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TECHNICAL ENVIRONMENTAL REPORT

# *THE USE OF DRILLING BY THE U.S. ANTARCTIC PROGRAM*

M. C. Wade
Energy Division

J. W. Webb
Environmental Sciences Division

W. H. Hedberg
Hazardous Waste Remedial Action Program

August 1994

Prepared for the
National Science Foundation
Office of Polar Programs

by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
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MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
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## ACRONYMS, ABBREVIATIONS, AND INITIALISMS

| | |
|---|---|
| AMANDA | Antarctic Muon and Neutrino Detection Array |
| ASA | Antarctic Support Associates |
| BOD | biological oxygen demand |
| CEE | Comprehensive Environmental Evaluation |
| CFC-11 | trichlorofluoromethane |
| $CH_4$ | methane |
| CIROS | Cenozoic Investigations in the western Ross Sea |
| CRREL | Cold Regions Research Engineering Laboratory |
| DFA | diesel fuel, arctic grade |
| EIS | Environmental Impact Statement |
| GISP | Greenland Ice Sheet Program |
| GRIP | Greenland Ice Core Project |
| JP4 | jet propulsion fuel grade 4 |
| NBA | N-butyl acetate |
| NEPA | National Environmental Policy Act |
| NPDES | National Pollutant Discharge Elimination System |
| NSF | National Science Foundation |
| OPP | Office of Polar Programs (NSF) |
| PCE | tetrachloroethylene |
| PM | particulate matter |
| PICO | Polar Ice Coring Office |
| Protocol | Protocol on Environmental Protection to the Antarctic Treaty |
| SPS | South Pole Station |
| TCE | trichloroethylene |
| USAP | United States Antarctic Program |
| VOCs | volatile organic compounds |

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*Polar Ice Coring Office*, **J. J. Kelley**, Director, provided schematic drawings of various ice drilling and coring devices developed by PICO and several useful references; **V. Zagorodnov** provided discussion on the antifreeze-thermal electric drill (ATED); **K. Stanford** provided discussion and references on directional drilling, electrothermal systems, and the AMANDA hot water drilling project; **B. Burton** supplied information on the AMANDA, Vostok and other drilling projects; **T. A. Gosink** (retired) provided information on the various fluids used to stabilize drill holes.

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# 1. INTRODUCTION

This report on drilling in the Antarctic has been prepared by the U.S. National Science Foundation (NSF) to assist principal investigators and others in complying with the National Environmental Policy Act (NEPA) and the Antarctic Treaty of 1961. Implementing regulations for NEPA are spelled out in 40 CFR 1500-1508. Environmental protection under the Antarctic Treaty is addressed in the Protocol on Environmental Protection to the Antarctic Treaty (hereafter referred to as the Protocol), which was adopted by 26 countries in 1991. In the United States, responsibility for compliance with these requirements rests with the NSF Office of Polar Programs (OPP), which manages the U.S. Antarctic Program (USAP).

NEPA and its implementing regulations require that federal agencies consider the effects of an action on the human environment before deciding to act. The vehicle for this consideration is an environmental analysis (either an environmental assessment or an environmental impact statement, depending on the expected significance of the effects). A programmatic Environmental Impact Statement (EIS) assessing impacts of the USAP was published in 1980. A Supplemental EIS was published in 1991 and addressed the Safety, Environment and Health initiative undertaken by USAP.

The Protocol, in designating Antarctica as "a natural reserve, devoted to peace and science" (Article 2), spells out principles for protection of the antarctic environment (Article 3). In considering protection of the antarctic environment, the Protocol recognizes its wilderness and aesthetic values as well as its value as an area for the conduct of scientific research. Under Article 3 of the Protocol, environmental protection requires that activities in the Antarctic Treaty area be planned and conducted so as to limit adverse impacts on the antarctic environment and dependent and associated ecosystems. In addition, Annex II of the Protocol prohibits taking[1] of or harmful interference[2] with antarctic fauna and flora except in accordance with a permit. Because most of Antarctica is pristine or nearly so, these principles mean that disturbance which might be considered negligible elsewhere could be significant in Antarctica.

The USAP recognizes the potentially profound impacts that its presence and activities can have on the antarctic environment. In its extensive support of operations and research in Antarctica, the

---

[1] "Take" or "taking" means to kill, injure, capture, handle, or molest a native mammal or bird or to remove or damage such quantities of native plants that their local distribution or abundance would be significantly affected.

[2] Harmful interference is a prohibition not contained in the Antarctic Conservation Act, and includes activities that disturb concentrations of birds and seals, such as flying or landing helicopters, and operating vehicles in close proximity. Harmful interference also generally includes "any activity that results in the significant adverse modification of habitats of any species or population of native mammal, bird, plant or invertebrate."

USAP uses all practical means to foster and maintain natural conditions while supporting scientific endeavors in a safe and healthful manner. Reducing human impacts on the antarctic environment is a major goal of the USAP. The USAP's operating philosophy is based on broad yet reasonable and practical assumptions concerning environmental protection that are detailed by Draggan and Wilkness (1993).

The continent of Antarctica (Fig. 1) includes about $1.43 \times 10^7$ km$^2$ ($5.5 \times 10^6$ miles$^2$) and is completely surrounded by the southern oceans. About 98% of the land area is covered by ice and snow. Glacial ice of the continent forms shelves up to several hundred meters thick that extend from land out over the ocean in several places. The USAP maintains three year-round stations on the continent to support scientific research: McMurdo Station on Ross Island, the Amundsen-Scott South Pole Station near the geographic south pole on the polar plateau, and Palmer Station on the Antarctic Peninsula (Fig. 1). The Byrd Station in West Antarctica (Fig. 1) is also occupied intermittently during the austral summer. McMurdo Station is the major base for providing logistic support to the South Pole Station and numerous scientific field camps on the continent during each austral summer.

Research and associated support operations at these stations and camps sometimes involve drilling into ice, soil, or ocean sediments. In order to comply with NEPA and the Protocol, it is necessary for principal investigators and others to assess the environmental effects of drilling. This report has been prepared to assist in this process by

- describing various drilling technologies currently available for use in Antarctica,
- generally characterizing the potential environmental impacts associated with these drilling techniques, and
- identifying possible mitigation measures to reduce impacts.

Although the report is intended as a reference to assist in preparation of environmental analyses for specific undertakings involving drilling, it does not contain all the information necessary for all such evaluations. Project-specific environmental analyses require specific details on the site and the existing environment of the site, the technology to be used, and potential effects that are anticipated. Environmental impacts vary depending on depth and magnitude of drilling, duration of the drilling, size of support operations, consumption of fuel, technology used, and location of the drilling. There are currently a limited number of actual measurements of impacts from drilling activities.

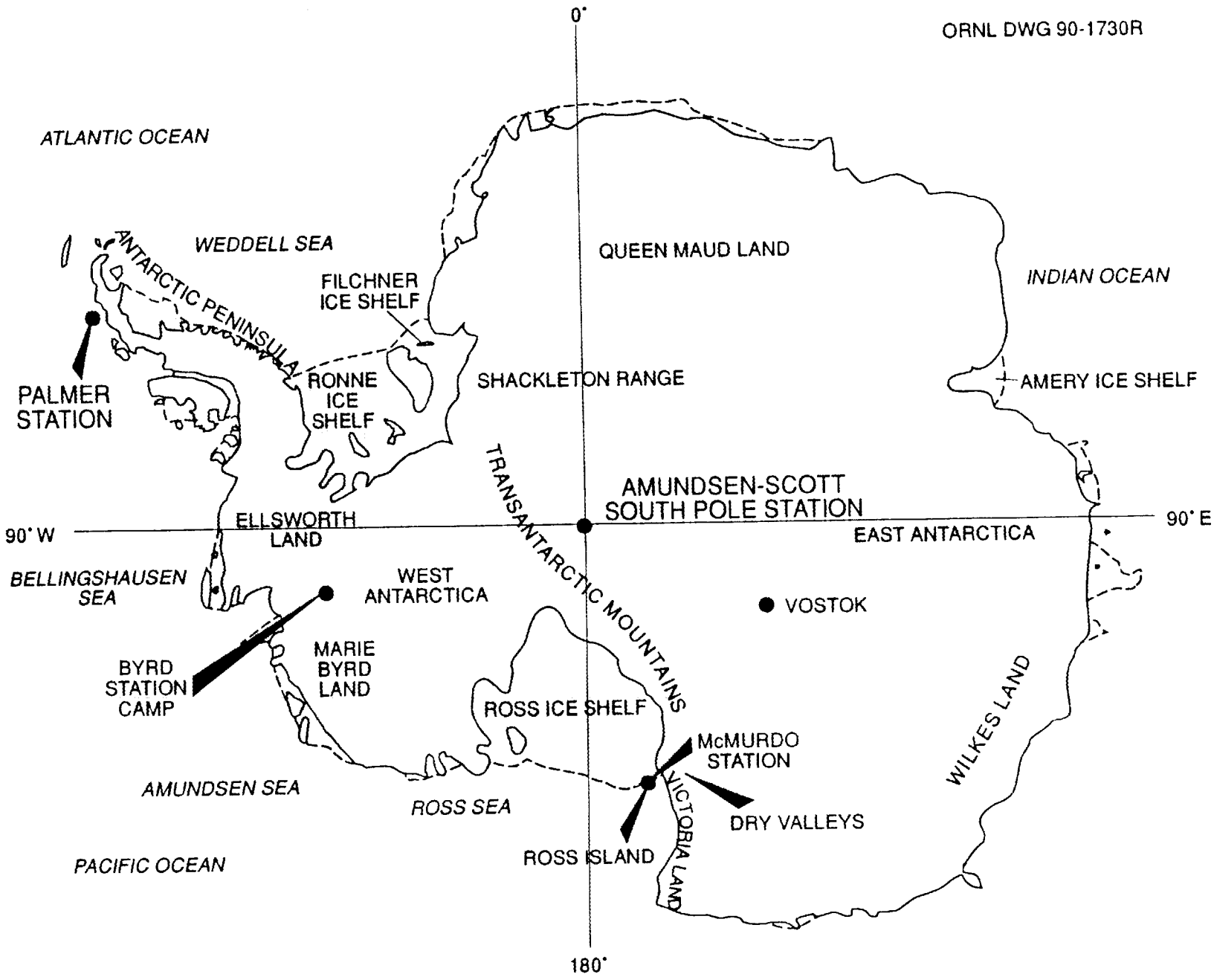


**Figure 1. Major features and location of USAP stations on the Antarctic continent.**

# 2. DRILLING TECHNOLOGIES

This section characterizes the drilling technologies currently used or expected to be used by the USAP. The focus is on those aspects of drilling that could cause environmental effects. In general, there are no environmentally preferable methods that could be substituted for drilling in the research and support circumstances under which it is employed. Continued operation of USAP research activities and facilities in Antarctica will unavoidably entail drilling operations as described below. The option of not drilling remains a possibility for any particular case in which considerations of funding, scientific merit or priority, and logistics cast doubt upon proceeding. Various research projects and activities that require drilling may consider alternative sites and drilling technologies, sometimes to minimize environmental effects; but in almost all cases, drilling is the only way to obtain the desired research material or conduct the selected activity. For some types of construction or support activities that use drilling, blasting is theoretically an option. However, the USAP is currently evaluating the environmental impacts of blasting in a separate report, *Technical Environmental Report, The Use of Explosives by the U.S. Antarctic Program* (NSF 1994). Thus, blasting will not be addressed here. Possible mitigation measures and recommended environmental safeguards for drilling are presented in Sect. 3.

Drilling, for the purposes of this report, includes penetration of earth (soil or rock) or ice using a variety of equipment types. Equipment ranges from small (i.e., diameter of a few centimeters) hand-operated or powered augers to sophisticated drilling apparatus requiring various fluids. Figure 2 illustrates the various types of drilling and coring systems that are currently used or planned for use by USAP scientific research projects in Antarctica. The following sections briefly describe these techniques.

## 2.1 CONSTRUCTION—ICE AND ROCK DRILLING

A wide range of mechanical equipment exists that may be used to obtain shallow ice or soil cores, drill holes in ice for the emplacement of equipment, or conduct other construction activities. These devices include hand powered ice and soil augers (Fig. 3); powered gasoline, electric, or pneumatic drills, augers, and air hammers typically used elsewhere for construction purposes; and track mounted or pulled drills capable of creating holes ranging from 120 to 360 cm in diameter. None of the above equipment requires a fluid in the hole for cooling or lubrication, and the basics of

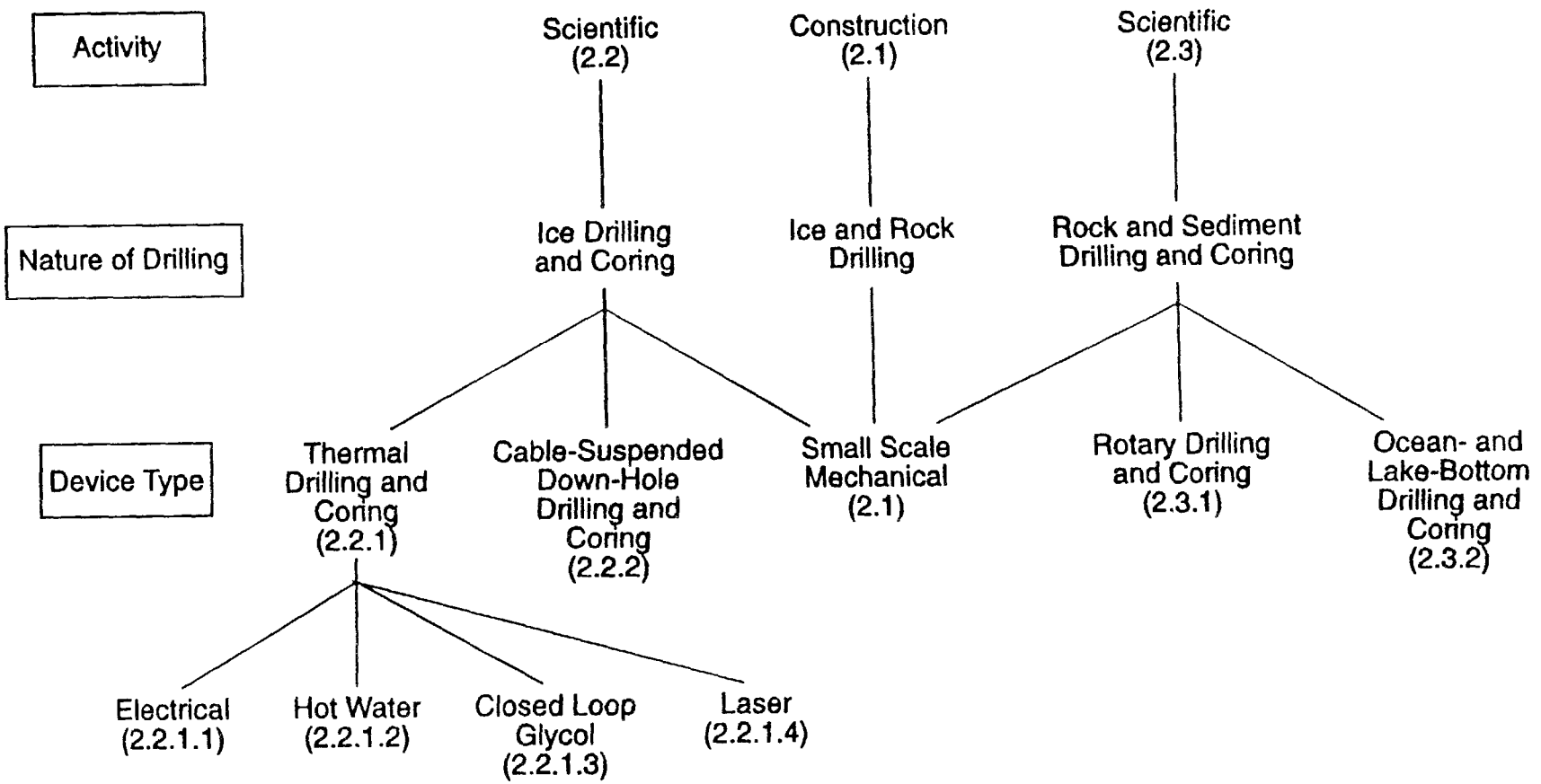


**Fig. 2. Types of drilling and coring systems used in the USAP.**
(Note: Numbers in parenthesis refer to section in text discussing system).

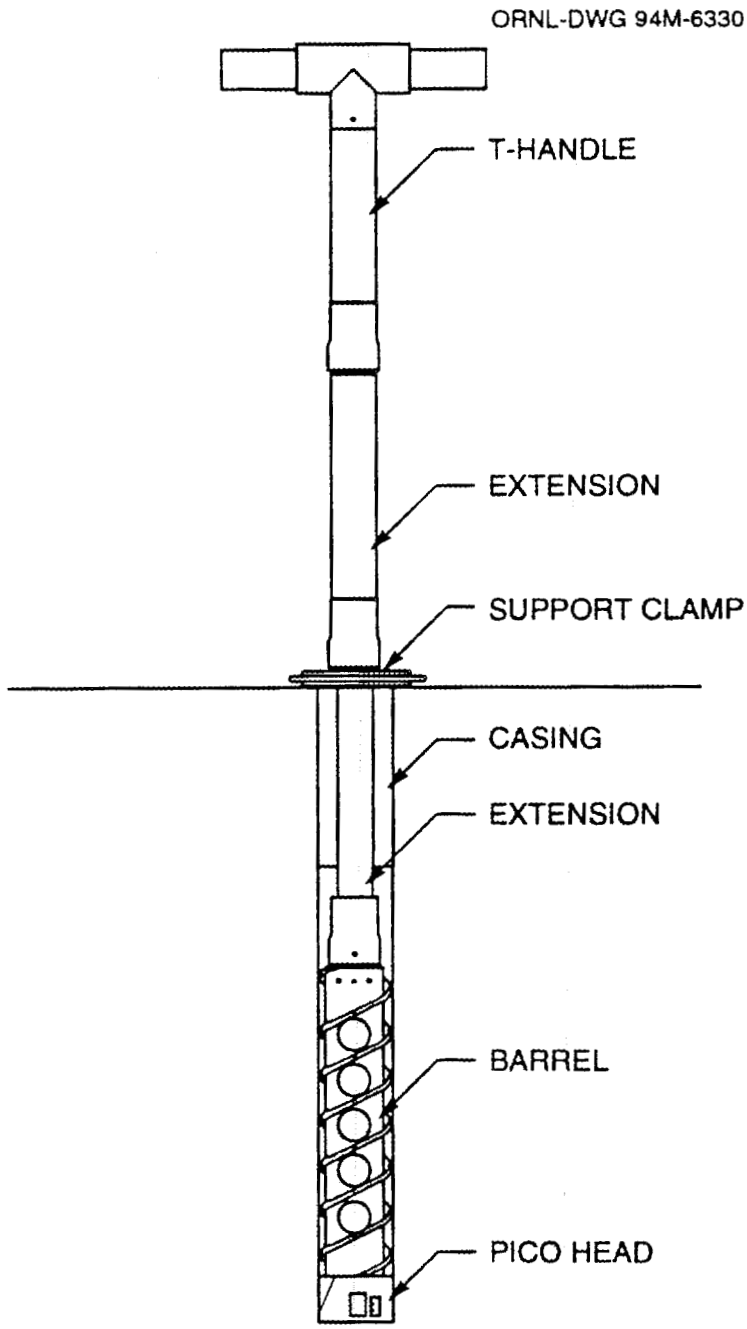


**Fig. 3. Lightweight hand auger with hole casing.** *Source:* Koci and Kuivinen 1984.

their operation is identical to that in milder climates. Characteristics of small-scale mechanical drilling equipment are summarized in Table 2.1.

**Table 2.1. Characteristics of small-scale mechanical drilling equipment used in the USAP**

| Equipment type | Hole/core diameter | Power-fuel | Mode of action |
|---|---|---|---|
| Pneumatic rock drills | 6–7 cm | Pneumatic electric or gasoline engine | Hammer or air hammer |
| Diesel-powered rock drill | 210 cm | Diesel-powered air compressor | Hammer |
| Ice drill/auger ("Jiffy") | 10–25 cm | Gasoline engine | Powered hand auger |
| Ice drill/auger (Reed drill) | 1–4 cm | Diesel vehicle attachment | Hydraulic auger |

Uses include the following:

- collection of samples for environmental analysis, such as contamination of ice by fuels;
- verification of substrate condition before construction or maintenance, such as studies of ice characteristics for blue-ice runways;
- installation of stanchions, antenna anchors, and posts for above-ground utilities (i.e., electric, sewer, water, communications);
- creation of boreholes for blasting; and
- creation of access and escape holes in tunnels.

Small-scale construction drilling can be carried out by one or two people using equipment that can be carried by hand or transported in standard vehicles (trucks, tracked vehicles, or helicopters). Fuel use and attendant emissions result from transportation equipment and small, low-horsepower motors used to power the augers. These construction activities require holes in the substrate ranging from less than 1 m in depth up to 30–50 m. For example, ice coring with a hand-held auger for either construction or research efforts is limited to a depth of about 50 m (Koci and Kuivinen 1984), while samples collected in soil or rock would usually be to a depth of less than 1 m.

The number of drilling activities varies yearly depending on support needs. During the 1993–94 season, the USAP support contractor, Antarctic Support Associates (ASA), planned to drill

approximately 200 holes for stanchion or similar installations and to take about 120 soil and ice cores in the McMurdo vicinity for pollutant analysis. The Cold Regions Research Engineering Laboratory (CRREL) planned to use small-scale drilling of about 70 holes to support tunnel construction at the South Pole Station in 1995.

## 2.2 SCIENTIFIC—ICE DRILLING AND CORING

Of the various drilling systems used for penetrating ice or obtaining cores, thermal methods (e.g, electrical, hot water, or laser and closed loop heated glycol) and electromechanical methods using fluid, involve techniques and problems that are unique to Antarctica.

### 2.2.1 Thermal Drilling and Coring

#### 2.2.1.1 Thermal—Electrical

A thermal electric drill consists of a heating element circularly embedded in the end of a core barrel. When the heated head is lowered into the ice, it melts a circular ring; as it penetrates deeper into the ice, the core being cut moves into the barrel. The heating element is hermetically sealed and pressure tight to 5000 psi. A typical heating element is 0.14 cm in diameter and can provide power in excess of 40 watts/cm$^2$. Heat transfer efficiency is high because the heating elements are in direct contact with the ice. Heat is dissipated in a 10-cm-diameter, 0.63-cm-thick ring fastened to the end of the barrels. The electricity to power the head can be provided by various sources including solar panels.

A variation on this technique that has recently been developed is the antifreeze-thermal electrical drill (ATED) system (Fig. 4). It has been field tested to a depth of over 800 m and can go deeper without freezing up. In addition to the heating element head, a piston is located inside the barrel. As the ice enters the barrel the piston is pushed up and, in the process, forces ethanol out of the cylinder, down passageways in the core barrel, and onto the surface of the drill bit.

Thermal electrical drills have been used successfully to obtain additional ice cores from existing boreholes through directional drilling. A device called a whipstock is inserted into the borehole and is used to mechanically deflect the path of the thermal electrical drill outwards (Fig. 5). This approach allows greater numbers of ice cores and lateral sampling to be performed without the environmental consequences (discussed in Sect. 3) of additional surface disturbance.

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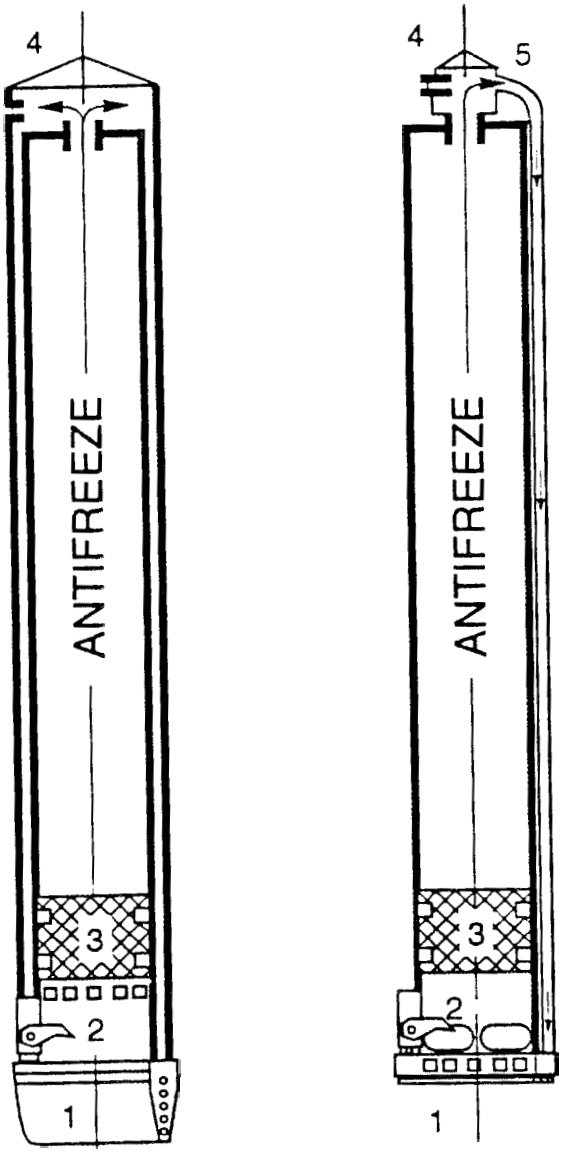


4a

1—Heater bit
2—Core dogs
3—Piston
4—Cable termination assembly

4b

1—Heater bit
2—Core dogs
3—Piston
4—Cable termination
5—Antifreeze bypass tube

fig. 4. Antifreeze thermal electrical drill. *Source:* Zagorodnov et al. 1992.

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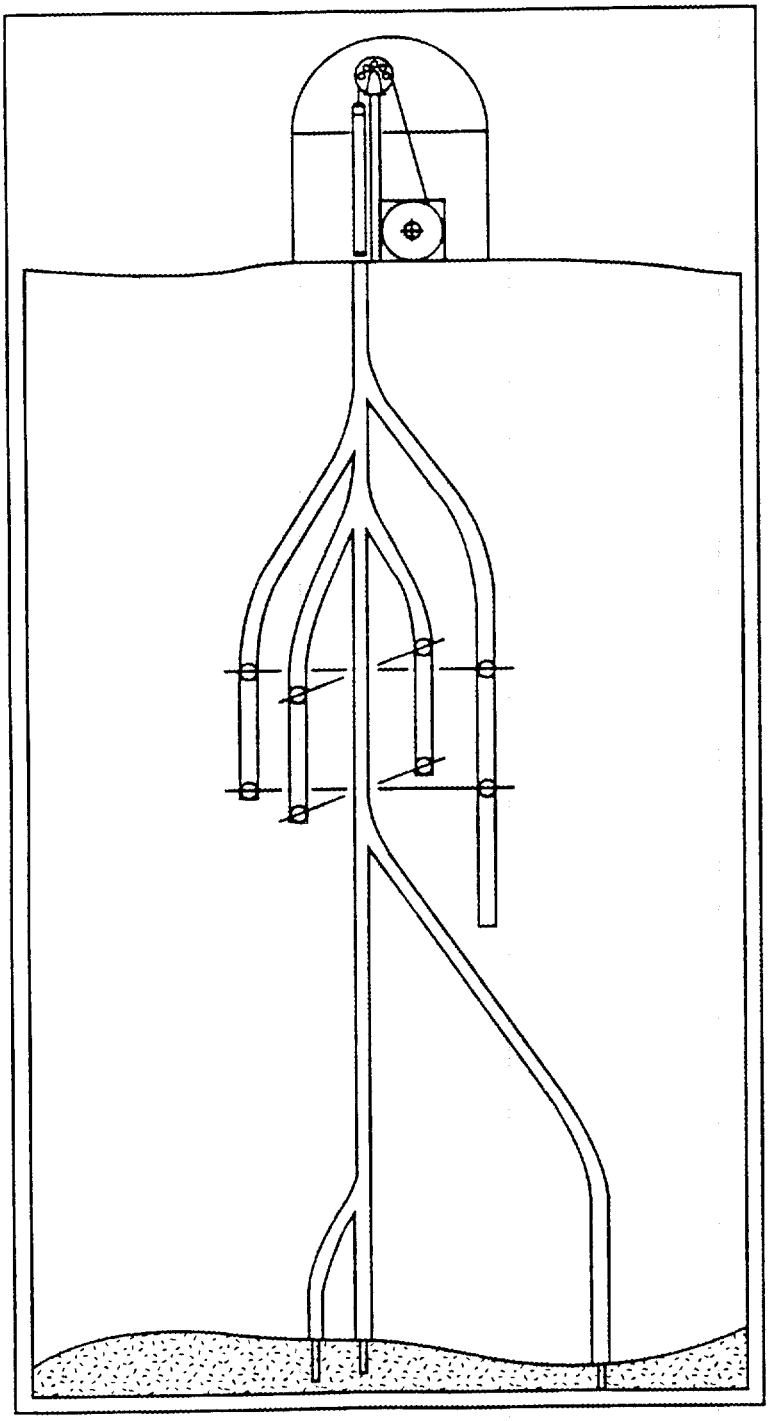

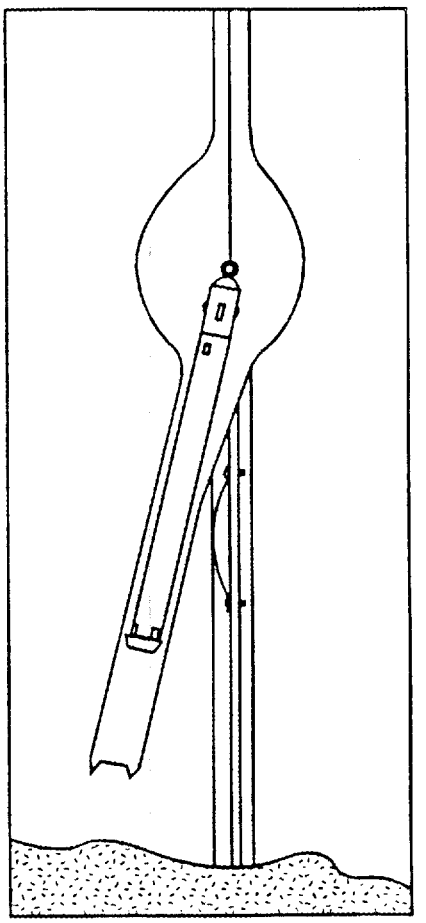

**Fig. 5. Schematic of branch holes created by directional drilling and a directional drill system showing the whipstock device.** *Source:* Zagorodnov et al. 1992.

Thermal electrical drills are useful for obtaining ice cores of shallow to intermediate depths but are considered too slow for coring at depths greater than 500 m. In Peru these drills have been used to obtain ice cores to a depth of 163 m, in China to a depth of 135 m, and in Greenland and Antarctica to depths from 300 to 600 m.

Ethanol is the only drilling fluid used in the ATED system.

#### 2.2.1.2 Thermal—Hot Water

The specific design of hot water systems used for ice drilling varies according to the depth of penetration desired. Hot water techniques are extensively used for shallow holes such as seismic shot holes in the 10–20-m depth range. The technique is also used extensively for situations in which a borehole of greater depth is required for emplacement of various scientific instruments in the ice. Depth ranges of 370–480 m (25-cm-diameter holes) have been achieved through the Crary Ice Rise at the South Pole Station, while 820 and 850 m depths have been achieved by the Antarctic Muon and Neutrino Detection Array (AMANDA) Project. Depths of 1100 m are projected for four holes planned for the AMANDA Project during the 1993-94 season. Borehole diameters required for the AMANDA Project are 50 cm.

For relatively shallow depths, the drill system consists of down-hole hoses and nozzles for spraying hot water, which is provided by sled-mounted car-wash heaters. Instrumentation on the drill stem includes inclinometers, thermistors, and calipers to measure the size of the hole.

For the AMANDA Project, a considerably larger version of the same basic system is used. The instrument package is about 0.9 m long and contains inclinometers, a sonar system, pressure and temperature devices, and calipers. The nozzle system consists of a flat plate spray head similar to a shower head on a length of pipe. The spray head itself is about 10 cm in diameter. Depending on its rate of penetration, the spray head can make holes about 0.5 m in diameter; the nozzle package is about 1.2–1.5 m in length. The unit and spray head are suspended above the bottom of the hole to allow melting of the ice. The interior diameter of the delivery hose is less than 3 cm. More recent systems also have an upper check-valve release: when the unit is removed from the hole the bottom valve at the head closes and an upper one opens to release hot water above the unit, thereby preventing freeze-back and sticking of the unit as it is removed.

In order to heat the water to an exit temperature of 180°F (82°C) diesel-fired car-wash heaters are used in a tandem system with 6 preheaters and 8 main heaters capable of generating 1–1.25 MW. The heated water is then pumped by two diesel driven triplex pumps (40–50 hp) through a winch-

operated hose and down the hole. At the AMANDA Project a 15-m derrick or tower with sheaves is used for the winched hoses and cables. In an effort to reduce the heating requirements, a cold-water reservoir is maintained below firn ice[3] at 80 m. The cold water from this reservoir is then pumped back to the surface and into the heater tanks to supply hot water. Even so, a constant supply of snow must be shoveled into the heater tanks. A typical hot water system is depicted in Fig. 6.

Besides the melted ice water, the only fluids added to the system are ethanol, propylene glycol, or ethylene glycol, which are used to prevent water from freezing in the hoses and pumps when shut-down occurs and to purge the system before adding water. Occasionally, ethylene glycol is used to start the hole for both shallow and deep hot water drilling. For the deep AMANDA holes, ethylene glycol may be put in the completed boreholes to prevent freeze-back before instrumentation can be emplaced. These fluids are only used in areas on the permanently frozen ice sheet, away from biota.

Fuel requirements for heating water and raising and lowering equipment are about 9000 L for a single 1100-m hole. Further details of the drilling system are provided in Morse (1993).

#### 2.2.1.3 Thermal—Closed Loop Ethylene Glycol

Ethylene glycol in a closed loop system is used in lake ice drilling in the Dry Valleys of Antarctica where relatively large diameter holes are required to collect water or allow divers through the ice. This system is used to minimize introduction of foreign substances into the lake where water chemistry and microbiology are being studied. The thickness of ice to be penetrated is generally 3–5 m. The equipment used is a closed loop consisting of ethylene glycol in copper tubing attached to a heater and circulated by a small motor. The tubing system is commonly known as the "hot finger." Initially, a pilot hole is mechanically drilled through the ice to water, and the heated glycol tubing is inserted. Holes used for water collection (0.6-m-diameter) are made in this manner, and a larger closed loop system is used to create 1.4-m-diameter holes. No drilling fluid other than ethylene glycol in the closed loop is used in this system.

#### 2.2.1.4 Thermal—Laser

Field experiments using an infrared carbon-dioxide laser to cut ice cores have been conducted in Antarctica, but the system has not yet been developed to the prototype stage. This system produces an infrared laser beam that melts an annulus in ice, thereby producing a core (Zeller et al. 1991). The

[3]Firn ice—snow partially consolidated by thawing and freezing but not yet converted to glacial ice.

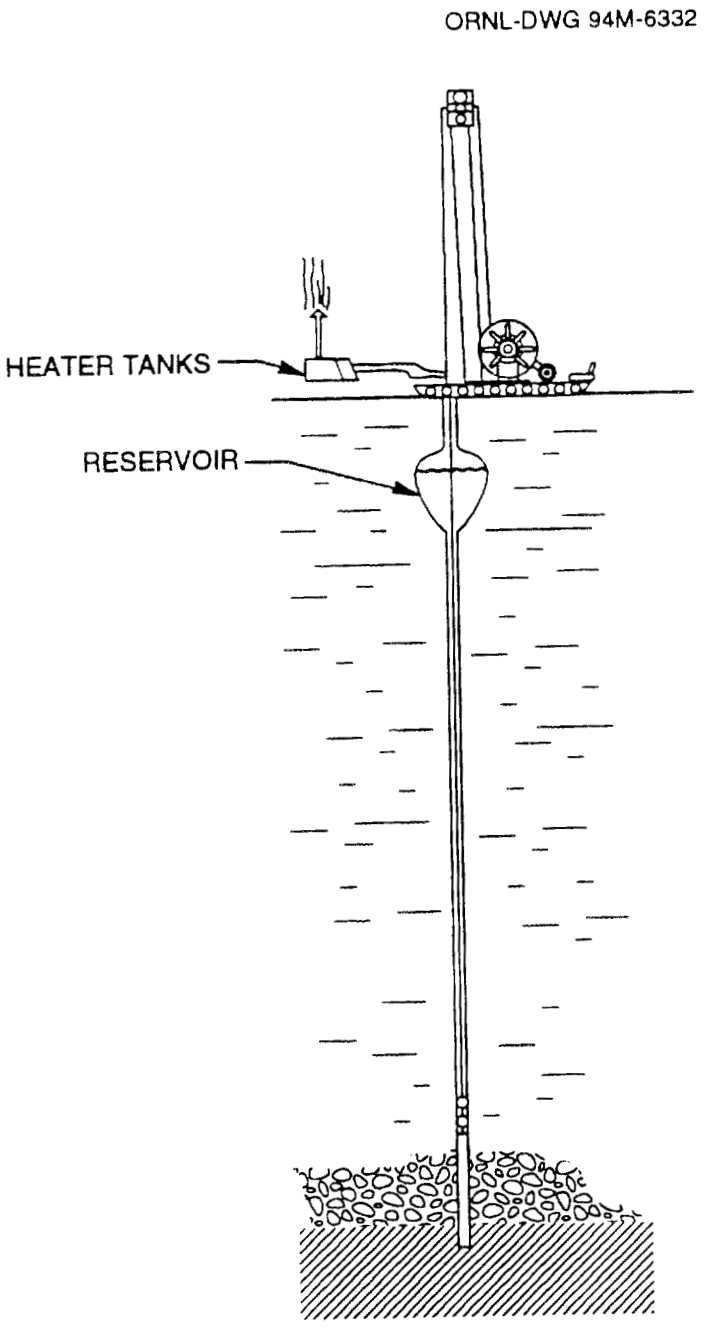


**Fig. 6. Hot water system.** *Source:* Proenza et al. 1990.

device uses a laser mounted vertically in the borehole on a rotating head with deflecting mirrors so that the beam can be directed downward against the ice (Fig. 7). The head is turned in a circle by a small, low-power DC motor to make a circular cut. Water developed in the annulus cut by the beam is removed by a small scavenger pump and transferred to a holding chamber at the top of the core barrel. It would be necessary to empty the tank each time the core barrel was withdrawn from the hole. The device would be constructed with two thin-walled concentric tubes with the space between the tubes used to contain the wave-guide fiber and the vacuum line to the pump. The laser beam would be redirected by mirrors at the bottom of the core barrel to cut the ice and retrieve the barrel. The power requirement, including that needed for lifting the equipment (ca. 90 kg) into place, is approximately 3 kW. This system could potentially be used in both open holes and in fluid-filled (deep) holes. Using this method, spills and emissions would be limited to small amounts of fuel used to power small pumps and motors; very small quantities of carbon dioxide used in creating the laser beam might also be released.

### 2.2.2 Cable-Suspended Down-Hole Drilling and Coring

Cable-suspended, electrically driven ice coring systems powered with a down-hole motor and using fluid are presently used for most deep ice coring (Fig. 8). While it is possible for the suspended down-hole motor to be hydraulically driven, no such working system is known to be in operation. The depth of penetration of the system would be limited only by the length of cable used to provide power to the down-hole motor system and to retrieve the down-hole unit. All deep ice coring, however, requires a drill fluid in the borehole during operation in order to keep the hole open and to compensate for the hydrostatic pressures acting to close it; the fluid also aids in ice chip removal and in dampening vibration of the drill/coring system. Additionally, in all deep ice core drilling, the fluid used for the operation is always left in the borehole upon its completion.

In cases where silty ice or till material is encountered or bedrock is reached, the down-hole 13-cm coring package used to core the ice is replaced with a cable-suspended rock coring drill (Fig. 9). The well screen sections are removed along with the large diameter core barrel and replaced with a weighted drive section and small diameter, diamond-tipped core barrel. This approach was successfully used in Greenland to retrieve a 1.5-m bedrock core at a depth of over 3050 m.

Fluids used up to the present may be categorized by whether or not a densifier is required to increase the density of the drill fluid to make it closer to that of the surrounding ice. N-butyl acetate (NBA) does not require a densifier and has been used successfully in the Greenland Ice Sheet

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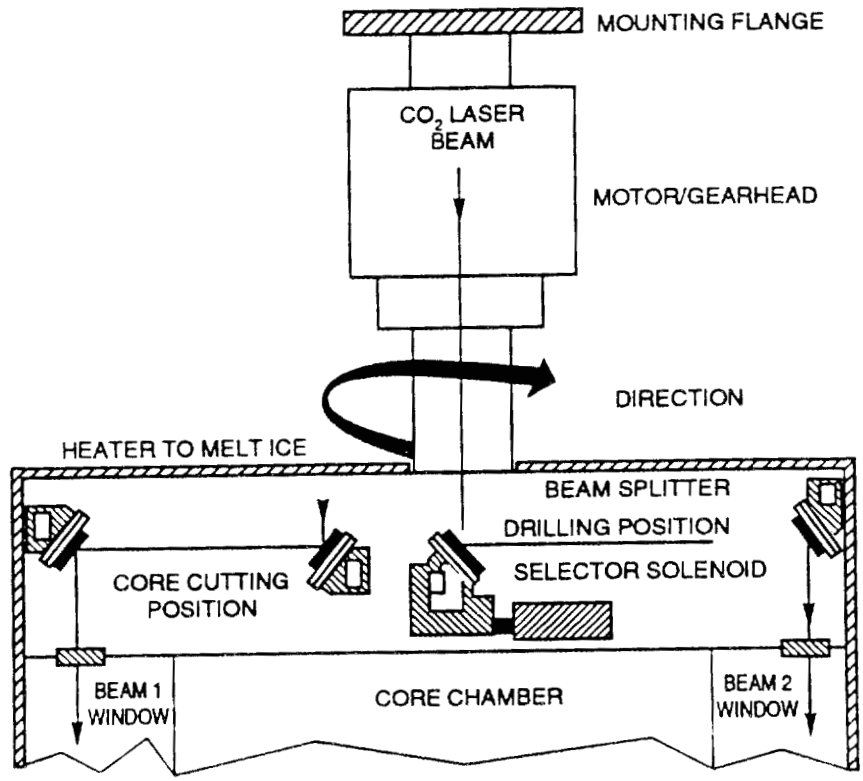


**Fig. 7. Typical design of a thermal laser system barrel.** *Source:* Zeller et al. 1991.

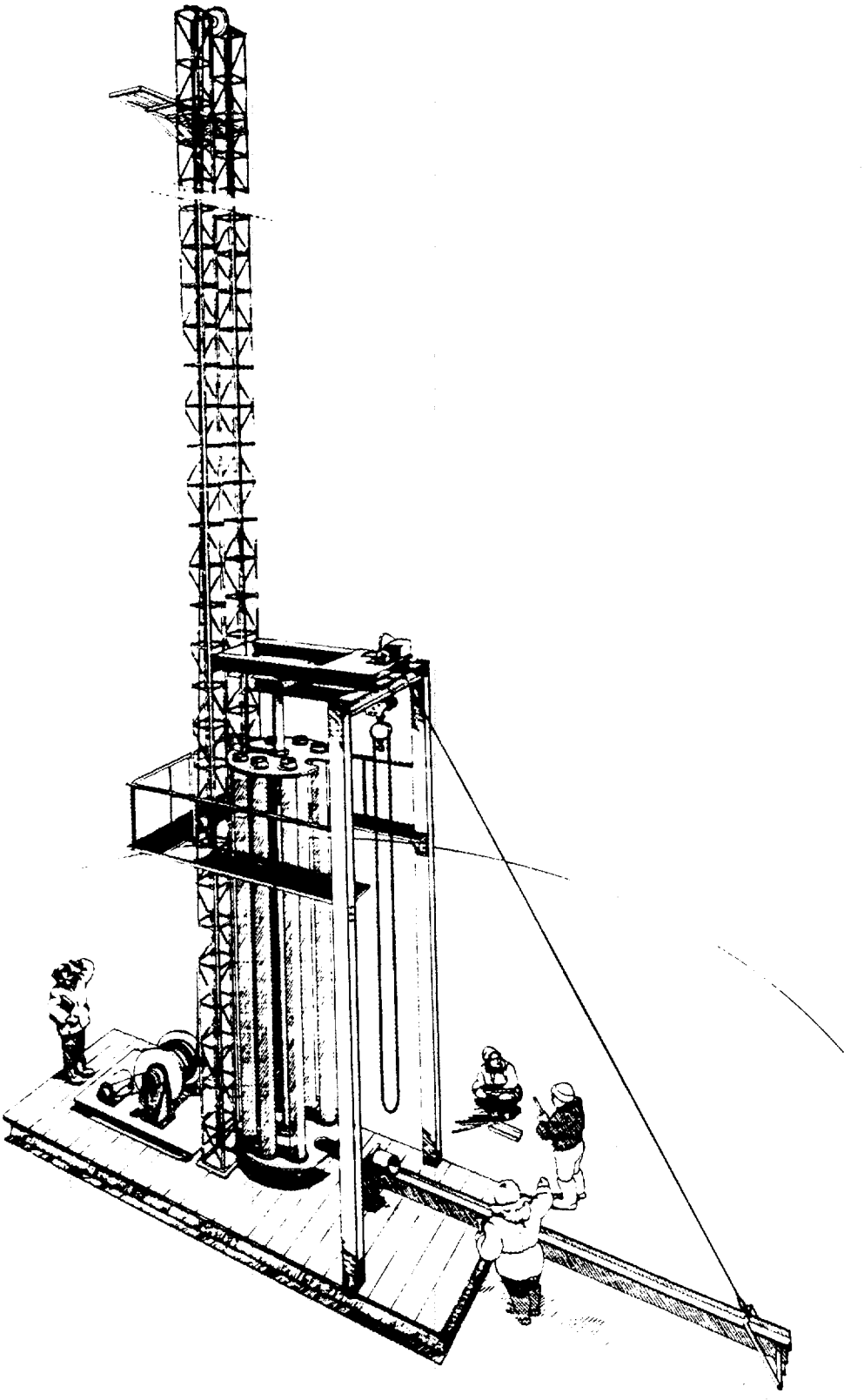

**Fig. 8. Typical cable-suspended down-hole drilling and coring rig.** *Source:* Proenza et al. 1990.

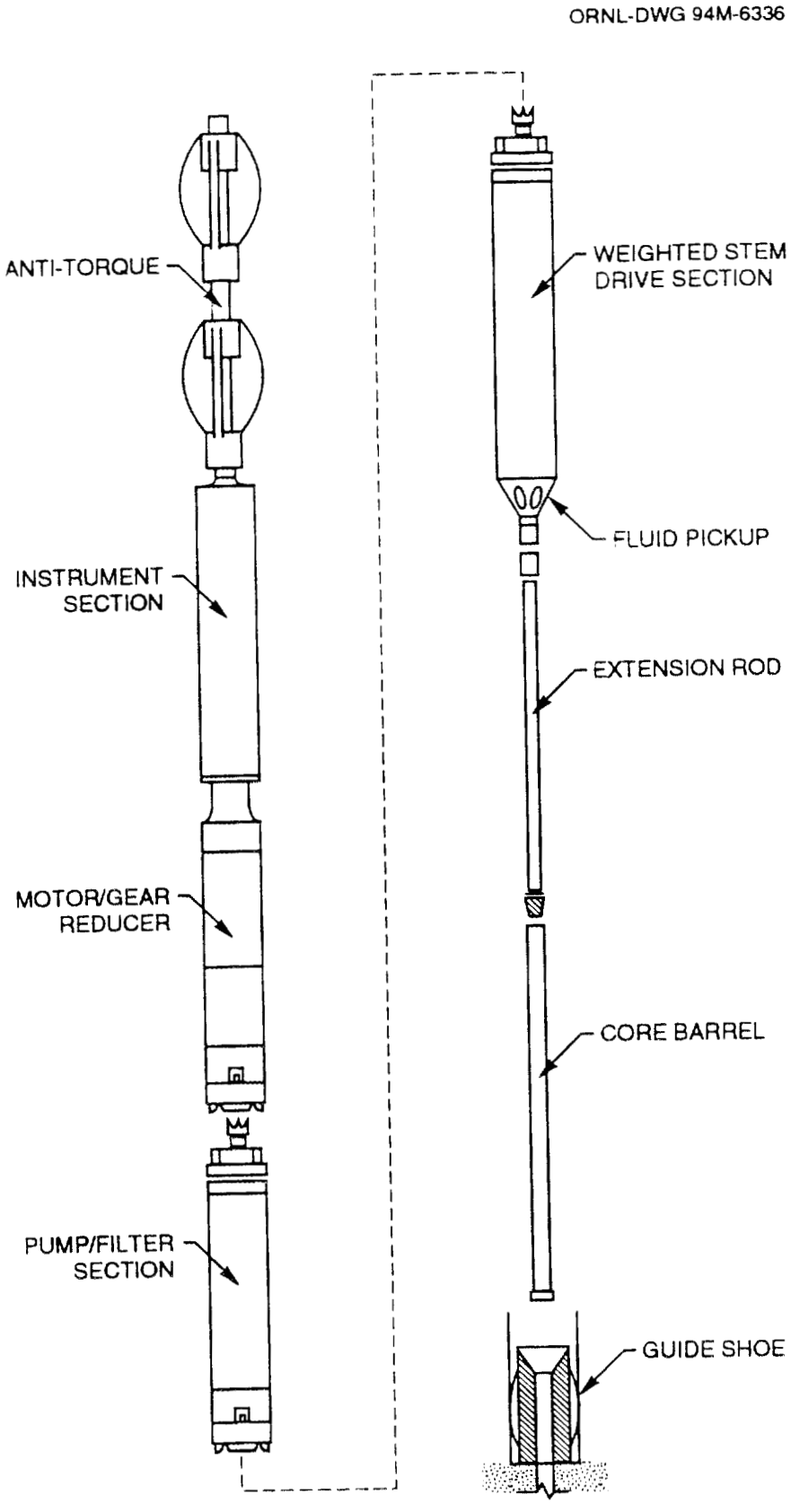


**Fig. 9. Rock coring drill.** *Source:* Figure supplied by the Polar Ice Coring Office.

Program (GISP) 2, coring to a depth of 3053 m. It will also be used in the 1993–94 season at the McMurdo Dome Project for coring to a depth of 600–700 m. Densifiers include trichloroethylene (TCE), tetrachloroethylene (PCE), and trichlorofluoromethane (CFC-11). Fluids used with these densifiers include kerosene; diesel fuel, arctic grade (DFA); and jet propulsion fuel grade 4 (JP 4). The ongoing Russian-US-French Vostok (Fig. 1) research project, presently at around 2700 m in depth, is using kerosene with a 10% concentration of the halogenated solvent CFC-11. After the mixture of CFC-11 and kerosene is in the hole, the borehole is capped with a layer of pure kerosene to minimize the loss of CFC-11 to the atmosphere by evaporation. All four previous Vostok holes drilled by the Russians used a very similar fluid combination, as did the European Greenland Ice Core Project (GRIP), which drilled to 3028 meters in 1992. Further details of the project are provided in Saltzman et al. (1993).

Environmental concerns (i.e., consequence of drilling fluid residual on the Antarctic environment) and the cost associated with providing the fluids makes fluid recovery highly desirable. A wiper-squeegee is used at the borehole casing exit to remove as much drill fluid as possible from the cables as the drill is being retrieved, and the drill tool is hung in the casing for several minutes to allow as much fluid as possible to drip back into the hole. Drip pans are used beneath the hoisting and lowering winch drum and below the cable and drill when they are suspended in the rig's drill tower. Further, during the process of recovering the ice chips from the core drill, the ice cuttings are centrifuged to remove and recover adhered fluid. The overall recovery of the drill fluid in cable-suspended drilling is estimated at 80% (Koci and Kuivinen 1984). At locations where the borehole is anticipated to be in the more permeable firn ice, steel casing is set to prevent diffusion of the fluid. Extensive recovery of drilling fluids as well as the small amount of residual fluid (338 L per year) preclude long term impacts occurring (Koci and Kuivinen 1984). It should be noted that the United States does not use CFCs in drilling operations.

GRIP, GISP-1, and presumably the Russian Vostok boreholes in Antarctica all used an electromechanical drill (i.e., basically an electrically driven down-hole motor coring system). At GRIP the drill package was 11 m long and was lowered down the hole on a thin steel cable. The core diameter was 10 cm and the typical core length recovered in one run was about 2.5 m. At the surface, the drill tower could be tilted to a horizontal position to facilitate the extraction of the core and prepare the drill for a new run.

The McMurdo Dome ice coring operation plans to use NBA as a drill fluid. The ice coring drill is similar to that used at GISP-2, consisting of a 6-m-long core barrel followed by a pump system to circulate ice chips and fluid back to two 6-m screened filter systems for storing the ice chips for fluid

retrieval. The system also includes a DC motor with gear reducer, instrumentation and switching section transformer, and an antitorque system. Its overall length is approximately 22–29 m long. The instrument section monitors depth, inclination in two axes, azimuth, fluid pressure and temperature, motor current, and cable tension. Because NBA caused cable and motor deterioration problems in the GISP-2 Project, the McMurdo Dome drill is suspended by a Kevlar cable with embedded wires.

## 2.3 SCIENTIFIC—ROCK AND SEDIMENT DRILLING AND CORING

More extensive rock and sediment drilling and coring is likely to occur in future scientific investigations in Antarctica. The techniques and systems employed will not be unique to Antarctica or substantially different from those already in use elsewhere. On land, shallow rock and sediment drilling and coring will include the same tools and small rigs already in use and except for a few techniques (e.g., the paleomagnetic coring discussed below), they will not require a drill fluid. For deeper drilling, conventional rotary drilling with a saltwater-polymer mud and a wireline coring system is used. In wireline coring, the necessity of pulling the drill pipe from the hole to recover each core is eliminated as the coring device is lowered and raised each time on a wireline inside the drill pipe. Other deep drilling in the open ocean that may be undertaken by NSF's Ocean Drilling Program is not addressed in this report.

The Pomeroy rock coring device, for paleomagnetic studies, is a specialty rock drill used on a limited basis to obtain small, 10-cm rock cores. The coring tool uses a chainsaw motor and a small diameter diamond-impregnated steel core bit to obtain a 2.54-cm diameter core. Ethylene glycol, used as a coolant-lubricant for the bit, runs out on the ice and is not recovered. It is estimated that about 11 L of ethylene glycol is used to drill 40 cores.

### 2.3.1 Rotary Drilling and Coring

Rotary drilling using a saltwater-polymer mud mixture and conventional wireline coring is proposed at several locations at Cape Roberts for 1995 and 1996. Borehole sites would be located on fast ice at water depths of 50–500 m; the thickness of the fast ice platform would be greater than 1.5 m. Drilling would require a riser system to allow for drill fluid recirculation and to bridge the gap between the sea bottom and the fast ice platform. Two options exist for the system. The first would be a multicasing riser similar to that used in the Dry Valley Drilling Project in the

southwestern Ross Sea and the Cenozoic Investigations in the western Ross Sea (CIROS). The second option would be a single tensioned casing with a sea floor guide.

Drilling would be carried out using a skid-mounted rig and wireline diamond bit coring system, similar to that used for the CIROS boreholes. Cores would be cut by a Christensen type core barrel system with the inner core tube retrievable through the drill string; the drill rods would remain in the hole until the core barrel's bit needed replacement.

The drilling fluid would be a 3% potassium chloride (KCl), seawater based, nontoxic polymer mud. The 3% KCl would be added to increase mud weight, lower the freezing point of the mud, retard loss of water from the mud into the borehole walls during drilling, and improve bore stability. The system, manufactured by Baroid, is known as EZ MUD and is similar to that used in CIROS. Additives [including nontoxic polymers based on plant extracts, plant products (walnut shells), sodium bicarbonate (baking soda) sodium carbonate (soda ash) and mica] may be added to alter various mud properties as needed. Toxic polymers based on hydrocarbons would not be used. Cuttings produced during coring and the water-based drilling fluid would be discharged to the ocean floor. This practice is an accepted procedure in off-shore drilling in the United States, unless restricted by National Pollutant Discharge Elimination System (NPDES) permit.

Detailed geophysical surveys have been made of the site, and, through a screening process similar to that used by the Ocean Drilling Program, locations have been selected to avoid the potential for encountering high pressure gas zones, basement faults, or closed geologic structures. Use of the mud system during coring allows rapid control by increasing mud weight if methane gas or other signs of overpressure are encountered. In addition, standard safety precautions developed by the petroleum industry would be employed to monitor entrained gas in the mud system. Indications of a decrease in drill string weight may indicate that an abnormally overpressured zone has been encountered.

### 2.3.2 Ocean- and Lake-bottom Drilling and Coring

To obtain soft bottom cores from various depths of water, sediment coring is performed by piston (Fig. 10) and gravity coring (Fig. 11) devices or by vibrocoring (pneumatic, hydraulic, or electric powered) (Fig. 12). In order to obtain hard-rock seafloor cores, especially from deep ocean bottoms, over-the-side remotely operated rotary drills are being employed (Fig. 13). These drills are in the early stages of development and utilize an open circulation of sea water to remove drill cuttings from the borehole.

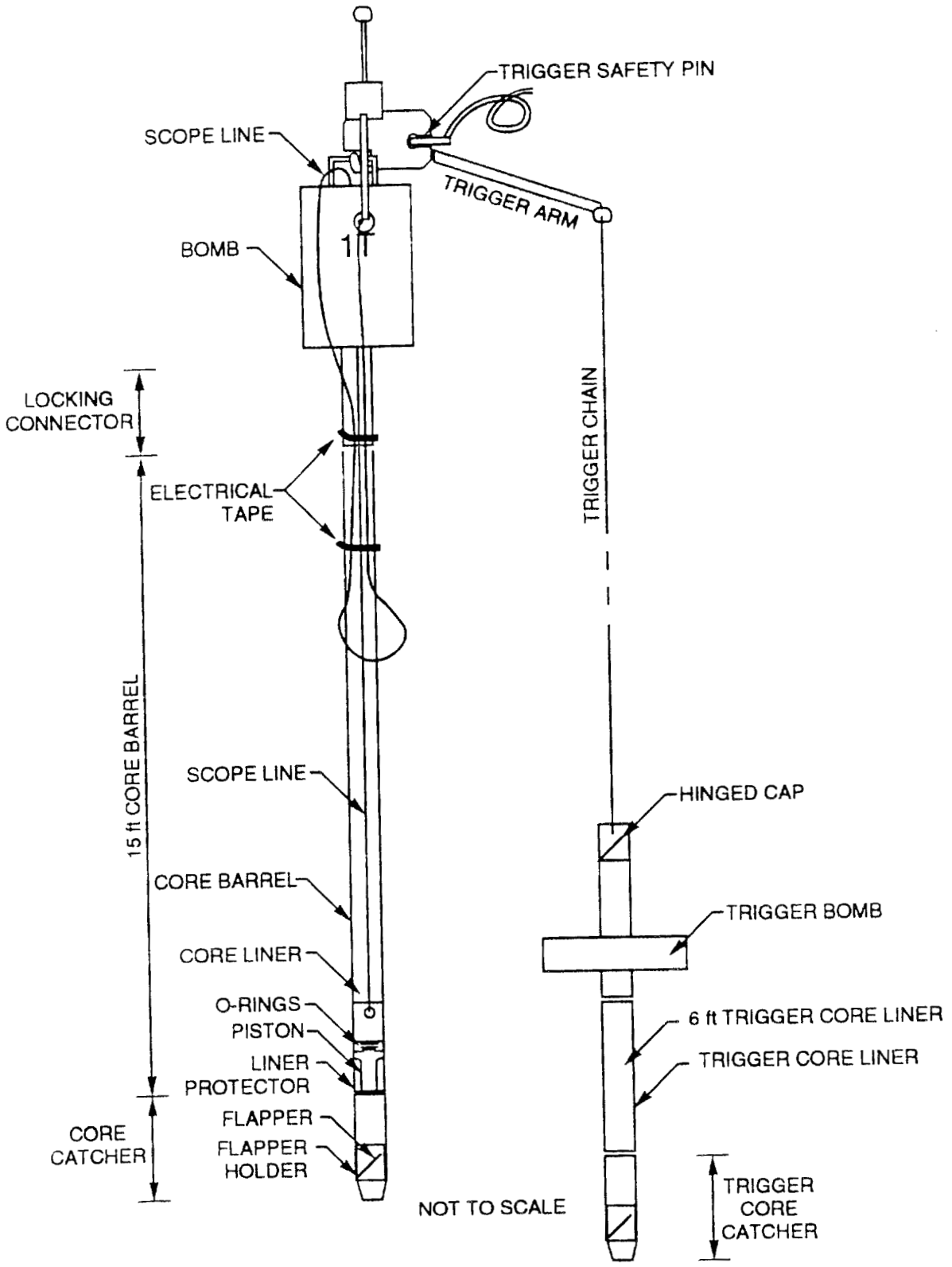


**Fig. 10. Piston coring rig.** *Source:* Sloan 1993.

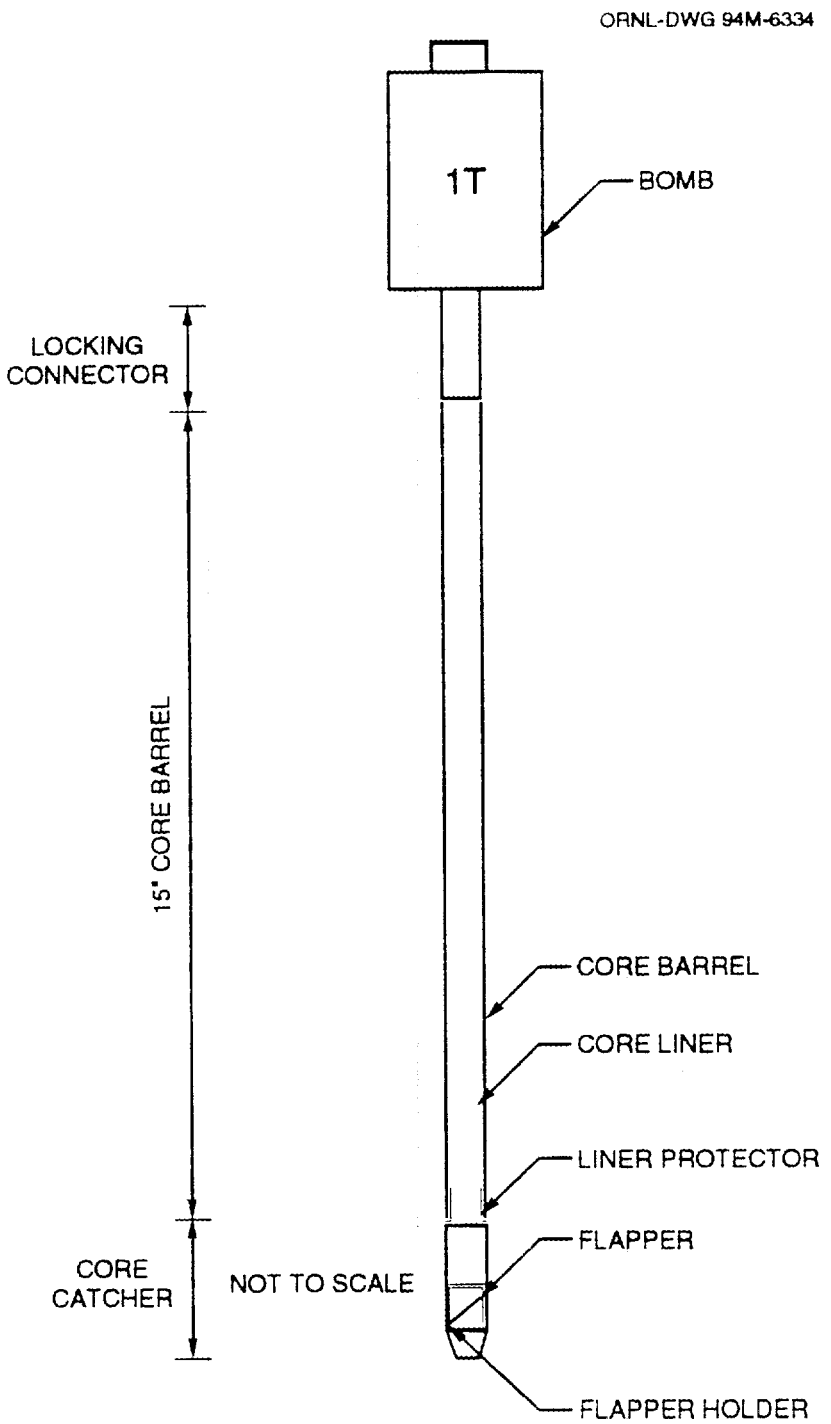


**Fig. 11. Gravity coring rig.** *Source:* Sloan 1993.

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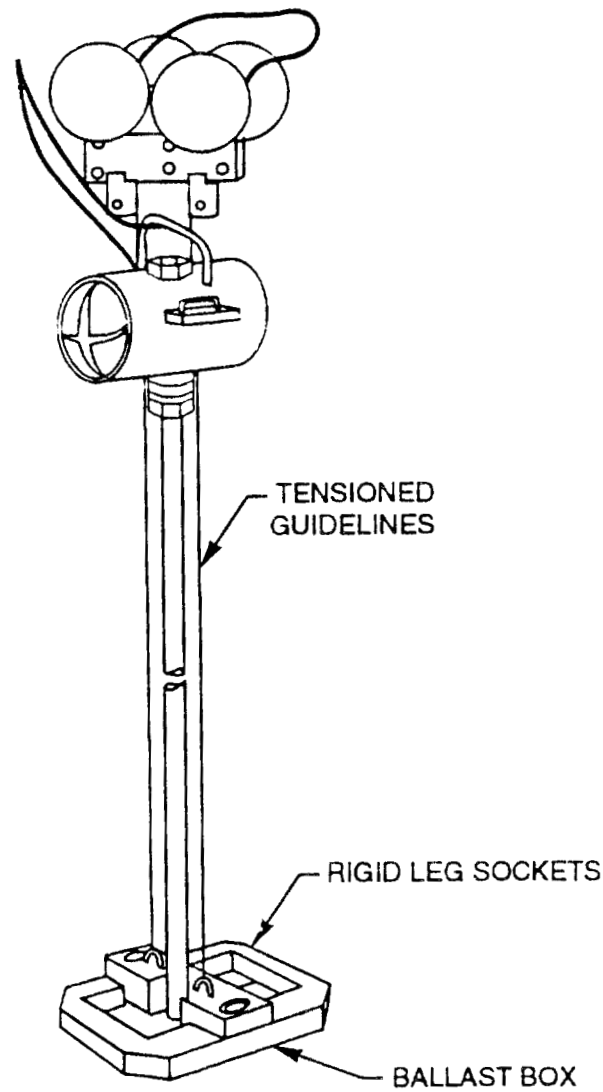


**BUOYANT FRAME MODE**

**Fig. 12. Electric powered vibrocoring rig.** *Source:* Rossfelder 1992.

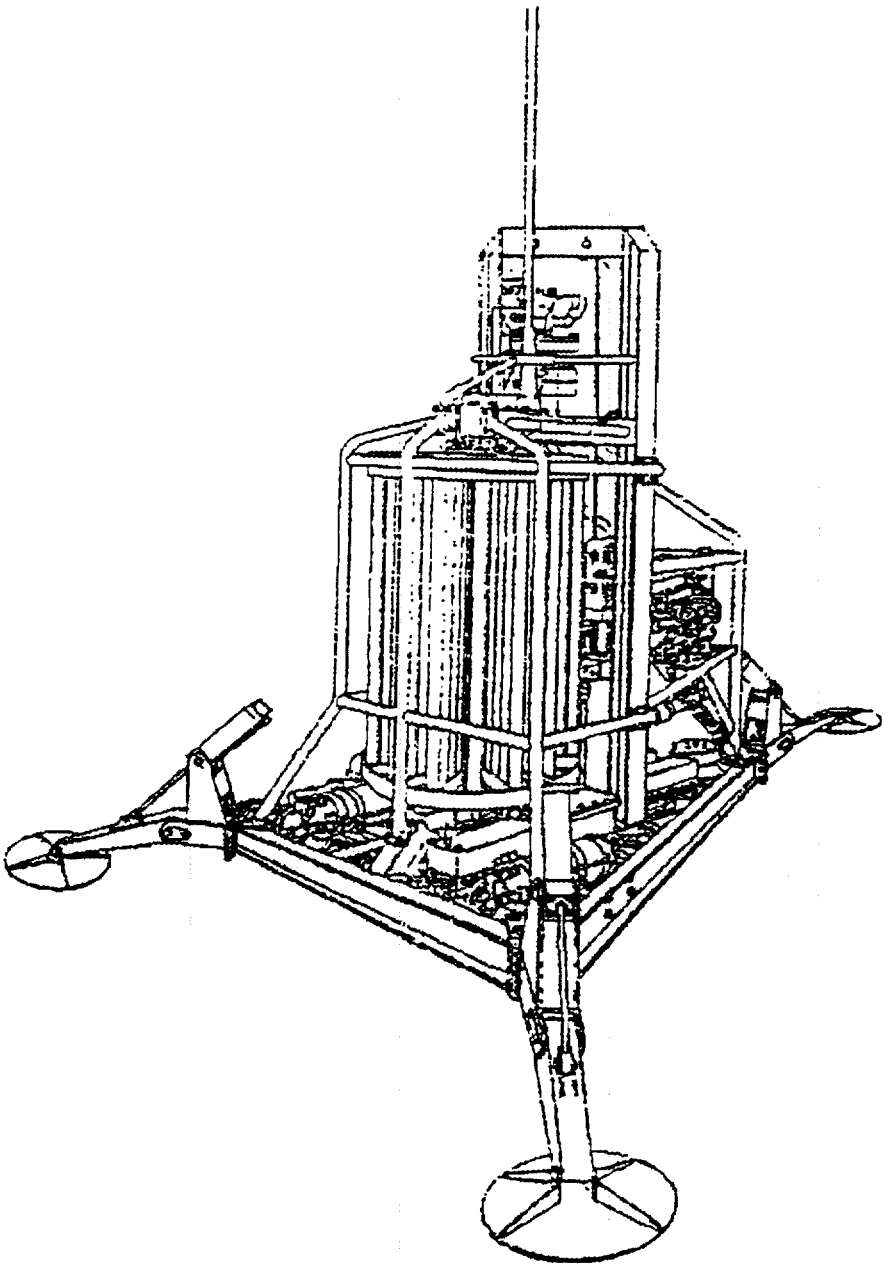

**Fig. 13. Remotely operated drill rig.** *Source:* Williams and Associates 1993.

## 2.4 SUPPORT FACILITIES FOR DRILLING

Large scientific drilling projects typically require support facilities and transportation support for several people. For example, drilling at McMurdo Dome in 1993–94 (Sect. 2.1 and 2.2.2) entailed establishing a remote camp for up to 11 scientific and 10 drilling personnel. An undertaking of such magnitude requires the following support:

- LC-130 aircraft support (up to 140 h);
- one Tucker tracked vehicle;
- several snowmobiles;
- one 931 Caterpillar tracked loader;
- tents, galley hut, generator shack (2), shower and laundry facility;
- several generators (5–60 kW);
- heater units; and
- food, fuel, and lubricants.

Similarly, for the proposed Cape Roberts Project, about 35 people would be required in the support camp for drilling (12 people), support (10 people), and science (13 people). Transportation of personnel to the camp via helicopter or ground transport from a permanent base station (e.g., Scott Base/McMurdo Station) would be required as well as ground transport of personnel to and from drill sites on the ice shelf. Equipment and supplies also would be moved overland from a permanent base or via helicopter from a ship. Annual fuel use would be about 11,000 L each for transportation and camp. The camp would be occupied for several months each year over 4 years. Facilities include those listed in Table 2.2.

**Table 2.2. Buildings required for Cape Roberts Project support camp**

| Prefabricated (rigid) buildings | Dismountable buildings |
|---|---|
| Galley (1) | Mess (1) |
| Laundry/bathing (1) | Sleeping (8) |
| Generator (1) | Recreation (1) |
| Standby generator (1) | Workshop, store (2) |
| Water-making unit (1) | Science (2) |
| Total: 5 | Total: 14 |

*Source:* Barrett and Davey 1992.

# 3. ENVIRONMENTAL CONSEQUENCES

The environmental consequences of drilling in the antarctic region are discussed in this section with regard to the technologies employed, as discussed in Sect. 2. In general, impacts are small and are related to the size of the base camp and other support facilities and operations; the depth, magnitude (number of holes), location, and duration of drilling; the amount of fuel burned; and the technology employed. For example, the draft CEE for the proposed stratigraphic drilling at Cape Roberts (Keys 1992) concluded that (1) the adverse environmental effects of the proposal would be small or insignificant in relation to the potential advantages to scientific research and knowledge, and (2) the most severe and lasting impacts would be a consequence of support activities rather than effects of drilling *per se*. Moreover, the impacts of the Cape Roberts drilling, though small, would be greater than for many other drilling projects because it would occur on the continent's edge, where marine biota are present. Drilling undertaken in the interior is unlikely to affect living organisms.

The impacts of greatest concern resulting from drilling itself have to do with fuel emissions and the characteristics of any drilling fluids used. Effects of drilling fluids are particularly important if fluid is to be left in the hole or if many deep holes are to be drilled. Larger drilling operations using drilling fluids are also more likely to experience spills. Efforts to minimize environmental impacts (Sect. 4) should center around spill prevention and control, fuel minimization, waste handling and minimization, and thorough postproject removal of support facilities and site cleanup.

## 3.1 GEOLOGY, SOILS, AND ICE

By its nature, drilling of any kind entails impacts to geology, soils, or ice because these materials are removed and, in some cases, replaced with others. Drilling for construction and support activities in existing stations generally takes place in environments already heavily disturbed by extensive and continuing human activity. The materials disturbed or removed are small both in comparison to disturbance from other normal ongoing activities (e.g., vehicular traffic, construction, blasting, and waste disposal) and in comparison to the surrounding undisturbed environment.

Drilling for research may involve depths up to several thousand meters. Despite the depths, the diameter of the holes or cores (generally 10–50 cm) is such that the material removed is small in any context. For example, a single hole for the AMANDA Project (Sect. 2.2.1.2) of 50 cm diameter and 1100 m depth would remove about 220 $m^3$ of material (ice). The presence and operation of relatively large drilling systems and support camps causes local physical and chemical changes due to the

presence of buildings and equipment, human activities, equipment emissions, and drilling fluids (when used). Most such impacts are common to all research activities in Antarctica and are localized, minor in areal extent and severity, and usually transitory—i.e., the effects are undetectable after several seasons—if proper waste handling and cleanup is conducted. The frequency of such impacts both locally and over the continent is much less than that of conventional drilling in the United States. Exploratory and production drilling for petroleum, geothermal energy, water, and other resources is far more common and extends into remote areas of the United States and offshore. For example, over a 20-year period, over 18,000 oil wells were drilled in U.S. waters (Zumberger 1981), and spill incidence from these wells was less than 0.1%.

Impacts unique to drilling result from the use of drilling fluids. Ice drilling and coring requires heated water with or without ethylene glycol as an antifreeze. Other drilling fluids that have been or are being used include NBA, aqueous ethyl alcohol, ethylene glycol in either an open or closed-loop system, DFA, and kerosene with densifiers. For geological drilling, fluids include minor amounts of glycol (used in paleomagnetic rock coring), bentonite or polymer mixtures suspended in salt water, or petroleum-based liquids. The drilling fluid NBA, which was used at McMurdo Dome and will probably be used in future drilling efforts, is intentionally left in the hole so it will remain open for future investigation. Little fluid leaching occurs because NBA is only slightly soluble in water (0.7%) and water is only slightly soluble (1.6%) in NBA (Gosink et al. nd). Because of the movement of the ice, fluid in the hole will eventually reach the sea after a period of many thousands of years (Sect. 3.3).

Environmental risks from drilling operations include accidental spills of hazardous fuel and drilling fluids or disposal of cuttings that can have local physical or chemical effects on geological substrates (i.e., soil, ice, sediment, or rock). Given the low frequency and magnitude of current and anticipated drilling, these effects would be very small both absolutely and in comparison to existing contamination at established antarctic stations. However, they could occur in remote, previously undisturbed locations, very slightly decreasing the pristine character of the continent. Perhaps the greatest concern associated with such impacts would be possible adverse effects on future science efforts in the same location (see Sect. 4). For some research drilling, instrumentation is installed with no intention of retrieval. For example, the AMANDA Project involves installing and leaving photodetectors in ten 50-cm-diameter holes in the ice. In addition, drilling equipment can become lodged or frozen in drill holes and have to be abandoned in place, eventually reaching the sea. A drill head was lost in this way during the first year of drilling for the AMANDA Project. Because the

number of drilling projects and the size of down-hole equipment are small, any effects from their continued presence should also be small.

## 3.2 INLAND WATER RESOURCES

The possibility of impacts to inland water resources from drilling occurs only in the Dry Valley region where water is found under the frozen lake surfaces (Fig. 1). Holes are melted in the ice surface at established seasonal research sites in the Dry Valleys using hot water or ethylene glycol in a closed loop system. Fuels, glycol, or other fluids which inadvertently enter the lake water could affect lake biology (Sect. 3.3) or alter water chemistry. The closed loop ethylene glycol drilling system is preferable to open holes using fluids (even water) because introduction of foreign materials into the water column is minimized (Sect. 2.2.1.3).

## 3.3 BIOTA

Most drilling in the antarctic occurs inland on the ice sheet where interactions with biota are impossible or unlikely. There is a greater likelihood of impacts from activities at coastal stations (Palmer and McMurdo), on the sea ice, or in Dry Valley lakes (aquatic micro-organisms). Effects at established stations would be a small part of the total effects of station occupancy.

For studying the under-ice environment, drilling holes in the sea ice is the method of choice because effects are less than those of alternative methods such as blasting. Nevertheless, the operation of a mechanical drilling device for creating such holes produces temporarily high noise levels. In some cases, noises on the ice have been shown to attract seals and penguins, which by nature are very curious animals (Dr. J. W. Testa, University of Alaska at Fairbanks, Institute of Marine Science, personal communication to J. T. Ensminger, Oak Ridge National Laboratory, Oak Ridge, Tenn., October 1992). In other situations, loud noises can disturb or frighten the animals, interfering with their normal behavior (e.g., reproduction) and resulting in a "taking" which would require a permit under Protocol rules (see footnote 1 on page 1).

Mechanical drilling operations may also introduce very small quantities of hydrocarbons into the water column. Spills of fuel and ethylene glycol in Dry Valley lakes could adversely affect algae and other micro-organisms in the lake. In addition, the introduction of hydrocarbons or other substances could interfere with water chemistry tests.

The expected impacts on biota of deep stratigraphic drilling in or near marine environments such as those planned near Cape Roberts in the Ross Sea [Keys (1992)], are as follows:

- disturbance of bird and mammal communities from noise, exhaust, and human presence in the vicinity of the support camp;
- destruction of terrestrial vegetation such as mosses and invertebrates through flattening, compaction, or contamination in the vicinity of the support camp;
- possible contamination of fast-ice biota from spills of fuel or drilling fluid;
- local damage to sub-ice plankton communities from loss of drilling fluid (a maximum of 5000 L) or fuel;
- local damage to benthic and seafloor communities from drill cuttings, cemented casings, and drilling fluid (a few tens of square meters around each drill hole);
- minor additions of nutrients to the nutrient-rich antarctic waters from inputs of human waste and washing water; and
- unlikely but possible destruction of terrestrial biota and damage to marine communities from a large fuel spill or transportation accident.

Historically followup studies have not been conducted on the impacts of past drilling operations. However, keys predicted that the most severe and lasting impacts to biota would result from support activities and human presence rather than drilling *per se*. These potential impacts to marine biotic communities could also occur on a much smaller scale from over-the-side ship-based operations (Sect. 2.3.2). Piston and gravity coring have the least environmental impact to marine communities because the mechanism for obtaining the soft sediment core is based on a spring loaded, free falling weight which forces a coring tube into the sea floor. No fluids are used, and the only contaminants are associated with the ship supporting the coring device.

Drilling at interior sites, such as McMurdo Dome and the South Pole, could lead to small quantities of equipment and material being carried into the sea by the ice movement over many thousands of years. Equipment would quickly sink and the metallic parts would corrode, but plastic tubing could endure for many years. Chemicals might include very small quantities (a few liters) of petroleum products and larger, but still small quantities (perhaps several thousand liters) of NBA or other fluids remaining in drill holes.

NBA is only slightly soluble in water (0.7%), evaporates quickly (one to three days), is relatively non-toxic (acute danger to human health at 10,000 ppm), and is biodegradable to relatively harmless

acetic acid and butanol and ultimately to oxides of carbon [Gosink et al. (no date); Grootes and Burton 1993]. It is therefore unlikely that NBA would cause any detectable effects to marine life.

Kerosene and CFC, used in the ongoing drilling at Vostok (Sect. 2.2.2), also have the potential to adversely affect living organisms including humans, but these potential effects are thought to be small (Saltzman et al. 1993). Briefly, emissions of CFC to the atmosphere could contribute an estimated 0.00025% to current global emissions. Global CFC in the stratosphere depletes ozone, which in turn has potential biological effects. The toxicity of CFC is very low and would possibly affect only humans because there are no biota at the Vostok site. Kerosene toxicity is higher but still low and again would likely affect only humans. Both of these chemicals are transported, stored, and handled with measures to minimize spills, leaks, and human contact (Saltzman et al. 1993).

Glycol is used in relatively small quantities in some drilling as a lubricant, as antifreeze in drilled holes or in equipment, or as a heat-exchanger. Toxicity to microorganisms, such as might be exposed in Dry Valley lakes, is low, ranging from about 2,000 to greater than 10,000 ppm. Toxicity for aquatic vertebrates is also low, ranging from about 5,000 to 50,000 ppm. Known mammalian toxicity from ingestion ranges from 1.4 ml/kg in human to 13.1 ml/kg in mice. Thus, a human would have to ingest at least 200 ml in a single dose, depending on weight, to risk death.

Large amounts of glycol in water can create a problem with biological oxygen demand (BOD) because degradation of the glycol by micro-organisms consumes oxygen that could be required by aquatic organisms. The small amounts of glycol likely to be released in lakes or seas would be easily oxidized without depleting dissolved oxygen for aquatic organisms.

## 3.4 AIR QUALITY

Atmospheric emissions from drilling activities would be limited primarily to emissions from equipment used to operate the drilling equipment. The combustion of diesel and other fuels (e.g., gasoline, kerosene, and JP4) in drilling equipment would generate localized and temporary emissions of $NO_x$, CO, particulate matter (PM), and $SO_2$. Emissions of PM and $SO_2$ depend heavily on the grade of fuel and the type of equipment used for drilling. Emissions from the drilled hole would be minor because caps would be used to control any release of pollutants [e.g., volatile organic compounds (VOCs), $CO_2$, and methane ($CH_4$)] to the atmosphere (Saltzman et al. 1993). As a measure of total impact of drilling to the atmospheric environment, representative drilling operations have contributed only about 10% of the total South Pole Station emissions at the SPS (Morse 1993). Based on the small fraction of total emissions that would be contributed by drilling, and because

emissions at a particular location would be temporary, air quality impacts from drilling activities are likely to be small.

## 3.5 CUMULATIVE IMPACTS

Significant cumulative impacts from drilling in the USAP are unlikely. Drilling for construction and support activities in the vicinity of permanent stations would contribute a very small increment to total levels of dusts, air pollutants, noise, chemical residues, and wastes. By far the largest contributor to these pollutants would come from air and ground transportation.

Drilling projects at established remote sites, such as the proposed Cape Roberts Project and any new drilling in Dry Valleys, would add incrementally to existing disturbance in these areas, but no qualitatively new impacts are likely. Minor increases would occur in fuel use, exhaust emissions, potential for spills and leaks, waste production, transportation, and disturbance from human presence. These impacts would be transitory once the activity ceased.

Drilling in previously undisturbed remote areas has the potential to introduce contaminants and other materials into previously undisturbed areas. Because the amounts involved would be small and widely separated in space or time, the cumulative effects of these introductions on the environment should be minor. However, the presence of an increasing number of previously drilled holes, sometimes filled with drilling fluids or lost equipment, could adversely affect future scientific undertakings if their locations were not known.

## 4. CONCLUSIONS AND RECOMMENDATIONS

The use of drilling is a necessary part of the USAP activities in Antarctica. Prohibitions or substantial limitations on drilling would compromise facility construction, replacement and maintenance of facilities, environmental compliance, environmental studies, human health and safety, and important aspects of antarctic research. Drilling can be a preferred option over other possible approaches; for example, the drilling of holes in the sea ice or in the ice covering the Dry Valley lakes is preferable to blasting. Similarly, technologies in drilling include some environmentally preferable components. For example, the use of NBA or salt/polymer formulations as drilling fluids is preferable to petroleum or other hydrocarbon formulations. Similarly, directional drilling may offer opportunities to minimize logistical support needs by optimizing equipment use and reducing surface areas of surface disturbance. It is difficult to reduce the need for drilling or further reduce the environmental effects without substantially changing the current direction of the USAP and developing new technologies. To minimize the environmental impacts of drilling as much as possible, adherence to the following standards and practices for drilling in the USAP is recommended:

- develop a Continental System Regional Oil Spill Contingency Plan;
- observe all applicable USAP safety and health protocols and additional contractor protocols where applicable;
- maintain a database of locations and characterization of research drilling efforts at remote sites for access by future scientific investigators;
- review drilling proposals to ensure that the currently least environmentally damaging technologies suitable to the needs of the research are being employed, and to identify additional information or analysis required if appropriate;
- carefully review drilling proposals using previously untested drilling technologies for environmental suitability and identification of follow-up analysis and investigations, as appropriate, to minimize impacts and verify expected impacts;
- investigate and monitor currently used drilling technologies to verify expected impacts;
- minimize use of hydrocarbons as drilling fluids; and
- encourage efforts to streamline and reduce base camp operations (e.g., directional drilling for multiple holes) to reduce environmental impacts.

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