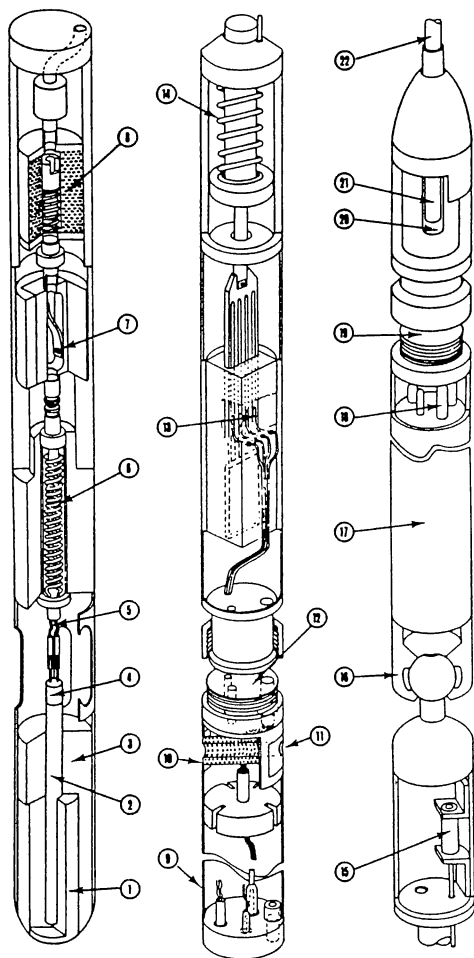
Practical percussive machines have a substantial reactive mass. For hammer-type machines, the ratio of blow energy to machines mass is typically in the range 1.5 to 6 J/kg. Projectile-type machines can have higher ratios—up to about 25 J/g.

The specific energy for percussive drills (drifters) working in typical hard rock is in the range 100 to 500 MJ/m³. Percussive drills have not had any serious use in ice, but on the basis of laboratory indentation tests the specific energy for the penetration process can be estimated in the range 2 to 20 MJ/m³. However, at very high frequencies percussion and vibration can become very inefficient in energetic terms, eventually tending to become melters (specific energy ≈ 300 MJ/m³).

Using unmodified commercial equipment, small diameter percussive drills have penetrated ice, frozen silt and frozen gravel at rates up to 46 mm/s. Solid steel rod of 0.1 m diameter has been driven in frozen silt at 14 mm/s and in dense frozen gravel at almost 2 mm/s. A big high-frequency vibratory unit has driven open-end pipe (0.15 m O.D.) into frozen silt and sand at rates up to 150 mm/s, and 0.11 m O.D. core tube into frozen gravel at up to 30 mm/s. A small downhole hammer has drilled at 12 mm/s in frozen silt.

THERMAL DRILLING

Some types of hard rock can be penetrated effectively by flame jets. The most efficient breakage process is thermal spalling, which seems to work best in dense rocks that have a high quartz content (the expansion coefficient of quartz is double that of other typical rock-forming minerals). High-temperature

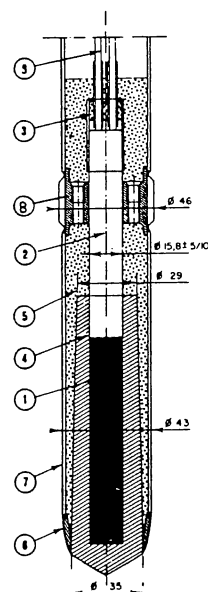


(1) Copper cylinder. (2) Heating cartridge. (3) Thermal insulation. (4) Glass metal sealing. (5) Water suction pipe. (6) Heating wire. (7) Flow gage. (8) Vibration pump. (9) Melt tank. (10) Filter. (11) Drain hole. (12) Connection. (13) Linear slip ring. (14) Suspension spring. (15) Linear transducer. (16) Ball and socket joint. (17) Electronic section. (18) Electrical connections. (19) Connector. (20) Electrical insulation. (21) Cable termination. (22) Armored cable. (Gillet et al., CNRS, Grenoble.)

combustion takes place in a high-velocity jet of well-mixed fuel and oxidant. Fuels used in the various systems include diesel fuel, propane, LNG, acetylene. Oxidants are compressed air or pure oxygen. High-velocity exhaust gases flush debris from the drill hole. Flame jets melt ice, frozen soils and some other materials, scouring away the melt layer by the jet action and thus permitting useful application of high power density. A flame lance, which burns a metal rod, can also be used as a penetrator.

In the early seventies a high-temperature hot-point for melting holes through rock was developed at Los Alamos. Power density at the melting tip was in the range 0.3 to 2.5 MW/m^2 , with a development goal of 5 MW/m^2 . The fused rock was supposed to displace radially and form a lining for the hole wall.

(1) High power density cartridge. (2) Cold part of cartridge. (3) Glass-metal sealing. (4) Copper cylinder. (5) Ceramic coating. (6) Stainless steel tip. (7) Stainless steel tube. (8) Cooling flange. (9) Copper power conductor. (Gillet et al., CNRS, Grenoble.)



Flame jets have driven holes of 0.2 m diameter in ice at a rate of 15 mm/s , and in frozen silt at 5 mm/s . The Los Alamos Subterrene penetrated very cold frozen silt at 0.14 mm/s under high thrust.

For drilling in ice, a variety of electrothermal drills were developed for core sampling and for plain hole-drilling. An electrothermal system is particularly attractive for deep coring, as the core barrel can be lifted and lowered rapidly by reeling the cable (as opposed to coupling and uncoupling rigid drill rods).

The heat-exchange surface of the hotpoint is aluminum or copper that contains sealed electrical-resistance heating elements. An early design goal was to maximize power density while assuring a good working life for the elements, and power densities in the range 1 to 3 MW/m^2 were achieved. However, the film-boiling phenomenon sets useful limits to the power density of a hotpoint that sits in its own meltwater, and 3.25 MW/m^2 seems to be about the useful upper limit.

The minimum energy needed to melt unit mass of ice or ice-bonded soil is the sum of the latent heat of fusion for the ice component and the sensible heat needed to bring the total mass up to the melting point. Multiplying this sum by the hole's cross-section area and the penetration rate, the minimum power needed for thermal penetration is obtained.

If a limit value for the power density is accepted, the maximum theoretical penetration rate can be estimated (ignoring heat losses). For pure solid ice at -5°C , a power density of 3 MW/m^2 gives a theoretical penetration rate of 9.5 mm/s , which is an order of magnitude lower than rates attainable by mechanical ice drills.

Rate limitations can be overcome by using a hot-water jet for penetration. Water is heated by fuel oil

or gas (e.g. in a tankless heater or a car-wash heater) and is then pumped under moderate pressure (1 to 10 MPa) to a discharge nozzle. Short-term penetration rates in the range 50 to 100 mm/s can be achieved and, unlike a rotary drill, a hydrothermal drill with flexible hose can give overall drilling rates that are not much lower than the short-term penetration rate. Water from the hole is recirculated to the heater. There need not be much heat wasted in the drilling process, so that specific energy is around 300 MJ/m^3 . Heater capacity and pump capacity limit the hole size for a given penetration rate, or vice versa. Multiple jets are used for big holes.

Closed-circuit hydrothermal units can cut very large cores of any cross-section, using heated pipes as the core-cutter. In this application, penetration rate is limited by film boiling in the same way as it is with electrothermal borers.

Steam drills have been used in ice, particularly in situations where light weight and simplicity is important. The steam jet can be driven just by boiler pressure.

When a drill melts its way through a semi-infinite mass of impermeable ice (as opposed to a floating ice slab), the meltwater normally has to be removed from the hole by pumping, blowing or baling. However, if the drill is simply implanting a string of sensors, the water can be allowed to refreeze. For deep penetration by a thermal sonde, a fixed wire can be paid-out from a reel inside the sonde.

A thermal sonde can generate its own heat by an internal exothermic chemical reaction. This is discussed under "Chemical Penetration". Limited penetration can also be achieved by letting a heated mass sink into ice. Theoretically, an iron rod can sink about its own length for each 100°C of initial temperature.

With 100% thermal efficiency and total melting, thermal drilling in solid ice has a specific energy of 306 MJ/m^3 at 0°C and 316 MJ/m^3 for ice at -5°C . Electrothermal penetrators working in moderately cold ice typically consume 500 to 700 MJ/m^3 , i.e. they have thermal efficiencies from 45% to 55%. Higher efficiency can be achieved; in fact, some of the performance reports in the literature imply efficiencies in excess of 100%.

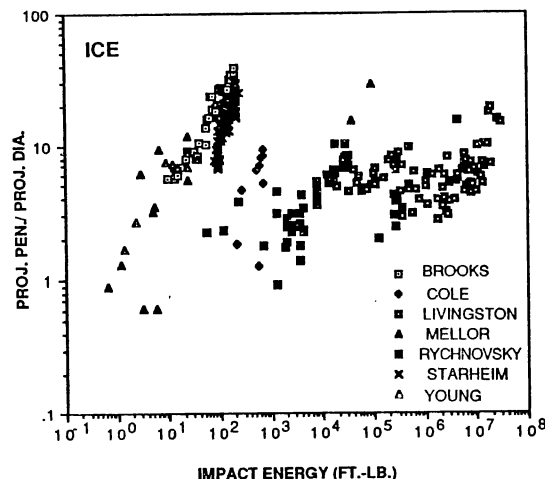
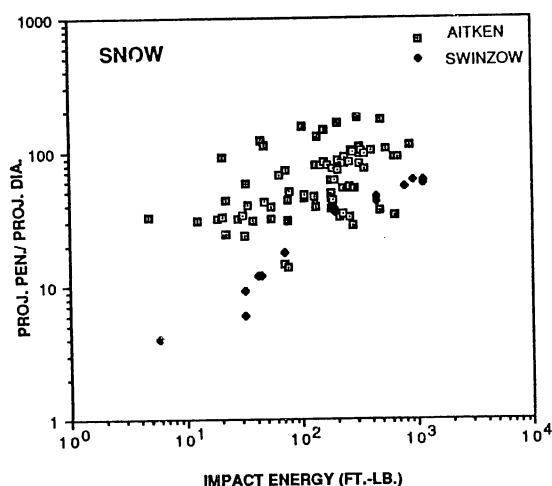
Lasers, including pulsed and focussed lasers, have been considered for drilling in ice, but there is a practical problem in removing meltwater when boring downward. In tests where a CO_2 laser was used for linear cutting, the process specific energy was 414 MJ/m^3 (76% thermal efficiency).

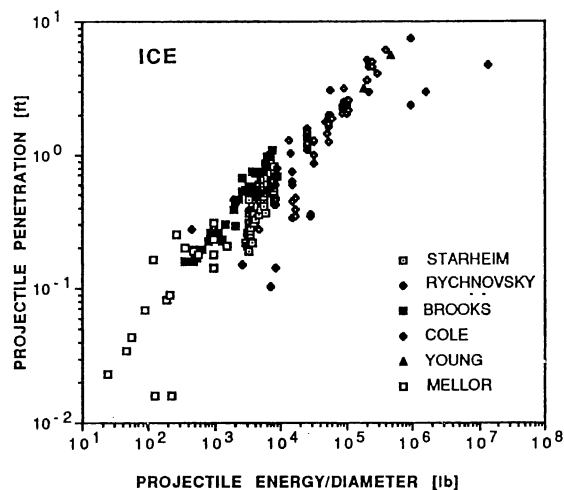
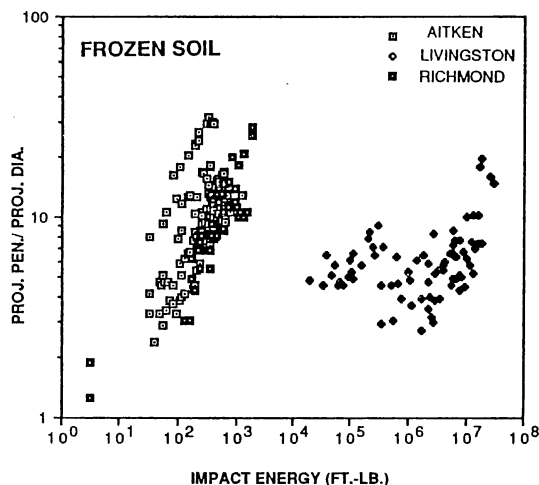
BALLISTIC PENETRATION BY A SINGLE PROJECTILE

Moderately deep penetration can be achieved by a single impact from a kinetic-energy projectile (i.e. an "inert" projectile, as distinct from an explosive

one). This is not a standard drilling process, though it is used for driving steel studs and nails into building materials and it is applicable to certain penetrators used for research or military purposes. High-velocity projectiles can develop very high energy and power per unit frontal area.

When a fast projectile first strikes a solid target material it propagates a stress wave and forms a conical surface crater. For planar impact with good impedance-matching, the stress wave amplitude in the target material is given by the product of density, elastic wave (sonic) velocity, and impact velocity. With sufficient energy (and strength), the projectile continues to bore into the target material from the base of the surface crater. It comes to rest when its energy is exhausted, sometimes after losing directional stability and "tumbling". From low-speed ice penetration tests with blunt-end rods, it seems that the penetrator has to develop contact pressures of approximately 30 MPa in order to sustain penetration in solid ice. Specific energy for ice penetration is in the range 1.5 to 15 MJ/m^3 .



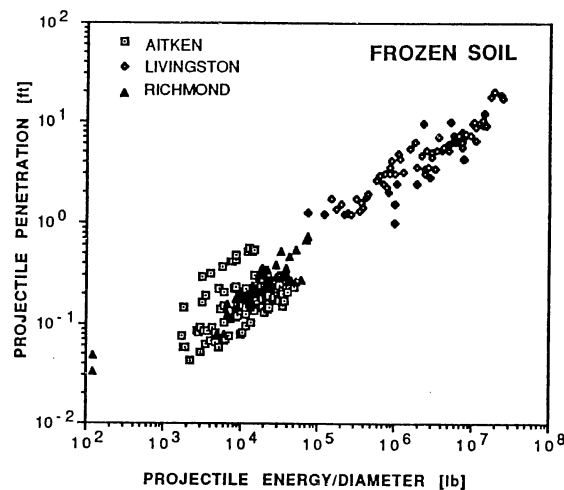
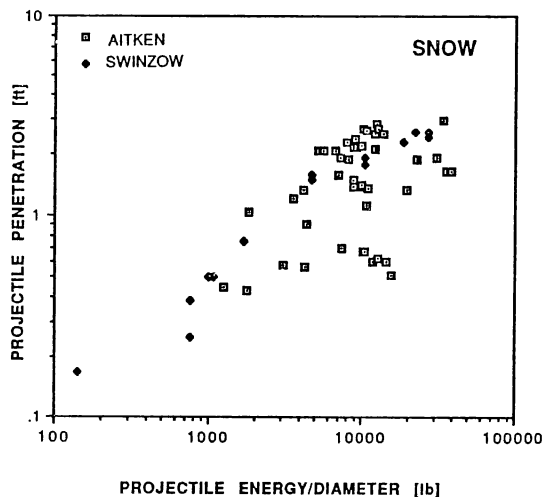


High-speed projectiles such as bullets can penetrate ice and frozen silt to depths of approximately 30 diameters (calibres). In moderately dense snow, penetrations up to 180 diameters can be attained. When conventional guns are fired in air, the maximum impact velocity is about 1.0 to 1.2 km/s, but in vacuum much higher velocities are attainable.

Test data for deep penetration in ice, frozen soil and snow have been compiled by us, but not analyzed. Data are for small bullets and for large inert shells and bombs. In preliminary attempts to unify the results from different investigations on the basis of power-law regression, we chanced upon a curious relation that, for some unknown reason, gives a good representation of the data. If P is penetration, E is impact energy and D is projectile diameter,

$$P = K(E/D)^n$$

where $n \approx 1/2$. The parabolic relation is probably an approximation for part of an overall exponential relation, but the significance of E/D is still a mystery.



PENETRATION BY HIGH-PRESSURE LIQUID JETS

High pressure liquid jets, continuous or pulsed, can be used to penetrate and cut rocks and frozen materials. A continuous jet is driven by a special pump unit, which may contain a high-pressure feed pump, an intensifier and an accumulator. A discontinuous jet is, in effect, a series of liquid projectiles fired from a nozzle by an impact device or an explosive propellant. The nozzle has a conical or flared entry, with a short, narrow hole of uniform diameter for final discharge. Because nozzle erosion is a problem, a hard liner is required.

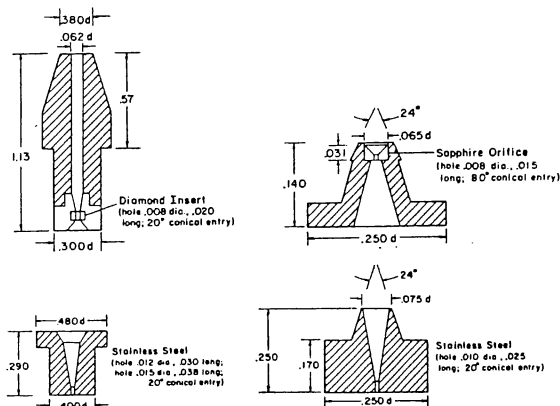
For a continuous jet, denoting nozzle pressure by p , nozzle diameter by d , discharge velocity by v , flow rate by q and hydraulic (nozzle) power by P :

$$v \propto p^{1/2}$$

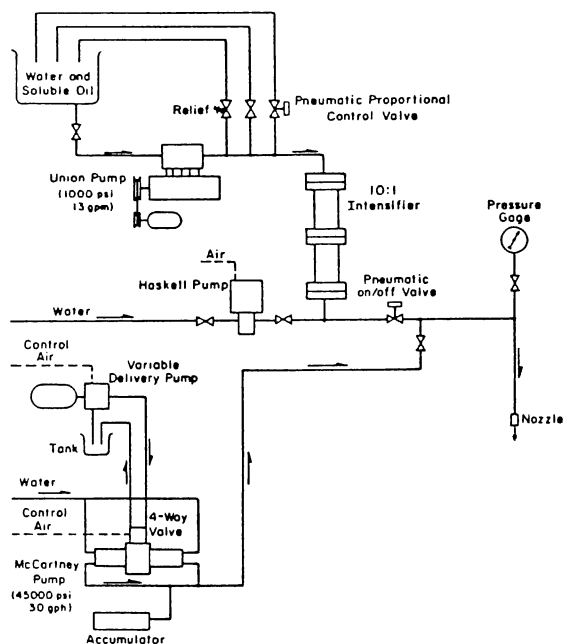
$$q \propto d^2 p^{1/2}$$

$$P \propto d^2 p^{3/2}$$

To develop very high velocity and pressure, the power demands are high and nozzle diameter cannot be very large. The power per unit area in a water jet is very high— $2.6 \times 10^4 \text{ MW/m}^2$ for a pressure of 69 MPa (10^4 lbf/in.^2) and $8.1 \times 10^5 \text{ MW/m}^2$ for a pressure of 690 MPa (10^5 lbf/in.^2).



Continuous water jets with nozzle pressure from 69 to 690 MPa have been tested in ice and frozen soils. Penetration of frozen material by a stationary jet is limited by the coherent length of the jet, which itself is limited because it is normally submerged in air. High pressure jets firing in air from small nozzles have dynamic (effective) lengths of about 2500 to 4000 nozzle diameters. In our tests, total penetration in ice was about 2000 nozzle diameters.

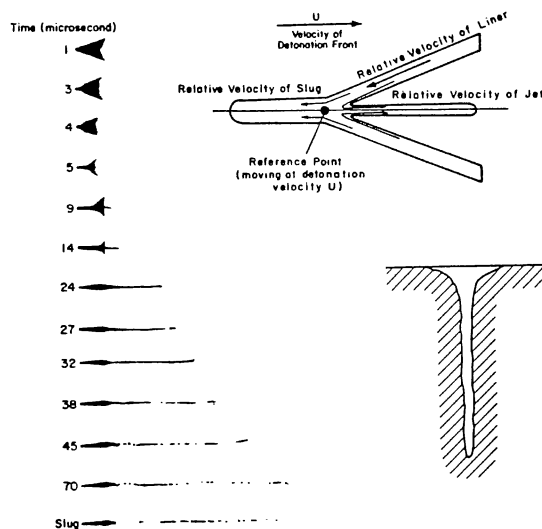
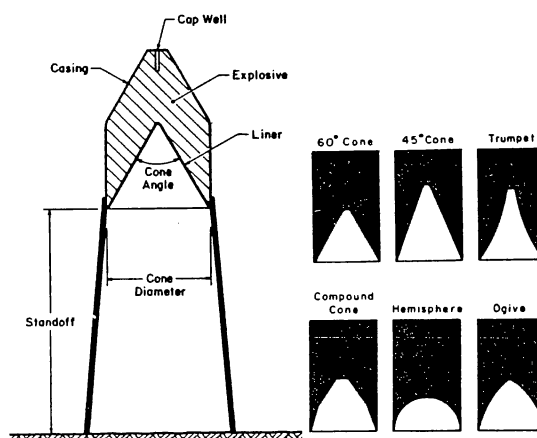


Jet-cutting is optimized by traversing the jet to produce a slot. Optimization relations that relate penetration to pressure, diameter and traverse speed have been developed for ice and frozen soil. Even under the best of circumstances, the specific energy for jet-cutting in ice is comparable to the latent heat (specific energy for melting), i.e. the energetic efficiency is very low.

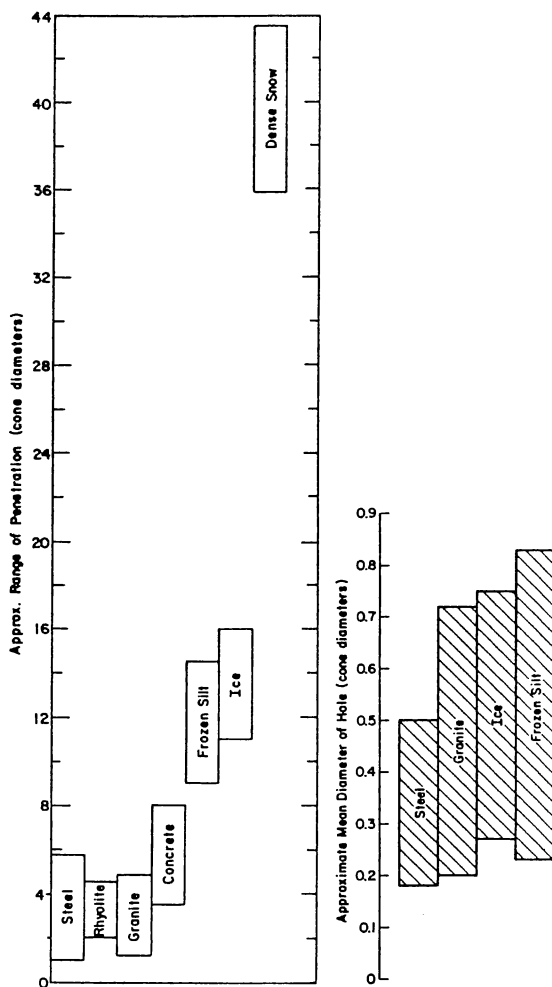
EXPLOSIVE JETS (SHAPED CHARGES)

A hole can be drilled by the explosive jet which forms when a detonation wave propagates axially along a cylindrical charge that has a cavity in one end. The shaped charge (hollow charge, cavity charge) forms a plasma jet whose velocity is comparable to the detonation velocity of the explosive. A liner of metal or glass inside the cavity introduces a stream of high-density particles into the jet.

The jet penetrates the target material like a projec-



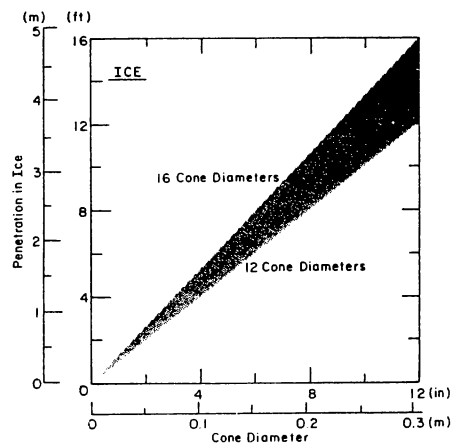
Small Shaped Charge, 45° Cone Angle, 19 mm Dia.



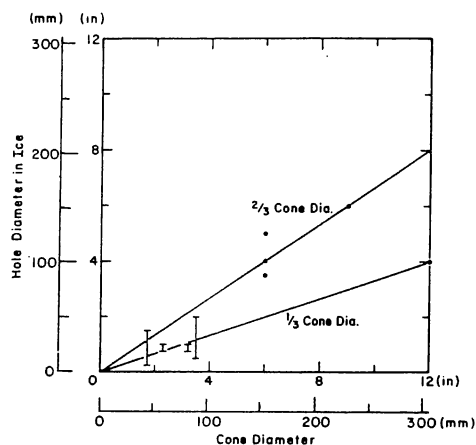
tile, expelling debris in an annular counterflow. The resulting hole is deep and narrow, with a broad shallow crater at the surface. Linear dimensions of the hole are proportional to the charge diameter. For a given type of charge, the penetration depth is, to a rough first approximation, inversely proportional to the square root of target density.

In strong target material, penetration holes become deeper and narrower as the density of the charge liner increases. There is also an optimum thickness for the liner, about 2% to 7% of the cone diameter, depending on the liner density. There is also an optimum charge standoff, needed to permit formation of the jet before it enters the target.

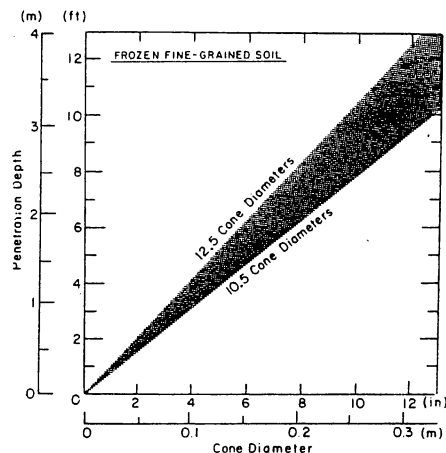
The cone angle, which can range from about 20° to 90°, affects the penetration depth and the hole diameter. General-purpose shaped charges typically have a cone angle of about 60°. Penetration of relatively weak ground material is not highly sensitive to cone angle.



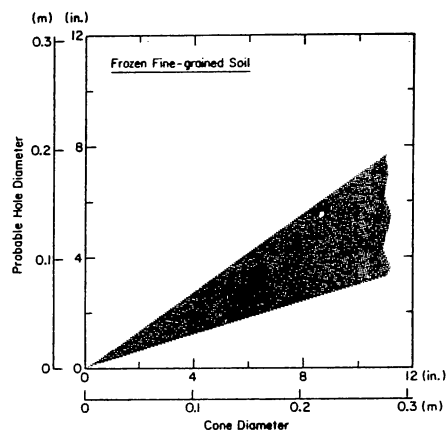
Well-optimized shaped charges firing into semi-infinite ice penetrate from 12 to 16 cone diameters. The hole diameter at mid-depth ranges from one-third to two-thirds the cone diameter.



In ice-bonded soils such as frozen silt, the penetration is a bit less than in ice.

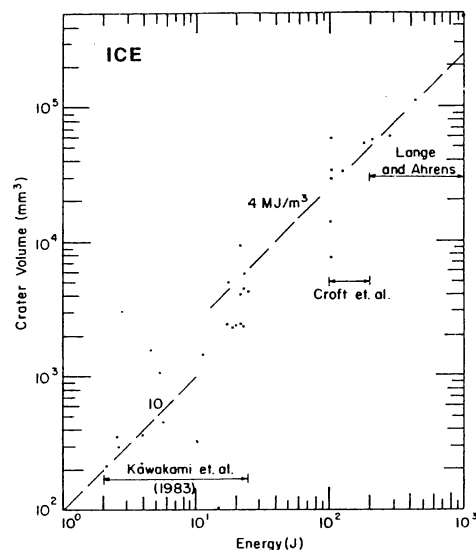
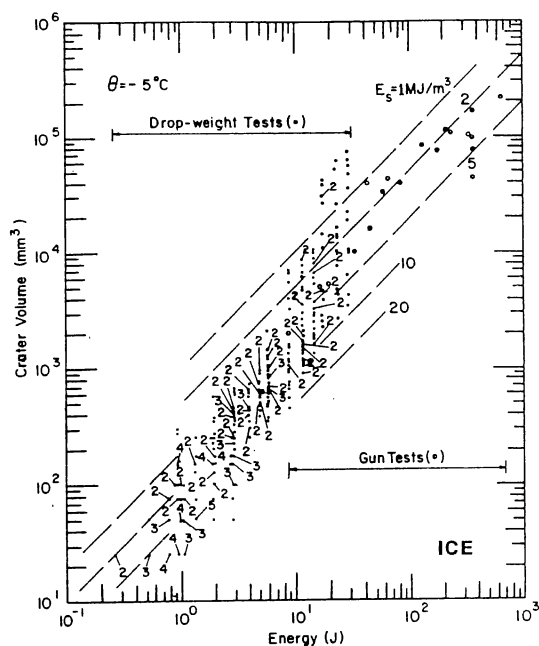


When fired in air, a shaped charge produces air blast. In water, it propagates a shock and creates a gas bubble. In vacuum, it can be expected to produce an expanding shell of high-velocity particles.

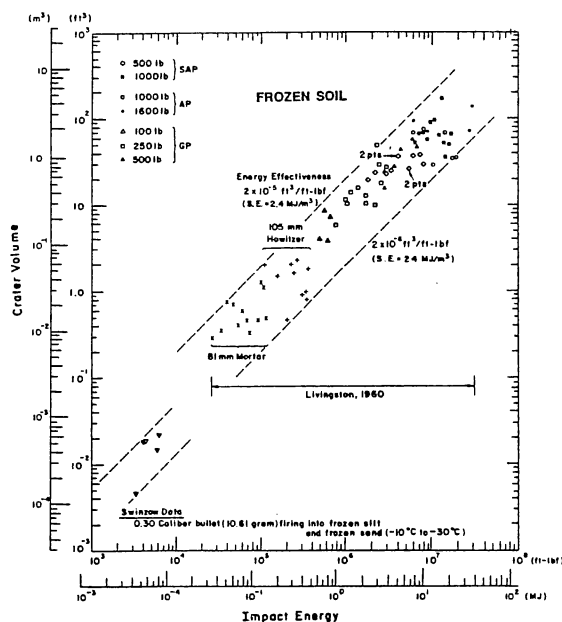


EROSION BY A PARTICLE STREAM

In principle, a hole can be bored by firing a stream of high-velocity solid particles, such as coarse sand or steel shot. Excavation experiments were made in frozen soil, using pea-gravel projectiles propelled by an air eductor. The idea of driving a tunnel by firing concrete shells from an artillery piece was taken seriously and given significant government funding. The snag is that the ratio of excavated mass to projected mass is unfavorably small unless the impact velocity is very high (as it can be in the absence of atmosphere).



The specific energy for cratering, E_s , is the ratio of impact energy to crater volume. For projectiles cratering relatively warm ice surfaces, measured values of E_s are in the range 1 to 20 MJ/m^3 . For projectiles hitting frozen soils, measured values of E_s are in the range 2.4 to 24 MJ/m^3 .



CHEMICAL PENETRATION

Chemical penetration can be thought of as any drilling process which depends on a chemical reaction at the advancing face of the drill hole. There are two obvious processes: (a) direct interaction between ice and a melting-point depressant, (b) an exothermic reaction at the base of the drill hole.

Soluble salts and fluids such as ethylene glycol and methyl alcohol are melting-point depressants that can be used to melt ice. However, no practical system has been developed so far. The active chemical has to be kept at an appropriate concentration at the ice surface and meltwater has to be removed; both meltwater yield and reaction rate decrease significantly with decreasing temperature, dropping to zero at the eutectic temperature. At about -6°C , sodium chloride can melt up to nine times its own mass, but if the required reaction time is not to exceed 15 minutes the meltwater yield reduces to about 1.5 times the mass of salt.

Exothermic reactions can be induced in an open system, by dumping into the hole something that reacts with the ice (e.g. sodium hydroxide), or they can be induced in a closed container that then becomes a "hotpoint", as discussed earlier under the heading of Thermal Drilling. It is not easy to see how a practical open system can be achieved.

As regards closed systems, the idea of drilling with thermite is exhumed with irritating frequency. Thermite is 73% black iron oxide (Fe_3O_4) and 27% granular aluminum, sometimes with a burn accelerator such as barium sulphate added. The heat of reaction is modest ($\approx 3.3 \text{ kJ/g}$) but the reaction temperature is high (2200°C). In ice, it fizzles, crackles, pops and steams in a satisfying way, without achieving much in the way of penetration.

DESIGN OF EXTRATERRESTRIAL DRILLING SYSTEMS

The first step in designing for an extraterrestrial drilling project is to draw up performance specifications in basic terms, i.e. without implicit prejudgment about techniques and equipment. In other words, give the science requirements (such as implantation of passive sensors, in situ testing by active devices, or extraction of samples). Depths and dimensions should be given, together with predicted ground properties and indications of the uncertainty about these properties. The performance specifications should be accompanied by a list of technical constraints, such as limits to size, reactive mass, total available energy, maximum power, environmental contamination concerns, and other relevant factors.

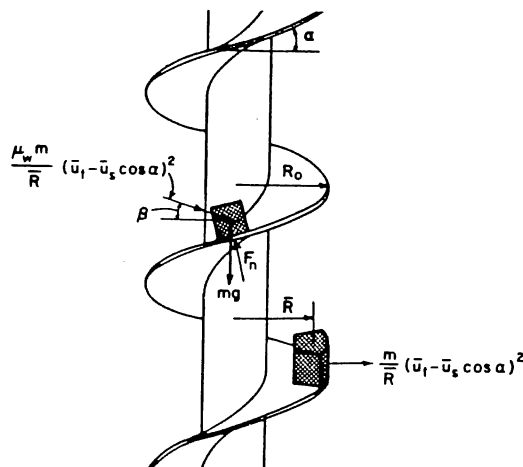
With the problem defined, it should be examined from first principles. This examination should be based on common sense, a knowledge of basic physics and some acquaintance with the *broad* aspects of relevant technology. The problem should not be passed immediately to a person, or group, with great expertise in a very narrow area of drilling technology.

A major difficulty is lack of knowledge about the composition of the target material and its physical state. This could mean that the drilling system has to be one that is effective in different types of material,

not in just one closely-defined type. However, there are limits; it is unlikely that a single device can drill all conceivable materials.

The working environment is likely to be very different from that on Earth. With little or no gravity, there is no significant weight to provide static reaction to thrust and torque. With no atmosphere, conventional compressed air systems are not useful, and air-breathing power sources are ruled out. On the other hand, there may be some advantages. With no gravity body-forces the hole is not prone to collapse and with no gravitational resistance it is easier to convey cuttings from a vertical hole. With no atmosphere, free projectiles can be accelerated to higher velocities and hot wires are less likely to burn-up.

Systems that require static reactions to forces are not necessarily ruled out, but it seems likely that some kind of anchoring would be required, necessitating pre-drilling by some other principle (e.g. inertial or thermal). If rotary drilling were to be used, it would be important to maximize energy efficiency, to minimize thrust and torque requirements, and probably to minimize the power level (i.e. the drilling rate). Electric drive would probably be attractive. Continuous-flight auger would be a simple way to clear cuttings, but might be somewhat different from an auger that is designed for work under gravity.



Inertial systems are clearly of interest. Percussive driving might be a possibility, but it is not easy to see how chips and dust would be cleared in more conventional percussive drilling. Projectiles driven by chemical propellents should certainly be capable of penetration; whether projectile penetration serves a useful purpose is another question. High-velocity fluid jets are not likely to be appropriate, but explosive shaped charges would certainly work.

If there is high probability that the target material is ice, or has a high ice content, than thermal drilling might be a possibility. The choice of one thermal system over another would depend on the target ma-

terial and the purpose of the drilling. An open-system liquid jet is unappealing and a flame jet would have to be designed very carefully to get the best from such a high-potential system. Electrothermal melters might have trouble in dirty ice or ice-bonded soil.

Once the general approach has been selected it should be relatively easy to find applicable technical data and experienced specialists capable of the necessary detail-design. Test facilities for drilling experiments are available, both in natural settings and in controlled environments.