ELSEVIER

Cold Regions Science and Technology 22 (1994) 243–251

cold regions science and technology

Hydrophilic liquid in glacier boreholes

V.S. Zagorodnov[a,*], V.A. Morev[b], O.V. Nagornov[c], J.J. Kelley[d], T.A. Gosink[d], B.R. Koci[d]

[a]Institute of Geography, the Russian Academy of Sciences, 29 Staromonetny per., Moscow, 109017, Russia
[b]Arctic and Antarctic Research Institute, 38 Bering Str., St. Petersburg, 199226, Russia
[c]Moscow Engineering Physics Institute, 31 Kashirskoe Shosse, Moscow, 115409, Russia
[d]Polar Ice Coring Office, University of Alaska Fairbanks, Fairbanks, AL 99775-1710, USA

(Received 22 December 1992; accepted after revision 9 August 1993)

Abstract

Environmental impact is a primary criterion for selecting any liquid used for filling boreholes in glaciers. Antifreeze solutions based on ethanol and other high molecular weight alcohols are among several potential fluids used for drilling deep holes in the Arctic and Antarctic glaciers. At relatively high ice temperatures in boreholes, the concentration of ethanol in the solution can be low. Therefore, using such drilling fluids causes less environmental impact. Ethanol–water solutions (EWS) have been used for filling boreholes at various temperatures from 0 to −58°C (Morev et al., 1988; Zagorodnov, 1988a; Zotikov, 1979). Ethanol requirements for deep drilling are significantly less than the volume of the borehole. Under normal operating conditions, ice core dissolution is about 1-mm ply per 40 min. Use of EWS for thermal drilling leads to slush formation. However, experience has shown that this is not a major drilling problem. The lifetime of the boreholes in central Antarctica is not less than one year.

1. Introduction

When drilling in glaciers, the boreholes must be filled with a non-freezing liquid to compensate for hydrostatic pressure. The liquids need to satisfy the following conditions: (1) low ecological impact and personal safety; (2) low ice core contamination; (3) low viscosity; (4) should not damage instrument components.

Currently, oil-based liquids are widely used for filling deep holes in glaciers (Gundestrup, 1988; Kudriashov et al., 1984). Such liquids have the advantage of low viscosity, but they have a number of drawbacks, including a negative environmental impact (Gosink et al., 1991a). In recent years, new liquids for filling boreholes have been tested in different countries. Hopefully, these will be free of many of the drawbacks.

For the last twenty years, EWS has been used for thermal drilling of deep holes in glaciers at temperatures (T_i) from 0 to −58°C (Korotkevich et al., 1979; Morev et al., 1988; Raikovskiy et al., 1990; Zagorodnov, 1988a,b; Zotikov, 1979). The deepest borehole (870 m) has been drilled by antifreeze thermal electrical drill (ATED) in central Antarctica filled with an EWS. At 800.6 m depth the drilling has been stopped for eleven months and the operation was resumed without any difficulty (Morev et al., 1988). On the Amery Ice Shelf, a 252-m deep borehole, at a minimum temperature of

*V.S. Zagorodnov is presently a visiting research professor at PICO, University of Alaska Fairbanks.

0165-232X/94/$07.00
SSDI 0165-232X(93)E0022-B

−16.3°C, has also been preserved approximately eleven months, after which drilling was continued (Raikovskiy et al., 1990). The borehole at Dome B location (central Antarctica, $T_i = -58°C$, pore close-off 120 m) reached 780 m depth in 1988 after seven weeks of drilling. Four years later, only the upper 40 m of the hole have been accessible. The ethanol requirement varied from 3 to 80% of borehole volume. Measurements indicate that the temperature of the EWS in the borehole comes to a stable equilibrium 120 hr after drilling is finished (Zagorodnov and Arkhipov, 1990).

Two major advantages of the EWS attract attention: (1) environmental and personal safety and (2) low ethanol requirements. However, when thermal drilling has been performed at glaciers with temperatures below −25°C, the following drawbacks were exhibited: high viscosity, slush formation and penetration of ethanol into the ice core. Slush formation seems to be the most challenging obstacle for application of EWS at temperatures below −25°C. Based on the experimental data (Morev et al., 1988; Zagorodnov, 1988b; Raikovskiy et al., 1990; Zotikov, 1979) we assumed that, at temperatures above −25°C, slush formation does not significantly affect penetration rate. The present paper pools the experiences of drilling nine deep boreholes in central and peripheral areas of the Antarctic Ice Sheet (Morev et al., 1988) and nine boreholes in the Arctic (Zagorodnov, 1988a). The estimated quantity of heat generated during drilling procedures in a hypothetical 3700-m deep borehole in the central Antarctic ice sheet is presented. General properties of EWS, mechanisms of slush formation and methods of its removal are considered. The causes of ethanol penetration into the ice core are discussed.

2. Physical properties of ethanol-water solutions

The freezing point of the water solutions of alcohols, acids, sodium chloride, dextrose, sucrose and others is below 0°C (Eggers et al., 1964; Pauling, 1970). The freezing point of pure ethyl alcohol is −114°C. It is the so called "hydrophilic" liquids which have a tendency to combine with ice and dissolve it at temperatures below 0°C. The term "hydrophilic liquid" implies the major dissimilarity from other types of drilling fluids (DFA, kerosene, and butyl acetate) which have antagonistic or hydrophobic tendencies (i.e., they do not combine with ice).

If the quantity of ice is infinite and the quantity of ethanol is finite, a thermodynamic equilibrium will occur: $T = T_{eq}$ and $C = C_{eq}$, where T_{eq} and C_{eq} are the equilibrium temperature and concentration, respectively. If one of these conditions breaks down, ice dissolution or ice formation will occur. Equilibrium of the EWS in the boreholes can be reached when $T_{eq} = T_i$. The experimental relationship approximated by $C_{eq} = -0.01334 T_{eq}$, $(-60°C < T_{eq} < 0°C)$ is shown in Fig. 1. The addition of a small amount of glycerin will decrease the T_{eq}. Within the temperature range of 0 to −52°C, the density of EWS is greater than the density of ice (Figs. 2 and 4).

If the specific weight of the aqueous ethanol solution should be increased, a high molecular weight alcohol such as glycerin or ethylene glycol can be added. All components are soluble in any proportions and form stable solutions. The addition of 1% glycerin to an ethanol-water solution increases the latter's specific weight by 0.3% at −20°C and by 0.6% at −40°C.

As compared to other filling liquids, EWS is characterized by a higher viscosity (Fig. 3). The viscosities of JAT A-1 (Gundestrup et al., 1984)

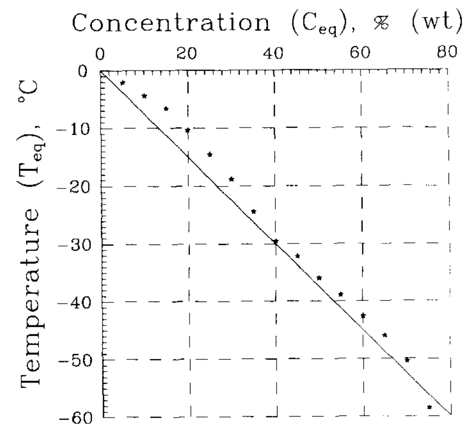

Fig. 1. Equilibrium temperature of EWS.

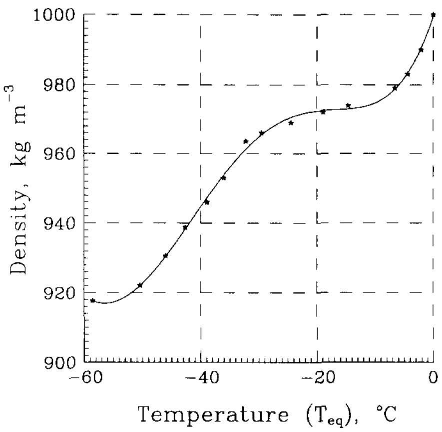

Fig. 2. Density of the EWS at the equilibrium temperature.

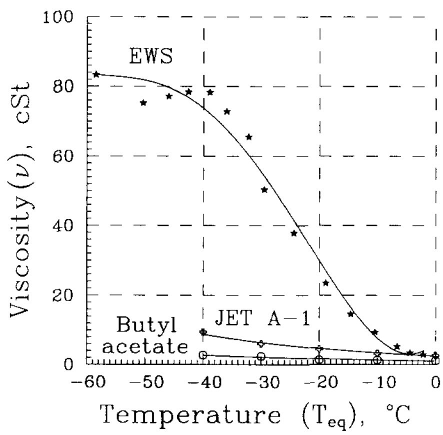

Fig. 3. Viscosity of EWS at equilibrium temperature compared with JET A-1 and butyl acetate.

and butyl acetate (Gosink et al., 1991a) are shown for comparison in Fig. 2. Nevertheless, in the range of temperature from 0 to −25°C the lowering speed of the thermal drill (length 3.2 m, weight 60 kg) has been 0.4 m/s (Zotikov, 1979), At a temperature of −53°C (Antarctica, Komsomolskaya Station) the lowering speed of the drill (length 5.5 m, weight 100 kg) was about 0.2 m/s. Drilling performance on an 800-m deep borehole in central Antarctica demonstrates a 70-m/week penetration rate (one 12-hr shift).

3. Slush formation

Thermal drilling operation is accompanied by heat release along the whole length of the borehole and therefore the EWS equilibrium is disturbed. Antifreeze solutions at temperatures higher than T_{eq} melt the surrounding ice (Gosink et al., 1991a). As the solution cools, water refreezes out of solution and T_{eq} approaches T_i. Lamella- and needle-shaped ice crystals freeze out from the solution, producing slush. The following estimations are based on the borehole and drill parameters presented in Table 1 and the temperature distribution shown in Fig. 4. The heat generated by the instrument is presented here as quantity of ice which can be melted from the borehole wall.

Table 1
Drill and borehole parameters used in estimations of ice slush quantities formed during drilling of polar glaciers.

Hole depth $H_{bh}=3{,}700$ m
Hole diameter $2R_0=120$ mm
Core diameter = 80 mm
Power of the heating bit $P_h=2.6$ kW
Heater efficiency = 85%
Energy losses in cable $\Delta P=0.5P_h=1.3$ kW
Rate of drilling-melting $S_m=5$ m/h
Drill mass $M_d=100$ kg
Mass of 1 m of cable $M_c=0.28$ kg
Length of ice core, taken during one run $L=6$ m

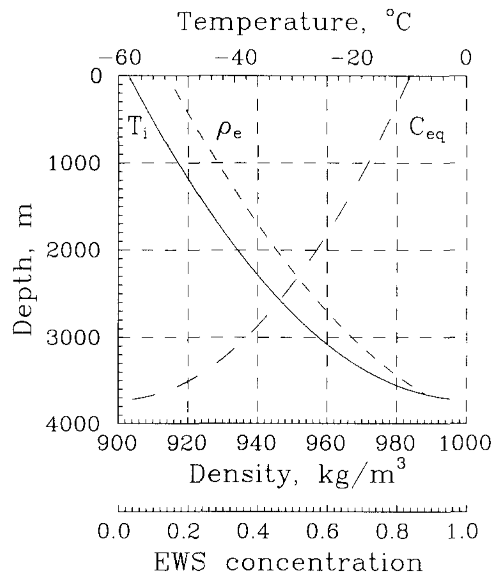

Fig. 4. Calculated temperature of ice (T_i), density (ρ_e), and concentration (C_{eq}) of EWS in the borehole.

3.1. Heat losses during the drilling–melting process

About 15% of the heat generated by the heating bit is consumed on warming the ice around the borehole wall, core and drilling solution during drilling. Calculations based on the temperature of the solution just after drilling and the equilibrium temperature of the solution (Figs. 5 and 6) indicate that about half of the heat energy is consumed for heating the solution inside the borehole and the rest for heating the core and the hole wall. If we assume that the surplus energy in the solution will be expended for ice melting, then the concentration of EWS comes to T_{eq}. Then the mass of ice dissolved on the borehole wall (m_i) will be as follows:

$$m_i = 0.15 \Delta P H_{bh} / (S_m \lambda) \qquad (3.1)$$

where S_m is the rate of drilling–melting λ is the latent heat of dissolution. Therefore, when drilling to a depth of 3,700 m, about 1.7 m^3 of ice could be dissolved.

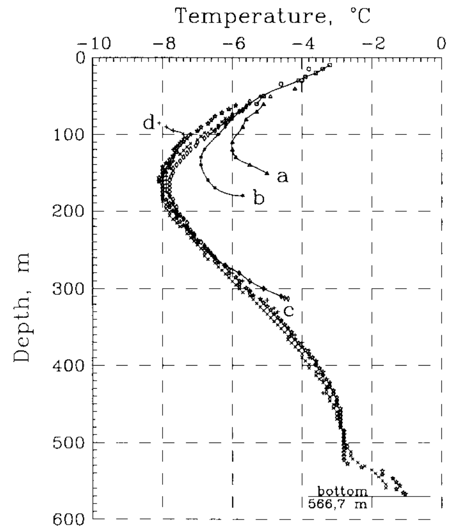

Fig. 5. Temperature distribution in the Austfonna borehole: (a, b, c) measured after break of drilling on respective depth; (d) measured after input of additional ethanol to the borehole.

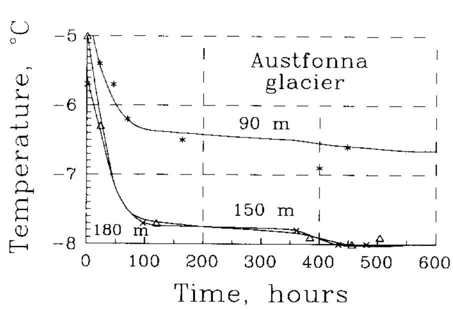

Fig. 6. Time-scale variation of the temperature in the Austfonna borehole.

3.2. Energy losses in the electric cable

Approximately half of the transmitted energy is lost to electrical resistance in the cable, thus heating of the cable and the surrounding solution causes dissolution of the ice from the borehole wall. Experimental data (Figs. 5 and 6) show that about 60 hr after drilling, the temperature of the solution reaches equilibrium, having dropped by about 0.2°C. If all of the cable heat was consumed for heating of the solution and thus for melting ice from the borehole wall, then:

$$m_i = \Delta P H_{bh} / (2 S_m \lambda) \qquad (3.2)$$

In reality, when the cable is lowered from depth z to $z + dz$, the mass of ice dissolved is equal to $dm_i = \Delta P z dz / (S_m \lambda)$. The mass of ice formed during refreezing is obtained by integrating this equation from 0 to H_{bh}. During the entire drilling time, the volume of ice could be dissolved from the wall could be as much as 23 m^3.

3.3. Heat transfer by instrument passage

In the central part of the Antarctic Ice Sheet near the surface, $T_i = -50$ to -60°C; T_i at the bottom is close to the melting point of ice (Fig. 4). Under these conditions, when moving along the borehole the drill and cable will transfer heat. When the cold drill and cable are lowered into the warmer layers, ice will form on their surfaces. When raised, the warmer drill and cable will heat the EWS and the borehole wall will be dissolved. If the borehole depth is 3,700 m, the lowering and raising of the drill will take at least two hours. Drilling a 6-m ice core will take about one hour. Thus, in conditions of intensive hydrodynamic heat exchange, there is ample time for the drill and cable to reach ambient temperature. Since $T(z)=\alpha+\beta z/H_{bh}$ (Fig. 4), where $\alpha=-60$, $\beta=57$, and z=the current depth, the mass of ice formed or dissolved when the cable moves at a distance dz is $\mathrm{d}m_i(z)=C_{dc}\beta z\mathrm{d}z/(\lambda H_{bh}^2)$. Integrating from 0 to z_k, the mass of ice formed when the drilling depth is z_k will be $m(z_k)=C_{dc}M_c\beta z_k^2/(2\lambda H_{bh}^2)$. The total mass of ice could be dissolved by the cable displacement during drilling is

$$m_i=\sum_{k=1}^{N} m(z_k) =\frac{N(N+1)(2N+1)C_{dc}M_c\beta L^2}{12\lambda H_{bh}^2} \quad (3.3)$$

where C_{dc} is the specific heat of the material from which the drill and cable were made (462 J/kg), $N=H_{bh}/L$ is the number of drilling runs and L is the length of ice cores. The mass of ice dissolved by the drill displacement during one run is $m(z_k)=C_{dc}M_d\beta L/(\lambda\rho_i H_{bh})$, where the drilling depth is $z_k=kL$, and k is the number of runs. The total mass of ice dissolved by the drill displacement is

$$m_i=\sum_{k=1}^{N} m(z_k)=\frac{N(N+1)C_{dc}M_d\beta L}{2\lambda\rho_i H_{bh}} \quad (3.4)$$

The total volume of ice would be $m_i=13.1$ m^3.

Hydraulic friction of the EWS during raising and lowering of the drill generates heat. At the top of the borehole, viscosity of the EWS is high. For that portion of the borehole, approximately half of the winch power is transformed into heat. Near the borehole bottom, the hydraulic friction is significantly lower. Calculations similar to Eqs. 3.3 and 3.4 give the value $m_i=60$ m^3. Hence, drilling operation gives up enough heat to dissolve 98 m^3 of ice in the borehole. Calculations below show that most of the heat radiates from the borehole.

4. Correlation of the ice dissolution effect and thermal diffusivity in surrounding ice

To estimate the portion of heat energy going into the surrounding ice, a mathematical model of the interaction between the heated EWS and the ice wall was developed. Assuming that the sum of all heat sources discussed above, radiates from an axial cable of diameter r_0, the temperature of the solution will rise and the thermodynamic equilibrium will be disturbed. As a result, the ice wall will be dissolved, the ethanol concentration will be lowered, and some portion of the heat will penetrate the surrounding ice. If heating is stopped, then the initial position of the phase boundary R_0 will be re-established after some time t. If we simplify the problem by assuming cylindrical symmetry, then all variables depend on the radius r and time t. The heat flow in the borehole is then governed by

$$\frac{\partial T}{\partial t}=\chi_m\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \quad t>0,\ r_0<r<R \quad (4.1)$$

where T is the temperature, χ_m is the thermal diffusivity of the ethanol–water mixture, and r_0 and R are the radius of the cable and the borehole, respectively. The heat conduction in the ice is described by

$$\frac{\partial T}{\partial t}=\chi_i\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \quad t>0,\ r>R \quad (4.2)$$

where χ_i is the thermal diffusivity of ice. The ethanol concentration C is defined by

$$\frac{\partial C}{\partial t}=D\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}\right) \quad t>0,\ r_0<r<R \quad (4.3)$$

where D is the diffusivity coefficient. We assume the following initial conditions:

$$T(r,0)=T_i \quad r>r_0 \quad (4.4)$$

$$C(r,0)=C_{eq}(T_i) \quad r_0<r<R_0 \quad (4.5)$$

where R_0 is the initial location of the phase boundary (borehole wall). The following conditions on the boundaries are assumed:

$$k_i\frac{\partial T}{\partial r}-k_s\frac{\partial T}{\partial r}=\lambda\rho_i,$$

$$-D\frac{\partial C}{\partial r}=C\frac{\mathrm{d}R}{\mathrm{d}t} \quad r=R \quad (4.6)$$

$$-k_s \frac{\partial T}{\partial r} = \frac{q}{2\pi r_0} \qquad r = r_0 \tag{4.7}$$

and

$$C(R,t) = C_{eq}(T) \tag{4.8}$$

where k_s and k_i are the thermal conductivities of ethanol–water solution and of ice, respectively, λ is the latent heat of ice melting, and ρ_i is the density of ice.

The above problem, defined by Eqs. (4.1) through (4.8), was solved using finite-difference expansions of the derivatives and retaining accuracy in the first-order time derivative and second-order spatial derivatives. If the heat flux from the heated mixture is consumed only for dissolution of ice (as in Sections 3.1 to 3.3), Eq. (4.6) is reduced to

$$-k_s \frac{\partial T}{\partial r} = \lambda \rho_i \frac{dR}{dt} \qquad r = R \tag{4.9}$$

Equations (4.1) through (4.5), (4.7) and (4.8) are unaltered.

For estimations, the following parameters were assumed: $\lambda = 3.3 \times 10^5$ J/kg, $T_i = 265$ K, $\rho_i = 917$ kg/m^3, $k_i = 1.33 \times 10^{-6}$ J/(m s K), $k_s = 1.5 \times 10^{-7}$ J/(m s K), $R_0 = 0.06$ m, $r_0 = 4.3 \times 10^{-3}$ m, $\chi_i = 2.22$ m^2/s, $\chi_m = 0.53$ m^2/s, $D = 1.5 \times 10^{-8}$ J/(m s K), $q = 2$ W/m. We also assumed that the parameters of the mixture are constant because the absolute temperature drop along the radius does not exceed one to two K, and displacement of the phase boundary is much less than the initial radius of the borehole.

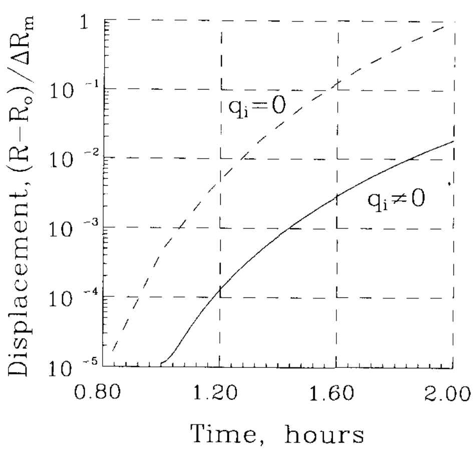

Fig. 7. Time dependencies of phase boundary displacement.

Numerical solutions of the above problems at $Q_i = -k(\partial T/\partial r)$, and $q_i = 0$ are presented in Fig. 7 (ΔR_m is the boundary displacement when $q_i = 0$). During one drilling run, a less than 1×10^{-3}-mm thick ply of the borehole wall is dissolved. The calculations show that the heat conduction from the borehole into the surrounding ice is about 98% of the total energy discharged in the borehole.

5. Discussion

5.1. Slush formation

Actual thermal drilling operations (borehole depths of 570 to 720 m, ice temperatures of −8 to −28°C) have shown that the volume of slush is 3 to 5 times greater than the estimated volume of dissolved ice obtained from Eqs. 4.1 to 4.8 ($q_i \neq 0$) and does not exceed 3% of the magnitude predicted by Eqs. 4.1 to 4.5 and 4.7 to 4.9 ($q_i = 0$). It can be concluded that a large percentage of heat from the borehole goes into the surrounding ice.

As the depth of drilling increases, the mass of slush also increases, primarily due to the movement of equipment through the borehole. The number of drilling runs N increases linearly as depth increases, but the mass of ice formed is proportional to N^3. A decrease in core length L results in an increase of $N = H_{bh}/L$ and ice mass increases proportionally by $1/L$. Decreasing both the mass and heat capacity of the drill and cable results in a proportional decrease in ice formation. Since only a small percentage of thermal energy is consumed for ice dissolution, less than 5.9 m^3 of ice slush will be formed (approximately of 5% of the calculated slush volume ($q_i \neq 0$). Addition of ethanol into the borehole dissolves the slush.

5.2. Ice core contamination

Penetration of ethanol up to 2.0 cm has been measured in a core obtained by a mechanical drill

(Gosink et al., 1991b). Chemical analysis of ice cores obtained by thermodrilling in boreholes filled with kerosene at Vostok and Dome C stations in Antarctica (Boutron et al., 1988), showed that these admixtures also penetrated into the ice core up to 2.5 cm.

We anticipate three reasons for ethanol penetration into the ice core: (1) micro-cracks at the ice core subsurface layer; (2) putting the ice core into a plastic bag and thermal container immediately after extraction from the core barrel (i.e., ethanol has not evaporated); (3) ice dissolution and prolonged diffusion of ethanol into the core could occur during transportation when the temperature of the ice core increases.

We suggest that ethanol has penetrated into the ice cores taken by ATED. The sample preparation technique enables the collection of a cleansed sample (rids the sample of admixtures) of the ice core and obtains true values of isotope and microparticle composition (personal communication with P.M. Grootes, L.G. Thompson, Y.K. Punning, R.A. Vaikmiae). Studies of microparticle concentration and oxygen-isotope composition of the J-9 ice core pointed out that below pore close-off the ice core is less subject to contamination. Taking into account the δ-elevation gradient, the average values of $\delta^{18}O$ of the J-9 ice core have good correlation with oxygen-isotope composition of the Byrd Station ice core and Ross Ice Shelf shallow ice cores (Grootes and Stuiver, 1982, 1986, 1987; Thompson and Mosley-Thompson, 1982; Clausen et al., 1979). The Komsomolskaya Station (central Antarctica) ice core has been obtained by ATED. The $\delta^{18}O$ profile of this ice core fits well with Vostok ice core isotope profiles (unpublished data, V.I. Nikolaev, personal communication). Numerous studies of the oxygen-isotope composition of Arctic ice cores obtained by ATED also demonstrated data reliability (Vaikmiae and Punning, 1984).

The quality of the ice core can be significantly improved by reduction of thermal stress (Nagornov et al., 1994). In this case, the ice core becomes less fractured and ethanol penetration is decreased. Evaporation of the EWS before wrapping the ice core will also diminish ice core contamination.

5.3. High viscosity of EWS

The high viscosity of ethanol solutions slows down deployment and retrieval of equipment in the borehole. The speed of the drilling operation can be increased by increasing the clearance between the drill and the hole wall (Augustin et al., 1988). With a greater clearance (presumably by 180% of tested ATED), the speed of lowering and raising the drill in the borehole will be 0.5 to 0.7 m/s. Under the above condition and at T_i below $-25°C$, a penetration rate of about 350 to 450 m/wk can be achieved when thermodrilling with a 6-m long core barrel is employed.

5.4. Ethanol requirements

If the temperature distribution in a glacier is known, the ethanol required for a borehole can be computed. If the borehole has a volume V_{bh}, the volume of ethanol required is

$$V = V_{bh}/H_{bh} \int_0^{H_{bh}} C_{eq}(z)dz/100 \qquad (5.1)$$

where $C_{eq}(z)$ is equilibrium concentration of ethanol at depth z. Taking into account the linear relationship between C_{eq} and T, and z and T_i, one can obtain

$$V = (0.5b\beta + a + b\alpha + 273b)V_{bh} \qquad (5.2)$$

Substituting numerical values for the constants a, b, α, β, which were defined earlier, we get $V = 0.44V_{bh} = 16.3$ m^3. To dissolve $V_i = 2.94$ m^3 of ice slush, an additional volume of ethanol (V_a) must be added to the borehole:

$$V_a = \frac{C_{eq}}{100 - C_{eq}} \frac{\rho_i}{\rho_e} V_i \qquad (5.3)$$

where C_{eq} is an equilibrium concentration of ethanol on the top of the borehole, ρ_i, ρ_e are the densities of ice and ethanol, respectively. If $C_{eq} = 76\%$ (Figs. 1 and 4), the volume of additional ethanol required is $V_a = 0.19V_i = 10.8$ m^3.

The total amount of ethanol required for drilling a 3700-m borehole is $V=0.73V_{bh}=27.1$ m^3.

Finally, the problems related to the specific properties of ethanol–water solutions at low temperatures can be overcome by improving drill design and maintaining an optimum ethanol–water ratio in the borehole. More exact estimates of the ethanol consumption for drilling deep holes in low temperature glaciers will require further theoretical and laboratory investigations on heat- and mass-exchange processes in boreholes filled with EWS.

6. Conclusions

EWS has a lower environmental impact compared to many alternative drilling fluids, with practically acceptable physical properties. The ethanol requirements for drilling deep boreholes in central Antarctica is approximately 75% of the borehole volume. At glacier temperatures higher than −25°C, the ethanol requirement is less than 50%. Ethanol contamination is not a great obstacle for studies of oxygen isotope and microparticle composition of ice cores taken by ATED at temperatures ranging from −2.1 to −53°C.

High viscosity of EWS and slush formation at low temperatures is a major drawback of antifreeze thermal drilling methods. The major cause of EWS equilibrium disturbance and slush formation is the lowering and raising of equipment in the borehole. Approximately 98% of the heat generated in the borehole during drilling activity radiates into the surrounding ice.

Greater clearance between the drill and the borehole wall decreases hydraulic resistance and increases the lowering and raising rate of the drill. As a result, at temperature ranges of −25 to −60°C, slush formation and percentage of ethanol required will be decreased and the penetration rate will be 250 to 450 m/wk.

Presumably the addition of ethanol into the borehole yearly keeps the borehole open.

7. List of symbols

a,b,c	constants
$C=C(r,t)$	ethanol–water mixture concentration
C_{dc}	the specific heat of the drill and cable
$C_{eq}(T)$	equilibrium concentration
D	diffusivity coefficient
g	gravity acceleration
H_{bh}	the borehole depth
k_s, k_i	thermal conductivity of ethanol–water solution and ice
L	the length of ice core
M_c	the mass of 1 m of cable
M_d	the drill mass
m_e	ethanol mass in unit volume of solution
m_i, m_w	mass of surplus ice and water, respectively
N	number of drilling runs
P_h	the power of the heating bit
q	thermal flux of cable
q_i	thermal flux into surrounding ice
R	current radius of the borehole
R_0	the initial borehole radius
r_0	radius of cable
S_m	the rate of drilling–melting
T_{eq}	equilibrium temperature
T_i	temperature of the ice
V	volume of ethanol
V_{bh}	volume of the borehole
V_i	formed volume of ice
z	the current depth
z_k	drilling depth of run
α, β	constants
β_t	coefficient of volume expansion of the solution
ΔP	energy losses in cable
ΔR_m	displacement of phase boundary without heat conduction into surrounding ice
λ	the latent heat of dissolution
ν	kinematic viscosity of the solution
ρ_i, ρ_e	density of ice and ethanol, respectively

χ_i thermal diffusivity of ice
χ_m thermal diffusivity of ethanol–water mixture

Acknowledgments

The authors are grateful to their colleagues from PICO and the faculty members of the University of Alaska Fairbanks for cooperation in the development of new ice drilling technology that will protect the environment. Thanks to financial support from the National Science Foundation, the authors are participating in the improvement of antifreeze-thermodrilling technology now continuing at the PICO facility at the University of Alaska Fairbanks. The authors also wish to thank the Institute of Marine Science Publications staff for their assistance with the technical editing and preparation of this paper.

References

Augustin, L., Donnou, D., Rado, C., Manouvrier, A., Girard, C. and Ricou, G., 1988. Thermal ice core drill 4000. In: C. Rado and D. Beaudoing (Editors), Ice Core Drilling. Proceedings of The Third International Workshop on Ice Drilling Technology, Grenoble, pp. 59–65.

Boutron, C.F., Patterson, C.C. and Barcov, N.I., 1988. Assessing the quality of thermally drilled deep antarctic ice cores for trace elements analysis. In: C. Rado and D. Beaudoing (Editors), Ice Core Drilling. Proceedings of The Third International Workshop on Ice Drilling Technology, Grenoble, pp. 182–197.

Clausen, H.B., Dansgaard, W. and Nielsone, J.O. 1979. Surface accumulation on Ross Ice Shelf. Antarct. J. USA, 17(5): 68–72.

Eggers, D.F., Jr., Gregory, N.W., Halsey, G.D., Jr. and Rabinovitch., B.S., 1964. Physical Chemistry. Wiley, Chichester, 783 pp.

Gosink, T.A., Tumeo, M.A., Koci, B.R. and Burton, T.W., 1991a. Butyl acetate, an alternative drilling fluid for deep ice-coring projects. J. Glaciol., 37(125): 170–176.

Gosink, T.A., Koci, B.R. and Kelley, J.J., 1991b. Aqueous ethanol as an ice drilling fluid. PICO TR 91-2, University of Alaska Fairbanks, Fairbanks, AL, 12 pp.

Grootes, P.M. and Stuiver, M., 1982. Ross Ice Shelf and Dome C oxygen-isotope analysis. Antarct. J. USA, 17(5): 76–78.

Grootes, P.M. and Stuiver, M., 1986. Ross Ice Shelf oxygen isotopes and west Antarctic climate history. Quat. Res., 26: 49–67.

Grootes, P.M. and Stuiver, M., 1987. Ice sheet elevation changes from isotope profiles. IAHS Publ., 170: 267–281.

Gundestrup, N.S. 1988. Hole liquids. In: C. Rado and D. Beaudoing (Editors), Ice Core Drilling. Proceedings of The Third International Workshop on Ice Drilling Technology, Grenoble, pp. 51–53.

Gundestrup, N.S., Johnsen, S.I. and Reeh, N., 1984. ISTUK, a deep ice core drill system. CRREL Special Report, SR 83-34, pp. 7–19.

Korotkevich, E.S., Savatiugin, L.M. and Morev, V.A., 1979. Trough drilling a shelf glacier in the region of Novolazarev Station. Sovetskaia Antarcticheskaia Ekspeditsiia. Informatsionni Builleten, 98, WDC No. 81001417. CRREL No. 35001057.

Kudriashov, B.B., Chistiakov, V.K., Pashkevich, V.M. and Petrov, V.N., 1984. Selection of a low temperature fillerd for deep holes in the Antarctic Ice Sheet. CRREL Special Report, SR 83-34, pp. 137–138.

Morev, V.A., Manevskiy, L.N., Yakovlev, V.M. and Zagorodnov, V.S., 1988. Drilling with ethanol-based antifreeze in Antarctic. In: C. Rado and D. Beaudoing (Editors), Ice Core Drilling. Proceedings of The Third International Workshop on Ice Drilling Technology, Grenoble, pp. 110–113.

Nagornov, O.V., Zagorodnov, V.S. and Kelley, J.J., 1994. Effect of a heated drilling bit and borehole liquid on thermoelastic stresses in an ice core. In: Proc. 4th Int. Workshop on Ice Drilling Technology, Tokyo, 1993, in press.

Pauling, L. 1970. General Chemistry. Freeman, San Francisco, CA, 959 pp.

Raikovskiy, Yu.V., Samoilov, O.Yu., Pron', N.P., Smirnov, K.Ye. and Arkhipov, S.M., 1990. Glaciological investigations of the Amery Ice Shelf in 1987–1989. Academiia Nauk SSSR. Institut Geografii. Materialy Glatsiologicheskikh Issledovanii, 68: 5–8 (in Russian).

Thompson, L.G. and Mosley-Thompson, E., 1982. Microparticle concentration and size-distribution determination from the J-9 core, Ross Ice Shelf. Antarct. J. USA, 17(5): 83–85.

Vaikmiae, R. and Punning, I.M., 1984. Isotope-geochemical investigations on glaciers in the Eurasian Arctic. In: W.C. Mahaney (Editor), Correlation of Quaternary Chronologies, Symposium, York University, Toronto. Geo Books, Norwich, pp. 385–393.

Zagorodnov, V.S. 1988a. Recent Soviet activities on ice core drilling and core investigations in Arctic region. Bull. Glacier Res., 6: 81–84.

Zagorodnov, V.S. 1988b. Antifreeze-thermodrilling of cores in Arctic sheet glaciers. In: C. Rado and D. Beaudoing (Editors), Ice Core Drilling. Proceedings of The Third International Workshop on Ice Drilling Technology, Grenoble, pp. 97–109.

Zagorodnov, V. and Arkhipov, S., 1990. Studies of structure, composition and temperature regime of sheet glaciers of Svalbard and Severnaya Zemlya: methods and outcomes. Bull. Glacier Res., 8: 19–28.

Zotikov, I.A. 1979. Antifreeze-thermodrilling for core through the central part of the Ross Ice Shelf (J-9 Camp), Antarctic. CRREL Report 79-24.