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Thermal electric ice-core drills: history and new design options for intermediate-depth drilling

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ABSTRACT. Ice coring of temperate and polythermal glaciers demonstrates some limitations of most electromechanical (EM) and thermal electric (TE) drills. Most TE drills are heavy, require a heavy power system, work slowly and cannot operate in boreholes going through the cold–temperate ice transition. Antifreeze thermal electric drills (ATED) are capable of operating in polar ice caps, polythermal and temperate glaciers, in boreholes filled with water and/or hydrophilic fluids. Performance of the ATED drill can be improved by using an open-top core barrel and low-power and narrow-kerf coring head. ATED-type drills can be modified for an open-top core barrel equipped with low-power coring head and include a new scheme for drilling-fluid circulation using two pumps. A small metering pump releases pure ethanol above the top of the drill, and a second pump enables circulation of the borehole fluid, an ethanol–water solution (EWS), above the kerf. Use of a narrow-kerf coring head reduces power requirements and makes it possible to design a lightweight drilling system that includes the EM and TE drills for shallow and intermediate-depth drilling.

KEYWORDS: glaciological instruments and methods

INTRODUCTION

Under some thermodynamic conditions in glaciers, it is more effective to use the antifreeze thermal electric drill (ATED) than electromechanical (EM) drills. Other types of thermal electric (TE) drill are not functional where a transition between cold and temperate, water-saturated ice occurs and are too heavy to transport in complex terrains. In temperate and polythermal glaciers, EM ice-core drills (with rare exceptions) cannot operate efficiently below the firn–ice transition or at pressure-melting temperatures (PMT) (Kohshima and others, 2002; Thorsteinsson and others, 2002; Neff and others, 2012; personal communication from M. Gerasimoff, 2004; personal communication from P. Ginot, 2013). In cold firn and ice, it is possible to use a shallow EM drill up to 150–200 m and to switch to an ATED drill below that to complete the drilling down to bedrock (Zagorodnov and others, 2005, 2012). This option also includes drilling through the transition from cold ice to PMT and/or water-saturated ice below. These polythermal conditions are typical for subpolar, high-altitude and shelf glaciers (Zagorodnov and others, 2014). Three types of TE drill were designed for coring in shallow, intermediate and deep boreholes (BHs). The general characteristics of some TE drills are presented in Table 1 and Figure 1. A total of 20 TE drills were developed in the period 1964–2005. Most are no longer used since the dry and fluid EM ice-core drilling systems are lighter and faster and produce cores of better quality.

The principal components of the cable-suspended TE or EM ice-core drilling systems (Fig. 2) are: downhole drill/sonde (1), EM cable (2), winch (3), hoisting mast (4), power controller (5) and power system (6). The general design of the TE drills (downhole sonde; Fig. 3) includes hollow, electrically heated coring head (Fig. 4), core barrel, fluid circulation system and cable termination.

During operation of TE drills, the coring head is powered, melts ice and forms the ice core contained in the core barrel. After the designed length (1–3 m) of ice core is drilled, the winch lifts the drill to the surface. On the surface the ice core is removed from the drill, the drill is serviced and the next drilling run begins. Servicing of TE drills includes draining of the meltwater removed from the kerf (Fig. 3b). Servicing of ATED (Fig. 3c) drills includes removing the ice core and filling the drill with ethanol–water solution (EWS). EM drills can operate with the same hoisting system (Fig. 2) as TE drills. TE drills require an EM cable of lower electrical resistance than the cable used in EM systems.

The main objective of our analyses of the design and performance of existing TE drills is a better understanding of the capabilities of TE drills in polythermal conditions and the selection of design options that may improve TE drill performance. In the following sections we review three types of TE drill and present two design options that may increase the efficiency of ATED-type drill performance at drilling sites that are difficult to reach, including high-altitude glaciers, and may significantly reduce the logistic burden of any ice-coring operation. We also provide general comparative estimates of the effectiveness of TE drills.

The motivation for new TE drill development is to reduce the coring-head power from 4–5 kW to 1.5 kW. A smaller power system and less fuel can then be used. Currently a 1.5 kW power system is used with the intermediate-depth ice-core drilling system (Zagorodnov and others, 2002, 2005). When the EM drill is switched for the TE drill, an additional 3 kW power source and ~1 L m^{-1} of fuel are delivered to the high-altitude drilling site. Using a 5 kW power source at or above 6000 m a.s.l. imposes a significant logistic burden. We provide the expected performance characteristics of an open core barrel, low-power ATED drill at ice temperatures above –30°C.

The estimated performance characteristics of open-top ATED (hereafter ot-ATED) presented in this paper are based on the parameters of three field-tested versions of the ATED drill: ETB-3, ETB-5 and ATED. Open core barrel ATED

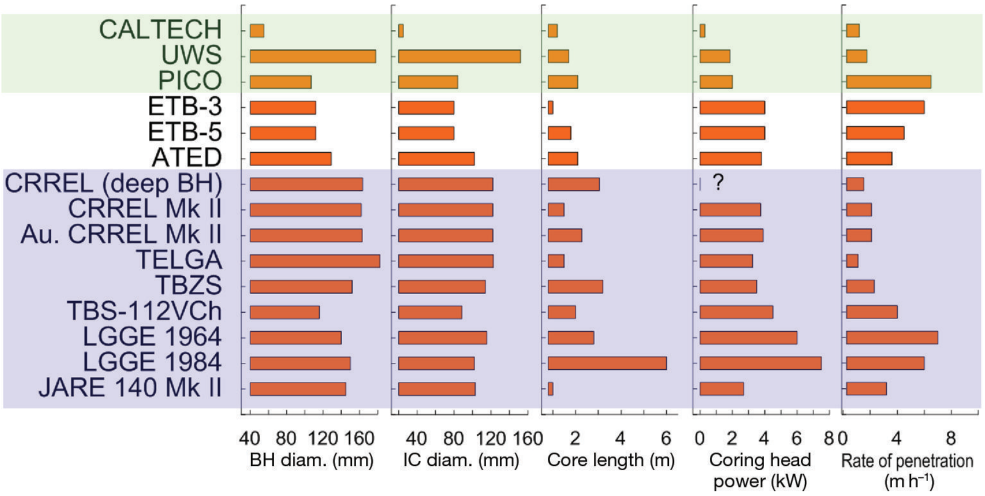

Fig. 1. Major characteristics of TE ice-core drills (see Table 1 for sources and acronyms). Top three drills (green shading) are used in temperate glaciers only; the next three have been used in cold, temperate and polythermal glaciers; the lower nine drills (blue shading) operate only in cold ice. ?: value unknown.

allows for compensation of slowed penetration due to narrow kerf and low-power coring head.

TEMPERATE-ICE TE DRILLS

TE drills were designed for the study of temperate glaciers and were intended to operate submerged in meltwater that could completely or partially fill a BH. These drills (Table 1: CALTECH, UWS and PICO; Figs 1 and 3a) are simple, lightweight and require relatively low power. They can operate in temperate ice only and do not have BH fluid circulation systems. They are also suitable for coring cold firn at any temperature. The drill is slightly longer than the ice core recovered during one drilling run. Drills of this type have an open-top core barrel and therefore low hydraulic drag, and while moving through a BH demonstrate high travel speed. The PICO TE drill equipped with a narrow cross-section coring head (Fig. 3a) has a high penetration rate at relatively low applied power (Zagorodnov and others, 1994a). The low logistic burden associated with this type of drill makes it possible to core high-altitude glaciers (Koci, 2002).

COLD-ICE TE DRILLS

A few TE drills for cold ice coring were developed for operations in the Antarctic and Greenland ice sheets and glaciers: Dome C (905 m deep BH; Lorius and Donnou, 1978), Vostok station, (952 m and 2755 m deep BHs; Vasiliev and others, 2007) and Mizuho station (700 m deep BH; Narita and others, 1994); the 2755 m deep BH at Vostok

Table 1. Characteristics of TE drills (see also Fig. 1)

Year(s)	Type of drill	Fig. 3	Ice temp. °C	Borehole fluid	Source
1964	CALTECH	a	PMT	Air–water	Shreve and Kamb (1964)
1974	UWS	a	PMT	Air–water	Taylor (1976)
1983	PICO	a	PMT	Air–water	Koci (2002)
1972–89	ETB-3	c	PMT to –28	Air–water-EWS	Bogorodsky and Morev (1984)
1978	ETB-5	c	PMT to –60	EWS	Bogorodsky and others (1984)
1997–2009	BPRC ATED	c	PMT to –30	Air–water-EWS	Zagorodnov and others (2005, 2014)
1961–64	CRREL (deep BH)	b	–30	DFA+TCE	Ueda and Garfield (1968)
1963–66	CRREL Mk II	b	–30	Air	Ueda and Garfield (1969)
1968–74	Au. CRREL Mk II	b	–30	Air	Bird (1976)
1969–72	TELGA	b	–6 to –57	Air	Korotkevich and Kudryashov (1976)
1974–81	TBZS	b	–6 to –57	DFA+TCE	Vasiliev and others (2007)
1990–93	TBS-112VCh	b	–6 to –57	DFA+TCE	Vasiliev and others (2007)
1968	LGGE 1964	b	–15	Air–water–DFA	Gillet and others (1976); Donnou and others (1984)
1984	LGGE 1984	b	–54	DFA+TCE	Augustin and others (1988)
1972	JARE 140 Mk II	b	–35	air	Suzuki (1976)

Notes: ATED: antifreeze thermal electric drill (ETB-3 and ETB-5 (double chamber) are the same type of thermal electric drill); Au. CRREL Mk II: Australian Antarctic Expedition drill, version of the CRREL Mk II drill; BH: borehole; BPRC: Byrd Polar Research Center, Ohio State University, USA; CALTECH: California Institute of Technology, Pasadena, CA, USA; CRREL: US Army Cold Regions Research and Engineering Laboratory; DFA+TCE: mixture of diesel fuel arctic grade and trichloroethylene; ETB-3 and ETB-5: thermal electric drills, Arctic and Antarctic Research Institute, Russia; EWS: ethanol–water solution; JARE 140 Mk II: Japan Antarctic Research Expedition ice-coring drill; LGGE: Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France; PICO: Polar Ice Coring Office (now IDDO–IDPO at University of Wisconsin, National Science Foundation contract), USA; TELGA, TBZS and TBS-112VCh: drills developed in Leningrad (St Petersburg) Mining Institute (Mining University), Russia; UWS: University of Washington, Seattle, WA, USA.

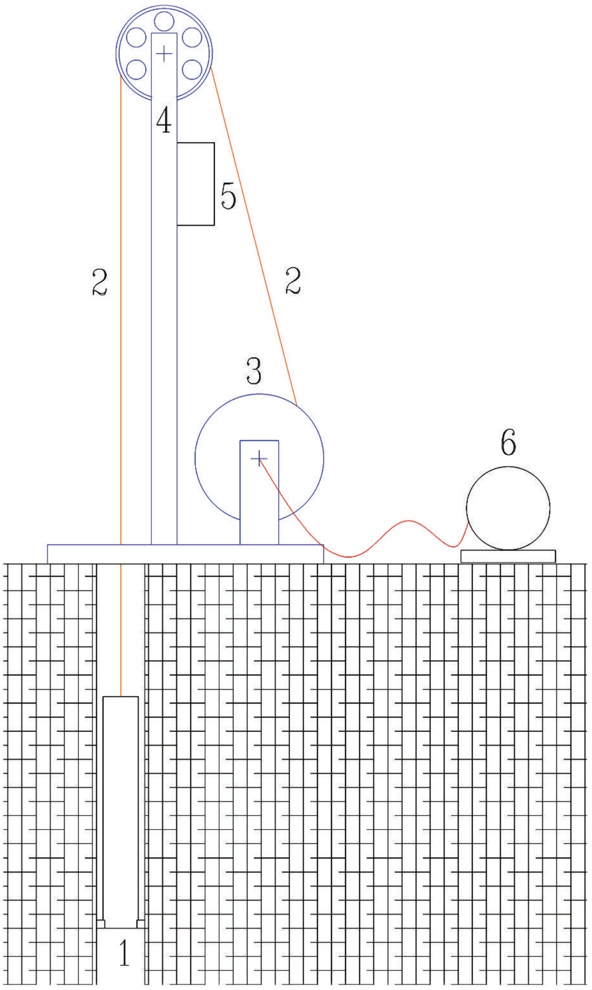

Fig. 2. Electro-drill (cable-suspended) drilling system: 1. downhole drill/sonde; 2. EM cable; 3. cable winch; 4. hoisting mast; 5. drill/winch controller; 6. source of electric power.

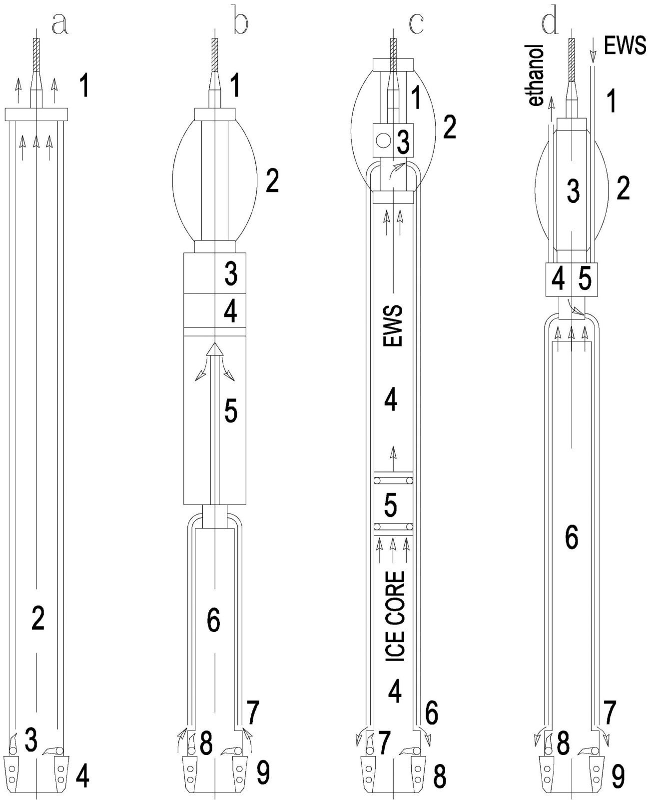

Fig. 3. General schematic of the TE drills: (a) TE drill for temperate ice: 1. cable termination; 2. core barrel; 3. core catchers; 4. coring head; (b) conventional TE dry and fluid drill removes meltwater from the kerf: 1. cable termination; 2. centralizer; 3. telemetry/control electronics; 4. vacuum (water) pump; 5. meltwater container; 6. core barrel; 7. water-sucking tubes; 8. core catchers; 9. coring head; (c) p-ATED: 1. cable termination; 2. centralizer; 3. EWS filling socket and valve; 4. core barrel/EWS container; 5. piston; 6. EWS injection tubes; 7. core catchers; 8. coring head; (d) new-concept drill: 1. cable termination; 2. centralizer; 3. antifreeze container; 4. metering antifreeze pump (N1); 5. EWS circulation pump (N2); 6. open-top core barrel; 7. EWS injection tubes; 8. core catchers; 9. coring head.

station was filled with hydrocarbon-based antifreeze. These drills remove meltwater from the kerf and store it in the container above the core barrel (Figs 1 and 3b; Table 1: CRREL Mk II; Au. CRREL Mk II; TELGA; JARE 140 Mk II). They are slow (penetration rate <1.5 m h^{-1}), require considerable power input (5–10 kW) and their operation requires substantial time for servicing on the surface. As a result, the ice-core production rate is low (~0.5–1 m h^{-1}). This type of drill includes water pumps and heating elements for sucking tubes and the water tank. Because the drill operates in air-filled BHs, the travel speed is hardly affected by friction and is mainly determined by winch motor power. These drills are long, operate with heavy EM cable, are not appropriate for regions with limited logistic support and are not suitable for operation in temperate glaciers. Their most unsatisfactory feature is poor ice-core quality due to the thermoelastic stress caused by drilling–melting (Nagornov, and others, 1994).

An air-filled BH is subject to overburden ice pressure and rheological closure. The closure rate depends on ice temperature, BH depth and diameter (Talalay and Hooke, 2007). The maximum operating depth of a dry BH reached with a TE drill in cold ice (<–50°C) is ~952 m; in warmer ice it is ~200 m at PMT. To increase the maximum ice-coring depth it is necessary to compensate for the overburden ice pressure. This is achieved by filling BHs with non-freezing fluid of greater density than that of ice. Filling BHs with hydrophobic or hydrophilic antifreeze compensates for overburden ice pressure and permits ice coring virtually to any depth at any ice temperature.

A second generation of this type of TE drill was developed for fluid-filled BH operations. In general, these drills are similar in design to the TE drills described above

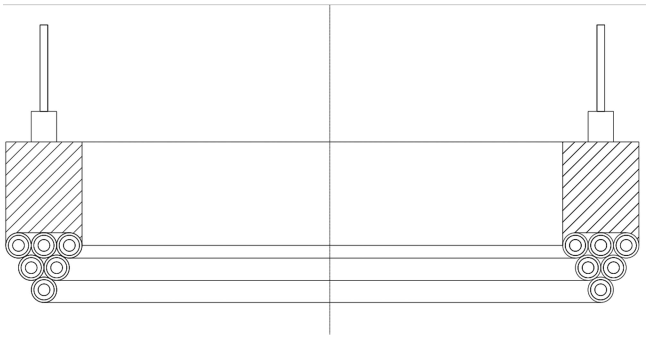

Fig. 4. Cross section of a narrow-kerf PICO TE drill; gray is stainless-steel base; pink is high-resistance wire of the small-diameter (~1 mm) coiled tubular heating element.

(Figs 1 and 3b; Table 1: TBZS; TBS-112VCh; LGGE 1964; LGGE 1984). In these drills the meltwater is also pumped from the kerf, stored in the drill and removed to the surface. The BH is filled with hydrophobic hydrocarbon-based non-freezing fluid from the surface.

The design of the coring head in the TBS-112VCh drill enables reduction of the kerf area, the drill power consumption and the diameter and weight of the EM cable. The drill equipped with the new coring head operates at penetration rates up to 4.2 m h^{-1}. However, its production drilling rate remains low due to the lower travel speed of a drill in a fluid-filled BH. Other fluid TE drills operate at comparable or higher penetration rates, use more power, produce a kerf of larger area and therefore are less effective.

Apart from the benefits of having increased maximum depth capabilities, this type of TE drill shows limitations similar to those of dry-hole TE drills, including poor ice-core quality (Nagornov, and others, 1994). The travel speed of these drills is lower in fluid-filled than in air-filled BHs, so the increased penetration rate does not increase the ice-core production rate (TBS-112VCh; 0.5 m h^{-1} below 1500 m). Some of these types of TE drill operate in both dry and fluid-filled BHs.

TE DRILL FOR COLD, TEMPERATE AND POLYTHERMAL GLACIERS

The third type of TE drill is the antifreeze thermal electric drill (ATED) (Table 1: ETB-3, ETB-5 and ATED; Figs 1 and 3c and d) (Bogorodsky and Morev, 1984; Bogorodsky and others, 1984; Zagorodnov, and others, 1994a,b). This was developed as a light and portable drilling system to increase ice-coring capabilities in difficult-to-reach sites in high-altitude environments (Abramov glacier, Pamir mountains, in 1972; Ueda and Talalay, 2007) including the coldest glaciers in central Antarctica (Komsomolskaya station and Dome B, Antarctica; Manevskii and others, 1983; Morev and others, 1988).

In these drills, hydrophilic antifreeze (EWS) is injected into the kerf during penetration and mixes with the meltwater (Fig. 3c). When the ATED coring head is powered, the ice core enters the core barrel, pushes the piston up and displaces EWS to the kerf through the side channels. The mixture at ethanol concentration close to equilibrium remains in the BH (Bogorodsky and Morev, 1984; Bogorodsky and others, 1984). The volume of injected EWS is approximately equal to the volume of ice core recovered from the BH. On the surface the EWS is pumped to the core barrel above the piston and delivered to the BH bottom with the drill.

Compliance between the freezing (equilibrium) temperature of EWS and ice temperature is achieved by appropriate ethanol concentration in the EWS delivered with the drill to the BH kerf. The lower the ice temperature, the higher the required ethanol concentration in EWS (Morev and Yakovlev, 1984; Zagorodnov and others, 1994a). Since the ice-core cross-sectional area is close to the melted kerf area, concentration of ethanol in the drill is about twice as high as the equilibrium concentration of ethanol in the BH at given ice undisturbed temperature. When the injected EWS mixes with meltwater in a 1 : 1 proportion, the mixture concentration comes closer to the equilibrium concentration. Ethanol as a base of the BH fluid was found to be a low-environmental-impact antifreeze. EWS stays in the BH and provides BH wall stability long enough for deep drilling (≥11 months; Manevskii and others, 1983; Morev and others, 1988).

The drill is of simple design, with no powered pumps and only one moving part: a piston inside the core barrel used for drilling-fluid circulation. Fluid circulation in the BH is achieved through the weight of the drill only. The core barrel of the drill is also used as the antifreeze container and the ice-core barrel/container. Thus, the ATED drill length exceeds that of one drilling-run ice core by only 10–20%. The ATED drill is equipped with an efficient coring head that provides a 4–6 m h^{-1} penetration rate at a power input of ~4 kW. Relatively thin and lightweight steel armored coaxial cable (outer diameter 8.8 mm; 28 kg (100 m)$^{-1}$) allows reduction of the weight and power of the hoist system. ATED-type drills do not require heating of their structure and therefore require less power than the other cold-ice TE drills. Based on previous experience of Austfonna (Svalbard) ice-core drilling operation, we estimate that set-up of a total weight of <1000 kg is capable of reaching ~1000 m depth in 500 drilling hours (Zagorodnov, 1988; Zagorodnov and others, 1998). Lighter, smaller and power-efficient ATED drills operate in smaller shelters and require less fuel and smaller power systems than other cold-ice drilling systems.

A double-chamber ATED (ETB-5) was designed to drill a deep BH (>1000 m) in central Antarctica (Bogorodsky and others, 1984). In spite of successful drilling operation in cold ice (–53 to –50°C; Komsomolskaya station, Antarctica), this drill is long, heavy, complex and inferior to other fluid EM drills (Manevskii and others, 1983).

The final modification of the ATED drill was designed to improve the core quality, increase the production drilling rate and reduce the total weight of the drilling equipment and power system to make it suitable for high-altitude (>6000 m a.s.l.) ice coring (Zagorodnov and others, 2005). This drill, equipped with a 2 m long core barrel, produces an ice core of 100–104 mm diameter at a production drilling rate of 2 m h^{-1} and a power input of ~4 kW. The ice-core quality was improved by reducing thermoelastic stresses and the ice-core diameter (Nagornov and others, 1994; Zagorodnov and others, 2005). The weight of the 550 m drilling set-up and power system was reduced to 300 kg. Up to 470 m deep BHs were cored using a combination of dry-hole EM and ATED drills at Bona–Churchill Col, Alaska, and at Bruce Plateau, Antarctic Peninsula (Zagorodnov and others, 2002, 2005, 2012).

The ATED drills have demonstrated the cited capabilities at different polar and high-altitude glaciers at ice temperatures above –30°C (Morev and others, 1988; Koci and Zagorodnov, 1994; Zagorodnov and others, 1998, 2005; Ueda and Talalay, 2007). The most useful capabilities of the ATED drills were realized in intermediate-depth BHs drilled through polythermal and shelf glaciers (Zotikov, 1979; Morev and others, 1988; Zagorodnov, 1988; Zagorodnov and others, 2005, 2014). In some of these operations, ATED drills provided high ice-core production rates of close to 420 m week^{-1} (assuming 20 hour d^{-1} operation; Zagorodnov, 1988).

ATED DRILL MODIFICATIONS

The major goal of new TE ice-core drill development is to reduce the power required by ATED, in order to allow the use of small, lightweight hoisting and power systems and reduce fuel consumption. At the same time it is desirable to

Table 2. ATED, ETB-3 and ot-ATED drills travel speed (V_t) in EWS-filled boreholes

Drill	L* m	m_d kg	μ kg m^{-1} s^{-1}	T_{ice} °C	V_t observed m s^{-1}	V_{tc} (Eqn (3)) m s^{-1}	V_{to} (Eqn (4)) m s^{-1}	V_{ot} expected m s^{-1}
ATED/ot-ATED	2.3/3.5	48	0.001	PMT	<0.7	1.7/1.1	24.4/14.8	9.8/5.9
ATED/ot-ATED	2.3/3.5	48	0.0281	–16	0.3–0.4	1/0.1	14/1.32	5.6/0.53
ATED/ot-ATED	2.3/3.5	48	0.0484	–24	0.2–0.4	0.54/0.05	7.44/0.7	2.86/0.28
ETB-3	3.6	75	0.0010	PMT	?	31.6	312	n/a
ETB-3	3.6	75	0.0281	–8	~0.5	5.4	53.3	n/a
ETB-3	3.15	60	0.0484	–25	0.5	0.72	7.1	n/a

Note: ETB-3 and ATED drills are closed-top drills equipped with a piston.
*Drill length, with the core barrel length shorter by 0.3 m for ATED and 0.5 m for ETB-3.

have operational capabilities similar to ATED, i.e. achieving maximum depth and a high production drilling rate in polythermal glaciers.

The total drilling time (t (hours)) of a BH with a cable-suspended drill can be represented as

$$t = H\left(\frac{1}{V_p} + \frac{t_s}{\ell} + \frac{H}{V_t \ell}\right), \qquad (1)$$

where H is BH depth, V_p is penetration rate, t_s is time required for drill servicing, ℓ is the length of ice core recovered in one drilling run and V_t is the average speed of drill travel (lowering and raising). Equation (1) shows that the average production drilling rate H/t depends on the drill's penetration rate, servicing time, the length of ice core recovered per drilling run and the average drill hoisting speed. Based on practical values of the parameters in Eqn (1) ($V_p = 4\,\mathrm{m\,h^{-1}}$, $t_s = 0.17$ hour, $\ell = 2$ m and $V_t = 3600\,\mathrm{m\,h^{-1}}$; Table 2), in intermediate-depth (≤1000 m) BHs the penetration rate determines ~53% of the average production drilling rate. The drill surface time and core barrel length account for ~18% of the production drilling rate, while only ~29% of the rate and total time depend on drill travel speed.

Following Nizery (1951) and Harrison (1972), the penetration drilling rate of the TE drill below PMT is

$$V_p = \frac{P}{S_k \rho_i [(T_i - \mathrm{PMT}) c_i + \lambda_i] + A}, \qquad (2)$$

where P is coring head power, $S_k = \frac{\pi}{4}\left(D^2 - d^2\right)$ is kerf melted area, D is BH diameter, d is ice-core diameter, T_i is ice temperature, c_i is ice specific heat capacity, λ_i is ice latent heat of fusion, ρ_i is ice density, A is lateral heat loss and PMT is pressure-melting temperature of ice. Nizery (1951) estimated $A = 20\%$ of applied power; field measurements show $A = 15\%$ (Zagorodnov, unpublished information 1978). It should be stated that the precision of analog panel meters used for power measurements in the past is low (optimistic best guess ±2.5%), and using old data (including the authors') could cause significant discrepancies.

The desirable power to allow effective use of the EM drill hoisting winch and power system is less than 1.5 kW. This is 2.7 times smaller than the required power for the 3.6 m h^{-1} penetration rate currently achieved with the ATED; the 2 m drill time is 33.3 min and the complete drilling run time is close to 58 min. To provide the same drilling penetration rate at the desired power of 1.5 kW, the kerf area has to be reduced by 2.7 times the current ATED design. In order to have the same ice-core diameter ($d = 0.102$ m), the kerf width should be 5.5 mm. This width seems too small for the design of the core catchers and will be associated with small clearances between the drill and BH wall, reducing the drill travel speed (see next section). At the maximum coring head power of 1.5 kW and assumed kerf width of 8 mm, the penetration rate will be 2.36 m h^{-1}. At this rate, drilling of a 2 m long ice-core section will take 50.5 min. This penetration time is 17.2 min (51.6%) longer than that of prototype drills powered at ~4 kW. This time cannot be compensated for with t_s, ℓ and V_t. The only way to achieve a 2 m h^{-1} ice-core production rate is to reduce the kerf area by reducing the ice-core diameter.

A penetration rate of 1.1 mm s^{-1} (4 m h^{-1}) is achievable with a drill that produces ice core of 85 mm and BH of 105 mm diameter at 1.5 kW power and total power losses of ~30% on power transmission and lateral heat dissipation. A low-power (<1.5 kW) TE drill can operate at 200–250 V. It allows use of small-diameter (7–8 mm) and lightweight (11–9.5 kg (100 m)$^{-1}$) Kevlar EM cable.

The first narrow-kerf ice-coring head was developed by the Polar Ice Coring Office, Lincoln, NE, USA, in the early 1980s. An example of a narrow-kerf coring–melting head is shown in Figure 4. In this design a small-diameter (~1 mm) tubular electric heater is coiled and brazed to a stainless-steel ring. An open-top core barrel TE drill for temperate ice equipped with a narrow coring head was used to drill through Quelccaya ice cap, Peru, in 1983. The drill was powered with a 2 kW array of solar panels (Koci, 1985; Thompson and others, 1985).

ICE-CORE DRILL TRAVEL SPEED IN FLUID-FILLED BH

Lowering and raising of cable-suspended drilling tools in fluid-filled BHs is associated with hydraulic drag. There are two types of wireline BH tools: closed- and open-end tools. Ice-core drills for temperate ice (Fig. 3a) are open-type drilling instruments. As such a drill moves down, the BH fluid passes through the hollow center of the core barrel and through the clearance between the drill and the BH wall. When the drill is hoisted up, the ice core blocks fluid from passing through the core barrel and may then be considered a closed tool. The drills shown in Figure 1b and c are closed-end tools. When they travel through the BH the fluid transfers between the drill and the BH wall. The bigger the clearance between the drill and the BH the less the hydraulic drag and the faster the drill can travel and/or the less power is required to pull the drill up the BH.

Gravitational force drives drills down, whereas a winch pulls drills up. To achieve a high lifting speed, the winch pulling capacity should exceed the drill's weight and the drag forces. The heavier the drill the faster it can descend. At the same time, heavy drills require more hoist power, a bigger power source and more fuel delivered to the drilling site. Increasing the clearance around the drill to reduce the drag requires more power for a thermal-drill coring head and increases the length of an EM drill in order to store more cuttings. In this case, the lowering speed of a cable-suspended drill can be increased either by increasing the weight of the drill or by reducing the hydraulic drag. The latter is preferable since it does not require additional power for hoisting the drill up. Therefore, to achieve high travel speeds of an ice-core drill in a fluid-filled BH requires optimization of its weight, length, cross-sectional geometry and the power of the winch.

The problem of travel of open- and closed-type tools (wireline tools) in fluid-filled BHs was analyzed by Onishin and others (1990). The experimental and theoretical investigations were applied to ice-core drilling (Fujita and others, 1994; Zagorodnov and others, 1994a; Talalay and Gundestrup, 1999; Vasiliev, 2002; Vasiliev and Kudryashov, 2002). Currently, the semi-empirical solution (Onishin and others, 1990) appears optimal, yet is not free of limitations. We consider the ice-core drill as (i) a closed- and (ii) an open-end pipe. Equations (3) and (4) describe the gravity-lowering speed of closed (V_{tc})- and open (V_{to})-type drills traveling in a fluid-filled BH (Onishin and others, 1990):

$$V_{\mathrm{tc}} = \frac{gD^2}{4\mu L}\left[\left(1+r_{\mathrm{a}}^2\right)\ln\frac{1}{r_{\mathrm{a}}} - \left(1-r_{\mathrm{a}}^2\right)^2\right]\left(\frac{4m_{\mathrm{d}}}{\pi D_{\mathrm{d}}^2} - \rho_{\mathrm{fl}}L\right),\ \frac{4m_{\mathrm{d}}}{\pi D_{\mathrm{d}}^2 L} > \rho_{\mathrm{fl}}, \tag{3}$$

$$V_{\mathrm{to}} = \frac{gD^2}{4\mu L}\left[\left(1-r_{\mathrm{a}}^4+r_{\mathrm{c}}^4\right)\ln\frac{1}{r_{\mathrm{a}}} - \left(1-r_{\mathrm{a}}^2\right)^2\right]\left(1-r_{\mathrm{a}}^2\right)\left(\frac{4m_{\mathrm{d}}}{\pi D_{\mathrm{d}}^2} - \rho_{\mathrm{fl}}L\right),\quad \frac{4m_{\mathrm{d}}}{\pi D_{\mathrm{d}}^2 L} > \rho_{\mathrm{fl}}, \tag{4}$$

where g is the acceleration of gravity (m s^{-2}), D is BH diameter (m), μ is the dynamic viscosity of the BH fluid (kg m^{-1} s^{-1}), $r_{\mathrm{a}} = \frac{D_{\mathrm{d}}}{D}$, D_{d} is the drill outer diameter (m), m_{d} is the mass of the drill (kg), L is the drill length (m), ρ_{fl} is the density of the BH fluid (kg m^{-3}), $r_{\mathrm{c}} = \frac{D_{\mathrm{cb}}}{D}$, and D_{cb} is the inner diameter of the core barrel (m). Equations (3) and (4) have a limited range of parameters that provide realistic lowering-speed estimates.

The results of the estimates of the lowering/raising speed of ATED, ETB-3 and ot-ATED are presented in Table 2; parameters of the ot-ATED are the same as those of ATED. The lowering rate of the ETB-3 drill at PMT was not measured but is presented in Table 2 as an average calculated from the drilling-run times of a few intermediate-depth BHs (Zotikov, 1979; Zagorodnov, 1988). Equation (3) shows that the V_{tc} value for ATED is two to three times higher than that observed in EWS-filled BHs (0.3–0.5 m s^{-1} at –10 to –24°C). The lowering-speed data presented here are worst-case: most of the time the slurry is more viscous at the top of a BH where lowest lowering speed is observed.

Bailing of EWS from a few BHs shows that the equilibrium EWS is composed of liquid phase and ice crystals, i.e. a slurry. The viscosity of EWS-ice slurry in a glacier BH has never been measured. Therefore the observed discrepancy between estimated (Eqn (3)) and observed ATED travel speed can be explained by laboratory values of the EWS dynamic viscosity used in our estimates. The previously published data represent EWS dynamic viscosity without or with low ice crystal concentration (Morev and Yakovlev, 1984; Zagorodnov and others, 1994a). In the cited experimental study of the equilibrium state, EWS was defined as the appearance of the first ice crystals. In this study, the viscosity of EWS was measured in a glass vessel, so it is likely that the results represent the viscosity of supercooled EWS, i.e. of the liquid phase only.

Our recent experiments show that in a glass vessel the first ice crystals appear several hours after EWS was supercooled, and that the crystals grow very slowly. At the same time, if ice chips are placed in the vessel, the ice crystals appear in a much shorter time (minutes) and grow quickly. Therefore the equilibrium EWS has to be considered as a slurry, and its viscosity has to be measured in properly arranged conditions: the ice has to be constantly present in the vessel containing the EWS.

The dynamic viscosity of slurries can be described relative to the viscosity of the liquid phase as (Thomas, 1965)

$$\mu_{\mathrm{s}} = B\mu, \tag{5}$$

where μ_{s} is viscosity of the slurry, B is a dimensionless coefficient and μ is viscosity of the accommodating liquid. Thus, the estimations of the ATED drill travel speed have to be made using μ_{s} instead of μ.

A number of models have been developed to describe coefficient B depending on the volume concentration of the solid particles in a slurry. The following equations, (6) and its simplified form (7), fit the empirical data (Thomas, 1965):

$$B = 1 + 2.5\phi + 10.05\phi^2 + be^{C\phi}, \tag{6}$$

$$B = 1 + 2.5\phi, \tag{7}$$

where ϕ is the volume concentration of solid particles, $b = 0.00273$ and $C = 16.6$.

To match the modeled and observed travel speed of ETB-3 and ATED drills in Table 2, the viscosity value in Eqn (3) should be multiplied by factor of two to three ($A = 2$–3). For the following estimates, we assume $A = 2.5$ as the correction factor for closed- and open-end drills.

Using the observed free lowering speed of the ATED and Eqn (6), the volume concentration (ϕ) of ice crystals in EWS slurry can be estimated at

$$\phi = 0.4(B - 1). \tag{8}$$

From Eqn (8), the effective volume concentration of ice crystals in the BH EWS slurry is 40–80%.

Judging from Eqn (4), the open-end drills can travel one order of magnitude faster than the closed-end tools (Table 2). Application of the correction factor 2.5 (the same as for closed-top drills) to the values of V_{ot} in Table 2 yields the expected lowering speed of open-top ATED, which is generally five times faster than closed-top ATED of the same length. The expected lowering-speed values also allow us to suggest that at low temperatures the length of the core barrel would still be a limiting factor for open-top ATED. At $T_{\mathrm{ice}} = -24$°C the travel speed of a 3.8 m long open-top drill is about the same as that of a 2.3 m long closed-top drill. Hence, a 4 m long open-top core barrel drill can be considered to represent the practical maximum length of ATED drills operated in EWS-filled BHs. Depending on drilling conditions (most importantly ice temperature, maximum depth and logistic support options) the practical design of the ot-ATED requires optimization of the following drilling system parameters: weight, length and geometry of the downhole sonde and power of the winch motor.

Therefore, the ot-ATED can travel significantly faster than closed drills. At the same time, the speed of upward travel cannot be significantly increased without increasing the power of the winch and the weight of all components associated with a drilling system. From practical experience with ice coring, the highest possible lowering speed seems to be ~2 m s^{-1}. Certainly, this speed can be achieved with a relatively lightweight drill, while hoisting upward speed is limited to 0.3–0.7 m s^{-1} by a 0.5–1.0 kW winch motor. A more powerful winch significantly increases the weight of a drilling system. Thus, the average travel speed (V_t) of ot-ATED cannot exceed 1.2–1.3 m s^{-1}. Average two-way travel time in a 250 m deep BH can be estimated at 7 min.

NEW CONCEPT FOR AN OPEN-TOP ATED DRILL

A general scheme of the ot-ATED is shown in Figure 3c. The major differences between this drill and the prototypes are: the absence of a piston, addition of two electrical pumps to provide EWS circulation and a separate, detachable antifreeze container, in line with the core barrel. One pump (N1, 18 W) releases pure ethanol (or other hydrophilic antifreeze) from the antifreeze container (3 in Fig. 3d) just above the drill. This pump has low, adjustable production, so release of antifreeze can be set in accordance with the drilling rate and ice temperature. The second pump (N2, <100 W) accomplishes general, high flow (1–3 L min^{-1}). Circulation of EWS through holes located above the heating element (Fig. 4; Zagorodnov and others, 2005) did not slow down the penetration rate of the coring head. The N2 pump inlet is located at some distance above the drill (<0.5 m) where the pure ethanol is mixed with the EWS solution in the BH. The N2 pump delivers the cold EWS solution at close to equilibrium concentration to the kerf and removes excessive heat from the ice-core/BH wall, thus reducing thermoelastic stresses in the ice core and in the BH wall (Nagornov and others, 1994).

Another beneficial consequence of BH fluid circulation through the core barrel during drilling and hoisting is purging of slush inside the core barrel that forms in the closed ATED during its raising through the cold section of a BH. Slush jams the ice core, and its recovery would require additional time and slow down production.

Using pure ethanol instead of EWS reduces the labor and power resources needed to prepare EWS; EWS preparation includes making water from snow and mixing it with ethanol. A detachable antifreeze container filled with ethanol replaces the empty one before the subsequent drilling run.

Since the volume of the ice core removed from a BH is larger than the volume of ethanol released, the level of BH fluid in the BH will gradually decrease at a rate of ~1 m for each 2 m drilled. In cold ice (–16°C) our intermediate-depth ice-coring operations were successful down to 470 m depth with the level of BH fluid below 250 m (Zagorodnov and others, 2005, 2012). No signs of BH closure were observed in the course of several days. If necessary, however, the BH fluid level can be raised by adding EWS from the surface.

We will be able to derive detailed information on power reduction after the geometrical details have been settled and calculations have been performed, but the rough estimates provided in this paper indicate significant potential for reducing the installed power and thus weight of the system.

NEW THERMAL DRILL SURFACE TIME

The average surface time of the ETB-3 drill during intermediate-depth ice coring is 18 min. The ATED drill requires ~10 min on the surface. This time is divided approximately evenly between core removal from the barrel and pumping the EWS into the drill. Ice core that is not jammed by slush may be removed from the drill faster than from the prototype drills, and ethanol containers can be exchanged in 1–2 min, with the container for the next drilling run refilled with ethanol in the course of a drilling run. Therefore the estimated surface time of the ot-ATED drill is ~6 min. The expected average complete drilling run time of the ot-ATED in intermediate-depth BH is ~1 hour. The expected ice-core production drilling rate of ot-ATED equipped with 2.0 m core barrel capacity is ~2 m h^{-1}.

CONCLUSIONS

The limitations of EM drills in ice coring of temperate and polythermal glaciers can be overcome using thermal drills. A new ATED drill concept has been presented here. It is expected to eliminate some of the drawbacks of the old TE drills, i.e. poor ice-core quality, low production rate and heavy set-up. The open-top core barrel, pure ethanol injection into the BH above the drill and circulation of EWS through the kerf will make it possible to recover ice core of better quality and accomplish a high production drilling rate. A smaller ice-core diameter and narrow-kerf coring head will reduce the power requirements from 4.5 kW for the prototype to 1.5 kW. It is expected that ot-ATED will also allow for the high production drilling rate (2 m h^{-1}) achieved in the prototypes. Like all previous versions of the ATED drill, the new-concept drill can be used in temperate, polythermal and cold ice without modifications or adjustments.

The advantage of the new drill, which uses a lightweight hoisting winch and requires less power, is that it reduces the logistical burden by allowing the use of a smaller-diameter (7–8 mm) EM cable along with a smaller and lighter power system. The operational data obtained using the ATED in BHs of intermediate depth (400–600 m) indicate that using EM drilling to depths of 150–200 m and then switching to TE drilling below those depths significantly reduces drilling time and logistical requirements compared to using the TE drill from the surface. It is also likely that the new-concept drill will prove effective in the lower portion of deep BHs at temperatures close to the PMT. Thus, considering the design, fabrication and operation, it is believed that the new drill will be more economical than any of the currently available fluid EM drills. The light weight and lower power requirements make the drill ideal for remote sites requiring the use of porters, and thus particularly useful in high-elevation environments.

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