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# Antifreeze thermal ice core drilling: an effective approach to the acquisition of ice cores

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## Abstract

Antifreeze thermal electric drills have a long history of ice drilling in temperate, subpolar and polar glaciers. Shallow, intermediate and deep ice cores have been obtained in Arctic, Antarctic and on high elevation glaciers. Many merits and drawbacks of antifreeze thermal technology have been discovered over the past 25 years. A modified version of the antifreeze thermal electric ice coring drill has recently been developed and tested in the laboratory and in the field for use with an ethanol–water solution. This thermal drill reduces thermal stresses in an ice core by a factor of 5 compared to that of conventional thermal drills and produces good quality ice core. The new drill was used to obtain a 315-m ice core in Franz Josef Land in the high Russian Arctic. It is viewed as a practical and cost-effective alternative to the electromechanical fluid-operated drills for intermediate depth ice coring in subpolar and remote high elevation glaciers. Alternating an electromechanical drill with the antifreeze thermal drill in the bottom of Antarctic Ice Sheet may provide a cost effective way for acquiring good quality multiple ice cores. This approach would also reduce possible environmental impact on subglacial lakes and allow making multiple access holes. Previous results of ice coring with an ethanol–water solution are summarized below. Then, the new thermal drilling equipment along with the results of laboratory and field tests are presented. All aspects of the antifreeze thermal electric drilling process are discussed along with prospects for further improvements. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* Antifreeze thermal electric drills; Ice cores; Glaciers

## 1. Introduction

Most of the deep and intermediate (300–600 m) depth boreholes were drilled either in cold (below $-30°C$) or temperate ice (Ice Core Drilling, 1976; Ice Drilling Technology, 1984; Ice Core Drilling, 1989; Ice Drilling Technology, 1994). Deep and intermediate ice coring was done with large thermal or electromechanical drilling systems using hydrophobic and hydrophilic borehole liquids (hydrophilic liquids have tendency to combine with ice, hydrophobic liquids do not combine with ice). Dry borehole coring to a depth of 350 m was possible

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with portable electromechanical systems (Schwander and Rufli, 1988; Clausen et al., 1989; Mosley-Thompson et al., 1990; Schwander and Rufli, 1994; Blake et al., 1998). For non liquid filled boreholes, a thermal drill can go deeper due to its large clearance. The depth range of 800–1000 m was achieved with thermal drills in cold ice, but the core quality was poor and not suitable for many of modern analytical methods (Ice Core Drilling, 1976; Ice Drilling Technology, 1984, 1994). Considering ice core quality as a major criterion a dry borehole coring in moderate temperature ice is limited to 200 m depth because of borehole closure and ice core fracture. The presence of fluid in the borehole drastically reduces the ice core fracturing. Therefore, good quality ice core down to 400 m can be obtained efficiently with the combination of dry and liquid filled borehole techniques. Both conventional electro-mechanical and thermal fluid drills are big and heavy (Table 2). None of these drilling methods are practical for intermediate depth coring of subpolar (above −20°C) glaciers. Due to the heavy weight of deep borehole drilling systems, their transportation to mountains and some small ice caps is difficult to impossible.

At the same time antifreeze thermal electric drilling technique have been successfully used for shallow, intermediate and deep ice coring in a wide range of ice temperatures: from −58°C to 0°C (Table 1). The antifreeze thermal electric drill (ATED) was invented by V.A. Morev in 1972 (Morev, 1972, 1974). The new drill was field tested in summer 1972 on Abramov Glacier in the Pamir Mountains. This cable-suspended drill was capable of operating in boreholes filled with water or ethanol–water solution (EWS). It produced good quality 80-mm diameter ice core, while sustaining high ice core production rates (Table 2, Fig. 1). In subsequent years shallow, intermediate and deep ice cores have been taken in mountain, Arctic and Antarctic glaciers. Thirty-six boreholes with an average depth of 357.5 m have been drilled using ATED (Table 1). Drilling of intermediate depth boreholes in Arctic and high

Table 1
Bore holes drilled with ATED and m-ATED

| Site (elevation, m above sea level) | Year | Depth, m | Temperature, °C |
|---|---|---|---|
| *Mountains* | | | |
| Abramov Glacier, Pamir Mts. (4400) | 1972, 1973, 1974 | 137, 50, 110 | temperate |
| Obruchev Glacier, Polar Urals (500) | 1974 | 87, 64 | temperate |
| Elbrus, Caucasus (4100) | 1987 | 72, 72 | temperate |
| Guliya Ice Cap, China (6200) | 1992 | 198–308[a] | −6 |
| Huascaran, Peru (6048) | 1993 | 30–160[a]; 30–166[a] | −5 |
| *Arctic* | | | |
| Spitsbergen | 1975–1987 | 114–567 (nine holes) | −8–0 |
| Vavilov Ice Cap, Severnaya Zemlya (700) | 1974–1988 | 150–560 (six holes) | −11– −8 |
| Akademiay Nayk, Severnaya Zemlya (800) | 1986–1887 | 560, 761 | −15– −6 |
| Windy Dome, Franz Josef Land (500) | 1997 | 36, 315 | −11– −6 |
| *Antarctic* | | | |
| Lazarev Ice Shelf | 1975, 1976 | 374, 356, 412 | −15 |
| Novolazarevskaya Station region (1500) | 1977 | 812 | −18 |
| Shackleton Ice Shelf (30) | 1978 | 202 | −20 |
| Ross Ice Shelf (30) | 1978 | 416 | −28 |
| Mirnyi Station region (300) | 1979 | 320 | −20 |
| Komsomolskaya Station (3000) | 1982–1983 | 870 | −54 |
| Dome B (3300) | 1988 | 780[b] | −58 |
| Emery Ice Shelf (20) | 1987–1989 | 252 | −16 |
| Total | 1972–1997 | 12.869 (36 boreholes) | −58–0 |

[a]Depth interval drilled with ATED.
[b]Hole drilled with dry hole thermal drill, and filled with ethanol–water solution.

Table 2
Specifications of the ice core drilling systems

| Parameter | Thermal, m-ATED, EWS | Thermal, ATED, EWS | Thermal, PICO, water | Thermal, TBS-112, DFA | El. mech., PICO, Butyl | El. mech., UCPH, DFA |
|---|---|---|---|---|---|---|
| Temperature, °C | −40–0 | −32–0 | 0 | −60–0 | −60–0 | −60–0 |
| Environmental impact | small | small | none | some | small (?) | some |
| Precautions | none | none | none | none | respirator, suit | none |
| Ice core production (depth 600 m, 24 h), m/week | 252 | 420 | 400 | ? | 130/310 | 170/180 |
| Length: drill/core, m | 2.9/2.1 | 3.2/2.7 | 2/1.8 | 6.2/2 | 29/6 | 11.5/2.5 |
| Power, kW | 3.5 | 5 | 3 | 6 | 2.2 | 0.5/9 |
| Diameter: core/hole, mm | 100/130 | 80/120 | 90/106 | 89/120 | 132/180 | 102/130 |
| Directional drilling | Yes | Yes | Yes | Yes | No | No |
| Silty ice penetration | Yes | No | No | Yes | Yes | Yes |
| Personal (1 shift) | 2 | 2 | 2 | 2 | 4 | 2 |
| Weight: drill/surf. equipment, kg | 25/400 | 60/600 | 10/350 | 120/1200[a] | 500/15,000 | 180[a]/5000 |
| Drilling fluid requirements, ton/100 m | 0.7 (−32°C) | 0.5 (−32°C) | none | 1.8 | 2.4 | 1.5 |
| References | this paper | this paper | this paper | Chistyakov et al., 1984 | Ice Drilling Technology, 1994 | Ice Drilling Technology, 1994 |

[a]Author's estimations.

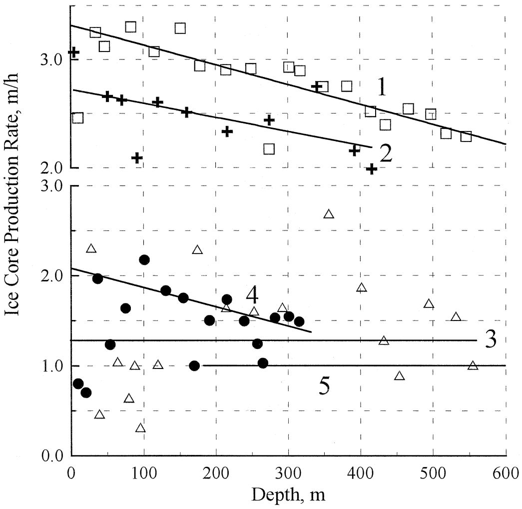


Fig. 1. Mean ice core production rate as function of depth: 1—Austfonna, ATED; 2—J9, ATED; 3—Taylor Dome, PICO electromechanical drill; 4—Windy Dome, m-ATED; 5—GRIP, electromechanical drill.

elevation glaciers ($>6000$ m above sea level) was possible because of ATED's portability and low logistic requirements. A combination of dry hole electromechanical drilling techniques and ATED provided the most effective approach to acquiring intermediate ice cores in high elevation glaciers. In Antarctica, 400–800-m ice cores have been obtained in a single field season. A team of two to four specialists operated the drill, and conducted ice core processing and made the borehole measurements. The use of an ethanol–water solution as a drilling fluid has been described as a cost-effective and environmentally safe way of ice coring in glaciers (Gosink et al., 1993).

Operation of an ATED at temperatures below $-15$°C results in the ice core becoming fractured (Nagornov et al., 1994). In order to obtain better quality ice core at low temperatures and to have the advantages of ATED, several modifications were proposed (Zagorodnov et al., 1994a). Recently, a modified light-weight version of the drill (m-ATED) has been built. It possesses the merits of ATED and produces a good quality 100-mm diameter ice core. The m-ATED was used on Windy Dome on Franz Josef Land (Eurasian Arctic), where a 315-m ice core was obtained during the spring of the 1997 field campaign.

To compare the core quality obtained with different drills three grades were used: (1) excellent, (2) good, and (3) poor. Excellent core is defined as crack free ice. Excellent is a single piece ranging from 0.5–2 m long sections. Good quality core has no cracks from surface to the core's center, and appears in section longer than 0.1 m; the ends of the pieces however match together (see Fig. 2A in Zagorodnov, 1989). Poor core has cracks propagated from surface to the center of the core (see Fig. 11 in Narita et al., 1994; Fig. 1 in Nagornov et al., 1994) or appears in sections and pieces shorter than 0.1 m. The best way to detect cracks is to make thin sections. The use of ATED in Arctic and high elevation glaciers showed that antifreeze thermal drilling technology ensures good quality ice cores (Thompson et al., 1995a,b, 1997).

The main purpose of this paper is to present the advantages and to analyze the problems of antifreeze thermal electric ice coring. Particular attention is given to the compiling and discussing of data from previous drilling programs.

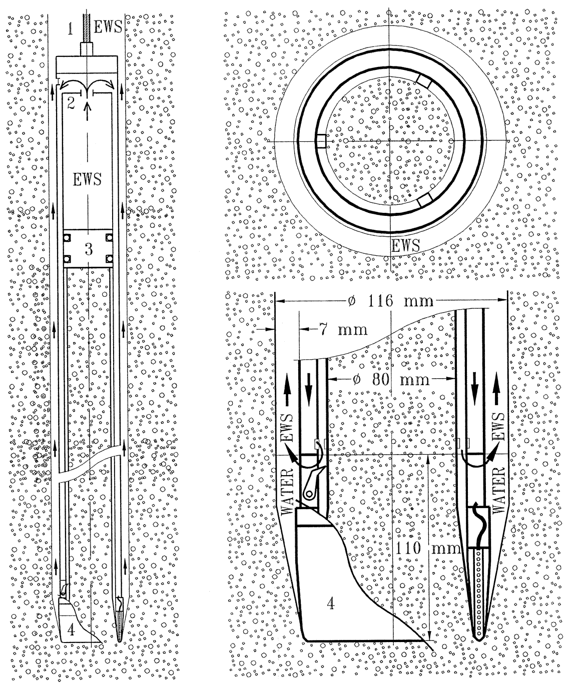


Fig. 2. Schematic of ATED: 1—cable termination: 2—manifold; 3—piston; 4—coring head; arrows show EWS flow.

## 2. Antifreeze thermal electric drill (ATED)

### 2.1. Operation and design

A schematic of ATED is shown in Fig. 2 with specifications presented in Table 2. The drill's body consists of two thick coaxial stainless steel tubes fixed with an annular clearance of 1.5–2 mm. At the lower end three core catchers and the coring head are attached. A free-moving piston divides the core barrel into two sections. The lower section is dedicated to the ice core and the upper one to the drilling fluid. The space above the piston works as a drilling fluid container, and is hydraulically connected to the annular channel between the tubes. Before drilling starts, the space above the piston is filled with EWS, and the piston occupies a lower position, just above the coring head. During penetration an ice core entering into the core barrel pushes the piston up and EWS is released to the borehole kerf through the annular channel. Ideally, each drilling run yields a 2.7-m length of ice core after which the core barrel is refilled with drilling fluid. An inlet at the top of the drill is used to pump the drilling fluid the space above the piston. Because the core barrel is used as a drilling fluid container as well as an ice core container, the length of the drill is short. This rather simple design with minimum moving parts makes the ATED drill, light-weight, reliable, robust, and short as compared to other ice drills (Table 2).

The penetration takes place when the electrically heated hollow coring tip melts the ice and the cylindrical ice core at the center moves into the barrel. The heat is generated with a nichrome wire placed between heat-conductive (copper) rings. The thermal and electrical insulation of variable thickness is arranged in such a way that most of the heat is concentrated at the lower end of the coring head. The heat directed downward results in the high penetration rates (Fig. 3) and low (25%) heat losses. The heating element of the coring head is hermetically sealed in a stainless steel shell and is capable of withstanding a pressure of 400 bar. Specifications of this coring head are presented in Table 3.

In order to prevent the melt water from freezing, the drilling fluid is routinely injected into the kerf. Injection takes place when an ice core, formed during penetration, pushes the piston up. Then the EWS gets to the kerf through the inter-tube space, through the holes in the core barrel, and through the core catcher's windows. Therefore, the drilling fluid is delivered to the bottom of the borehole continuously during every drilling run. Mixing of melt water with hydrophilic antifreeze eliminates the need to recover melt water from the borehole.

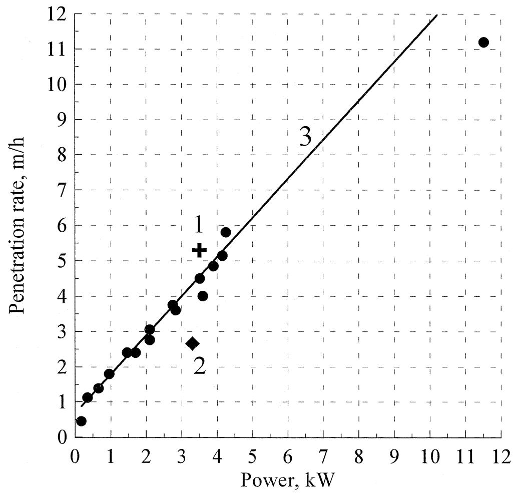


Fig. 3. m-ATED penetration rate as function of power: 1—ATED; 2—m-ATED, EWS circulates through coring head; 3—m-ATED no circulation.

### 2.2. Borehole fluid

To keep the borehole open the following conditions have to be satisfied: (1) the borehole liquid should not freeze, and (2) the ice overburden pressure should be compensated. To maintain the first condition, the EWS concentration should be chosen according to the ice temperature, i.e., the lower the ice temperature, the higher the ethanol concentration. The equilibrium ethanol weight concentration ($C_{eq}$) can be determined from the following experimental relationship: $C_{eq} = -0.0133T$ ($-60°C < T < 0°C$), where $T$ is the ice temperature in °C (Morev and Yakovlev, 1984; Zagorodnov et al., 1994b). If the equilibrium conditions are violated then ice dissolution or ice formations occur in the borehole. A higher ethanol concentration causes an increase of the borehole diameter, while a lower concentration causes a slush formation.

Table 3
Specifications of the coring heads

| Specifications | ATED | m-ATED[a] | m-ATED | m-ATED[b] |
|---|---|---|---|---|
| Diameter: outer/inner, mm | 108/84 | 124/105 | 124/105 | 126/103 |
| Diameter: borehole/ice core | 116/80 | 135/102 | 128/100 | 130/100 |
| Height: heated/total, mm | 47/66 | 12/40 | 12/40 | 12/40 |
| Resistance, Ω | 18 | 20 | 20 | 20 |
| Operation power, kW/V | 3.5/250 | 3.3/255 | 5.0/316 | 1.5/170 |
| Disruption power, kW/V | 5/300 | 11/480 | 11/480 | 1.6/180 |
| Penetration rate in ice, m/h | 5.30 | 2.67 | 6.0 | < 1.0 |

[a]EWS circulates through the coring head.
[b]Firn coring head.

In accordance with the drill geometry the ratio of injected EWS volume and melt water produced in the kerf during penetration is 1:1. Therefore, the concentration of injected EWS should be twice the equilibrium concentration. Knowing the temperature at various depths in the glacier is vital to minimizing ethanol usage. It was experimentally found (Zagorodnov et al., 1994b) that the temperature at the lower part of the borehole is 3–5°C higher than the ambient ice temperature during drilling activity. Scheduled borehole temperature measurements make it possible to determine the ambient ice temperature with an accuracy of 3–5°C and to extrapolate it for the greater depths. Such inaccurate temperature predictions result in an additional 10–15% usage of ethanol per borehole.

At ice temperatures between −50°C and 0°C the density of equilibrium EWS exceeds the density of ice, and the second condition of a permanently open borehole is met. The experimental relationship of equilibrium density ($\rho_{eq}$) and temperature can be expressed as: $\rho_{eq} = 999.2 + 4.72 \cdot T + 0.31 \cdot T^2$, (kg $m^{-3}$).

If the ice temperature increases with depth, then a positive gradient of EWS density is maintained and the vertical convection of borehole liquid is prevented. When a reverse temperature profile (i.e., temperature decreasing with depth) occurs the EWS develops a vertical convection. Under reverse temperature conditions in the borehole, a significant amount of slush (20–30 mm in diameter and 0.1–0.3 mm thick ice disks) is formed within 3–4 days. Slush can be removed with a borehole filter or it can be dissolved with ethanol added to the borehole. Both techniques show positive results in 500–600-m boreholes (Zagorodnov, 1989) and neither slows down the drilling process. For several reasons the first deep drilling with an ATED required 20–30% more ethanol than necessary to fill the borehole. The reasons for this were heat dissipation in the borehole due to heat losses at the coring head, heat losses in the electric cable, and heat transfer by the drill and cable during passage (Zagorodnov et al., 1994b).

Premature EWS injection during drill lowering causes excessive usage of ethanol and is a shortcoming of the ATED. Drilling fluid loss occurs as the piston is pushed up by the hydrodynamic pressure arising during drill lowering. At the high rate of lowering (> 0.5 m/s) sometimes only half of the EWS volume is delivered to the borehole bottom. In such cases, intensive slush formation during penetration can stick the drill. Slow lowering of the ATED helps to avoid premature EWS injection.

### 2.3. ATED performance

Since 1973 ice coring with an ATED has been performed in Severnaya Zemlya, Polar Urals, Svalbard and Antarctica, where good quality ice cores were obtained at ice temperatures above −15°C. The best results with respect to ice core quality and production rate were achieved in 1987 on Austfonna (Zagorodnov, 1989). On Austfonna, the drilling procedure and equipment were adjusted to glaciers with a reverse temperature profile (discussed in Section 2.2). For 12 working hours, an average ice core production rate of 2.75 m/h or 199 m/week (12 h/day operation) was achieved (Fig. 1).

A new directional drilling (DD) technique for taking additional ice cores from the bottom part of glaciers has been tested in the Austfonna borehole (Zagorodnov, 1989). An additional 2.6 m of ice core was recovered from the bottom of the glacier using this technique. For this purpose, a whipstock was fixed at the borehole bottom. This device allows the ATED to deflect from the main borehole and permits drilling a secondary inclined hole. Since ATED is much shorter and lighter than other drills, the DD was achieved with a simple whipstock. Whipstock mounting and drilling required about 5 h. A more sophisticated whipstock was developed later and tested in an ice well (Zagorodnov et al., 1994c). This new whipstock allows multiple ice coring at any depth of previously drilled boreholes.

J9 ice core was taken with the ATED in Antarctic in 1978 (Zotikov, 1979). This drilling represented one of the fastest ice core recovery operations conducted with 416 m of core drilled in only 13 days. The average ice core production rate of 357 m/week (24 h/day operation) was achieved below 150 m (Fig. 1). This operation allowed penetration through the ice shelf glacier and recovery of the very bottom ice sample.

The level of EWS in this borehole was kept below the hydrostatic equilibrium depth. Therefore, when the borehole reached the water permeable ice, the ocean water came into the borehole. Thus, no spill of EWS into the ocean water underneath the glacier occurred. Since the specific gravity of EWS is less than that of the ocean or fresh water, the EWS mixing with underglacial water was insignificant. It is believed that the drilling tools and research equipment that passed through the borehole carried little EWS residue to the ocean beneath the ice shelf. Considering the environmental impact of drilling through glaciers one may view ATED technology as a good option for the study of ice shelves and glaciers with oceans or lakes beneath them.

The deepest borehole of 870 m was drilled at Komsomolskaya Station (Central Antarctic) with the ETB-5 drill (version of ATED; Morev et al., 1981) suitable for operation in ice at −54°C. This borehole was drilled during two summer field seasons of 1981–1982 and 1982–1983. During the first season 800.6 m of depth was reached and drilling was terminated with the intention to continue the following summer season. Eleven months later, in January of 1983 drilling was resumed and almost 70 additional meters of ice core were taken. Unfortunately, a problem with the coring head power connector resulted in the drill being stuck at the borehole bottom. This coring was done in the coldest ice ever drilled with an ATED. The high viscosity of EWS at low temperatures and the resulting hydraulic drag slowed down the core production rate to 70 m/week on a 12 h/day operation.

In 1992 and 1993, a new area for ATED application was discovered. Two high elevation glaciers were successfully cored to the bottom: (1) Guliya Ice Cap, (Koci and Zagorodnov, 1994; Thompson et al., 1997), and (2) Huascaran, (Thompson et al., 1995a). A hand auger, a dry hole electromechanical drill, and the ATED were utilized in these borehole drillings. Specifically, the Guliya ice core was taken with a PICO electromechanical dry hole drill to the depth of 198 m, and completed to the bottom at 308 m from the surface with the ATED. Two Huascaran ice cores were obtained with a hand auger from the surface to the ice-firn transition (30 m) and with the ATED down to the bottom, 166 m from the surface.

Dry hole electromechanical drilling was not used to reach bedrock on the Guliya Ice Cap for two reasons: (1) core fracture due to stress release, and (2) the high rate of borehole closure below 198 m. It was believed that even with a partially compensated hydrostatic pressure in the borehole and a closing rate of 1 mm/day (Johnsen et al., 1980) the ATED would have produced a large enough clearance to allow the drill to pass through the hole during the few days in spite of the borehole closure.

### 2.4. Merits and drawbacks of the ATED technique

Summarizing all of the above, the merits of ATED technology are: good quality ice core (at temperatures above −15°C), high ice core production rate, low power requirements, reliability, portability, short set up time, low drilling fluid requirements and environmental safety. These merits are accompanied by the following drawbacks: ice core fracture at temperatures below −15°C, small core diameter, the complexity and high cost of the coring head, an disproportional usage of EWS and slow drill lowering at temperatures below −25°C.

## 3. Modified antifreeze thermal electric drill (m-ATED)

### *3.1. m-ATED design*

Three main requirements for a new drill were considered: (1) the possibility of obtaining bigger (100 mm diameter) ice cores, (2) reducing the weight of the drill, and (3) increase lowering and raising rates. The m-ATED was designed with provisions for simplicity, portability and low fabrication cost. A schematic and specifications of the m-ATED are presented in Fig. 4 and Table 2, respectively. The operating principle of the m-ATED does not differ from the ATED drill. However, some important modifications described below make it possible to eliminate most of the shortcomings of the ATED drill.

The new drill body consists of a thin wall stainless steel tube. In this drill EWS passes to the kerf through eight 6-mm tubes attached on the outside of the core barrel. Such an arrangement practically doubled the clearance between the drill and the borehole wall and reduced the hydraulic drag significantly. It allowed lowering and raising rates of the m-ATED at $-10°C$ to be 0.5 m/s and 0.82 m/s, respectively (Fig. 5). A wedging mechanism keeps the piston fixed at the lower position during drill lowering. The piston is set free when the drill touches the borehole bottom.

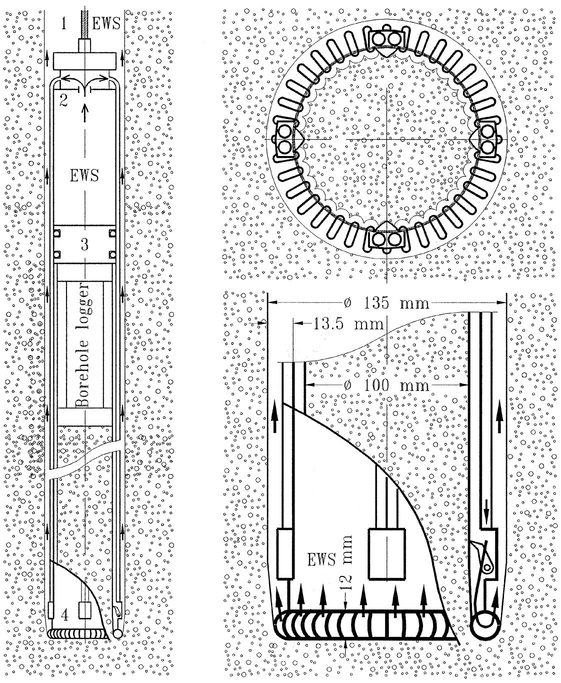


Fig. 4. Schematic of m-ATED: 1—cable termination; 2—memifold; 3—piston; 4—coring head; arrows show EWS flow.

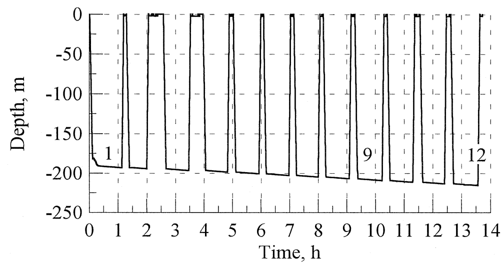


Fig. 5. Windy Dome drilling log data. 11th day of drilling; numbers are drilling runs.

Recent studies show that thermal expansion of the subsurface layer of the core during penetration is one cause of ice fracture (Nagornov et al., 1994). Thermo-elastic stresses in the ice are proportional to the penetration rate and the height of the heating zone. The height of the heating zone is determined by the height of melt water in the kerf, which is 110 mm for the ATED and 12 mm for the m-ATED (Figs. 2 and 4). The slower drilling rate and the higher melt water level at the kerf cause greater thermo-elastic stresses that lead to core fracture. In order to reduce thermal stresses a new coring head was developed. The design of the new drilling head is similar to the French thermal drill 4000 (Augustin et al., 1989). The new coring head consist of three parts: (1) a stainless steel base ring, and (2, 3) two identical electrical cable heaters (1.62 mm OD sheath; 40 Ω) coiled to 12 mm outer diameter. Bottom end of the base ring has 72 holes and each coil of the heaters are interwoven into the hole. After the heaters are plait into the base ring each coil is slightly bent to conform to an exact shape and width. The heaters stay in position without screwing, welding or brazing. Commercially available standard electric resistance heaters were used in the new coring heads. Coring down to the ice-firn transition at about 36 m depth was done with similar head equipped with four heaters (144 coils). Specifications of the m-ATED coring head are shown in Table 3. Closed core catcher frames enable EWS circulation through the pierced coring head and heat removal from the ice core (Fig. 4). As a result, the heating zone is only 12 mm which is eight times less compared to the ATED.

### 3.2. Drilling setup

In general, all cable-suspended drilling systems have similar drilling setups which include: a winch, a hoisting mast and a controller. The Windy Dome, Franz Josef Land drilling was conducted with a modified PICO winch (Koci, 1984) equipped with 740 m of Kevlar-coaxial cable. The same DC motor was used for raising and lowering the drill as well as for cable feeding during penetration. A hoisting mast of 4.2 m in height consisting of a 180-mm diameter fiberglass tube and sheave, is supported in a slightly inclined position by two aluminum tubes. In order to measure cable travel (depth) the pulley is equipped with an optical encoder (1050 ppr). The sheave assembly is mounted on two beam type load cells. A tilting table (TT) makes it possible to rotate the drill into a horizontal position, while the hoisting mast is immovable. The TT is about 2-m long aluminum channel with removable base on the lower end, rotating on a horizontal shaft. Normally, the TT is in vertical position. When the drill is placed on TT and cable fed they rotate to horizontal position by gravity. The drill firmly stays on TT without clamping. The winch motor is used to raise the drill and TT into initial vertical position. This TT was also used with heavy (> 80 kg) electromechanical drill during two high elevation ice coring expeditions and saved a lot of manpower. The total shipping weight of the drilling setup including cable (740 m), controller, spare parts, two drills, and accessories is about 600 kg.

### 3.3. Cable

Compared to electromechanical drills, the ATED requires relatively high power and prolonged drilling runs. Therefore, low power losses in a cable are essential for intermediate or deep drilling. The specifications for the steel armored and Kevlar-‘Hiwire’ cables, used with the ATED, are presented in Table 4. Both cables proved to be practical. A steel cable requires a smaller winch, while a Kevlar cable is lighter and more flexible. A new Kevlar-coaxial cable was used with the m-ATED, which possessed all of the above advantages. This cable has a 35% smaller cross section, is 22% heavier than the Kevlar-‘Hiwire’ cable, and insures only 50% of the power losses of conventional Kevlar cable. In addition, the new cable has a smooth plastic cover which reduces the amount of the drilling fluid carried out of the borehole as the drill is raised during each run.

### 3.4. Controller

The controller was developed to monitor input and output power, as well as the drill’s weight and position (depth). To drill plumb boreholes special attention was given to the control of the drill’s pressure on the kerf. For this purpose, load cells constantly measured the drill and cable weight. The amplified output signal from the load cell was monitored and used as feedback to the motor controller. This allowed us to keep the pressure on the kerf at 40–50% of the pressure of the full drill weight.

The sheave encoder and up/down electronic counter measure the drill position (cable length) with

Table 4
Specifications of the drilling cables used with ATED and m-ATED

| Specifications | Steel armored, coaxial | Kevlar-‘Hiwire’ | Kevlar-coaxial-A |
|---|---|---|---|
| Diameter, mm | 8.2 | 11 | 8.9 |
| Specific weight: air/water, kg/100 m | 28/18 | 14/8 | 17.3/10.3 |
| DC loop resistance, $\Omega$/100 m | 1.0 | four and three conductors in parallel 1.225 | 0.57 |
| Breaking strength, kN | $\geq 50$ | $\geq 40$ | $\geq 30$ |
| Breaking voltage, kVdc | $> 1$ | $> 1$ | $> 1$ |

Table 5
Specifications of the borehole logger

| | |
|---|---|
| Diameter/length, mm | 60/600 |
| Weight in air, kg | 3.6 |
| Maximum depth in water, m | 1000 |
| Channels range/resolution: | |
| Temperature, °C | −40–0/0.02 |
| $X$ and $Y$ inclination, degrees | ±20/0.01 |
| Pressure, bar | 1–100/0.25%FSC |
| Reading frequency, s | > 7 |
| Maximum stored readings | 7000 |
| Computer support | DOS, Serial port |

1 mm resolution within a 0–1000-m interval. The repeatability of the depth measured between drilling runs was 20–50 mm at 300 m. The drill performance data were obtained with a depth counter via RS232 interface which allowed us to continuously feed drill position data to the computer.

### 3.5. Borehole logger

The temperature and inclination of the borehole are among the most critical parameters necessary during drilling operation. A portable, stand-alone borehole logger was developed to operate in fluid-filled boreholes up to 1000 m in depth. The specifications for the borehole logger are presented in Table 5. The geometry of the logger makes it possible to place it inside of a m-ATED core barrel ahead of the piston (Fig. 4). Using appropriate end caps allows the logger to be mounted in any core barrel for any drill, or alternatively it can be used with its own housing. The logger does not occupy any space in the drill during routine drilling and does not require a communication cable during logging. The position of the logger in the borehole can be determined with a sheave encoder and a pressure gauge.

## 4. m-ATED performance

### 4.1. Ice core quality

From the surface to the depth of 315 m, the quality of the ice core was ranged from excellent to good. Only the deepest ice core sections developed 2–3 fractures per 2 m sections. Longitudinal fracturing occurred in some ice core sections below 106 m depth. None of the section exhibited brittle behavior during ice core processing, cutting or storage. The quality of the ice core taken with the m-ATED is considerably better than that obtained with a prototype drill at the same depth and temperatures (Nagornov et al., 1994). This improvement was achieved because the ice core was subjected to heat for a much shorter time during penetration. Calculated thermo-elastic stresses in the ice core taken with a m-ATED are five times smaller than what was possible with the ATED. The increase in ice diameter also helped to improve the core quality.

### 4.2. The penetration rate

The penetration rate of a m-ATED without EWS forced circulation is shown as a function of power in Fig. 3. In general, this relationship is linear. Windy Dome was drilled with 3.3 kW average power available on the coring head. Using forced circulation the average penetration rate was only 2.67 m/h, while penetration rates without circulation at that power was almost doubled to 4.25 m/h. Therefore, when EWS passes through the drilling head it carries heat away from the kerf and slows down the penetration rate substantially. The maximum penetration rate of almost 11 m/h was achieved with a prototype drilling tip at 11.5 kW. Therefore, a power of 5–6 kW was found to be the optimum operation power of the new coring head. To avoid heaters burn-out, the firn coring was conducted with low power (1.5 kW) which resulted in low penetration rate (< 1 m/h).

Fig. 6 shows the m-ATED penetration rate at 212 m depth. This figure shows how a feedback signal

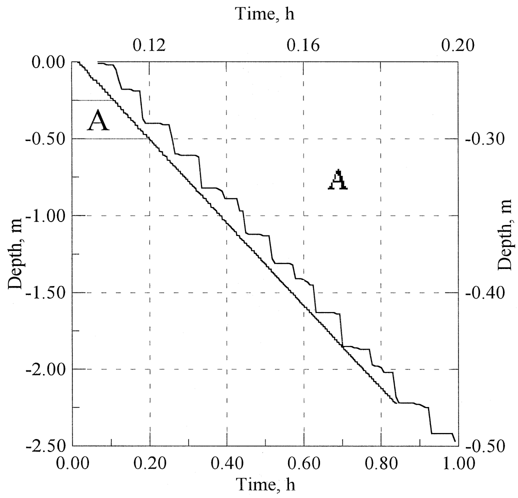


Fig. 6. Depth vs. time during penetration: drilling run #9 in Fig. 5.

from the load cells activates the winch motor. The motor feeds 20 mm of the cable down the borehole every 24 s. At shallow depths, feeding intervals were 4–6 mm. This pulse feeding does not affect the ice core diameter: it remains homogeneous along its length. The elasticity of the cable buffers pulse feeding to some degree.

### 4.3. The ice core production rate

The ice core production rate characterizes the performance of the whole drilling setup including the support equipment (Fig. 7). The m-ATED demonstrated an average ice core production rate of 1.5 m/h (252 m/week with a 24-h operation) in a 300-m borehole, similar to that which was demonstrated by a PICO 30-m long electromechanical drill at Taylor Dome (PICO drilling log data). In Johnsen et al. (1994), the average ice core production rate of a GRIP electromechanical drill was about 1 m/h or 170 m/week with a 24-h operation.

On the other hand, m-ATED performance was slow as compared to ATED for two reasons: (1) the lack of available power (3.3 kW), and (2) the heat losses due to forced EWS circulation, discussed above. With the increased power and modifications presented below the penetration rate could potentially be doubled and service time could be reduce by up to 50%. According to data presented in Fig. 5, lowering, raising and service time together represented about 30% of the total drilling time. Having 5 kW power (expected penetration rate 6 m/h) and shorter service time (6–7 min/run) could increase the ice core production rate up to 2.0 m/h or 335 m/week (24 h/day).

### 4.4. m-ATED field operation

The light-weight of the drill leads to the following shortcomings of m-ATED: (1) thin wall tubes are potentially vulnerable to deformation or damage during transportation or field operation, (2) difficulty in maintaining a plumb borehole, (3) possible freezing of EWS inside of the circulation tubes, and (4) slow lowering rate. The first two drawbacks did not affect the Windy Dome drilling (borehole inclination was 11° at 75 m and 4° at 315 m), but revealed potential difficulties in maintaining the verticality of deeper (> 600 m) boreholes and the possibility of unexpected drill damage.

The freezing within circulation tubes has never been observed before and can be explained by a cold environment in the drilling shelter. Ambient air temperature in the drilling shelter varied from −10°C to −26°C, while the equilibrium EWS concentration was adjusted to −6°C to −12°C. Therefore, the

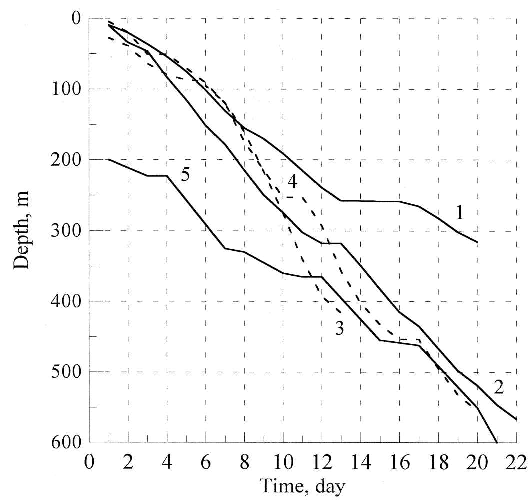


Fig. 7. Progress of boreholes: 1—Windy Dome, m-ATED; 2—Austfonna, ATED; 3—J9, Ross Ice Shalf, ATED; 4—Taylor Dome, PICO electro-mechanical drill; 5—GRIP, electro-mechanical drill.

tubes filled with equilibrium EWS were periodically exposed to colder temperatures when the drill was raised to the surface. Perhaps evaporation of ethanol also cooled down the drill. When the problem was detected before lowering the drill into the borehole it was heated with a propane torch and the ice plugs were melted. Operation of a drill with partly frozen tubes causes a slush formation between the drill and the borehole wall which increases the danger of getting the drill stuck. In essence, all problems discussed are not critical to the m-ATED drill operation up to 500 m, but reveal areas for further drill improvement.

## 5. Discussion

### 5.1. Ice core quality

Valuable scientific information was obtained from Guliya and Huascaran ice cores taken with the ATED in 1992 and 1993, respectively. Visually, the Guliya ice core quality improved substantially from 198 m down to the bottom. Precise isotopic (including $Cl^{-36}$), chemical and microparticle analysis of the ice core did not show any change in base line levels, below 198 m where the electromechanical dry hole drill was replaced with the ATED (Thompson et al., 1997). We believe that the compatibility of dry hole electromechanical and ATED technologies is fully demonstrated by this experiment.

Comparison of isotope, chemical and microparticle composition of shallow core taken with hand auger in 1994 and ice core obtained with m-ATED in 1997 from Windy Dome (Franz Josef Land) show close values and no sign of ice contamination during drilling. The better quality of 315-m ice core obtained with m-ATED implies getting quality cores from greater depths in the future.

### 5.2. Borehole liquid

Borehole liquid is a very critical component of the ice core drilling operation. Two types of borehole liquids have been used: (1) hydrophobic (DFA, Kerosene, Butyl Acetate), and (2) hydrophilic (ethylene glycol; ethanol). Both types of liquid have advantages and disadvantages (Ueda and Garfield, 1969; Ice Core Drilling, 1989; Ice Drilling Technology, 1994). Borehole liquid makes up a sufficient fraction of the total weight that has to be delivered to the drilling sites. In Fig. 8, borehole liquid requirements are shown as a function of ice temperature. Obviously, the hydrophobic liquids require 100% of the borehole volume. When the borehole is filled with EWS, the ethanol accounts for only a fraction of the borehole volume. Specifically, at $-10$°C ethanol consumption is 12–15% of the borehole volume. By applying a combination of dry hole electromechanical and thermal drilling techniques for intermediate depths, the consumption of drilling fluid can be reduced and the best features of the both drill systems can be used.

Depending on glacier temperature, the use of EWS make it possible to reduce the amount of ethanol that has to be delivered to the drilling site by a factor from 1.25 to 10 compared to the hydrophobic liquids. However, excessive requirements of EWS at low temperatures (Zagorodnov et al., 1994b) results in increased transportation costs. Thus, the ATED technique does not have an advantage over any other drilling technologies under very cold conditions, but does reduce the environmental impact with the use of ethanol–water solution.

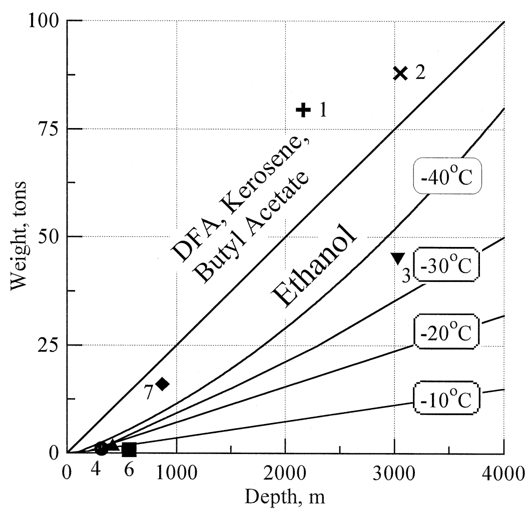


Fig. 8. Borehole liquid requirements: 1—Byrd Station; 2—GRISP2; 3—GRIP; 4—Windy Dome; 5—J9; 6—Austfonna; 7—Komsomolskaya Station; lines are estimation for 180-mm borehole diameter.

The m-ATED drill is suitable for operation in a borehole filled with hydrophobic liquids. At temperatures above −15°C, the density of EWS is lower than DFA-densifier mixture, but higher than water. Therefore, during drilling the EWS will not mix with hydrophobic drilling fluid and will stay in the lower part of the borehole. At the same time, when the drill reaches water permeable ice near the bottom of the ice sheet, the EWS will stay above the melt water. These advantages of ATED technology can be fully realized in the bottom part of Antarctic and Greenland ice sheet, where the ice temperatures are above −15°C. Thus, in addition to the logistic advantages, there are two more reasons to alternate mechanical and ethanol-thermal techniques in deep drilling: (1) environmental concerns associated with the pollution of bottom of shelf glaciers and ice sheets, including subglacial lakes, by hydrophobic borehole liquids when conventional electromechanical drills are used, and (2) the possibility of using directional drilling technique. Thus, a combination of conventional electromechanical drilling with m-ATED allows for multiple ice coring with a reduction in the potential environmental impact.

### 5.3. Future m-ATED development

Two modifications of the m-ATED are being considered: (1) heavier and more robust core barrels and (2) coring heads with EWS circulation above the heater. The first modification will allow an increase in the lowering rate, and would make it easier to maintain borehole verticality as well as safe drill transportation and operation. One option is to build a longer drill which would allow both an increased drill weight, as well as an increase in the ice core production rate. The second modification will increase the penetration rate as well as the ice core production rate. If the EWS passes to the borehole through the holes above the coring head during drilling, the heating zone will increase by only 30%, while the penetration rate will be doubled (Fig. 3). Therefore, an ice core will be subjected to heat for a shorter time, and the thermal stresses will be even smaller than the stresses exhibited in the ice core taken with m-ATED. With 5 kW of power on the coring head and a 3-m core barrel, one may expect up to 6 m/h penetration rates and about a 400 m/week ice core production rate under 24 h/day operation. However, these numbers are valid for only the subpolar (above −15°C) glaciers. To achieve such high core production rates in colder ice, the m-ATED weight and core barrel length would have to be increased substantially.

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