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Equipment for making access holes through arctic sea ice

Malcolm Mellor

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Navy Underwater Construction Teams require a capability for making access holes through arctic sea ice. Required hole diameters range from less than 4 in. (100 mm) to more than 10 ft (3 m) in ice up to 15 ft (4.6 m) thick. Small diameter holes are to be completed in less than 4 hr and large diameter holes in less than 8 hr. The report first gives brief descriptions of the working environment, site access considerations, and probable operational procedure. Principles and techniques for penetrating sea ice are summarized, with an initial list of 14 topics. Twelve of these items are identified as potentially relevant, and are discussed more fully. They include: 1) projectile penetration, 2) shaped charge penetration, 3) high pressure water jets, 4) blasting, 5) flame jets, 6) electrothermal devices, 7) hydrothermal devices, 8) rotary drilling, 9) percussive and vibratory penetration, 10) mechanical cutting, 11) chemical penetration, 12) exotic concepts. The final selection, which takes into account practical concerns and field experience, recommends the following things as basic tools: a) small diameter auger drills (less than 4 in. diam), b) large diameter auger drills (≈9 in. diam), c) chain saws, d) a hot water system for drilling and cutting. The discussion of associated equipment covers electric generators, hoists and lifting

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tackle, hand tools, and blasting supplies. Consideration is also given to single-fuel operation, bulk melting, and possibilities for use of compressed air. Recommendations for development work by NCEL are given.

PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Physical Scientist, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was done for the Naval Civil Engineering Laboratory, Port Hueneme, California, under reimbursable order number N68305 86WR60128.

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MALCOLM MELLOR

Introduction

Until recent years, most of the human activity on arctic sea ice was research work by small scientific parties. Some of the work was done from small camps set up for brief periods. Other work was based at small stations that were maintained over periods of years on thick ice floes or on small tabular icebergs known as ice islands. Over the past decade, the pace of activity increased, largely as a result of oil and gas exploration in the waters around Alaska, Canada, and Greenland. Since the earliest days of scientific research on the arctic sea ice, investigators from the U.S.S.R. have been very active.

The U.S. Navy has now renewed its research activity in the arctic, and it is expected that there will be a continuing Navy demand for the drilling and cutting of access holes to permit entry and recovery of instruments, equipment and divers. The Navy Civil Engineering Laboratory (NCEL) is preparing to meet these demands by developing techniques and equipment that can be used routinely by small groups, particularly Underwater Construction Teams (UCTs). As a first step, CRREL has reviewed the relevant technology and, on the basis of research findings and practical field experience, made preliminary recommendations for the selection of equipment. After a final selection of equipment types is made, NCEL will develop, standardize and procure equipment for the Navy field teams.

Task description

This report responds to the following task description, which was issued by the U.S. Navy Civil Engineering Laboratory:

Arctic throughice access holes. Conduct a study of the state-of-the-art techniques for making access holes through first-year and multi-year Arctic sea ice. The study shall include methods for penetrating the ice, clearing debris, and maintaining the access holes in an open condition. It is particularly important in gaining access through the ice to ensure that the surrounding ice remains competent for support of operating equipment and personnel. The study shall address gaining access in first-year or multi-year ice up to 15 ft thick for holes in the following ranges of sizes:

- small (less than 4 in. dia.) access holes for instrumentation
- holes to 4 ft diameter for equipment and divers
- holes from 4 to 10 ft diameter
- holes larger than 10 ft

It is necessary that tools and equipment for through ice access be compatible with the skill levels of Navy enlisted personnel with training and skills in the Construction and Blasting ratings. Through ice access is required in remote areas where there is no heavy moving or lifting equipment and there are only limited means of transporting the equipment to the access site. As a goal, it is desirable to provide full through ice access for holes to 4 ft in diameter in less than 4 hours, and for larger holes in less than 8 hours. The result of this study is a report that discusses currently available techniques including at least:

- a description of operation
- equipment needed (sizes and weights)
- engineering parameters involved
- limitations (environmental, hazards, etc.)

The report shall include recommendations for developments that can provide a significantly improved capability over SOA techniques.

Environment and site access

Arctic sea ice varies in character from place to place, and it varies throughout the course of the year (Welsh et al. 1986). For present purposes, the main concern is with ice thickness, surface topography, and general strength and stability.

During the mid-winter period, when arctic ice is thick, strong and relatively stable, certain characteristic zones can be identified at different distances out from the coast.

Close to shore is the *land-fast ice*. This ice, formed over nearshore waters, is usually first-year ice that remains firmly anchored to the coast by capes, headlands, islands and suchlike. The ice surface is smooth and level over large areas, the ice thickness reaches about 1.8 m (6 ft) off northern Alaska, and the water under the ice is likely to be fairly shallow. The salinity of first-year ice is about 4‰, compared with the 35‰ salinity of sea water.

By contrast, the ice far offshore is *pack ice*, which breaks repeatedly into separate slabs (ice floes) and drifts with the ocean currents. This ice sometimes opens up to reveal open water between the floes (when the drift field is diverging). At other times, when the drift field is converging, the pack ice consolidates, with floes overriding each other (rafting) or crushing together into ridges of massive ice rubble (pressure ridges). The more massive ice accumulations, which are frequently more than 10 m (33 ft) thick, can survive the summer melt period to become multi-year floes or multi-year ridges. This multi-year ice has very low salinity, since the salt leaches out during summer by a process of preferential melting and gravity drainage of the brine.

Between the land-fast ice and the moving pack ice are *transition zones* where the ice breaks up from time to time and where there is slow, and often intermittent, movement. The most dramatic transition zone is the *shear zone*, where there is an abrupt transition from almost stationary ice to rapidly moving ice. Huge *shear ridges* of ice rubble can form at boundaries of this kind.

At the boundary between pack ice and the open ocean is the *marginal ice zone*, where waves and swells have a significant effect on the motion, concentration and condition of the ice.

The amount of ice cover, the thickness of the ice, and the general strength of the ice all vary seasonally. In spring and early summer the ice close to shore thaws, rots, melts, breaks up, and finally disperses to leave open water. In the pack ice zones during summer the extent of ice cover shrinks, gaps between the ice floes can open up, surface melting occurs, and the ice becomes soft and weak. Formation of new ice begins near shore and in sheltered water in early autumn, and there is then progressive ice growth until the end of winter.

Drilling sites can be located in any of these ice zones, and operations could be required at any time of year. On the land-fast ice, access to sites is relatively easy in winter and spring; surface vehicles, helicopters and fixed-wing aircraft can all be used, provided that snow cover, lack of daylight, and low temperature are not overwhelming problems. In the zones where the ice surface is broken and hummocked, where there are ice ridges, or where open-water leads occur, it is usually impractical to plan on using either surface vehicles or fixed-wing aircraft. For rapid and reliable access to unprepared sites, helicopters are necessary. In summer and early winter, when the ice can be weak and the ice surface wet, helicopters are much safer than surface vehicles or fixed-wing aircraft.

In summary, the arctic sea ice is not a permanent and limitless plain of smooth, level ice a few metres thick. Much of the sea ice has a rough surface, with hummocks, ridges and snowdrifts, and over large areas the thick ice floes are separated by open water or thinly frozen channels. Ice thickness often exceeds 10 m (33 ft). Most of the ice is weak, unstable, or moving at some time of the year. For rapid and unrestricted access to drilling sites, only helicopters are reliable for year-round operation. Personnel and equipment requirements should therefore be compatible with helicopter transport. In other words, the working party should be small and the equipment should be light and compact, with low fuel demands.

Description of operation

It is assumed that a UCT group deployed to provide access holes will comprise a minimum of three people who are strong and healthy (a minimum detachment is understood to be five men). Additional workers are likely to be available at some sites (UCT personnel, scientists/engineers, and so forth). It is also assumed that the group and its supplies will be either transported to the site by helicopter (212, 205, 204 size), or deployed from a ship or shore station by surface vehicle (tracked vehicle, ACV, etc.). The time required on site could range from less than one hour to more than one day. In the latter case, living facilities, radio, and a locator beacon would probably be required. For short stays (up to 12 hours), the helicopter or other vehicle would probably remain on site. In all cases, survival gear would be carried, all personnel would have undergone survival training, and weather forecasts would be monitored.

The team that provides access holes may sometimes operate as an isolated group. In other circumstances, scientists, engineers or other users of the holes would have to be on hand as soon as each hole is finished.

On arrival, the team would offload essential items, start up the primary power source (e.g. gasoline or diesel generator), and assemble the tools required for the job (e.g. auger drill or melting frame). On a simple drilling job, two men can go to work immediately while a third organizes the equipment. On a more complicated job, e.g. one that requires a hoist and lifting frame, the team would organize the site in accordance with established training procedures.

On completion of a hole, it is desirable for the users to take it over and use it immediately, before there is any chance for refreezing or influx of frazil or fragments from beneath the ice cover. If the hole has to be maintained for an extended period, it may be necessary to erect a shelter, to place surface insulation, or to heat the water in the hole.

The CB team will probably remain on site until the users have finished with the holes. However, if the users set up camp and have a capability for maintaining the hole (or holes), the CB team can move out, subject to availability of transport.

Techniques for penetrating sea ice

A wide range of physical and chemical principles can be applied to ice penetration, but some are impractical in the present context. The following is a checklist of potentially relevant principles, with brief comments.

Flexural breakage by normal force. This involves high force applied relatively slowly to produce dartboard flexural cracks over a wide area. It is completely unsuited to present needs.

Punching by a blunt penetrator. This is brought about by rapid thrust or impact of a blunt punch that has a diameter comparable to the ice thickness. The punching effect could not be produced in thick ice by any equipment suited to this project.

Piercing by a solid projectile. This involves deep penetration by a kinetic energy projectile whose diameter is small relative to the ice thickness. The penetrator could be similar to an inert bomb or a bullet.

Piercing by an explosive jet. A shaped charge, or lined cavity charge, can drive a hole through ice.

Piercing by a very high pressure water jet. Ice can be pierced by high pressure water jets, which are usually considered to be jets with nozzle pressure greater than about 10,000 lbf/in.^{2} (> 70 MPa).

Blasting with explosives or compressed gas devices. Holes in sea ice can be produced by explosions under the ice, within the ice, or on top of the ice.

Piercing by flame jets. Holes can be made through ice by flame jets of various kinds.

Drilling and cutting with electrothermal devices. Ice can be melted by various types of electrical heating elements.

Drilling and cutting with hydrothermal devices. Holes and slots can be produced by hot water jets that operate at low nozzle pressures.

Rotary drilling. Rotary drilling is a well established method for penetrating sea ice.

Percussive and vibratory drilling and driving. Ice can be penetrated by conventional percussive and vibratory drilling, or by "pile-driving" a rod.

Mechanical cutting and excavation. A variety of mechanical cutting devices, such as chain saws, disc saws, drum millers, cutterheads, routers, and suchlike can be used to cut slots or pits in ice.

Chemical penetration. Holes can be melted in ice by chemicals that produce exothermic reactions or depress the freezing point of water.

Breaking or melting by exotic concepts. Ice can be melted or broken by a variety of novel principles or devices. These include lasers (pulsed, focused), capacitor discharge (in ice or water), and microwave absorption (dissipation of energy inside the ice). None of the known exotic concepts offer any advantages for present purposes.

Briefly reviewing this list, the first two items, flexure and punching, are dismissed as being completely unsuitable for present purposes. All of the remaining items are discussed in the following notes.

Potentially relevant technology

The previous section gives a list of basic concepts that can be applied to ice penetration. Two of the items in that list were dismissed immediately as unsuitable for present purposes. The remaining items are discussed more fully below, and their relative merits are given.

Projectile penetration

Ice can be penetrated or pierced by a solid projectile that has high kinetic energy, especially energy resulting from high impact velocity. The projectile forms an entry crater at the ice surface, then "drills," or "tunnels," a narrow hole, and finally forms an exit crater at the lower surface. The projectile has to penetrate the ice surface near normal incidence; if it does not, it can deflect or turn back towards the entry surface. Projectiles that are optimized for stable flight in air are likely to be unstable in the ice, with a tendency to "tumble."

Bullets usually penetrate only a few inches (say up to 100 mm) in ice. Repetitive impact, say by an automatic weapon, would probably penetrate the ice eventually. "Point blank" projectile devices, such as stud guns or nailing machines, are not likely to exceed the penetration of rifle bullets. Specially designed projectiles (slender cones) dropped from high altitude can pierce most types of sea ice, provided the impact is near normal incidence (low air speed and high altitude at release, flat ice surface).

The minimum energy per unit contact area for penetration by "tunneling" seems to be about 0.3 MJ/m^2. The specific energy for the ballistic penetration process seems to be about 2.5 MJ/m^3 for blunt projectiles (Garcia et al. 1985), but it should be lower for optimized projectiles. This is roughly equivalent to the specific energy range for auger drills of moderate efficiency.

Projectile impact does not seem to offer any advantages for making access holes in sea ice. The basic process is moderately efficient in energetic terms, but it is hard to see how the principle could be adopted for simple and reliable drilling and cutting tools.

Shaped charge penetration (explosive jets)

A conventional shaped charge (Fig. 1) can blow a deep, narrow hole into any hard material, including ice. A linear shaped charge (Fig. 2) can blast a deep, narrow slot in hard target material. For routine work, shaped charges are a poor substitute for drills and mechanical cutters, but in certain circumstances they can be very useful.

The existence and general behavior of shaped charges is widely known, but even among engineers there is a lack of knowledge about the design and performance of shaped charges. CRREL has recently published a comprehensive technical review that provides relevant background information, with penetration data for a range of target materials, including ice (Mellor 1986a). This document explains how performance varies with charge size, standoff, cone angle, liner material, liner thickness, and explosive type. A very recent report (Mellor 1986c) gives new test data for ice penetration. Test data indicate that suitably designed shaped charges can penetrate to a depth of 16 to 19 cone diameters in semi-infinite ice, and it is probable that ice slabs up to 20 cone diameters thick can be penetrated. Thus a 9-in.-diameter charge could pierce an ice slab that is 15 ft thick.

One problem with standard military charges is that they are troublesome to acquire, store and transport. They are also expensive. In the civil sector, large shaped charges are not readily available from ordinary commercial sources. To provide inexpensive shaped charges that are easy to transport and store, CRREL is developing binary shaped charges. These are non-explosive until armed with a liquid ingredient shortly before use. They can be shipped by truck freight or parcel service, and do not require storage in an explosives magazine. Details are given elsewhere (Mellor 1986a).

Shaped charges set in water beneath the ice tend to localize the fracture while still providing a cratering action for the gas bubble. However, charge placement calls for special tools and techniques.

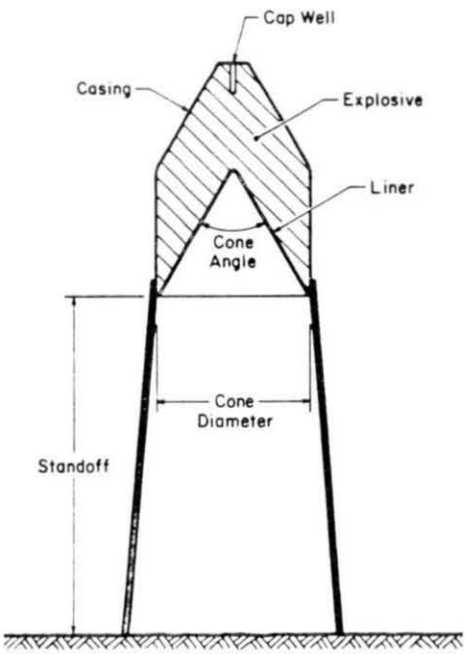


Figure 1. Basic features of a typical rotationally symmetrical shaped charge.

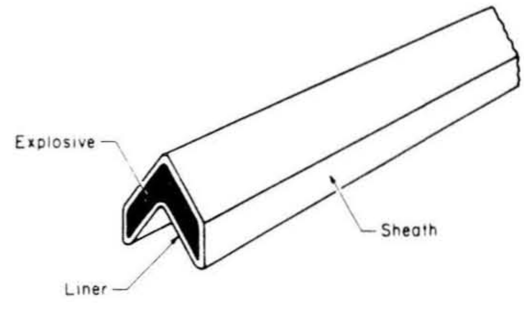


Figure 2. Linear shaped charge.

The disadvantages of shaped charges are the usual safety concerns that apply to all explosives and blasting operations. The main advantages are simplicity, speed and reliability. Shaped charges do not appear to be candidates for use as primary drilling tools, but they may well be useful in special circumstances.

High pressure water jets

High pressure water jets, with nozzle pressures in the range 10,000 to 100,000 lbf/in.^{2}, have been used with limited success to cut and penetrate a variety of materials, including hard rocks.* Tests were made on ice, and design parameters for various types of cutting systems were established (Mellor 1974). An experimental field unit for cutting ice from lock walls was also built (Calkins and Mellor 1976).

The energy efficiency of high pressure water jets is very low when cutting ice—almost the same as the energy required for melting. The equipment required to produce the jets is complicated, bulky, and expensive (Fig. 3). Water jets that rely on high pressure alone are not considered suitable for present purposes. Performance improves when the discharge water is heated, but for present purposes

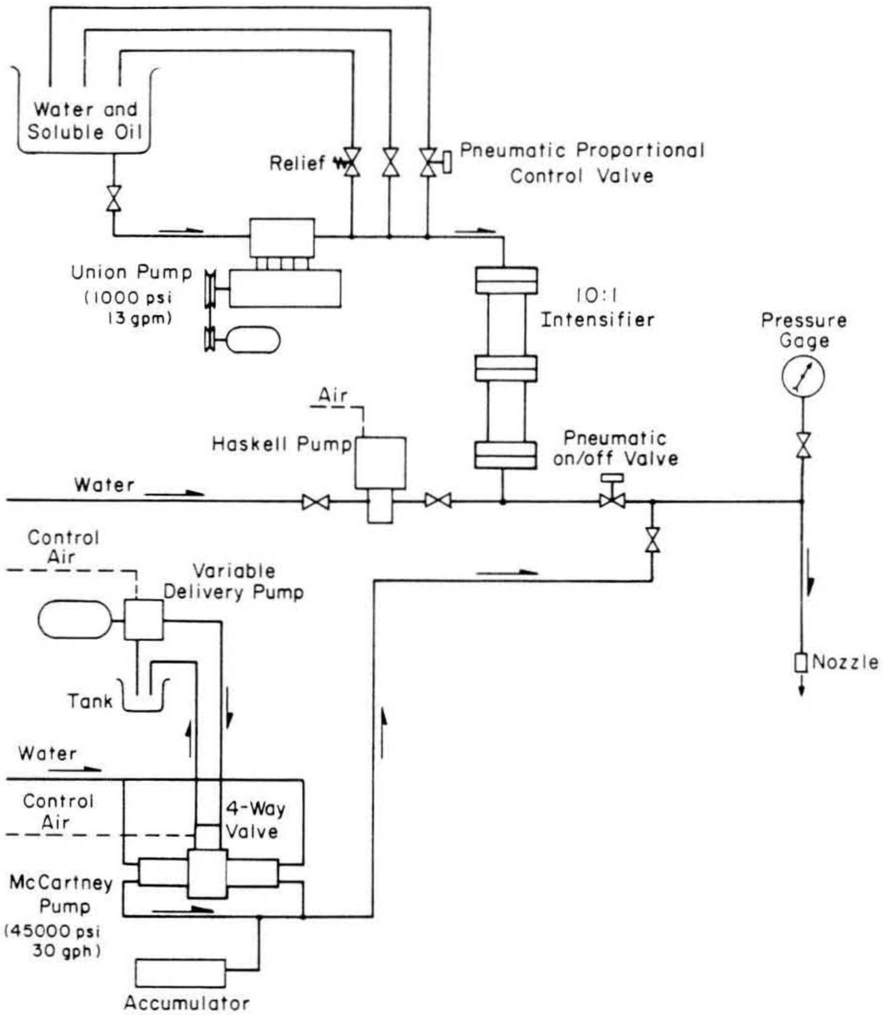


Figure 3. Example of equipment for high pressure water jet cutting.

* Since 1972, an International Symposium on Jet Cutting Technology has been held every two years, and proceedings for each meeting have been published by the British Hydromechanics Research Association (BHRA).

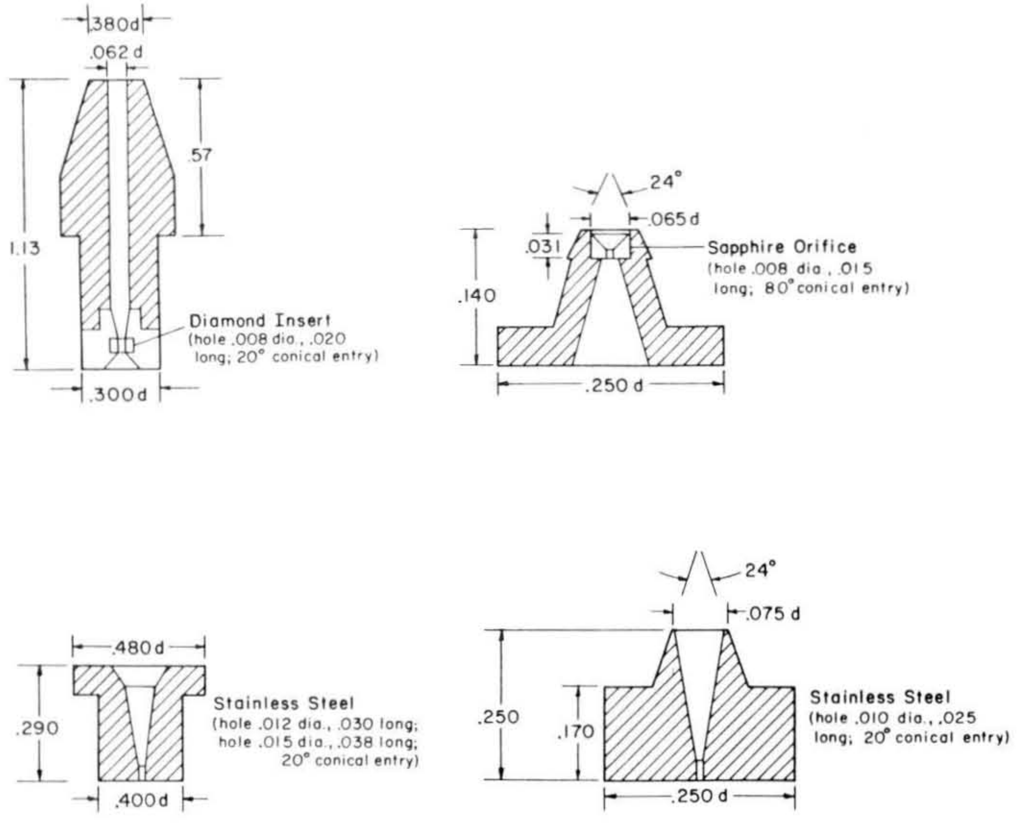
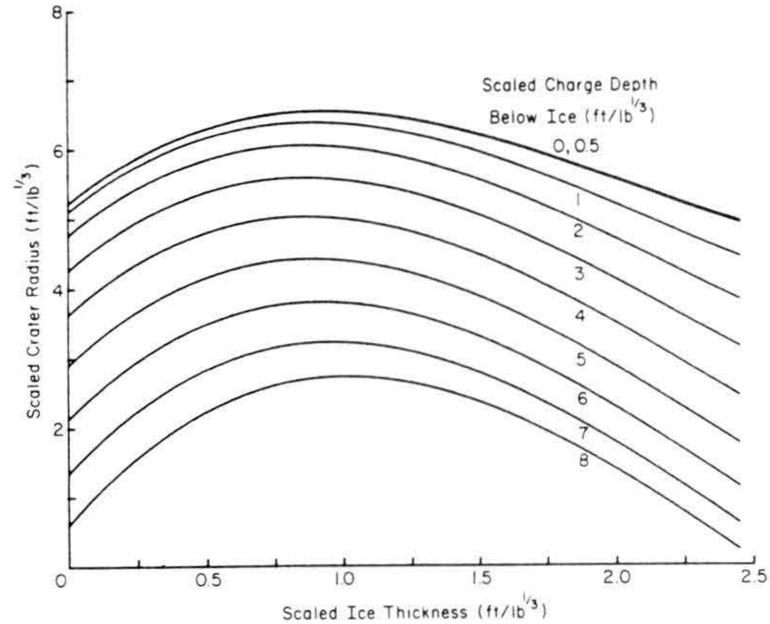
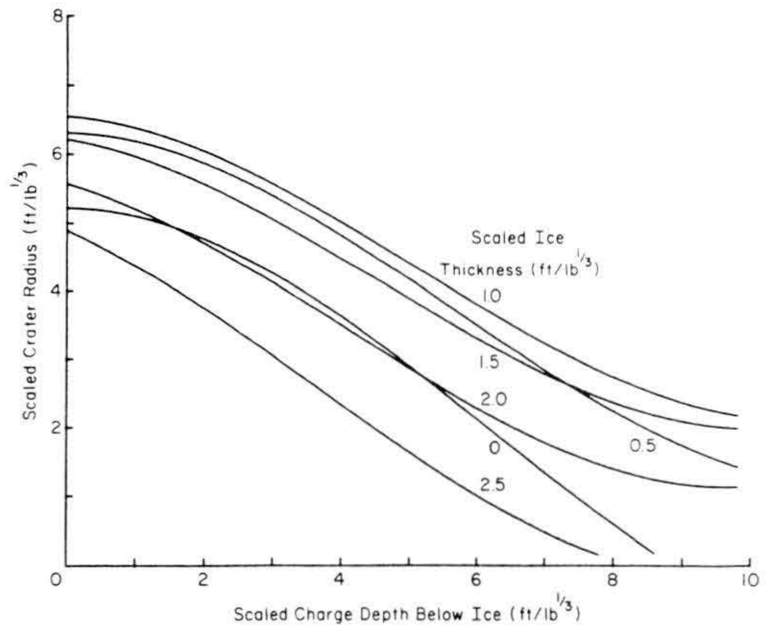


Figure 4. Examples of nozzles for high pressure water jet cutting.

Figure 5. High pressure water jet used for cutting ice from lock walls.



a. Scaled crater radius as a function of scaled ice thickness, with scaled charge depth as parameter.



b. Scaled crater radius as a function of scaled charge depth, with scaled ice thickness as parameter.

Figure 6. Design curves for ice blasting.

a combination of high pressure and high temperature will be considered as hydrothermal drilling, which is discussed separately.

Blasting

To blast a hole through sea ice, a charge can be placed on top of the ice, in the water, or within the ice sheet (Mellor 1982, 1986b). A conventional charge placed on the top surface of the ice is very inefficient, and it is not worth considering for routine use. A charge placed in the water under the ice maximizes the breakage for a given charge weight, and the greatest efficiency is achieved with a charge that is optimized for the prevailing ice thickness and set immediately below the base of the ice (Fig. 6). The snag here is that the hole will almost certainly be bigger than is necessary for an access hole, making the clearing of debris from the crater a major task. In broad terms, an optimum charge under the ice gives a crater diameter about 15 times the ice thickness. A single cratering charge placed inside the ice has to be designed and emplaced so that it breaks out to both upper and lower surfaces. If the crater diameter at the top and bottom surfaces is limited in order to facilitate the clearing of debris, there is likely to be an unacceptable constriction near mid-depth.

Compressed gas devices are an alternative to conventional explosives for ice blasting (Mellor 1984a), but the necessary equipment is bulky, heavy and expensive.

To break a narrow hole through thick ice, the best bet seems to be a delayed deck charge, with a clearing charge in the water well below the base of the ice (Fig. 7). A less efficient alternative is to set a well-coupled column charge in a drill hole, with a delayed clearing charge in the water below.

The standard safety considerations that apply to blasting operations are essential but inconvenient. Furthermore, explosives alone are not much use—a drill is required for charge emplacement. Under special circumstances, blasting is a useful expedient, especially if very large holes are required, or if diver access holes have to be produced rapidly. Ice blasting training should probably be provided for CB teams, and the use of binary explosives should be considered.

Flame jets

Flame jets, or cutting torches, typically burn liquid or gaseous hydrocarbon fuel at high rates by supplying a gaseous oxidant under pressure, typically compressed air or oxygen. Special nozzles facilitate rapid reaction, and the flame discharges at very high velocity. The flame temperature is high, and exhaust gas provides a powerful gas flow when the nozzle penetrates a solid material.

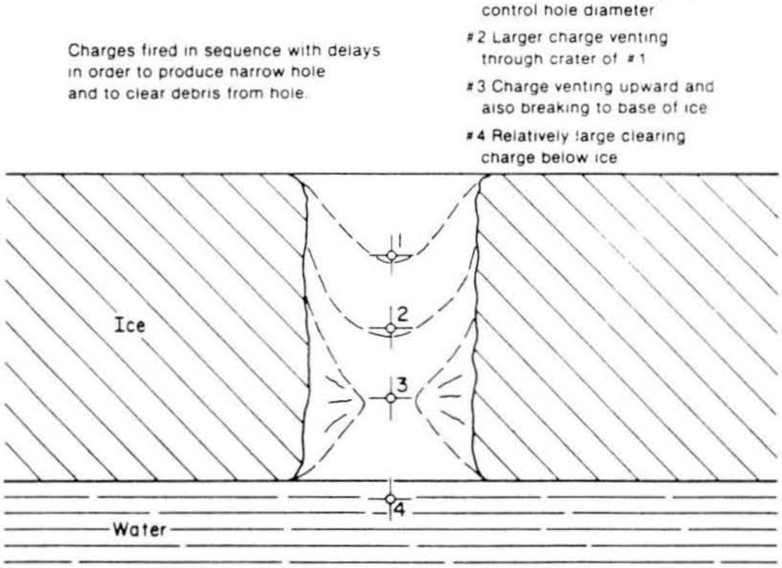


Figure 7. Use of delay deck charges to break a narrow shaft through very thick ice.

The torch, or lance, is compact and not extremely heavy, but the equipment that supplies the fuel and oxidant is often bulky and heavy. Flame jets penetrate ice by melting, which is inherently inefficient in energetic terms. Although the temperature of the torch may seem inappropriately high, the intense convection at the working surface ensures efficient heat transfer there. However, if the output of the torch is too high, there will be significant thermal losses in the exhaust gas. Furthermore, if the advance rate is too low, hole diameter becomes excessive and uphole gas velocity decreases.

Flame jets have been used to drill deep holes in ice, but existing commercial equipment seems unsuitable for making access holes in sea ice. The main drawbacks are weight, bulk and heavy fuel consumption. However, if flame jets seem appealing on general principles, simple experiments could be made with small-scale equipment in order to optimize the thermal output and efficiency. Use of cutting rods made from combustible metals might also be considered (tests are currently underway at CRREL).

Electrothermal drilling and cutting

Electrothermal systems, and some other devices, penetrate ice by bringing a hot solid surface into direct contact with the ice. In a typical device, an electrical resistance heating element is encapsulated inside a good thermal conductor, such as copper or aluminum. For a simple drill, the thermal device may be a conical tip. For a coring drill it is a heated annulus. For cutting devices it can be a heated strip, pipe, or cable. The general goal is to achieve maximum power dissipation per unit contact area, while protecting the electrical element from early burnout.

Practical experience so far indicates that the maximum power density for a long-life heater is about 3 MW/m^2. Higher power densities are not worth pursuing, as they only lead to film boiling at the ice interface, thus inhibiting more rapid penetration. The specific energy for penetration by melting is the latent heat of the ice plus the sensible heat required to raise the ice from ambient temperature to the melting point. The latent heat of sea ice varies with density and salinity, and ambient temperature varies with time, location, and depth. However, for present purposes the specific energy for melting sea ice, E_s, can be taken as 290 MJ/m^3 (assuming an ambient ice temperature of $-5\,°C$). Taking the maximum useful power density Q_m as 3 MW/m^2, the maximum attainable penetration rate U_m is, with 100% thermal efficiency,

$$U_m = Q_m/E_s = 3/290 \text{ m/s}$$

$$= 0.01 \text{ m/s} = 2 \text{ ft/min.}$$

It is easy to exceed this penetration rate by other simple methods, and electrothermal penetration is not considered especially attractive for present purposes. Should there be special considerations which make electrothermal drilling or cutting appealing, the required design calculations and equipment specifications are straightforward. No significant research is needed.

Hydrothermal drilling and cutting

A closed-circuit hydrothermal system, in which steam or hot water circulates continuously in a closed loop of pipe, is essentially the same as an electrothermal system. It has inherent rate limitations set by the film-boiling phenomenon. By contrast, an open-circuit system (Fig. 8 and 9), in which jets of steam or hot water scour the working surfaces, has the potential for considerably higher penetration rates. The relative merits of the two systems have to be decided on the basis of project requirements. However, it is comparatively easy to use a single hydrothermal system with either closed-loop or open-circuit melting units.

Small open-circuit hydrothermal drills (Fig. 10) can drive holes of 2- to 3-in. diameter at rates of 10 ft/min (3 m/min) or more using a single nozzle. Penetration rate increases with the temperature and flow rate of the fluid, and to some extent with nozzle pressure (i.e. with discharge velocity). With complete utilization of the thermal energy (discharge water cooled to the freezing point), the specific energy of the process is the latent heat plus the sensible heat, i.e. $\approx$ 290 MJ/m^3).

To cut large openings in sea ice, both open-circuit and closed-circuit systems arrange the hot pipes to melt the perimeter of the hole, either as an annulus or a rectangular slot. Vertical risers are used for supply and return, and also to manipulate the cutting loop. With an open-loop system, penetration rate is limited mainly by the rate at which fuel can be burned and water can be heated.

Lightweight hydrothermal drills have long been used by glaciologists (e.g. Koci 1984, Morev et al. 1984, Taylor 1984), and in recent years hydrothermal systems have been developed by a number of groups for penetrating sea ice (Hansen 1986,

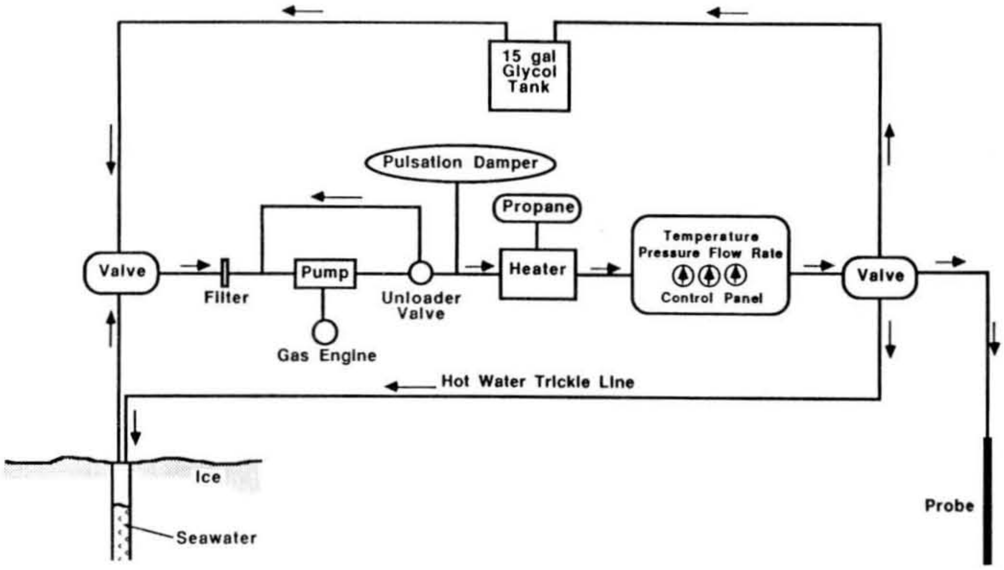


Figure 8. Example of equipment for hot-water drilling (Tucker et al., in press).

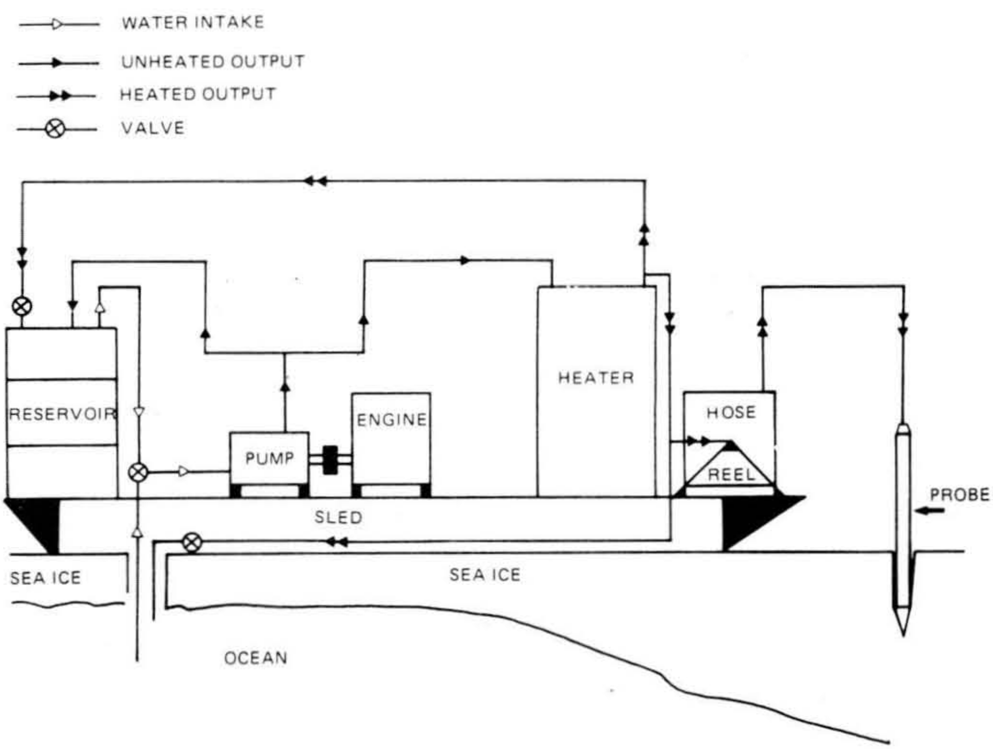


Figure 9. Example of equipment for hot-water drilling (Poplin et al., in press).

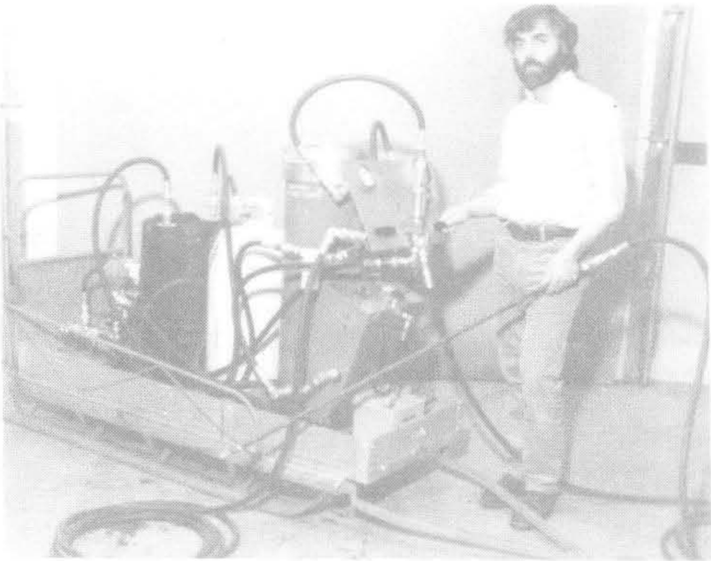


Figure 10. Hot-water drill packaged on a small toboggan for work at remote sites on arctic sea ice.

Poplin et al., in press, Tucker and Govoni, in press). Performance of these systems has met with general satisfaction, and they seem to be strong candidates for consideration by NCEL.

Rotary drilling

Drilling a hole involves three things: 1) penetration, 2) removal of cuttings, 3) support of the hole wall. For present purposes, (3) can be ignored, as the hole wall is self-supporting.

In rotary drilling, *penetration* can be obtained by using one of two types of drill bits: 1) drag bits (chisel or scraper type) or 2) roller bits (rotary indenters). Type (2) requires high downthrust and is probably unsuitable for present purposes.

Specially designed *drag bits* are very effective in ice, but inappropriate designs can be virtually useless. Each point on a drag bit penetrates along a helical path; these helical paths become progressively steeper as the center of the bit is approached, becoming almost vertical at the center. All cutters must be designed so that the relief angle is 5° to 10° steeper than its helical penetration path. This is practically impossible at the center of the bit, and special arrangements have to be made there. Possibilities are: 1) leave a space so that a small core forms and breaks periodically, 2) make a pilot bit that reduces the geometric scale of the problem. These arrangements having been made, the cutters should be made as sharp as possible, within the limits of necessary wear resistance. Cutters should be set on the bit so that the cutting action is balanced (no lateral vibration), and in such a way that cuttings flow freely away from the cutting edge. All these things have been investigated at CRREL, and documented in various reports (Mellor 1976, 1977, 1981, Mellor and Sellmann 1976, Rand and Mellor 1985). Test data are recorded in numerous unpublished technical notes that are held by the CRREL library.

Methods available for the *removal of cuttings* include: 1) continuous screw transport by a continuous-flight auger, 2) discontinuous removal by a short-scroll auger, 3) blow-out by air circulation, 4) wash-out by liquid circulation, 5) core extraction plus one of the foregoing methods for chip removal. For present purposes, method (1) is the simplest and probably the most suitable, although method (5) could find application.

CRREL has used drag-bit augers for shallow depth drilling in ice with diameters up to 24 in. (0.61 m). Coring augers have been developed to give cores up to 12 in. (0.3 m) and hole diameters up to 13.5 in. (0.34 m). For diameters up to 14 in. (0.36 m), the required torque can easily be provided by hand-held drive units when the bit is well designed, but the weight of flight and cuttings becomes too much for routine hand-held operation at diameters in excess of 9 in. (0.23 m) when drilling depth exceeds about 6 ft (1.8 m). When large diameter holes have to be drilled to depths exceeding 10 ft (3 m) or so, some kind of drill rig is needed. Small commercial drill rigs have been adapted for this purpose (Brockett and Lawson 1985, Rand and Mellor 1985). The rotation speed of an auger is important, as it affects the penetration, the torque, and the clearing of cuttings. Fast rotation is desirable for clearing the hole, but excessive speed reduces the cutting efficiency.

Specially designed drag-bit augers should certainly be included among the tools supplied to UCT personnel. Appendix A shows various ice augers and drive systems that have been used in the past.

Percussive and vibratory drilling and driving

Percussive drilling is a useful alternative to rotary drilling in situations where high thrust forces are needed but high static reaction cannot be provided. The percussive machine substitutes inertial forces for static forces.

The traditional percussive drill applies hammer blows to the top of the rod which enters the hole and carries the bit. The rod and the bit turn slightly between blows in order to attack a fresh part of the surface with each blow. Some modern percussive drills have independent rotation, permitting variation of rotation speed independently of blow frequency. There are limits to the penetration depth for traditional percussive systems because of flexural vibrations and losses in the drill steel, so for deep drilling there are downhole hammers, which mount directly behind the bit.

Pile drivers and impact breakers work in the same way as percussive drills, except that a rod or column is driven into the material without any attempt to remove the displaced material. The penetrating element is something like a captive projectile in the way it penetrates and displaces material.

Different percussive devices work in different frequency ranges. Low frequency "thunkers" have blow frequencies of the order of 1 Hz. Medium range machines have frequencies of the order of 10 Hz. High frequency vibrators have frequencies of order 100 Hz or more. The other significant variable is blow energy, i.e. the energy delivered in each hammer blow or each oscillation. The product of blow energy and frequency is the power of the machine. At the power levels that are readily attainable for existing machines, low frequency impactors have blow energies of order 10^4 ft-lbf (14 kJ) or more, mid-frequency units of order 10^3 ft-lbf (1.4 kJ), and high frequency devices of order 10^2 ft-lbf (0.14 kJ) or less. High blow energy usually implies larger diameter, keeping energy per unit bit area within certain limits.

In ice, penetration can be achieved with relatively low blow energy for a given diameter, and there is a tendency to over-crush the ice and to clog circulation ports on the bit. However, with adequate flushing a percussive system will operate in ice. High frequency vibratory devices tend to melt their way in by energy dissipation at the tip.

While percussive systems can certainly be adapted for use in ice, they are likely to be much more heavy, bulky and complicated than auger drills. For present purposes, percussive drilling seems unattractive.

Mechanical cutting and excavation

Various types of machines can be used to cut slots in ice, or to break and excavate large volumes of ice. For cutting slots, the most suitable machines are chain saws and disc saws. In principle, oscillating sabre saws could also be used, but we are not aware of any large sabre saws that could be adapted for cutting thick ice. Another possibility, at least in principle, is to use a vertical-axis milling tool, or a router.

Chain saws fall into a class of cutting and excavating machines that are known as continuous-belt machines (Garfield et al. 1976, Mellor 1976, 1978). The class includes machines that range from small chain saws up to large coal cutters, and ultimately up to big bucket-chain ditchers and dredges. For present purposes we are concerned with hand-held chain saws, carriage-mounted chain saws, and small tractor-mounted ladder trenchers.

In general, a continuous-belt machine has to perform three functions: 1) cutting and penetration of the work material, 2) removal of cuttings from the slot or trench, 3) support of the sides of the cut. Function number 3, which can be important in some soils and underwater sediments, is irrelevant in the present content.

All belt machines use tools of the drag-bit type for cutting. The cutting force on each tool can be resolved into two orthogonal components that are respectively parallel and normal to the cutting surface of the belt. The belt is usually driven in a direction such that the machine and the cutter bar tend to be pulled down into the work by the tangential cutter forces. The belt usually traverses through the work with its cutting surface either normal to the traverse direction or at a fairly steep angle to the traverse direction, and thrust is re-

Figure 11. Large woodcutting chain saw (deck saw) mounted on a small tractor for ice-cutting experiments.

quired to supply the normal component of cutter forces.

Cuttings are removed by the motion of the belt. In some cases, each cutting tool acts as a scraper to transport cuttings. In other cases, an array of cutting tools may be set on the lip of a bucket or a scraper bar that lifts out excavated material.

Commercial machines are normally designed to work in a particular type of material (e.g. wood, soil, weak rock, concrete), and they are optimized accordingly. To optimize a design, it is necessary to have an appropriate combination of speeds, forces, and power levels in the various machine elements, and to have suitable cutting tools. These things have been analyzed, and systematic design guidelines have been developed (Mellor 1976, 1978).

For work in ice, various commercial machines have been adapted, usually by modifying the cutting teeth on chain saws or small ditching chains (Garfield et al. 1976). CRREL has used modified hand chain saws for general ice cutting, and has also fitted a very small tractor with a logging industry deck saw, 14.3 ft long (Fig. 11). Another

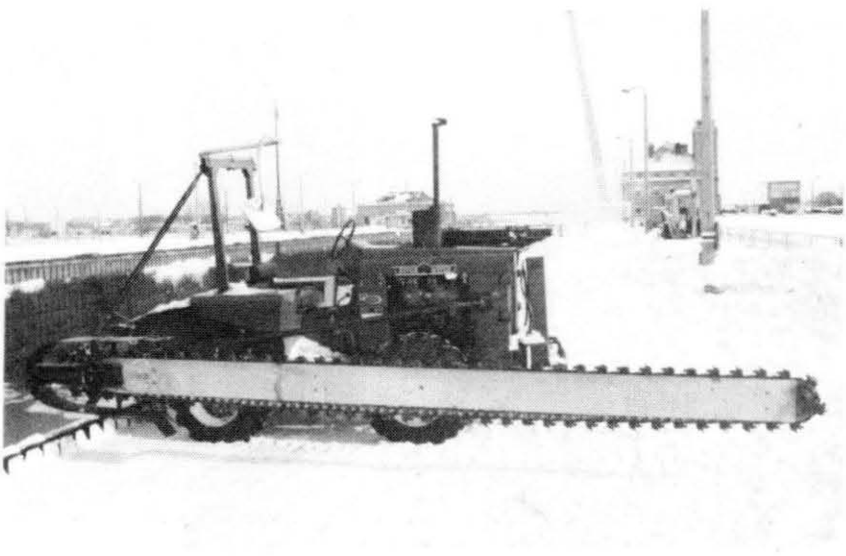


Figure 12. Large chain saw developed for cutting ice from lock walls.

Figure 13. Ice saw developed by NCEL.

small tractor was fitted with a narrow-kerf coal saw, 16 ft long (Fig. 12). A large coal saw was used for tunneling in ice in Greenland. NCEL made an efficient ice cutter by fitting the chain of a small soil trencher with very sharp conical bits (Fig 13). A similar machine had been used somewhat earlier by the University of Alaska for cutting ice.

In adapting a chain saw that has been designed to cut wood (Fig. 14), the main requirement is to change the spacing and geometry of the cutting teeth. Wood is shaved off by a chain saw, but thin shavings of ice tend to clog the chain. It is better to chip ice in relatively large fragments, and to have a capability for aggressive penetration. This can be achieved by increasing the tooth spacing, and by eliminating much of the flat top surface of a typical wood-cutting tooth. A "skip-tooth" chain (Fig. 15) can be ordered from a manufacturer of

Figure 14. Standard gasoline chain saw with 20-in. bar.

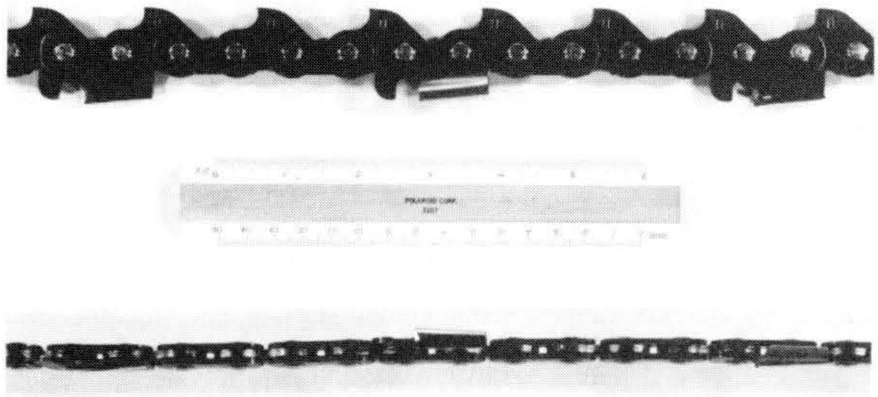


Figure 15. "Skip-tooth" chain for increasing the spacing between chain saw cutters. Note that the "flat" on top of each has been ground to reduce the cutter width.

cutting chains, or it can be improvised by grinding off some teeth from a standard chipper chain. Teeth must be eliminated in pairs so as to preserve the left/right cutting sequence in the remaining teeth. Part of the top surface of each remaining tooth can also be ground away. The bar should have good lubrication, and it is useful to have a splash guard to protect the engine (and the operator) from the water plume when the saw breaks through and turns into a pump. Alternatives to gasoline-engine drive include electric, hydraulic and pneumatic motors.

Disc saws and wheel excavators have certain advantages for cutting rocks, concrete and other hard materials, and their design and performance characteristics have been studied in detail at CRREL (Mellor 1975a, 1975b, 1977). Large disc saws have been tested and used on ice (Fig. 16, 17), but for present purposes they do not appear attractive, since typical machines have a maximum cutting depth that is less than the radius of the rotor. This means that a very large machine would be needed to penetrate arctic sea ice in one pass.

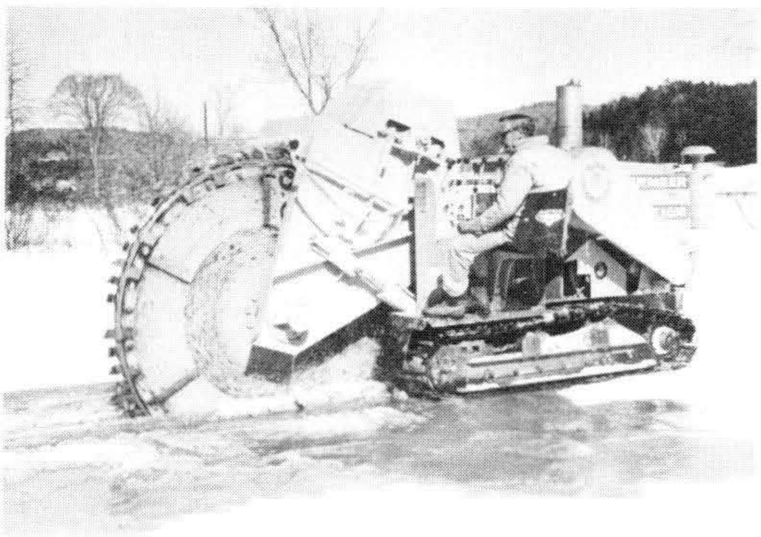


Figure 16. Vermeer disc saw cutting lake ice.

Figure 17. Ditch-Witch disc saw. These machines have been used for cutting ice near Prudhoe Bay.

Large *sabre saws* could be developed, following the same general design used for carpenters' and mechanics' hand tools. The idea would be to start the saw from a drill hole, traversing it with the blade held vertically. However, it seems likely that there would be difficulties in clearing cuttings.

Another possibility would be to develop a *vertical-axis milling machine*, or a *large router*. This would probably be a rotary drill with cutters along the drill stem. For example, it could be an auger with cutters on the edges of the flight. The scroll would transport cuttings, either up to the surface or down into the water. One problem would be to provide flexural rigidity and horizontal thrust while holding the diameter as small as possible.

Saws cut relatively narrow slots, leaving intervening blocks that have to be removed in a separate operation. As an alternative to this procedure, all of the ice to be excavated can be chopped up and removed continuously.

Machines for *continuous excavation* include a variety of milling drums which chop the ice into fragments for removal by a transport system. Horizontal-axis milling drums have been developed for planing ice surfaces and for tunneling in ice. In the mining and construction industries there are various types of continuous miners, roadheaders and tunnelers that can be adapted for large-scale jobs in ice. Dredge cutterheads for C-S dredges also have the capability to excavate ice. The transport systems used with these various machines may be mechanical, hydraulic, or pneumatic. For effective operation of excavating machines there is a minimum practical size, which is likely to be too big for present purposes. Put another way, the scale of the job is too small to justify the use of a machine designed for continuous excavation. The design principles of milling drums are dealt with in various CRREL reports (Mellor 1975a, 1977, Garfield and Mellor 1976).

Chemical penetration

Ice can be penetrated by using chemicals that either depress the melting point, or liberate heat for melting. *Depression of the melting point*, typically by soluble salts, is described by the phase diagram for water and the soluble chemical that is under consideration. Melting will not take place at ambient temperatures that are below the eutectic temperature, and the rate of melting varies with temperature as well as with concentration. Thus sodium chloride is not effective on very cold ice surfaces, and even calcium chloride has little effect when air temperatures are low, even if mechanical mixing is employed to maintain high concentration at the interface. *Exothermic reactions* produce more rapid results, either in direct contact with the ice or in closed containers. Fairly rapid reactions are necessary so as to avoid undue heat losses, but extremely rapid reactions (e.g. thermite) can be much too fast for effective heat transfer to the ice. Research on exothermic chemical penetrators is in progress, under sponsorship from the U.S. Navy (see Proceedings of 1986 Workshop on Ice Penetration, in press).

Exotic concepts for breaking or melting

A variety of exotic concepts for breaking or melting ice and frozen ground have been explored over the past two decades. The devices considered have included pulsed lasers and focused lasers, banks of large capacitors discharging into the ice (or underlying water), plasma torches, and high energy microwave systems designed to dissipate energy inside the target medium. Results have not been encouraging, and development is not sufficiently advanced to warrant consideration for present purposes.

Removal of blocks and slabs

When a large hole is produced by cutting only the perimeter of the hole, a large mass of ice has to be removed in some way. Ice density is in the range 0.89 to 0.93 Mg/m^3 (56 to 58 lb/ft^3) so 2 ft^3 of ice is the limit of what can be lifted directly by hand. To remove single blocks that are bigger than this, some kind of lifting gear is needed.

In principle, there are alternatives to lifting ice blocks out of the hole. One possibility is to thrust blocks down against their weak buoyancy, and then displace them laterally beneath the ice cover. We assume that this would be unacceptable because of the danger that blocks and debris could move back and foul the access to the hole. Another possibility is to chip the ice into small fragments so that it can be conveyed by a mechanical system, by a dredge pump, or by an air lift. Finally, all of the unwanted ice can be melted.

Mechanical removal of chips can be very efficient. For example, a simple 9-in.-diameter hand-held flight auger lifts out about 300 lb of ice while drilling through 12 ft of ice. However, devices that can remove bigger masses of ice, such as small trenching chains or small cutterhead dredges, are not likely to be justified unless there is a requirement for many holes to be cut.

Complete melting of a large hole tends to be discounted because of the large quantity of energy that is called for. In fact, complete melting of quite big holes in thick ice may turn out to be feasible and convenient. We examine the question elsewhere in this report.

The favored method for removing a very large block or slab seems to be direct lifting after the block has been cut into smaller pieces with chain saws. To use this method, three things are needed: 1) efficient methods for cutting small blocks and breaking them free from the parent block, 2) devices for picking up regular blocks, large irregular fragments, and random-size debris, 3) lifting tackle for hoisting and dumping the ice (Fig. 18, 19). These things are discussed separately in other sections of this report.

Figure 18. Simple gin-pole for lifting long sections of auger (can also be used to lift small ice blocks).

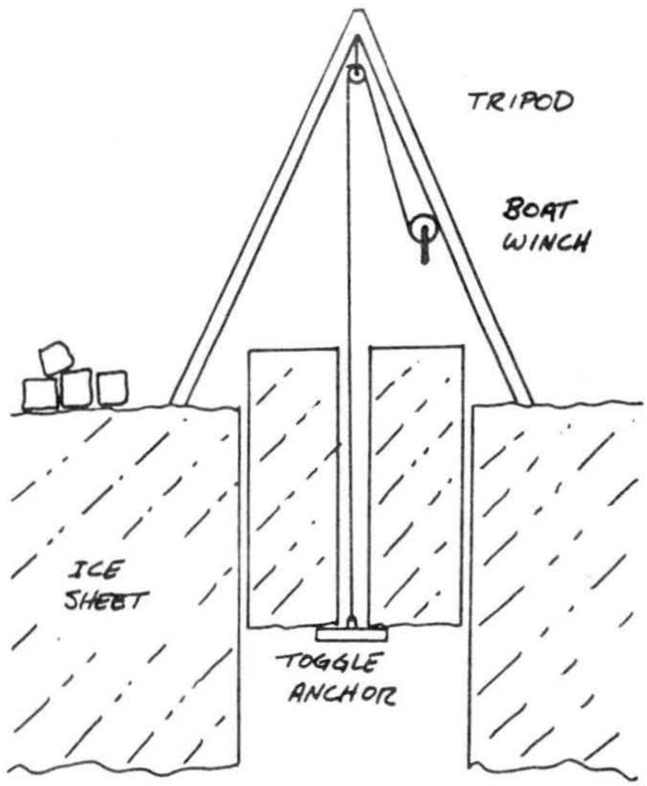


Figure 19. Simple tripod for lifting ice blocks (Hansen 1986).

Basic equipment recommendations for UCT operations

The foregoing summaries provide a brief but systematic review of all the principles that are potentially relevant to the current task. However, in making selections for equipment development, it is also advisable to take account of relevant practical experience by field teams that have operated in the Arctic. We have tried to do this, drawing on personal knowledge of polar field projects by a wide variety of groups over the last three decades. The following items have thus been selected as basic equipment for all operations where access holes of varying sizes have to be produced.

Small diameter auger drill

The task description lists a requirement for holes less than 4 in. in diameter. For this work, as well as for general tasks, we propose a continuous-flight auger with a diameter somewhere between 3 and 4 in., and perhaps a second auger with about 2 in. diameter. Rotary drills of very small diameter (e.g. 1 in.) tend to jam easily in thick ice, and it is usually just as easy to drill a 3- to 4-in.-diameter hole as a 1-in. hole. With good equipment and a skilled operator, penetration rates up to 13 ft/min (4 m/min) are attainable, although it is more realistic to expect about 7 ft/min (2 m/min) (see Mellor and Sellmann 1976).

The auger flight should probably have an outside helix angle of 30° to 35°, where the outside helix angle is $\tan^{-1}$ (pitch/OD). The stem at the center of the scroll will have the minimum diameter that is consistent with flexural rigidity and torque resistance. For hand operation, individual sections of flight should be just over 3 ft long (1 m). This is about the maximum increment unless the operator stands on a box or ladder. The coupling between sections can be of the plug-and-sleeve type, with a quick-release pin. Smooth finish and adequate clearance are necessary to avoid problems with ice and snow in the coupling. The helix should be continuous at the joints between sections. Mild steel will serve if the auger is painted, and if it is rinsed and oiled after an operation. Stainless steel and aluminum can be used, and it is possible that fibre-reinforced plastic could be attractive in the future.

The cutting head is likely to be a two-wing bit with sharp chisel-edge cutters (Fig. 20). The bit's cutting diameter should be slightly greater than the diameter of the auger flight, say by 1% to 3%. The cutter on each wing can be a continuous edge, or it can be a set of separated chisels. Ideally, the relief, or clearance, angle should be designed in accordance with the rotation speed and required penetration rate, increasing progressively towards the center of the bit. The included angle of the cutters can be fairly small, say about 30°. With these angles decided, the rake angle is determined automatically. At the center of the bit, a pilot or core-formation arrangement is needed. Design information is given elsewhere (Mellor 1976, 1977, 1981, Sellmann and Mellor 1986).

Some well-designed cutters (Fig. 21, 22, 23) are available commercially, e.g on fishermen's ice augers (Swedish or Finnish). Ice-fishing augers are typically available in diameters from 4 in. to 8 in. Bits designed for wood-machining (Fig. 24) can be adapted with reasonable success. Custom designs can be provided by CRREL.

The drive unit for a small diameter auger is likely to be a hand-held motor connected directly to the top of the flight auger by a custom adapter. For diameters up to 4 in., rotation speeds should probably be in the range 200 to 500 rev/min. The power required for cutting is not very great if the bit is well designed—well below 1 hp for high penetration rates. The power required for transporting cuttings (Mellor and Sellmann 1976) is almost negligible—of the order of 10^{-3} hp per foot of hole depth at reasonably high penetration rates. The required torque depends on hole diameter, rotation speed, penetration rate, and bit efficiency. For a realistic combination of these things, the torque might be of the order of 10 ft-lbf.

For holes less than 6 in. diameter, it is sufficient to have a drive unit equivalent to an industrial-grade electric hand drill rated at ½ in. to ¾ in. The drive could be an electric drill, a small gasoline engine, a flexdrive cable, a hydraulic motor, or an air motor. Electric drive has proved very satisfactory in many field projects.

Large diameter auger drill

For a hand-held auger drill, 9 in. diameter is a reasonable upper limit for handling total flight lengths up to 16 ft (5 m) or so. With bigger diameter drills, the torque and thrust are not excessive if the bit is well designed, but the flight becomes too heavy for hand operation.

The design of a 9-in. drill is similar to that described above for the small drill. However, the design of the flight is perhaps more important. The gauge of the helix should be heavy enough to do the job and withstand ordinary handling in the field, but it should be as light as possible to permit hand drilling through thick ice.

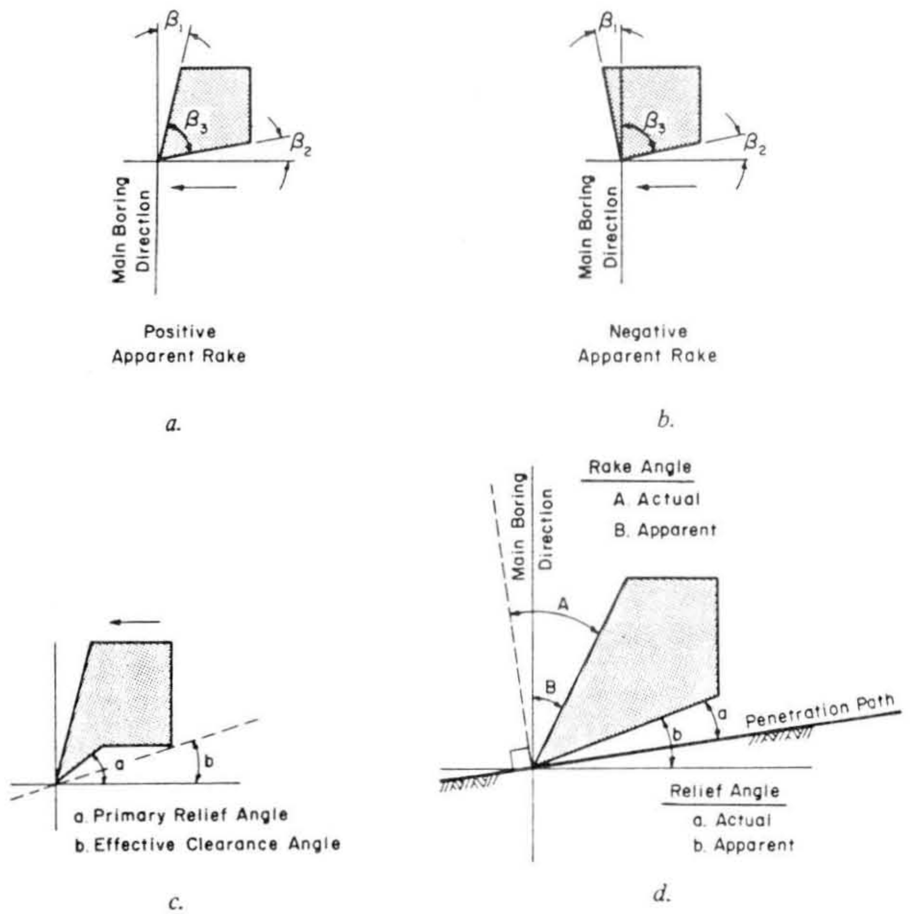


Figure 20. Tool angles for chisel-edge drag bits on rotary boring heads. The tool angles are normally specified in accordance with (a) (Mellor 1976).

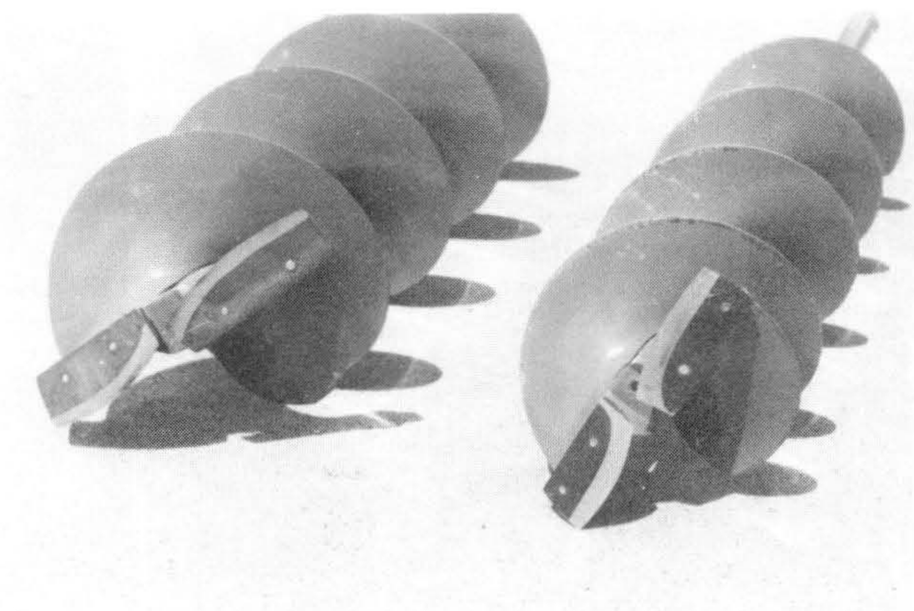


Figure 21. Steel wing cutters on ice-fishing augers. The cutters are ground to a keen edge, giving easy and rapid cutting as long as the edges stay sharp.

Figure 22. Finn-Bore 5½-in.-diameter Finnish ice auger. Can be turned by a 1-hp gasoline drive unit.

The bit of a 9-in. auger can be somewhat more refined than a small bit. It probably benefits from discrete cutting teeth (Fig. 25), with gaps between them, and the setting angles for the teeth are important. As with smaller bits, the teeth or blades should be kept very sharp. Bits can be adapted from existing commercial bits that are sold to ice fishermen, or they can be custom-designed.

The rotation speed should not be very high while the drill is cutting—probably around 200 rev/min or less for a 9-in.-diameter drill. However, it is helpful if the flight can be speeded up for clearing cuttings.

The power required for cutting can be significant (Mellor and Sellmann 1976)—perhaps approaching 2 hp for fairly rapid penetration. The power required for lifting cuttings remains almost insignificant. When the drill breaks through into the water and becomes a pump, the pumping load is significant, but the bit is no longer cutting. The required torque can be kept below 50 ft-lbf with proper design and operation. However, when the drive unit has high stall torque there is danger to the operator if the auger suddenly jams.

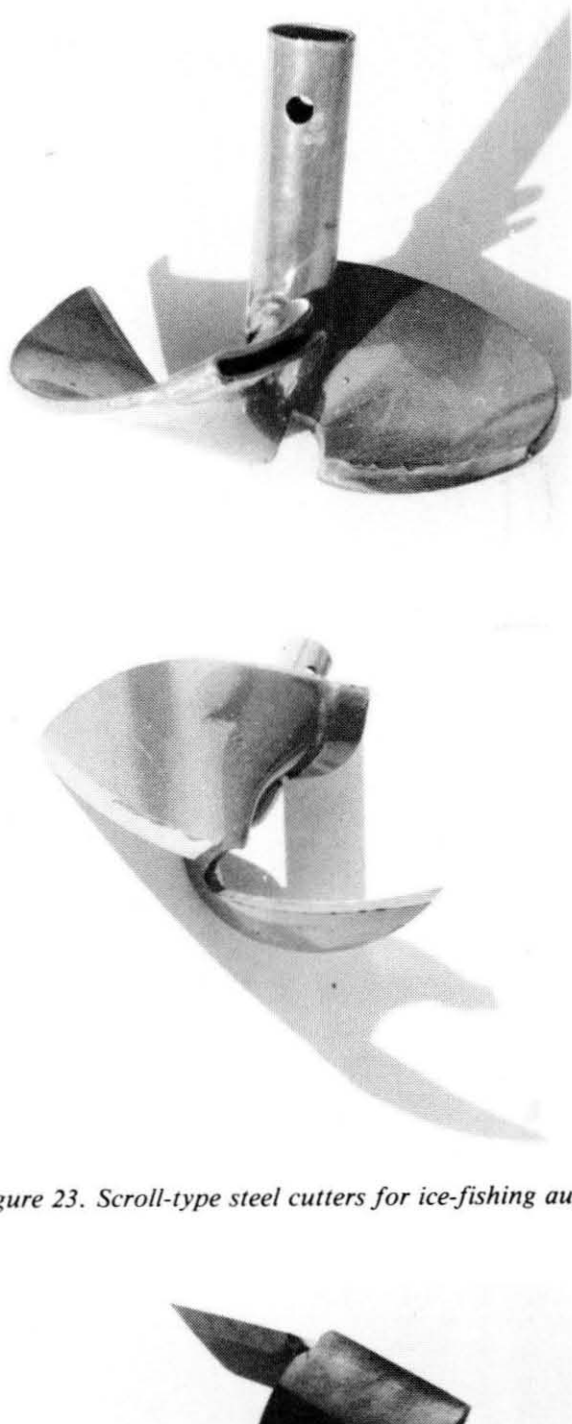


Figure 23. Scroll-type steel cutters for ice-fishing auger.

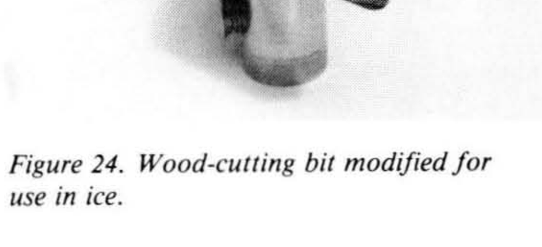


Figure 24. Wood-cutting bit modified for use in ice.

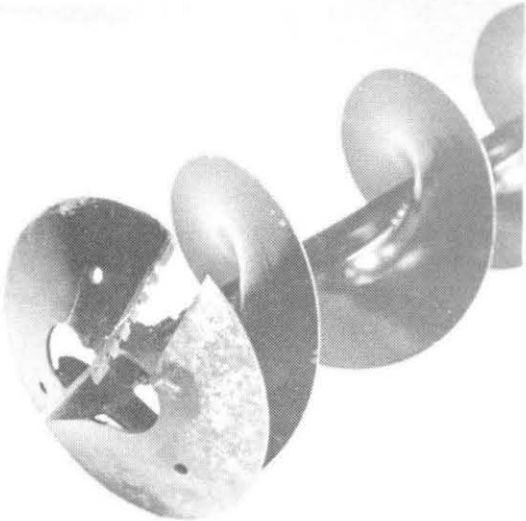


Figure 25. Nine-inch-diameter ice auger, showing cutting teeth and spear-point pilot bit.

The drive unit can be some kind of hand-held motor mounted directly on top of the auger flights. It is likely to be geared to give fairly low rotation speeds and reasonably high torque. In practical terms, a power rating of about 3 hp is sufficient. The drill will probably draw around 2 hp when drilling fairly fast in thick ice (4–7 ft/min).

Downthrust is not a problem with a well designed bit. The weight of the auger and the drive unit is more or less sufficient to provide the 40 to 90 lb that is likely to be needed.

Chain saws

A chain saw is useful for sinking a large pit through ice by cutting blocks. It can also be used to reduce a large ice core to manageable blocks when a thermal system is used to cut the perimeter of a hole.

For general utility, a bar length of about 20 in. is suggested. If the chain is driven at typical speeds for wood-cutting saws (2000–4000 ft/min), the spacing of teeth on the chain will probably have to

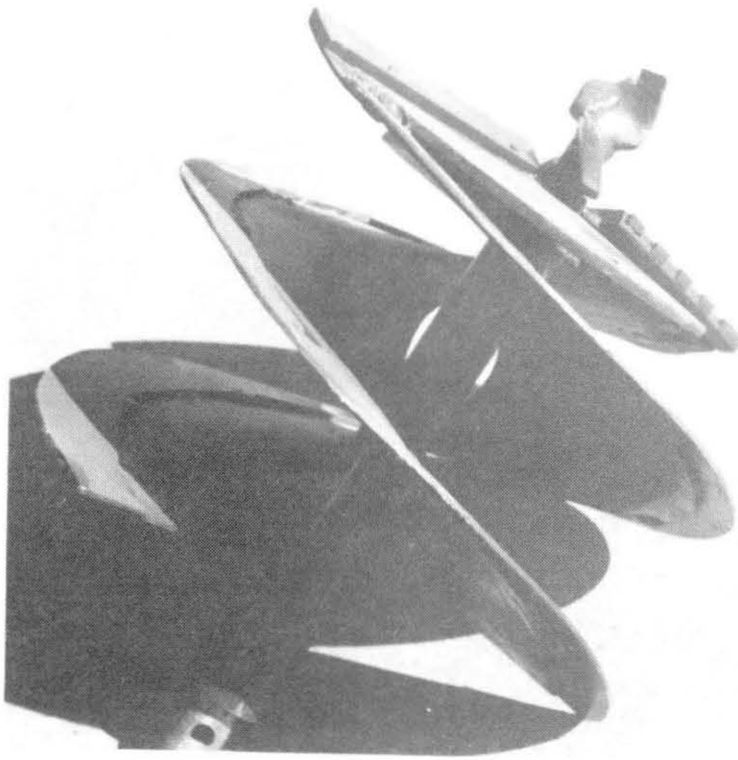


Figure 26. Fourteen-inch-diameter auger for drilling in frozen soil. The two-wing bit with pilot could easily be modified for ice drilling by using sharp steel cutters instead of the carbides shown here.

be increased from that of the typical wood-cutting chain, and the teeth themselves may require modification (see earlier notes on chain saws).

The drive for the saw can be a standard gasoline engine, an electric motor, a hydraulic motor, or an air motor. All of these things are available commercially. As far as is known, large electric saws have not yet been used for ice-cutting, but they may have advantages over gasoline drives, e.g. easy starting and light weight. An electric saw with a 20-in. bar is likely to draw 12 to 15 amperes at 115 volts. Very large electric saws use 220 or 440 volts.

Icing on the saw is not likely to be a problem, but water pumped onto the drive unit does cause problems with electrical systems, clutches, and bearings that can lose their lubricants. In cutting access holes, it will often be possible to avoid working with the bar in water.

Hot water drilling and cutting equipment

A set of equipment for hydrothermal drilling and cutting provides broad capabilities for making holes of almost any shape or size within the range specified by the task description. For single holes, penetration rates in the range 10 to 18 ft/min (3 to 5.5 m/min) are attainable. This penetration rate can be maintained indefinitely in thick ice, whereas the overall rate for an auger is much lower when extensions have to be coupled and uncoupled. The required equipment consists of a hot water source, with circulation pump, plus a flexible hose with a selection of nozzles and cutting frames.

The hot water source is a demand-type heater, of the type used for commercial car-wash operations. It has a coil for rapid heat transfer, and is fired by bottled gas or by fuel oil. Heating capacity is likely to be in the range 100,000 to 400,000 Btu/hr ($\approx$ 30–120 kW). For a small, lightweight unit, a gas-fired tankless heater is convenient, but freeze-up in the gas line is a problem. For a heavy-duty, general-purpose unit, an oil-fired heater with a gun burner and automatic ignition is probably more suitable.

The system will probably use seawater in an open circuit. To avoid corrosion problems, the equipment will be flushed after each field operation and treated with rust inhibitor. During shutdown periods on site, the system should be filled with a glycol solution to prevent freeze-up. During operation, waste heat can be used to prevent freezing in the system.

A single self-priming pump can be used for feedwater supply, internal circulation, and nozzle pressurization. The flow rate has to be matched to the boiler capacity, probably within the range 1 to 10 gal./min ($\approx$ 4–40 litres/min). The pump pressure determines the nozzle pressure, and hence the discharge velocity for a jet of given diameter. The nozzle pressure will probably be within the range 100 to 1000 lbf/in.^{2} ($\approx$ 0.7–7 MPa), perhaps around 400–500 lbf/in.^{2} ($\approx$ 3 MPa). However, it could be up to 2000 lbf/in.^{2}(14 MPa). The combination of flow rate and pressure determines the required pump power.

The pump can be driven mechanically, electrically, or hydraulically. The drive power is not likely to exceed 5 hp (3.7 kW). If an electric gun burner is used for oil-fired heating, an electric drive for the pump would be convenient.

The required diameter of the discharge nozzle is determined by the selected flow rate and the pressure. For a simple single-orifice nozzle, the diameter might be in the range 1.5 to 3.0 mm. The design of the nozzle itself is worth some consideration. There has been a great deal of research on nozzle design, in the field of jet cutting and elsewhere, and the present problem is an easy one, with no significant nozzle erosion to worry about.

The flexible hoses should be able to withstand temperatures up to the boiling point of water, and they should remain flexible at temperatures down to -40° (C or F). The diameter should be big enough to minimize friction losses but not excessive, so that heat loss is minimized. Quick-disconnect couplings are convenient.

A complete heavy-duty hydrothermal system (300,000–400,000 Btu/hr) is likely to weigh somewhere between 500 and 1000 lb ($\approx$ 230–450 kg). It should therefore be designed as a set of modules that can be separated for handling and transport, with the option of carrying the complete system on a single sled as a helicopter sling load.

Papers giving detailed descriptions of hydrothermal drills for sea ice will soon be available (Hansen, in press, Poplin et al., in press, Tucker et al., in press).

Recommendations for associated equipment

General considerations

The basic equipment recommended in the previous section includes: a) one or more small-diameter augers, b) one large-diameter auger, c) one or more chain saws, d) one set of equipment for hydrothermal drilling and cutting. To this list of basic equipment must be added other essential items, such as a primary power source and hand tools, and perhaps also equipment for lifting and pulling. Choices for these associated items of equipment depend to some extent on project logistics and operational preferences, particularly with respect to drive systems.

In research operations, independent gasoline drive units are often used for drills and saws, and gasoline/oil 2-cycle fuel is used. Small air-cooled generators, which typically use straight gasoline, are also used, both to power drills and to run instruments and recorders. When hydrothermal equipment is used, either bottled gas or fuel oil is used in addition to gasoline.

For UCT operations, it may be desirable to limit the number of fuel types, or to standardize drive systems. There also may be a preference for a particular type of drive, e.g. hydraulic, in order to standardize with existing NCEL diver hand tools.

In this report we tend to emphasize the convenience of electric drives for drills and saws. Electric drives are lighter to handle than gasoline engines, they are easy to start and stop in cold weather, and they reduce the number of different fuels that are needed on site. However, hydraulic drives could also be used, provided that all equipment, seals, fluids and lines are suitable for low temperature operation. Pneumatic drives could also be used, and they might be convenient if compressed air is needed at the site for other reasons. Air could be used to run drill motors, chain saws, and pumps.

Electric generators

Even when drills, saws and heaters are powered independently, it is hard to get away from a need for electricity at field sites. Some form of generator is therefore likely to be needed, even if it is only a little 1-kW unit. If the need for electricity is accepted, then consideration should be given to electric drives for drills and saws. With the generator as a primary power source for all equipment, it becomes the most important single item of equipment. Modern (Japanese) portable generators are much superior to the older types, in which a heavy gasoline engine is coupled to an alternator without any attempt at packaging or casing.

Hoists and lifting tackle

If heavy ice blocks or ice cores have to be lifted out of large holes, some kind of equipment may be needed for hoisting and swinging.

By cutting a ramp at the lip of the hole, blocks can be slid out by means of a simple winch or power-pull. For vertical lifts, it is necessary to employ some kind of gin pole (Fig. 18), tripod (Fig. 19), A-frame, gantry, or crane. To move the ice block away from the hole, the block has to be swung or traversed.

Simple tripods and A-frames are relatively easy to design or improvise. If there is a requirement for frequent heavy lifting, then special-purpose equipment may be justified. Two lines of equipment that could be useful have been examined. One is a line of small cranes, of the kind suitable for mounting on pickups or light trucks. Lifting capacity for the smallest of these is in the range 1000 to 2000 lb. One of these small cranes, which operate on 110 volts AC or on 12 or 24 volts DC, could be mounted on a base frame. The other line of equipment consists of movable gantries that are adjustable in height and span, and are also suitable for rapid disassembly. Development of an aluminum air-transportable gantry, or adaptation from stock equipment, would not be difficult. It could be fitted with an electric hoist or a manual hoist. Horizontal traverse of the hoist would be manual. The load capacity for small gantries is typically in the range 0.5 to 5 tons.

Hand tools

A selection of hand tools is required. This selection could include short-handle square-blade shovels (steel), a compact pickaxe (not lightweight mountaineering gear), a good tapered crowbar, a sharp woodcutting axe, and a sharp ice chisel with blade protector. Among arctic field personnel, GSA hand tools are regarded as unsatisfactory, as they often break easily and work badly.

Blasting supplies

Blasting is not recommended for routine operations, partly because ice debris is difficult to remove and partly because conventional blasting supplies complicate the logistics. However, since the UCT will probably include a trained blaster, blasting could be used under special circumstances. If blasting is contemplated, use of binary (two-component) explosives would simplify the transport and storage. Well-tried AN/NM binary explosives are available commercially, and CRREL has developed binary shaped charges (Mellor 1986a). The only sensitive items would then be caps (probably non-electric), and possibly detonating cord.

Related considerations

Given the equipment that is described in the two previous sections, it should be possible to make holes of the required dimensions in any stable ice cover in arctic waters. The equipment already exists and the procedures have been proven in the field, so there is no real uncertainty or risk in the proposals. However, as the plans of the UCTs develop, there may be special circumstances which justify consideration of somewhat different operating procedures.

Single-fuel operation

Most research parties working on the sea ice use two or three different fuels, in addition to the jet fuel of the aircraft. However, it is understood that the UCTs might prefer to operate with only one liquid fuel.

A diesel generator can be used as the primary power source to drive electric drills, saws, pumps, hoists, and suchlike. Diesel fuel can also be used to fire a water heater. Thus it would be possible to get by with only DFA (diesel fuel, arctic).

We regard electric drives for ice drills as fully satisfactory. We have no experience with large electric chain saws, but electric saws with 20-in. bars are readily available (e.g. Milwaukee, Skil, Stihl).

Melting access shafts

By comparison with mechanical cutting, melting is very inefficient in terms of energy utilization. It is therefore usually accepted that melting methods are suitable only for making small-diameter holes and narrow slots. However, if the cost and weight of fuel is of only minor importance in total project logistics, the simplicity of a melting method may be attractive for diver access holes and access holes and similar shafts through the ice.

For illustration, consider a 7-ft-diameter hole through 12 ft of ice. The volume of ice to be removed is 462 ft^3 (13.1 m^3). Taking the specific energy for warming (from −5°C)* and melting as 290 MJ/m^3, the energy required with 100% thermal efficiency is 3792 MJ, or 3.6 million Btu. Taking the calorific value of liquid fuel as 20,000 Btu/lb, the required amount of fuel is 180 lb at 100% thermal efficiency. If the specific gravity of the fuel is 0.8, 180 lb of fuel is equivalent to 27 gallons. If a thermal efficiency of 50% is assumed, the required amount of fuel is 54 gallons, or one 55-gallon drum. This is not much of a demand by the standards of polar operations, so it is worth considering briefly how this amount of fuel could be burned and utilized at a useful rate.

* Sensible heat is almost negligible compared with latent heat.

With a hydrothermal system, the perimeter of the 7-ft-diameter hole would be melted to define the hole walls. With an efficient power auger, holes of 6-in. to 9-in. diameter could be drilled fairly quickly in the remaining plug of ice. A central hole could be used to insert an umbrella cover of about 8 ft diameter to close off the base of the shaft against convection. Additional holes could be used to introduce hot water to melt away the main ice plug, with an insulating cover sitting on top of the job. To get the work done quickly, the water heater has to burn fuel at a rate of about 10 gallons per hour, which probably means that multiple heaters would be needed. With a more relaxed working schedule, say 24 hours of continuous operation, the rate of fuel consumption becomes quite manageable at 2.3 gallons per hour.

The attraction of this method is its simplicity. It requires no lifting gear, no chain saws, no great skill, and not much physical effort. The requirements are a hydrothermal drilling unit, one drum of fuel, a good lightweight power auger (essential for any field party), a "beach umbrella" convection shield, and a piece of insulating board or a surface shelter. The melters can run day or night without much attention, and it should be fairly easy to maintain the hole.

Compressed air

Compressed air is in widespread use in commercial drilling, mostly as a circulation fluid for flushing chips from the hole. It can also be used to drive pneumatic percussive drills, downhole hammers, impact breakers, and air-motor rotary units. Availability of compressed air at a field site could increase the options of the UCT.

Standard commercial air compressors typically deliver at pressures around 100 $lbf/in.^2$, with flow rates commonly in the range 100 to 350 ft^3/min (free air). These machines are usually heavy diesel-powered units, designed for hard use and long life, with a robust frame and housing, road wheels, and towing hitch. They are not well suited for remote sites on the arctic sea ice.

The basic component, say a vane compressor, is neither very heavy nor very bulky, and its power demands need not be excessive. It would therefore be feasible to build a lightweight air-transportable compressor by using a light, high-revving, air-cooled gasoline engine to replace the diesel, and by putting the unit on a light aluminum skid. If the field party has some kind of vehicle or stationary power plant, a light compressor could be driven by a power takeoff (PTO). If electricity is available, an electric compressor can be used.

Divers operating with standard scuba equipment require compressed air at pressures up to 3000 $lbf/in.^2$ A single air tank contains up to 80 ft^3 (free air) at 3000 $lbf/in.^2$ Scuba tanks have been used to power small air-driven ice augers for implanting temperature sensors.

Dive-team compressors, or charged air tanks, offer a source of compressed air for use in drilling and cutting operations, provided the air demands are modest. Certain precautions are needed to avoid freezing in the first-stage regulator at low temperatures.

Recommendations for development work

All of the equipment that has been recommended already exists in some form, and effective operation has already been demonstrated in the field. However, most of the recommended items have previously been assembled or modified from off-the-shelf commercial items. The required development work would consist mainly of design refinement, simplification, standardization of drives and power sources, and adaptation to special UCT needs.

Auger drills

For auger flights, consideration should be given to the relative merits of mild steel, stainless steel, aluminum, and fibre-reinforced plastics. Mild steel is easy to form, weld and machine, but it rusts when exposed to saltwater and sea ice. Stainless steel resists corrosion but is relatively expensive. Aluminum resists corrosion, but is easily damaged. Non-metallic composites are light, strong and durable, but so far have been used only for coring equipment in the ice drilling field. Direction of rotation should be standardized, preferably in the usual right-hand direction (some commercial flight is "left hand" to simplify reduction gearing in the drive unit). Couplings between sections of flight, and between the flight and drive unit, should be designed and fabricated for easy trouble-free operation in the field. Efficient drill bits could be custom designed to suit the exact diameters of the auger flights. After testing and acceptance it would be desirable to have a limited production run to provide an adequate supply of bits and spares. Drive units for the augers would have to be developed to ensure appropriate torque and rotation speed. For safety, it might be worth putting a mechanical torque-limiter between the drive unit and the auger flight. Alternatively, with electric drive the same result could perhaps be achieved with a current-limiting device. A retrieval procedure for jammed augers could be worked out (e.g. by introducing ethylene glycol or hot fluid).

Chain saws

Cutter chains for work in ice could be tested systematically, and perhaps improved. Special orders for ice chain could be placed with manufacturers. Lubrication ought to be examined for adequacy at low temperatures and in wet conditions, and consideration should be given to splash guards. Electric drive units should be tested in cold and wet conditions. Since there has been no quantitative testing of chain saws in ice, useful design data could be obtained by measuring cutting rates and power consumption. Low chain speeds, e.g. around 1200 ft/min, could be investigated.

Hydrothermal equipment

Systematic testing would be useful in order to define the dependence of penetration rate on flow rate, temperature, and discharge velocity. Nozzle design requires some attention. From results of these tests, a balanced system could be designed. Attention should be given to boiler efficiency and total energy utilization (e.g. exhaust preheat of water or fuel/air). Modular design for easy transport and handling needs attention, as does packaging and insulation.

Generators

Having decided on the type and capacity of the required generator (if any), careful selection and testing will be needed, perhaps followed by modification.

Explosives

Consideration might be given to two-component explosives that remain non-explosive up to the time of use. It might be worth investigating the enlargement of drill holes by linear charges, e.g. 400 grain/ft (85 g/m) detonating cord.

Training course

It might be appropriate for NCEL to develop a special training course for UCT personnel. This would include instruction in the use of drilling and cutting equipment, equipment maintenance, and correction of problems in the field.

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APPENDIX A: ICE AUGERS AND DRIVE SYSTEMS

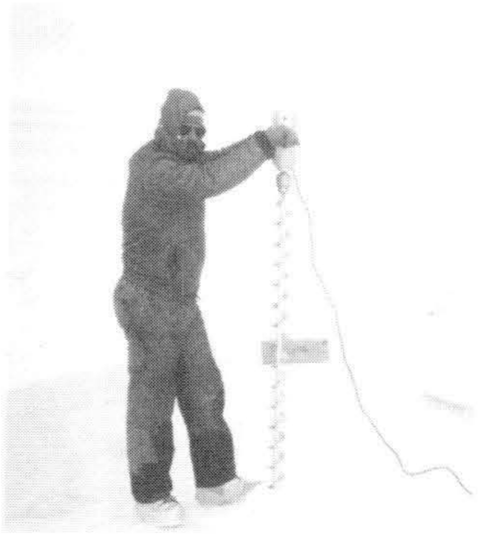

Figure A1. Electric drive unit on 3¼-in.-diam ice drill.

Figure A3. Very small gasoline drive unit on small-diameter ice auger.

Figure A2. Electric drive unit on ice-coring auger.

Figure A4. Gasoline drive unit on ice-coring auger.

Figure A5. Coring auger with flexible drive cable and separate 5-hp engine on a dolly.

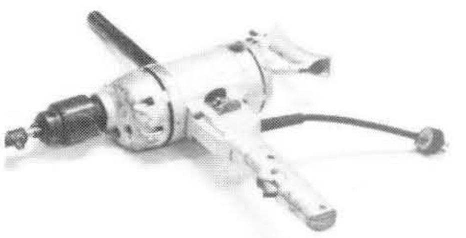

Figure A6. Low-speed 3/4-in. electric drill suitable for turning ice augers. For hole diameters up to 4 in., industrial grade drills rated at 1/2 in. and 5/8 in. are also satisfactory.

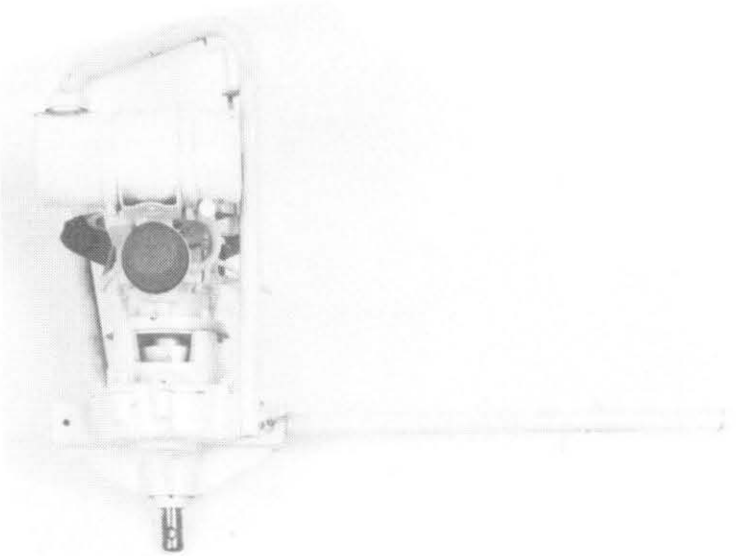

Figure A8. Gasoline drive unit with gear case to provide suitable rotation speed.

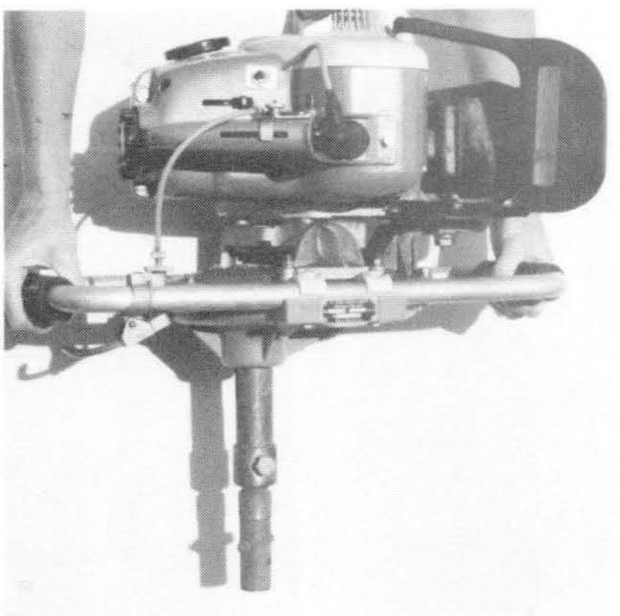

Figure A7. Stihl 4309 3.5-hp gasoline drive unit suitable for turning augers of moderate-to-large diameter.

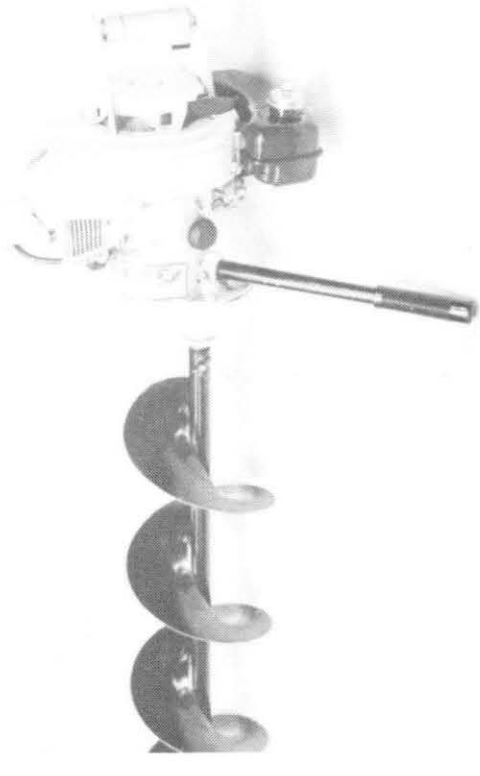

Figure A9. Three-horsepower gasoline drive unit on 9-in.-diam auger. The simple gearing gives left-hand rotation. The simple straight handle for torque reaction is considered safer than looped butterfly handles, which have been known to break the operator's arm.

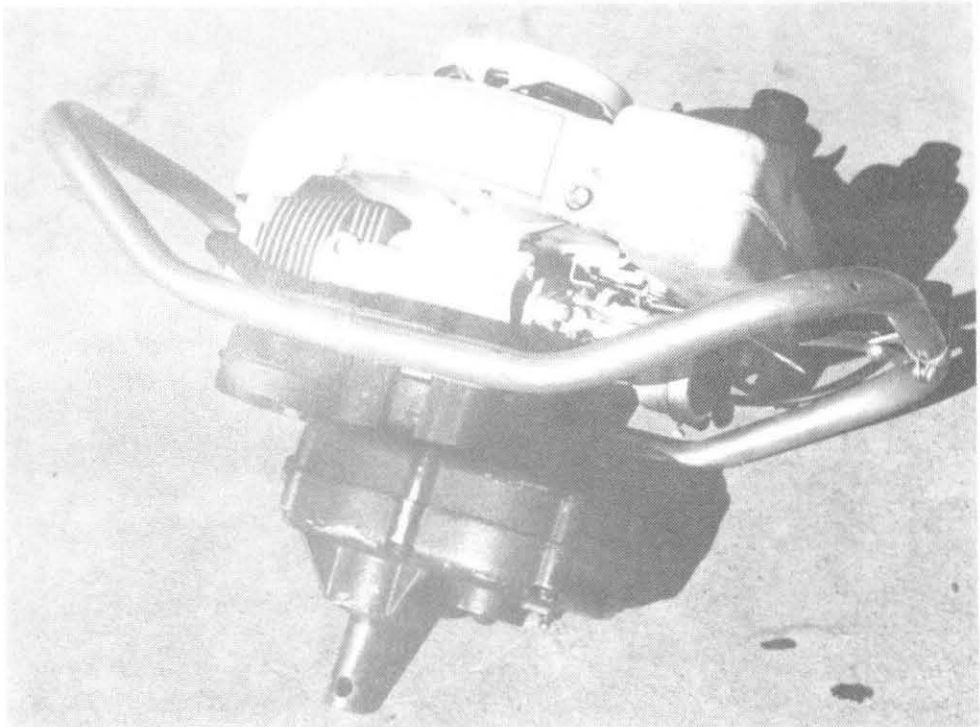

Figure A10. Gasoline drive unit, showing gear case.

Figure A11. Gasoline drive unit (3.5-hp post-hole digger) used to turn a 14-in.-diam auger in frozen ground. The butterfly handles are considered a hazard.

Figure A12. Small drill rig for making large diameter holes in thick ice. The mast extension is folded down, and a small generator is stowed on the operator's platform.

Figure A13. Simple auger for drilling small diameter holes in ice and fine-grained frozen soils.

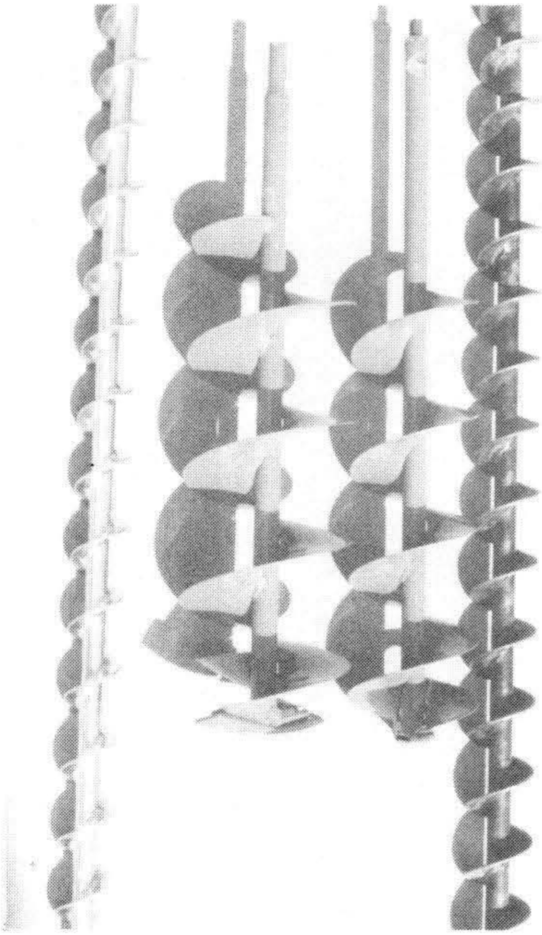

Figure A14. Auger flights with pitch and stem diameter suitable for ice drilling

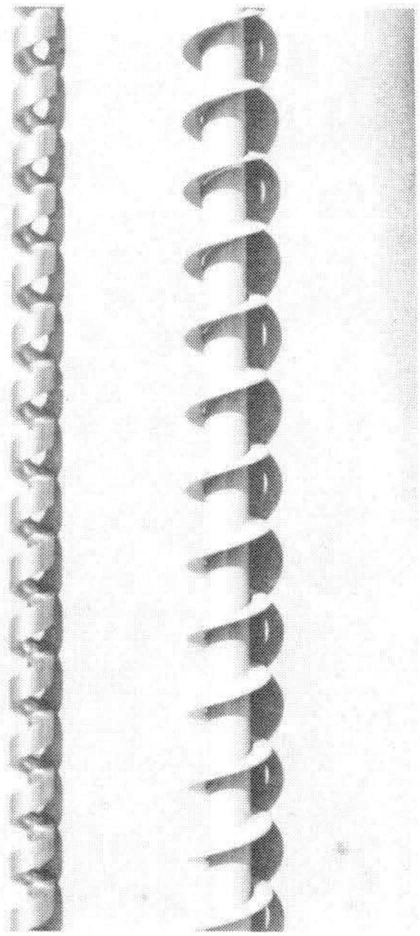

Figure A15. Auger flights that are not considered satisfactory for ice drilling. The ship auger on the left clogs easily. The flights on the right are too narrow relative to the stem diameter, again making the auger prone to clogging and jamming.