SOLID-NOSE AND CORING THERMAL DRILLS FOR TEMPERATE ICE

Philip L. Taylor
Department of Atmospheric Sciences
University of Washington
Seattle, Washington 98195

ABSTRACT

A generalized description is given of several hot-point drills, both coring and solid nose, which have been developed at the University of Washington for use in temperate ice. Drilling equipment is lightweight and readily transportable by small plane and hand-drawn toboggan, and has been used in support of research programs on Blue, Nisqually, and South Cascade Glaciers.

A coring hot-point drill is discussed which has been used to obtain continuous cores of firn and ice to depths of 90 m. The core is 15 cm in diameter, in lengths of 1.7 m, and its in situ *orientation is determined with a remote-reading inclinometer located in the drill barrel.*

Also discussed are solid-nose hot-points of several outside diameters which feature an inexpensive industrial cartridge heater which can be readily replaced in the field in case of burn-out. These drills range from 2.5 to 5 cm in diameter and advance at 6-8 m/hr utilizing 1000 to 2200 W. Depths of 210 m have been achieved. A tapered hot-point reamer has also been developed utilizing a 2200-W heater. This device has been used to control borehole refreezing, and as an aid in retrieving coring or drilling equipment which has become jammed in the hole.

Performance recommendations are given for solid-nose hot-points based on an optimized thermal efficiency.

Introduction

The development of portable, lightweight drilling equipment for glacier ice and firn has long been a challenge to glaciologists. For shallow depths (5 to 10 m) useful mechanical and steam drills have been described (Hodge, 1971; Kovacs *et al.*, 1973). For depths of 30-60 m, P. Kasser has designed a lightweight drill using pumped hot water (review by Shreve, 1962a). For greater depths the only practical solution seems to be offered by thermal drills utilizing electrical power. A review of the literature on thermal drills suggests that their development over the years has not evolved in any systematic way, but to have depended more on the needs of the particular drilling program and the materials and fabrication techniques that were at hand.

Successful solid-nose drills have been built with "Calrod" heater elements cast in copper (Stacey, 1960; Neave, 1968). Others have used hand-wound heaters (Shreve and Sharp, 1970).

A small-diameter drill using a silicon carbide resistance element has been described (LaChapelle, 1963). A small coring drill using a "Calrod" heater in circular form has been used (Shreve and Kamb, 1964).

High power densities are desired for fast and efficient drilling, yet lead to heater failures under the variable water and muck conditions encountered in a glacier borehole. Developments and experimentation will surely continue for a long time to come.

Large Coring Hot-Point Drill

A lightweight, portable thermal coring drill for temperate ice and firn has been developed and is illustrated in Figs. 1 and 2. The drill barrel is 6.75 in. (17 cm) in diameter by about 8.5 ft (2.6 m) long. The complete drilling system weighs approximately 400 pounds (180 kg) including a 3-kW gasoline-powered electrical generator. Transport by toboggan and set-up can be accomplished easily by two men. The barrel length was determined during the first field season to allow transport to the glacier aboard a small ski plane.

The drill is handled by suspending it from a collapsible 12 ft (3.7 m) tripod of aluminum tubing. A winch drum carrying 500 ft (150 m) of armored electrical cable is mounted between two legs, and the cable is run over a meter wheel sheave and down the hole. The winch is hand cranked for breaking off the core and for slowly approaching an end point. A variable-speed drill motor is used through a speed reduction to power the winch over long lifts. The meter wheel indicates depth of the drill in centimeters.

A fiberglass-epoxy pipe forms the body of the drill, supports all necessary components, and encloses the space for receiving the core. This pipe is lightweight and strong with a small wall thickness. It is electrically insulating, and its low thermal conductivity is useful in protecting the core.

Simplicity and ruggedness have been achieved in the drilling head by utilizing a ring of heavy nichrome wire operating at low voltage and high current (6 V, 360 A) directly exposed to the water. Special attention was given to the mechanical support and to the electrical connections to the heater ring to achieve a uniform temperature distribution around the ring, eliminating the cold spots and increasing the thermal efficiency. Power is fed to the heater ring through two sheet-copper conductors mounted on the outside of the fiberglass-epoxy pipe. These sheet conductors are connected to the secondary winding of a step-down transformer rated at 2.2 kW mounted in the upper section of the drill barrel above the core space. The transformer primary receives 220 V, 60 Hz single-phase power at about 10 A through the supporting cable. The transformer and all the connections to it are designed for direct water immersion.

Interchangeable thermal drilling heads are used for wet, impermeable ice and for dry drilling in firn. The heads are readily exchanged, are electrically identical, but differ in mechanical construction since the firn head operates at a higher temperature and has negligible side melting due to the lack of water. When drilling in firn, power input is reduced to about 70 per cent of full to prevent damage to the heater ring when part or all of it becomes suspended in air. As soon as the water table is reached the more efficient ice head is installed, and full power is applied.

A short loop of heavy resistance wire located on the inside diameter of the barrel near the drill head melts a small longitudinal groove in the core as the drill advances. This groove defines

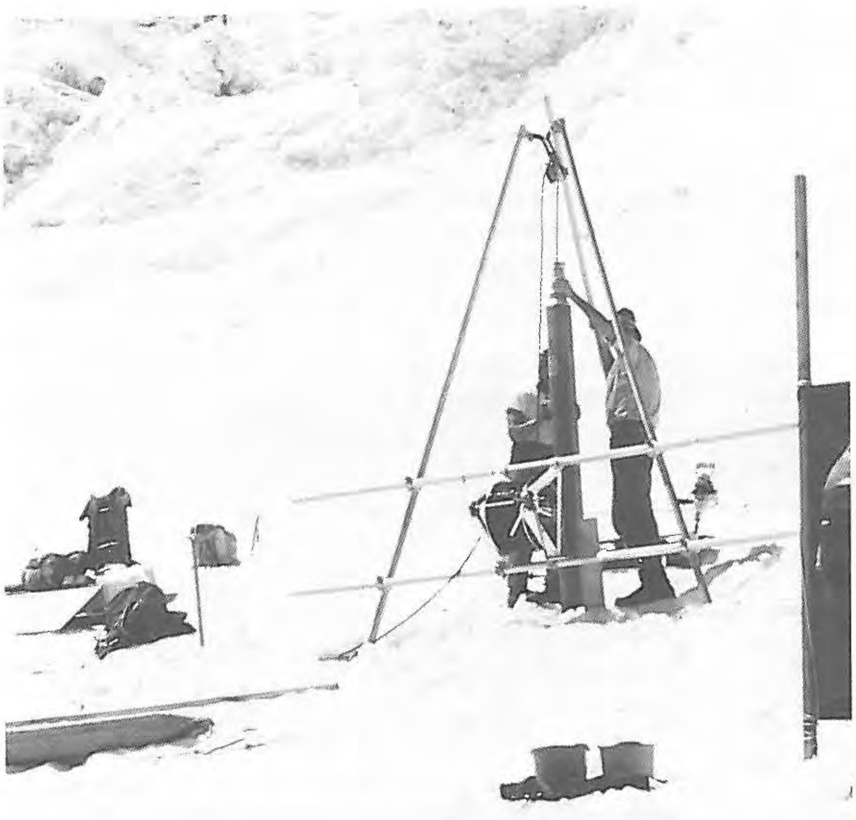

Figure 1. The thermal coring drill. Winch installation on the near side of the supporting tripod.

Figure 2. Core removal and display.

the orientation of the core in the barrel even though the core may fracture or move during retrieval. As the core fills the space available in the barrel a spring-loaded push rod activates a switch which signals the operator through a lamp circuit in the control box. Drill controls are illustrated in Fig. 3.

The core is broken off and captured by spring-loaded sharp steel fingers near the drill head. Pulling on the drill forces the fingers into the core. At a force of about 300 pounds (140 kg) in ice to about 500 pounds (230 kg) in firn the core breaks across and is held in the barrel. The core is removed on the surface by holding these fingers in a retracted position with lock pins.

The top end of the drill barrel consists of a tapered aluminum cone containing a heater which may be activated from the surface in case the drill becomes stuck in the borehole during retrieval. This "back-out" heater remains untested as no difficulty has ever occurred.

A remote-reading two-axis inclinometer and magnetic compass utilizing separate conductors in the cable is located in the upper section of the drill barrel. This device enables the operator to determine the *in situ* orientation of the drill barrel after drilling the core and before breakoff. Structure noted in the core after retrieval can be referenced to the longitudinal groove of the core marker and to finger scratches, and hence to the drill barrel, so that the *in situ* orientation of the core immediately prior to breakoff can be determined. Experience in the field has been that the core can be orientated to within 5-8 degrees in azimuth and to about 0.25-0.5 degree in tilt. Typical core cross sections are illustrated in Fig. 4 (90-m hole, Blue Glacier, 1971). The cores are used for stratigraphic studies of firn in the accumulation areas, for structural measurements of ice fabrics, grain size and shape, and for microscopic examination of vein structure and bubble properties.

Figure 3. Coring drill controls. Operator is reading the inclinometer prior to core breakoff and retrieval. Drill power controls in the foreground.

Drill rate in temperate ice at 210-220 V and 8.5 A (1.8-1.9 kW) at the generator end of the drill cable averaged about 1.7 m/hr, with a range of 1.5 to 2.0 m/hr (40- and 90-m holes, Blue Glacier, 1971). Voltage drop along the cable was estimated to be about 23 V, indicating a power at the drill transformer of 1.6-1.7 kW. Tests in block ice in the lab have given rates of 2.5 m/hr with 208 V on the transformer. At the full rated power of 220 V and 10 A on the transformer, a drill rate of about 2.8 m/hr would be expected. At the required reduced voltage input at the generator of 180 V for snow and firn the drill rate varies from 1.5 to 2.5 m/hr, depending on density and ice layers. Core diameter is about 6 in. (15.2 cm) and the hole is about 7 in. (17.8 cm) in diameter. Core length is usually 1.65-1.7 m.

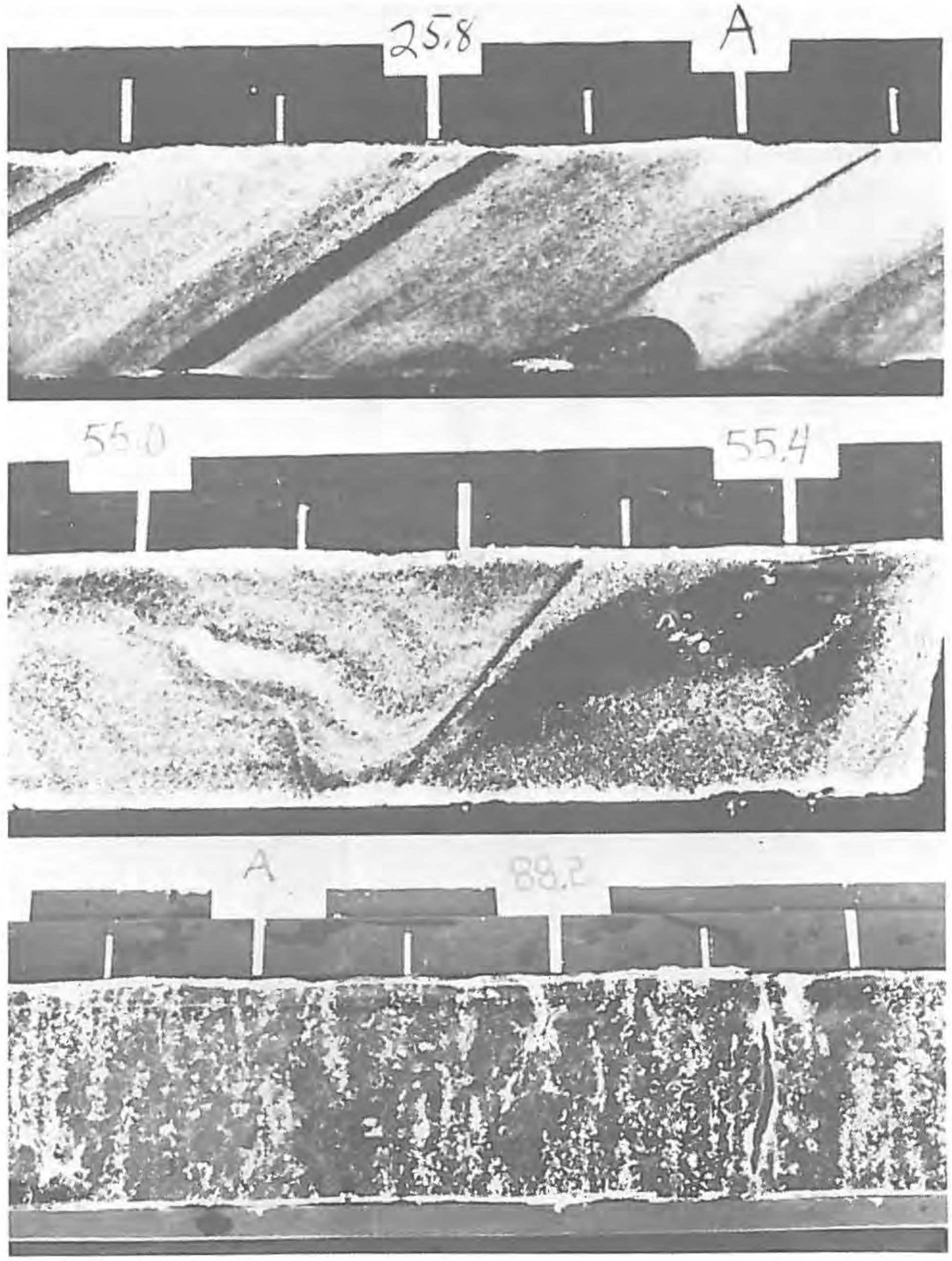

Figure 4. Samples of a continuous vertical core taken near the base of the icefall, Blue Glacier, Washington, 1971. Numbers indicate depth from the surface in meters; scale divisions are decimeters.

Hot-Points

The solid-nose hot-points that we have developed are modeled after the highly successful Shreve unit (Shreve and Sharp, 1970), the significant difference being in the utilization of an inexpensive (about $7) industrial cartridge heater. The hot-points are opened easily for maintenance and for replacement of the heater in case of burn-out. A cross-sectional view of the 2 in. (5.08 cm) diameter hot-point is shown in Fig. 5. The heater is rated at 2200 W, 220 V, and is inserted into the copper slug with a light push. The contact surface between the heater and copper is treated with a commercial silver plating compound to improve and maintain the heat transfer. This increases the reliability of the heater by reducing its operating temperature. The heater is wired through the watertight plug and is easily removed as a unit with a small pulling tool as illustrated in Fig. 6.

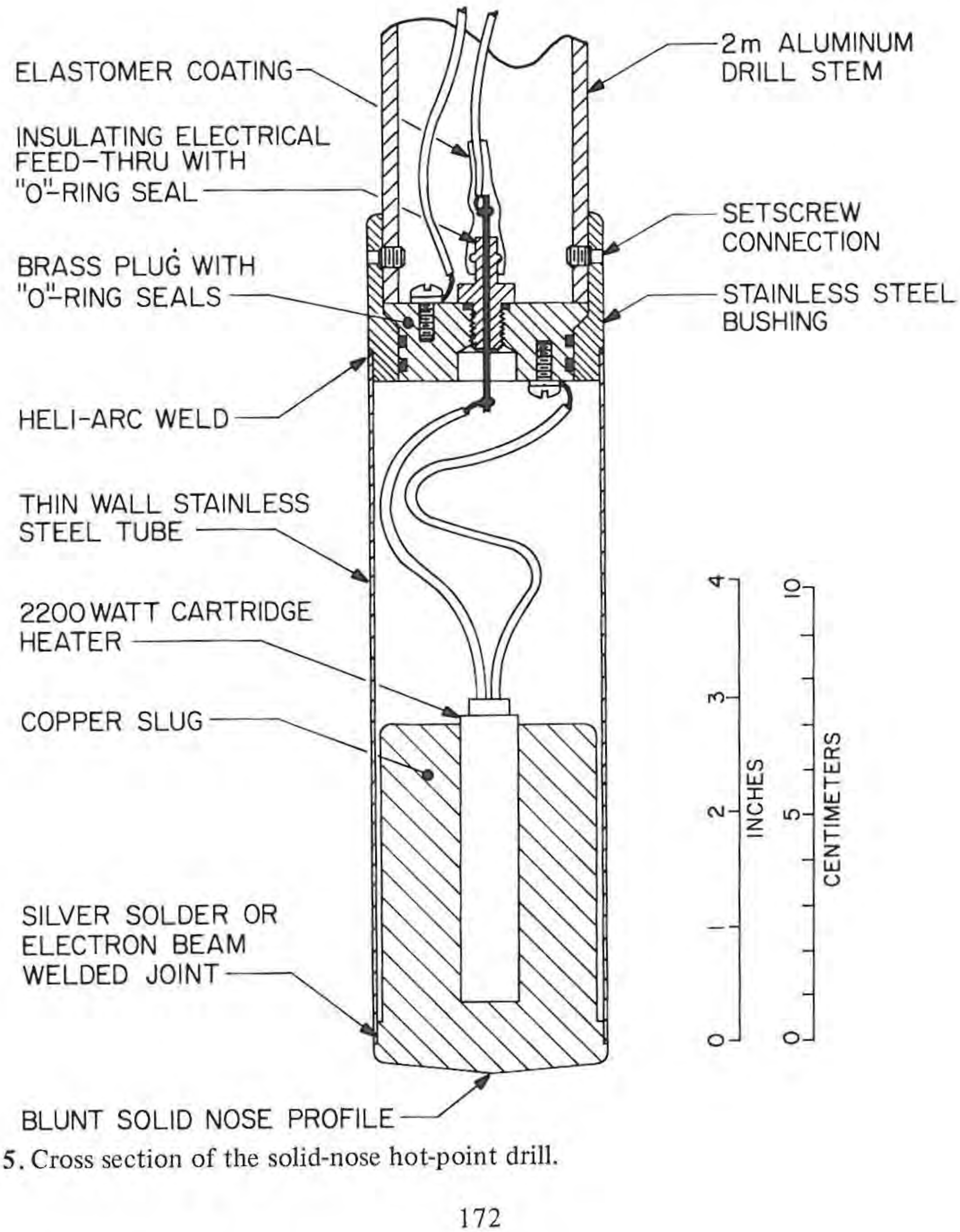

Figure 5. Cross section of the solid-nose hot-point drill.

To maintain thermal efficiency the nose is blunt (Shreve, 1962b; Shreve and Sharp, 1970) and a thin-wall stainless-steel tube of low thermal conductivity was chosen for the body. The hot-point is guided by a 2-m-long drill stem of aluminum tubing weighted with about 15 pounds (7 kg) of lead. This weight improves the thermal efficiency by decreasing the thickness of the water layer at the nose of the drill.

The surface platform is illustrated in Fig. 7 and contains a cable supply drum, meter wheel sheave, and power control box. The drum contains 500 ft (150 m) of cable, an electrical slip-ring, and friction drag.

Performance checks over several field seasons and hundreds of meters of boreholes have given typical drilling speeds of 5-6 m/hr at about 1300 W power input. Tests in block ice with 1800 W input gave a drill speed of 7.5 m/hr. Calculated thermal efficiencies range from 0.75 to 0.85, indicating that if generator and cable limitations could be overcome the drilling speed at the rated input power of 2.2 kW would be approximately 9 m/hr. These drills have been used for the installation of devices for measuring vertical strain rates in glaciers (Rogers and LaChapelle, 1974) and for probing glacier water systems (S.M. Hodge, South Cascade Glacier, personal communication, 1974).

The use of cartridge heaters allows ease of design in scaling to different hot-point diameters, and for ease of field substitution for different wattages and voltages depending on the electrical generator that is available. Hot-points of similar design with diameters of 1 in. (2.54 cm) and 1.25 in. (3.18 cm) have also been constructed using a similar cartridge heater rated at 1000 W, 110 V or 220 V, and measuring 0.5 in. (1.27 cm) diameter by 1.5 in. (3.8 cm) long. The drill cable termination is standardized to allow interchange of the different size hot-points and the reamer described below.

Figure 6. Solid-nose hot-point assembled, and with plug and heater assembly removed with small pulling tool. Scale in inches.

Figure 7. Solid-nose drill platform. Operator holds the drill stem; cable has been lifted off the meter wheel sheave. Cable drum and power control box on the right.

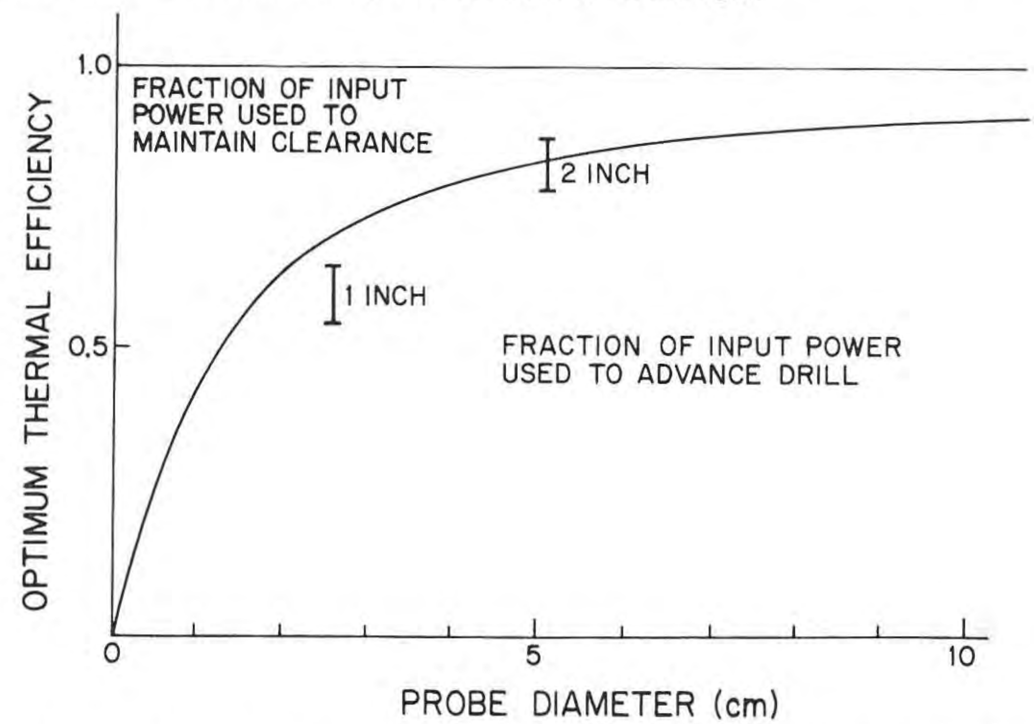

Figure 8. Optimum thermal efficiency for solid-nose hot-point drills operating in wet temperate ice. Clearance diameter is 5 mm between probe and hole. Bars show range of observed values.

Performance of the 1 in. (2.54 cm) hot-point is typically 6-8 m/hr at power inputs of 450-700 W, indicating that thermal efficiencies are 0.55 to 0.65. At least 1800 m of hole have been drilled, the maximum depth being 210 m. The boreholes have been used for verifying ice thickness (Hodge, 1974), planting thermistors (Harrison, 1975) and for probing glacier water systems (S.M. Hodge, South Cascade Glacier, personal communication, 1973).

Power must be reduced to about 25 per cent of maximum when drilling in snow to prevent burn-out. A long aluminum coring tube is used to get through most of the snow cover. A portable steam drill has also proven valuable (Hodge, 1971).

Another cartridge heater 0.5 in. (1.27 cm) diameter by 20 in. (51 cm) in length, rated at 2200 W at 220 V has been utilized in the development of a tapered borehole reamer measuring about 2.5 in. (6.3 cm) in diameter and 24 in. (61 cm) long. The reamer is machined from a solid aluminum round bar, with the heater inserted in a long hole on the cylinder axis. The electrical and mechanical connections are compatible with the solid-nose drill-cable termination. The reamer has been successful in controlling refreezing in existing boreholes to ensure safe passage of instrumentation. In the event that equipment does get jammed in the hole, or a cable tangle occurs, the reamer has proven to be indispensable in working its way to and around the obstruction and enlarging the cavity to enable retrieval.

Comments on Thermal Efficiency in Hot-Point Design

The solid-nose hot-point design problem is an interesting one in that for a given hole size and power available there is a whole family of drills of acceptable design depending on what trade-offs have been made between thermal efficiency, probability of irreparable damage or loss, and the cost of construction. Thermal efficiency of a drill for wet, temperate ice is considered here to be based on the probe cross-sectional area, the drilling speed, and the power input to the hot-point assembly. Assuming that all the input power melts ice, the thermal efficiency is also equal to the ratio of the area of the probe to the area of the hole. Beyond some point it does more harm than good to increase the thermal efficiency as the drill is more apt to hang up in the hole and be lost. A drill of low thermal efficiency wastes fuel and time as it makes a bumpy hole of irregular cross section because of the larger percentage of energy which goes to heat water which moves up and sideways and melts the ice in an uncontrolled manner.

The probability of a drill getting stuck in the borehole for a given stem length seems to be largely a function of the clearance between the drill and the hole. An intuitive guess based on observation and experience suggests a difference of about 0.2 in. (5 mm) between the probe diameter and the hole diameter as a good design guideline to achieve a useful, efficiently drilled hole of smooth and constant cross section with a minimum of risk. This means that there is an optimum thermal efficiency which is a function of the drill diameter, with smaller drills operating at lower thermal efficiency. This is illustrated in Fig. 8.

Fortunately, the tendency in scaling hot-points is in this direction, since power input for constant drill rate is proportional to probe area, while side losses tend to be proportional to probe circumference. One could then expect the ratio of side loss to power input to vary somewhat as the inverse of the probe diameter. This is close to the desired effect, and greatly simplifies the design process by making the optimum efficiency easier to achieve.

Figure 9 illustrates how drill rate and power input vary for drills operating at this optimum thermal efficiency, and is presented here as a design guide. The borehole diameter in all cases will be 0.2 in. (5 mm) greater than the probe diameter.

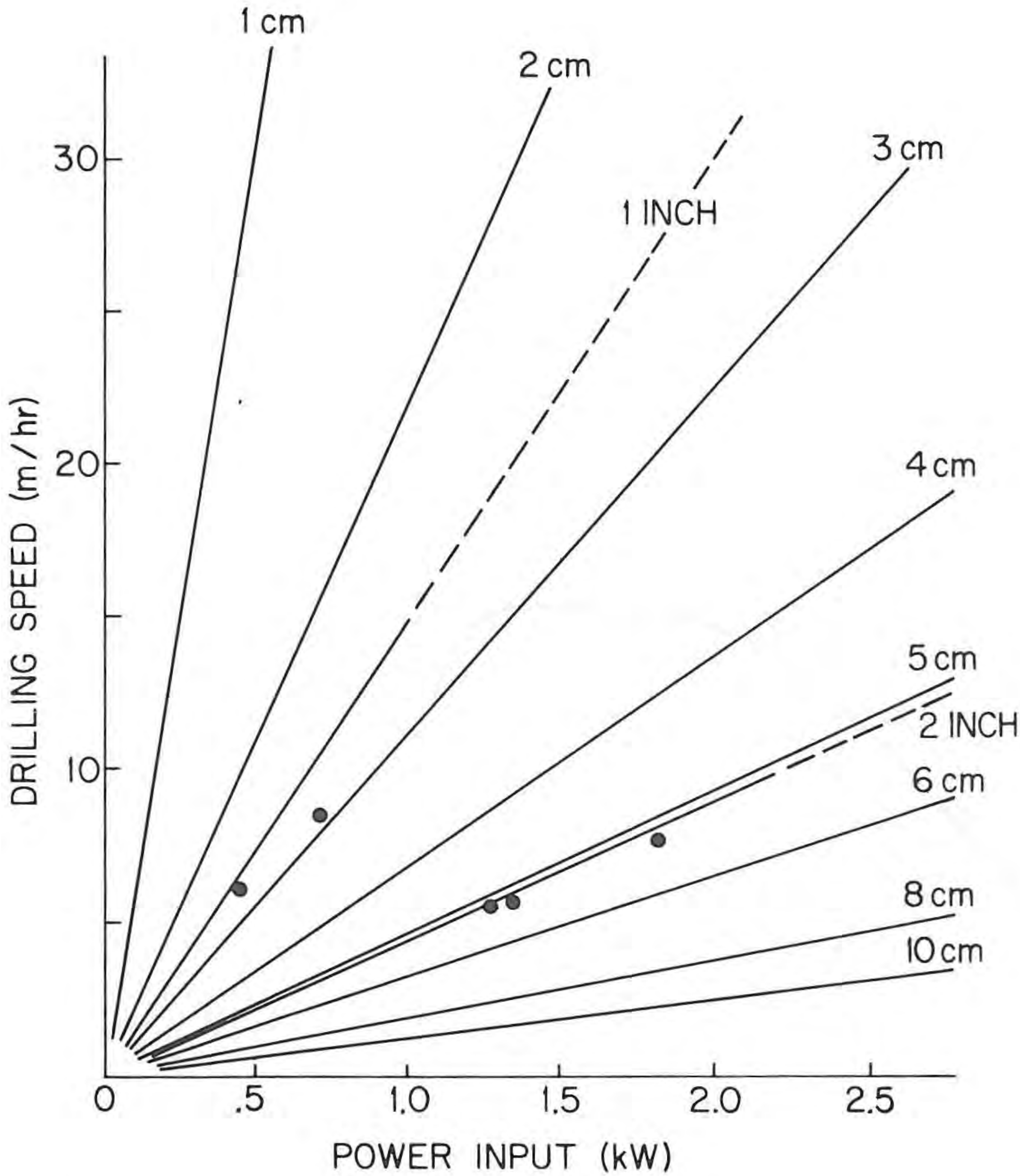

Figure 9. Drilling speed and power input for solid-nose hot-points operating at the optimum thermal efficiency shown in Fig. 8. Observed values for the 1-in. and 2-in. drills are shown as dots; dashed extensions are for power input above the cartridge rating.

Acknowledgments

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