HYDROPHILIC LIQUID IN GLACIER BOREHOLES

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ABSTRACT

Ecological integrity is a primary criteria of 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 central part of the Antarctic Ice Sheet. At relatively high ice temperatures in boreholes, the concentration of ethanol in the solution is low. Therefore, such drilling fluids have a much lower environmental impact than others. Ethanol-water solutions can be used for filling boreholes with temperatures from 0 to -60°C. Ethanol requirements for deep drilling are significantly less than the volume of the borehole. The penetration of ethanol into the ice core is essentially the same as kerosene. Given the correct technological regimen, ice core dissolution is about 1-mm ply per 40 min. The preparation of an antifreeze thermodrill takes from 5 to 15 min, which includes pumping the drilling solution into the drill while simultaneously extracting the ice core. The lowering or raising speed of the instruments in the boreholes with an ethanol-water solution at -53°C is 0.3 m/sec. By increasing the clearance between the drill and the hole wall, the movement speed could be 0.5 m/sec. At -53°C the penetration rate of an antifreeze thermodrill is about 120 m/week. Drills with 6-m length core barrels and large clearance will operate with about a 350 to 450 m/week penetration rate. Use of ethanol-water fluid for thermal drilling involves slush formation. Practice has shown that ice slush formation in boreholes is not a major drilling problem.

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1.0 INTRODUCTION

In order to compensate for the hydrostatic pressure of ice when drilling holes in glaciers, it is necessary to fill the borehole with a non-freezing liquid. There are several conditions that the liquids should satisfy. Ideally, the liquid should not be toxic or dangerous to the specialists who perform drilling or to the study of boreholes and ice cores. The lengthy presence of the liquid in boreholes, or in the pores of the cores, should not be detrimental to living organisms (such as biota under shelf glaciers, glacial lakes, etc.). It is also advisable that evaporation of the liquid not damage the atmosphere, such as chlorinated hydrocarbons which harm the ozone layer. The liquid's vapor inflammation at room temperature is also an important condition. Thus, ecological integrity is a major criteria for choosing the liquid for filling boreholes.

Furthermore, the liquid must provide prolonged preservation of the borehole. To accomplish this, its specific weight should be close to that of the ice. Also, for a relatively quick sinking and uplifting operation of the drill and research instruments, the liquid should be of low viscosity (for mechanical drilling systems more than 5, but less than 50 cp) and should not dissolve the instruments' components.

When drilling in regions of difficult access, a considerable part of the budget is spent on transporting the filling liquid. It is evident that low cost, as well as low use, of the liquid per unit of the borehole length should be counted among its advantages.

At present, liquids based on oil products are widely used for filling deep holes in glaciers (Gundestrup, 1988; Kudriashov *et al.*, 1984). Yet, alongside the advantages of oil products, such as low viscosity, there are also several drawbacks, primarily from the point of view of their negative impact on nature. 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, boreholes in temperate and polar glaciers, including the central regions of the Antarctic Ice Sheet, have been successfully filled by a liquid based on ethanol. Ethanol-water solutions were used for the thermal drilling of deep holes in glaciers at temperatures between 0 to -58°C (Korotkevich *et al.*, 1979; Morev *et al.*, 1988; Raikovskiy *et al.*, 1990; Zagorodnov, 1988a,b; Zotikov, 1979). The deepest borehole in the central Antarctic filled with an ethanol-water solution is 870 m deep. At the 800.6-m depth the drilling was stopped, but after eleven months the operation was resumed without any problem (Morev and Yakovlev, 1984). On the Amery Ice Shelf, the 252-m deep borehole, at a minimum temperature of -16.3°C, was also preserved approximately eleven months and drilling was continued (Raikovskiy *et al.*, 1990).

Measurements in the boreholes showed that 120 hr after drilling, the temperature of the ethanol-water solution in the borehole comes to a stable (equilibrium) value (Zagorodnov and Arkhipov, 1990).

When the ethanol concentration in the solution is correct, negligible core dissolution takes place during the drilling process. At ice temperature of -25°C, after 40 min, a 1-mm ply of ice was dissolved from the outer surface of the ice core in the core barrel (Zotikov, 1979).

The data presented in Gosink *et al.* (1991b) show ethanol penetration into ice samples. The authors consider the main reason for this phenomenon to be the presence of micro cracks in the ice, through which ethanol penetrated up to 2.0 cm into the core obtained with a mechanical drill. Ethanol penetrated to the center in one artificial ice specimen. The investigation of the chemical composition of ice cores from Vostok and Dome C stations in Antarctic (Boutron *et al.*, 1988), obtained by thermodrilling with the borehole filled with kerosene, showed that these admixtures also penetrated ice up to 2.5 cm.

In this paper, the properties of liquids based on water solutions of technical ethyl alcohol (ethanol) and technical glycerin, as well as specific and supplemental data published earlier are discussed (Morev and Yakovlev, 1984). When analyzing ethanol solutions, properties were based on the recent experimental data obtained by PICO researchers (Gosink, 1989; Gosink *et al.*, 1991b).

2.0 PHYSICAL PROPERTIES OF ETHANOL-WATER SOLUTIONS

The salient properties of ethanol-water solutions used for filling glacier boreholes are: 1) the temperature at which crystallization begins and 2) the density and viscosity of the solutions at those temperatures. When testing the solution, it was assumed that the temperature under which the intensive separation of ice crystals stops is the temperature of crystallization (T_c). If the temperature of the solution is higher than T_c, the ice crystals will dissolve and the concentration of ethanol will decrease. Conversely, at lower temperatures more ice crystals will form in the solution and the ethanol concentration will increase. The main condition for achieving T_c of the solution in the laboratory is the existence of some amount of ice together with the liquid state antifreeze (solvent).

Figure 1 shows T_c for ethanol-water solutions in the range from 0 to -60°C and, hence, can be used for filling boreholes in all known glaciers on Earth. The freezing point of pure ethyl alcohol is -114°C. The addition of a small amount of glycerin will decrease the T_c of the solution.

In the given range of temperatures, the density of ethanol-water solutions is greater than that of ice. An optimal compensation of load pressure, depending on the temperature in the ice stratum, may be reached by varying the level of solution in the

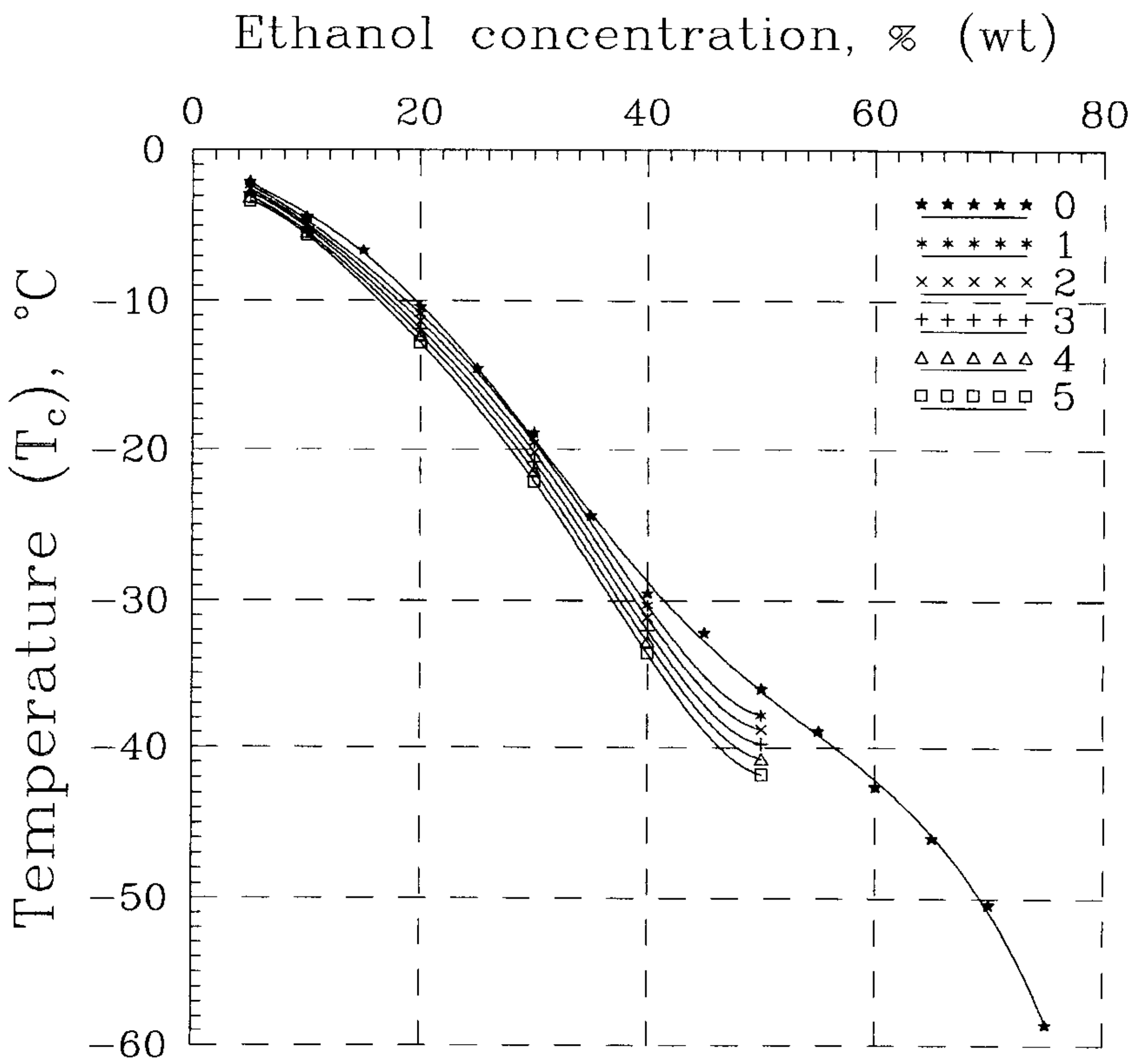

Figure 1. Dependence of the freezing (crystallization) temperature of ethanol-glycerine-water solution on glycerine-weight concentration: 0, 1, 2, 3, 4 and 5%.

borehole. For instance, when the mean temperature of the glacier sequence is -10°C, and the depth of the borehole is 1,000 m, equality between load pressure and the pressure of the filling liquid at the borehole bottom may be reached if the level of liquid is about 30 m below the glacier surface, lower if the firn layer density is taken into account. In particular, this feature allows the drilling of boreholes through the firn layer without casing. Due to the relatively high density of such solutions, specific cases permit drilling without adding liquid, which increases their specific weight.

A high molecular weight alcohol, such as glycerin or ethylene glycol, can be used as a densifier for the ethanol-water solution. All components are miscible in any proportion and form stable solutions. The addition of 1% glycerin to the ethanol-water solution increases the latter's weight by 0.3% at -20°C and by 0.6% at -40°C. Thus, the addition of glycerin to the ethanol-water solutions changes both T_c and the density within wide ranges and can provide a positive gradient of density of the solutions in the boreholes with different types of temperature distribution.

The dependence of viscosity of ethanol-water solution at crystallization temperature is shown in Figure 2. As compared to other filling liquids, ethanol-water solutions have a higher viscosity which is its specific feature. The addition of glycerin increases its viscosity still further. The question of using high-viscosity liquids for filling boreholes is mostly related to mechanical drilling systems. If the speed of sinking and uplifting instruments in a borehole of about 0.5 m/s is accepted, the high viscosity of ethanol-water solutions will not be a negative attribute. Viscosity of other fluids, JAT A-1 (Gundestrup *et al.*, 1984) and butyl acetate (Gosink *et al.*, 1991a), are shown for comparison in Figure 2.

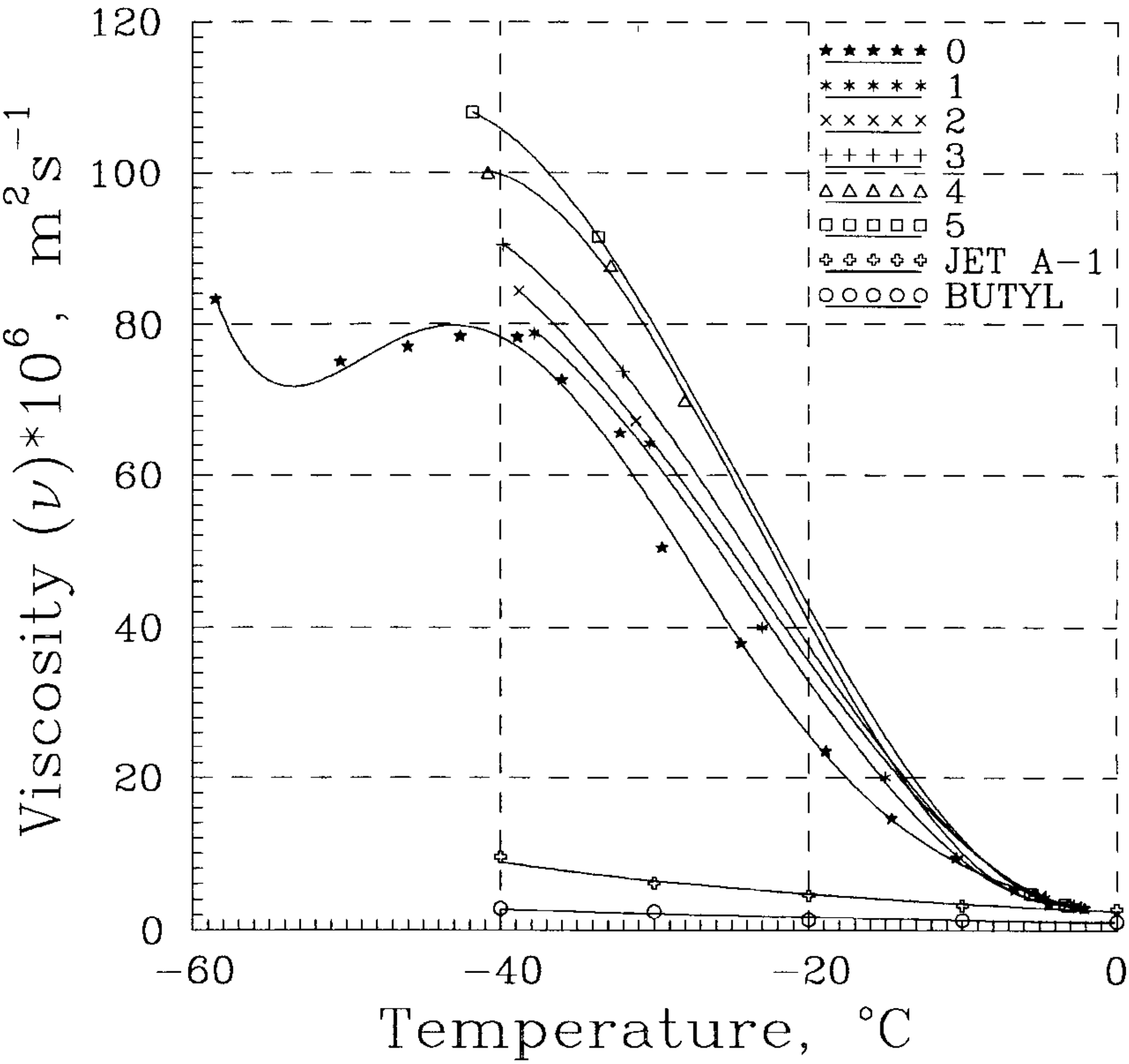

Figure 2. **Viscosity of ethanol-glycerine-water solution at crystallization temperature T_c; glycerine concentration: 0, 1, 2, 3, 4 and 5%, respectively, compared to JET A-1 and butyl acetate.**

3.0 STABILITY CONDITIONS OF THE FILLING SOLUTIONS IN BOREHOLES

An ethanol-water solution poured down the hole interacts with the ice wall when the content of ethanol is superfluous, causing the wall to dissolve, and when ethanol is insufficient, causing ice crystals to form. In the first case, the concentration of ethanol decreases; in the second case, when the water freezes out of the solution, the ethanol concentration in the solution increases. In either case, the beginning of crystallization is set up automatically, or in other words, a dynamic equilibrium is achieved between T_c of the solution and the temperature of the ice (T_i) at the given depth. Thus, the stable condition of the filling solution in the borehole takes place when $T_c = T_i$. The change of one of the parameters automatically causes the change of the other.

It is obvious that vertical movement of the solution in the hole with a temperature gradient will disrupt the equilibrium. Figure 3 indicates that a rise of temperature increases the density of the ethanol-water solution. Hence, if a glacier has a positive temperature gradient (warmer at the bottom), the solution in the borehole also has a positive density gradient. This prevents free vertical movement of the solution in the hole. For the solution not to freeze under the conditions of a negative temperature gradient, the concentration of ethanol in it should increase with increasing depth. In this case the dilution density will decrease, or the density gradient will become negative. Such a state cannot, naturally, be stable because it entails the development of vertical convective movement of the solution: the less dense but higher ethanol concentration solution from the lower part of the hole will rise to the depth where the temperature is higher, while the denser and less concentrated solution will sink to the cold layers. Simultaneously, in the upper part of the hole the ice will dissolve, and in the lower part water will be frozen out of the solution and slush ice will be bouyed to the upper part of the borehole.

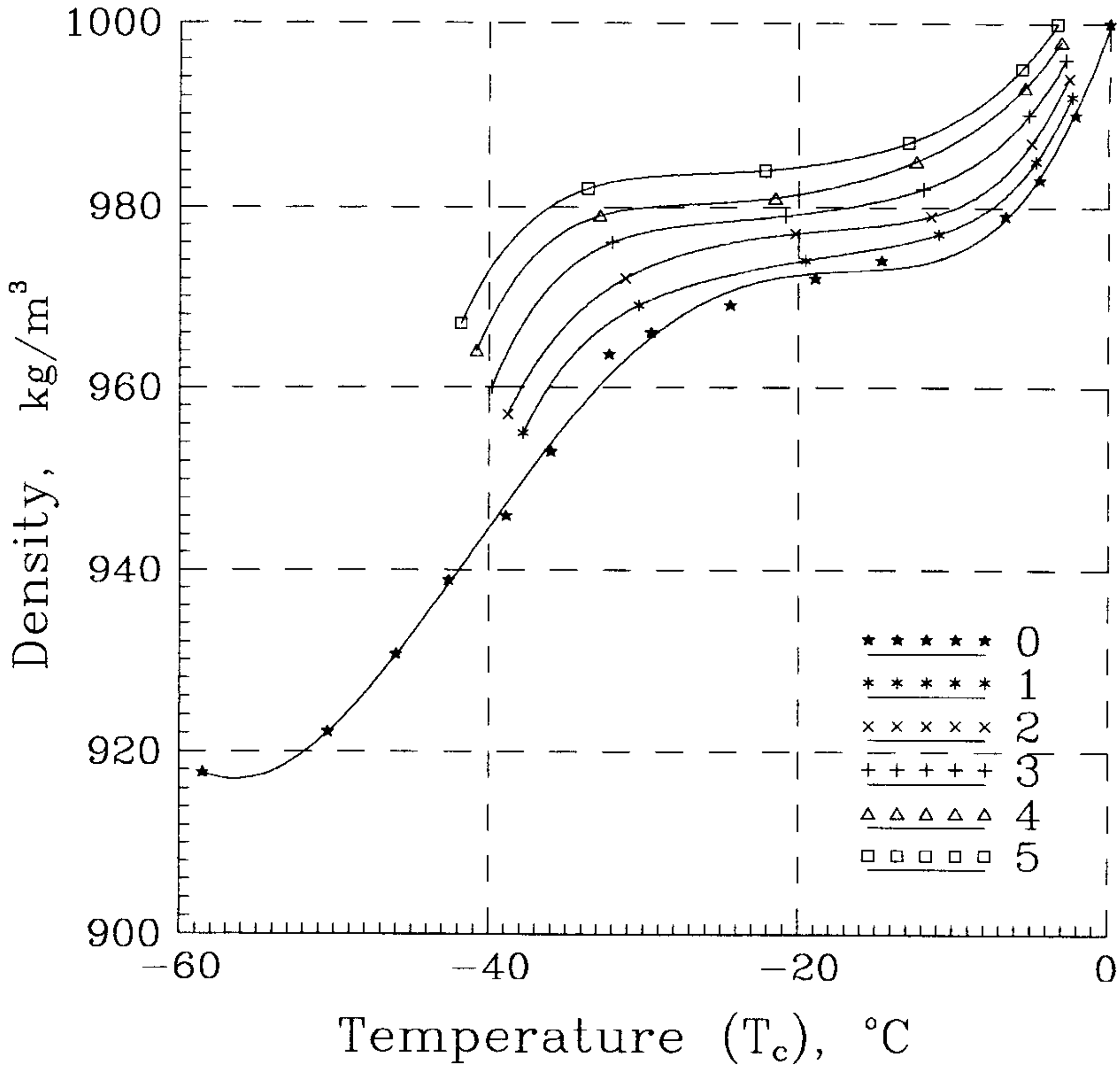

Figure 3. **Density of the ethanol-glycerine-water solution at crystallization temperature T_c; glycerine concentration: 0, 1, 2, 3, 4 and 5%.**

To estimate the opportunity for convective movement of the liquid in the borehole, we use the formula for the critical value of a negative temperature gradient (Morev and Yakovlev, 1984):

$$\frac{dT}{dz} = \frac{c\,\nu\,\chi_m}{g\,\beta_t\,R_0^4}$$

where: c is the constant, ν is the kinematic viscosity of the solution, χ_m is the thermal diffusivity of the solution, g is gravity acceleration, β_t is the coefficient of volume expansion of the solution and R_0 is the radius of the borehole. Estimation of the critical temperature gradient of a glacier with a borehole diameter of 115 mm is 10^{-3} to 10^{-2} °C/m in which convection will occur. It points out that in glaciers with relatively high temperatures of ice, from 0 to approximately -10°C, the formation of ice slush begins at small values of negative temperature gradient. Practical drilling of boreholes with a negative temperature gradient have essentially shown that formation of slush due to convective movement took place after some days.

4.0 CAUSE OF ICE SLUSH FORMATION

When decreasing the temperature of an ethanol-water solution below T_c, lamella and needle-shaped ice crystals are discharged from the solution, commonly called slush. The presence of slush in the bore hole creates hydraulic resistance for the lowering and raising of the drill instruments. For improvement in the technology of thermal antifreeze drilling, it is important to know the amount of ice slush that will form during the drilling of polar glaciers. The estimations shown below are based on the following arbitrary values with borehole and drill parameters of:

- 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.
- Ice temperature distribution presented in Figure 4.

During drilling-melting, the heat is spent on ice melting and heating the ice core and antifreeze solution, as well as on the ice wall of the borehole. It is shown (Gosink *et al.*, 1991a) that antifreeze solutions at temperatures higher than T_c dissolve the ice equivalent to the T_c increase. After cooling the solution, the ice is extracted and T_c approaches T_i. Let us study the main mechanisms of ice slush formation in the following subsections.

4.1 Insufficient Concentration of Ethanol in the Solution

One reason for slush formation is the use of a solution with insufficient ethanol concentration. This arises as a consequence of either using the wrong ice temperature data or a lack of knowledge of the penetration of melt water into the hole from either the surface or the bottom of the glacier. The amount of slush formed by these mechanisms depends on the difference between the crystallization temperature of the antifreeze solution in the borehole at the moment of drilling (T_c), and T_i at a given depth of the glacier. Let us examine two cases: T_i = -10 and -60°C; where T_c

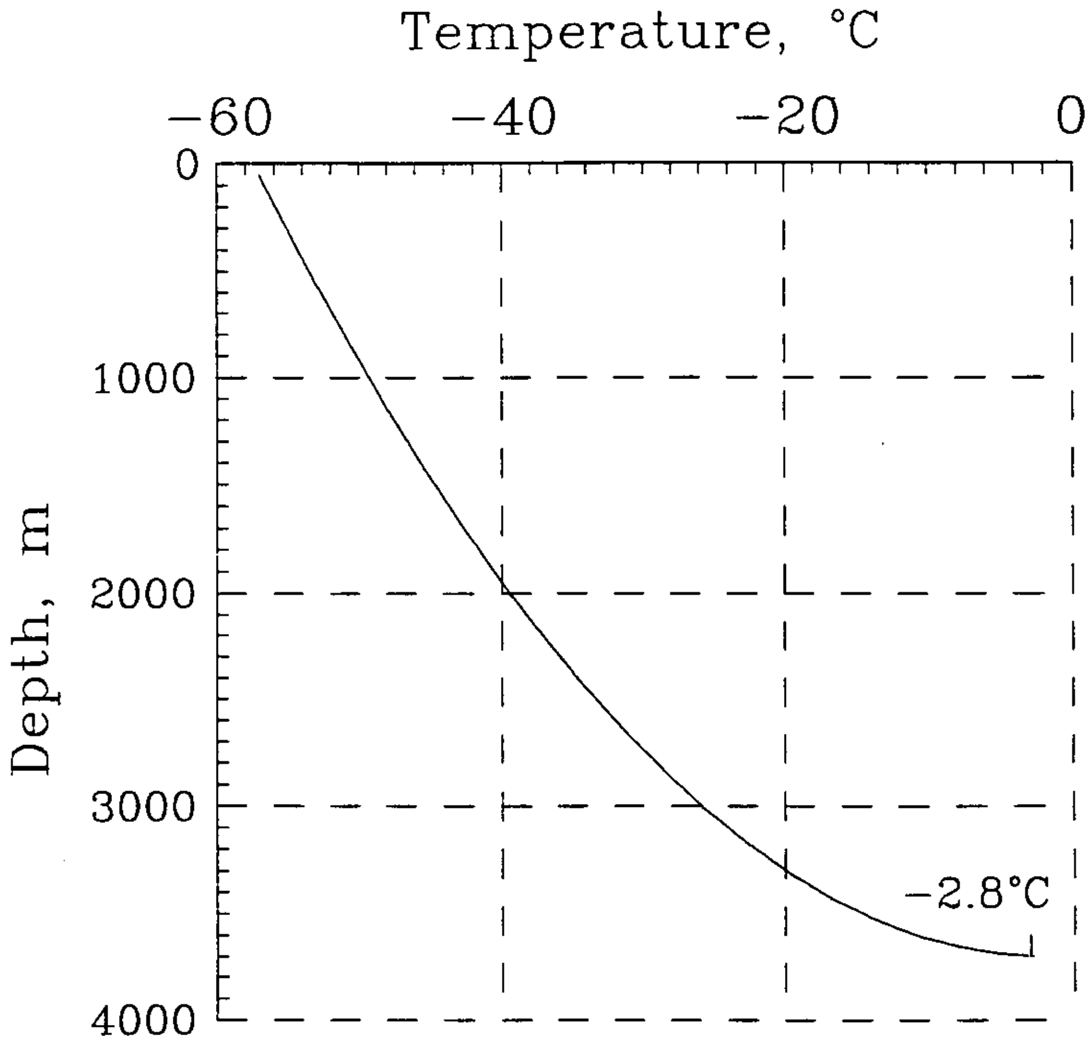

Figure 4. Temperature distribution in the Antarctic Ice Sheet at Vostok Station (calculated, steady state).

happened to be higher than T_i by 5°C. For our estimations, we assume a linear relationship of T_c and X_c (Fig. 1); then:

$$X_c = 100(a + bT_c)\,\%,$$

where $a = 2.83$, $b = -0.01$, X_c is an ethanol equilibrium concentration in the solution with T_c, weight %.

In order to maintain solution equilibrium in the borehole, the ethanol concentration must increase to equilibrium one. As a result of ice formation, part of the water will be removed from the solution. The mass of surplus water (m_w) and ice (m_i) formed from this water will be as follows:

$$m_i = m_e(1 - X_c^1/X_c)$$

where m_e is the ethanol mass in unit volume of solution at drilling moment, X_c, X_c^1 are the initial and the new concentration of ethanol in the solution, accordingly. In our case, in every 1-m section along the borehole there is formed a volume of ice V_i = $1.2 \cdot 10^{-3}$ m³ if T_i = -10°C and $V_i = 4.4 \cdot 10^{-4}$ m³ if T_i = -60°C.

The penetration of melt water into the borehole decreases X_c and increases T_c, causing intensive slush formation. It is possible to escape this situation only by choosing a period of time without any melting at the surface of the glacier or by casing.

If, at the moment when the drill reaches the bottom, the pressure of the solution on the kerf does not compensate hydrostatic pressure of the ice, then the glacier bottom meltwater will force the solution up. Then the change of solution level in the borehole will be directly proportional to the difference of pressures between the drilling liquid and the meltwater near the bottom. While raising the whole column of equilibrium solution, the conditions for ice formation, discussed above, will arise. If there is a large uplift of the solution level, ice will form everywhere along the borehole, which greatly increases the possibility of sealing the borehole by the slush. However, the comparatively high density of the ethanol-water solution should ensure an excess hydrostatic liquid pressure in the kerf over the ice pressure and will avoid any uplift of the solution level.

4.2 Heat Losses During the Drilling-Melting Process

About 15% of the heater energy is spent warming the ice around the borehole wall, core and drilling solution during the drilling-melting process. By having information about solution temperature just after drilling and equilibrium solution temperature (Figs. 5 and 6), it is not difficult to calculate that about half this energy is spent for heating the solution inside the borehole and the rest for heating the core and the hole wall. Until now, the thermodynamic conditions of heat and mass exchange of the dissolving ice by ethanol were unknown. Therefore, for estimating the maximum amount of ice formation from the solution after its cooling, let us consider that the energy surplus of the solution will be spent for ice dissolution. (As will be shown in Section 4.5, in reality, less of the energy surplus goes into dissolution.) As a result, the concentration of ethanol in the solution comes to equilibrium at the solution temperature. One hundred and twenty hours later, after drilling to a given depth (Figs. 5 and 6), the solution temperature approaches T_i, i.e., the solution will come to equilibrium condition ($T_c = T_i$). During this transition, ice will be formed. If all energy could go into dissolution with the following formation of ice, then the mass of formed ice is

$$m_i = 0.15\Delta P h_{bh}/(S_m \lambda)$$

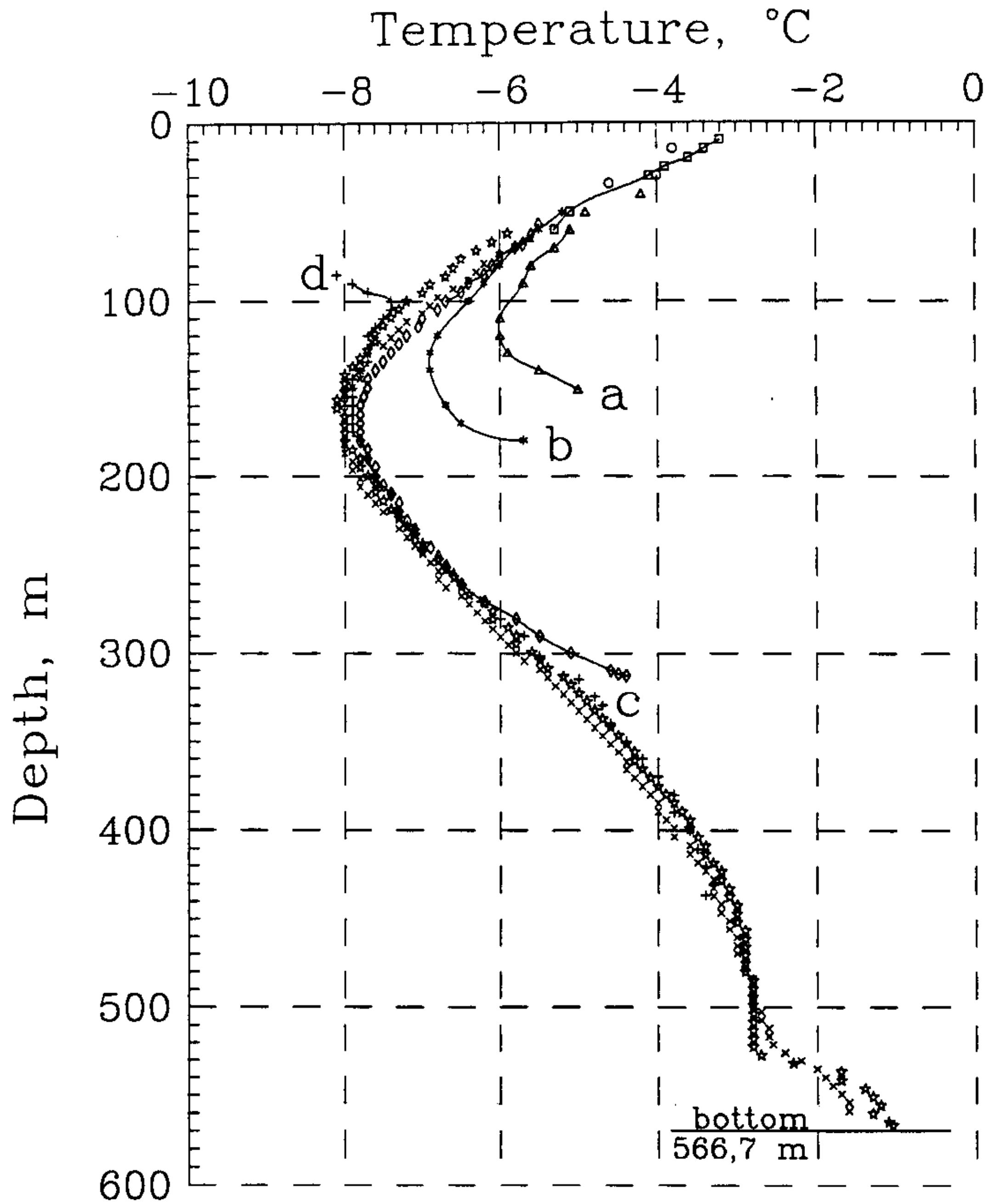

Figure 5. Temperature distribution in the Austfonna borehole; a, b, c – measured after break of drilling on respective depth, d – measured after input of additional ethanol to the borehole.

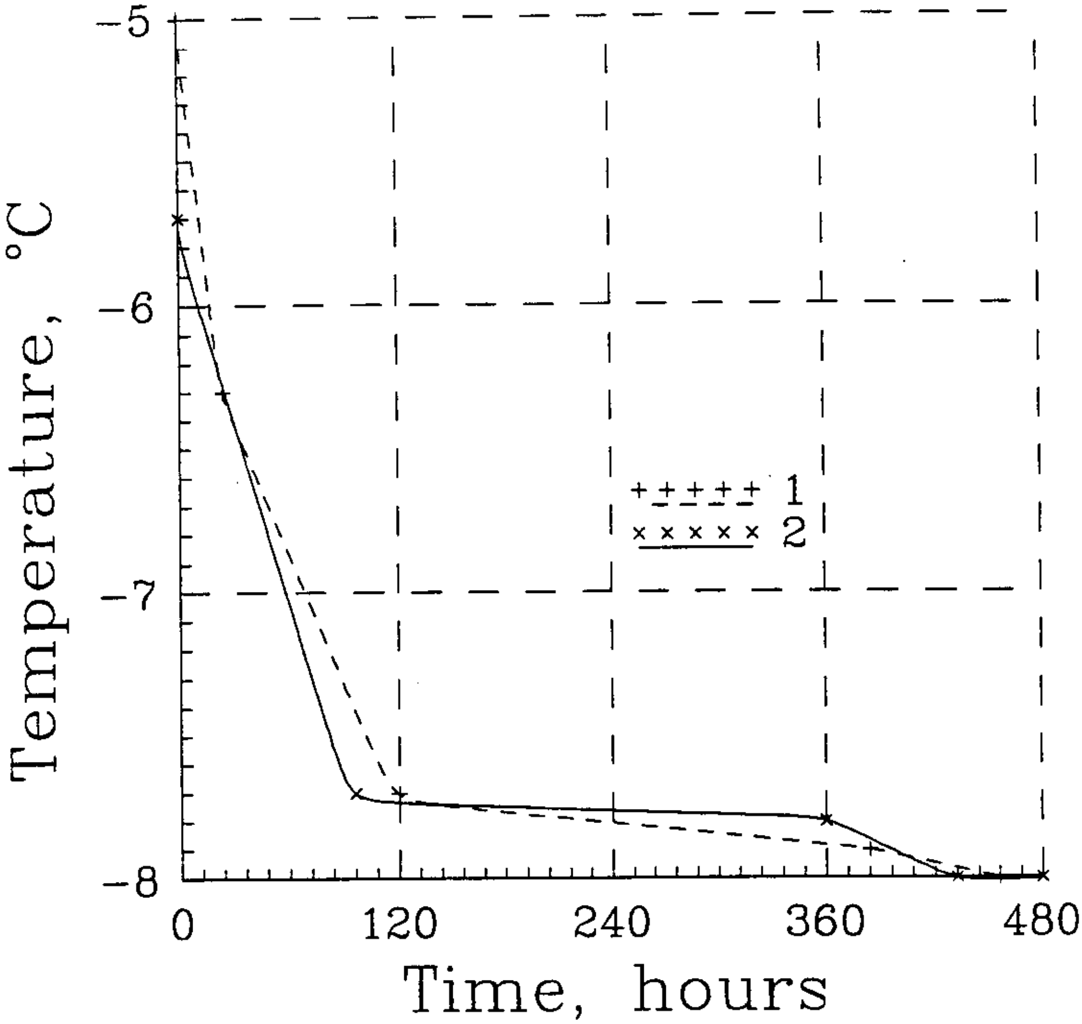

Figure 6. Time-scale variation of the temperature in the Austfonna borehole; 1, 2 – depth 150 and 180 m, respectively.

where m_i is ice mass, λ is the latent heat of dissolution. This means that during drilling to a depth of 3,700 m, about 1.7 m^3 of ice could be formed.

4.3 Energy Losses in the Electric Cable

Transmission of electrical energy to the heater drill is accompanied by heating the cable. It is known that about half the transmitted energy is lost to the electrical resistance of the cable. The cable heats the ethanol solution in the borehole, causing the ice wall to melt. When the heating stops, the solution returns to the ice temperature and slush ice is formed from the solution. Experimental data (Figs. 5 and 6) show that about 60 hr after drilling has stopped, the temperature of the solution reaches equilibrium condition after having dropped about 0.2°C.

Let us assume that the cable heat was spent only for heating the solution, and from that, the ice wall melted. When the heating stops, the solution returns to T_i and ice will be formed. If all the energy was not conducted into the ice wall and spent for ice dissolution, then the following mass of ice would be formed:

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

In reality, when the cable is lowered from depth z to one z+dz, there is dissolution of the ice mass $dm_i = \Delta P z dz/(S_m\lambda)$. Integrating this equality from 0 to H_{bh}, one can obtain the formed ice mass. During the entire drilling time, the volume of ice dissolved from the wall could be about 23 m^3.

4.4 Heat Transfer by Instrument Passage

In the central part of the Antarctic Ice Sheet near the surface, T_i = -50 to -60°C, the bottom T_i is close to the melting point of ice (Fig. 4). Under these conditions, the drill and the cable shifting along the borehole will cause heat transfer. When the cold drill and cable are lowered into the warm layers, ice will form on the surface. When raised, the warm drill and cable will heat the antifreeze solution in the borehole causing later ice formation when the solution cools. If the borehole depth is 3,700 m, the lowering and raising of the drill is expected to take at least two hours. The drilling itself will take about one hour. Thus, in conditions of intensive hydrodynamic heat exchange, there is ample time for the drill and cable to reach the environmental temperature. Taking into account dependence $T(z)=\alpha+\beta z/H_{bh}$ (Fig. 4), where $\alpha=-60$, $\beta=57$, and z = the current depth, we obtain the mass of ice dissolving under displacement of cable dz:

$$dm_i(z)=C_{dc}\beta z dz/(\lambda H_{bh}^2)$$

and by integrating from 0 to z_k, one can obtain formatting ice mass when drilling depth is z_k

$$m(z_k) = C_{dc}M_c\beta z_k^2/(2\lambda H_{bh}^2)$$

The total mass of the sum is

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

where C_{dc} is the specific heat of the material from which drill and cable were made (462 j/kg), $N=H_{bh}/L$ is the number of drilling runs, L is the length of ice core.

For the drill we obtain the value

$$m(z_k) = C_{dc}M_d\beta Lk/(\lambda\rho_i H_{bh})$$

where $m(z_k)$ is the mass of dissolving ice, when the drilling depth is $z_k = kL$, and k is the number of runs. Thus, the total mass of the sum is

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

If all the absorbed and released heat from the drill and cable during drilling of 3,700-m depth borehole were spent for ice state changes, then its volume would be $V_i = 13.1\,m^3$.

4.5 Correlation of the Ice Dissolution Effect and Thermal Diffusivity in Surrounding Ice

Estimations of Sections 4.2 to 4.4 are derived when all heat energy from the borehole spent for dissolution of the ice wall, and thermal flux into the ice wall is absent. Therefore, these estimations should be considered as excessive. So far, total mathematical modeling and laboratory measurement of the ethanol-water-ice composition properties at different thermodynamic conditions have not been carried out. Therefore, consider the interaction of the heated ethanol-water solution and the ice wall, and estimate the energy share going into the surrounding ice. Below, we discuss the mathematical formulation of the problem and the first results. A detailed solution is a separate subject.

Given an ethanol-water solution in temperature equilibrium is equal to the glacier temperature T_i, we assume that the heat power from the axial cable of radius r_0 at moment $t=0$ is equal to the sum of the heat power from all above mentioned processes and heat flux density is $q = 2$ w/m. Consequently, temperature increases and thermodynamic equilibrium is disturbed. As a result, the ice wall will dissolve, the ethanol concentration will be lowered, and a share of this heat power will go into the surrounding ice. If heating is stopped, then the initial position of the phase boundary R_0 will be set after some time.

We simplify the problem and consider cylindrical symmetry. Then all values depend on radial variable r and time t. The flow in the borehole is then governed by

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

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. Heat conduction in ice is given as

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

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

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r}\right), \qquad t>0,\ r_0<r<R \qquad (3)$$

where D is the diffusivity coefficient. It is supposed that the following initial conditions:

$$T(r, 0) = T_i, \qquad r>r_0 \qquad (4)$$

$$C(r, 0) = C_{eq}(T_i), \qquad r_0<r<R_0 \qquad (5)$$

where C_{eq} (T) is the equilibrium concentration, corresponding to temperature T_i (Fig. 1), and R_0 is the initial location of the phase boundary (borehole wall). The following conditions on the boundary are assumed:

$$k_i\frac{\partial T}{\partial r} - k_s\frac{\partial T}{\partial r} = \lambda\rho_i\frac{dR}{dt}, \qquad r=R \qquad (6)$$

and

$$-k_s \frac{\partial T}{\partial r} = \frac{q}{2\pi r_0}, \qquad r=r_0 \qquad (7)$$

and

$$C(R, t) = C_{eq}(T), \qquad (8)$$

where k_s and k_i are the thermal conductivity of ethanol-water solution and of ice, respectively, λ is the latent heat of ice dissolution, and ρ_i is the density of ice.

The above problem, defined by equations (1) through (8), was solved using finite-difference expansions of the derivatives and retaining accuracy in the first-order time derivative and second-order spatial derivatives. When the heat flux from the heated mixture is spent only for ice dissolution (case discussed in Sections 4.2 to 4.4), equation (6) is transformed to

$$-k_s \frac{\partial T}{\partial r} = \lambda \rho_i \frac{dR}{dt}, \qquad r=R \qquad (9)$$

Other equations of system (1) through (8) are the same.

For estimations, the following parameters were assumed: $\lambda = 3.3 \cdot 10^5$ j/kg, $T_i = 265$ °K, $\rho_i = 917$ kg/m^3, $k_i = 1.33 \cdot 10^{-6}$ j/(m s °K), $k_s = 1.5 \cdot 10^{-7}$ j/(m s °K), $R_0 = 0.06$ m, $r_0 = 4.3 \cdot 10^{-3}$ m, $\chi_i = 2.22$ m^2/s, $\chi_m = 0.53$ m^2/s, $D = 1.5 \cdot 10^{-8}$ j/(m s °K), $q = 2$ W/m. It has been assumed also 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.

Figure 7 shows the curves of the dimensionless displacement of the phase boundary from the initial radius R_0 (ΔR_m is the boundary displacement without heat conduction in the surrounding ice) depending on the current time in two cases:

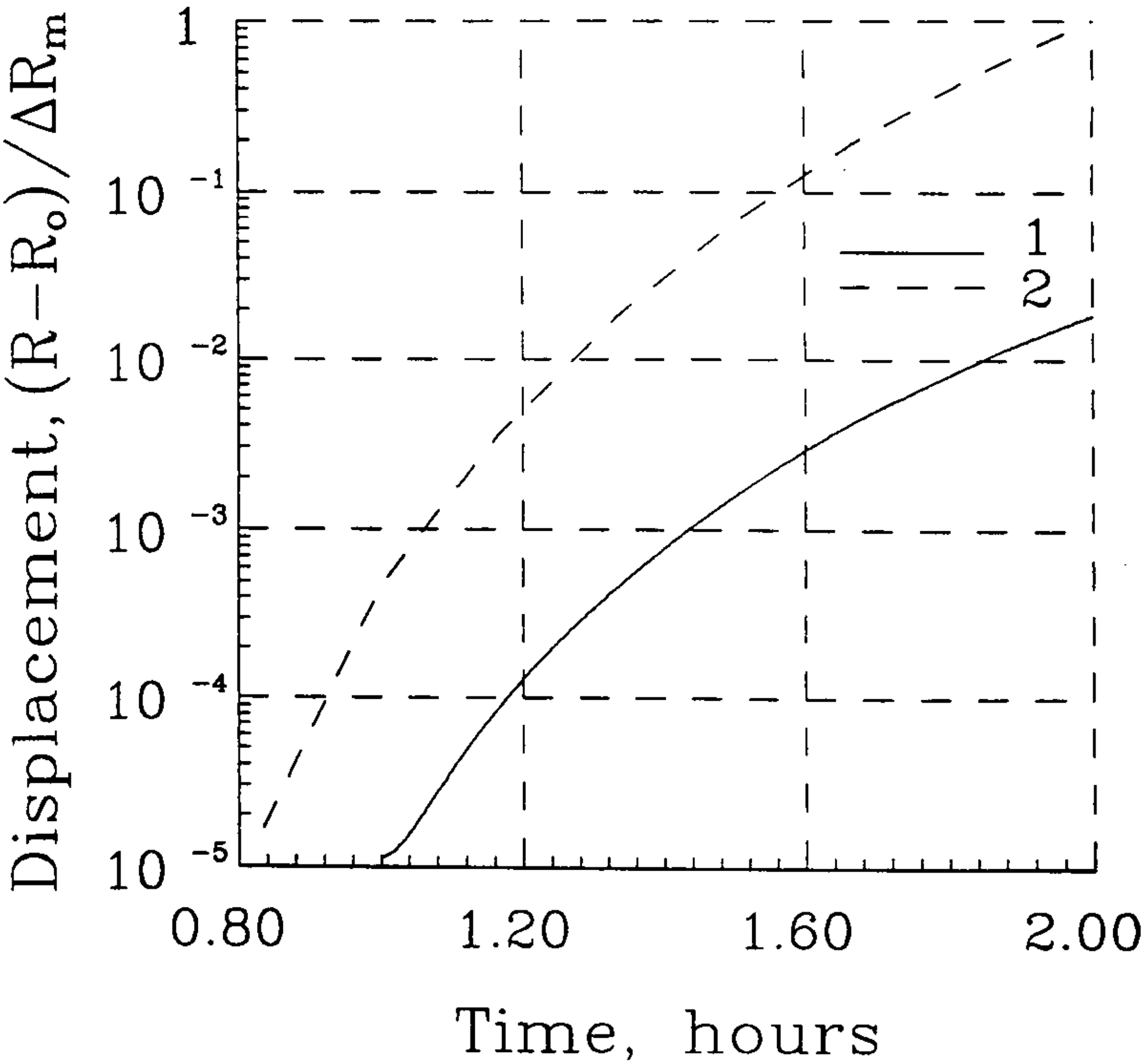

Figure 7. Time dependencies of phase boundary displacement. $1 - q_i \neq 0, 2 - q_i = 0$.

1) there is heat conduction in the surrounding ice

$$q_i = -k_i \frac{\partial T}{\partial r} \text{ , and}$$

2) there is no heat conduction in the surrounding ice

$$q_i = 0 \, .$$

A comparison of the numerical solutions shows that the greater share of thermal energy from the cable is spent into the ice wall, and the lesser share for ice dissolution.

4.6 Incomplete Mixing of Meltwater With Ethanol

Incomplete mixing of meltwater and ethanol causes the formation of needle-shaped ice crystals. The high viscosity of the water and the ethanol under low temperature and the low speed of drilling (1 to 2 mm/sec) reduces the efficiency of mixing the antifreeze with meltwater in the kerf. As a result, needle-shaped slush is formed at the kerf and covers the ice core in the core barrel when the core is extracted at the surface. Some portion of the slush remains in the borehole but it will be dissolved. The presence of some slush in the borehole does not perceptibly influence the travel speed of the drill.

4.7 Vertical Movement of the Solution in the Borehole

The vertical movement of the antifreeze solution takes place when the drill moves vertically in the borehole. Figure 5d shows that the temperature of the solution, after the input of an extra volume of ethanol in the upper part of the borehole, changes in the 30-m depth interval. This value shows the depth interval in which an intensive disturbance in the solution takes place. The temperature gradient in glaciers usually is 0.01 to 0.06°C/m. In this case, the variation of the solution temperature is 0.3 to 1.8°C. The relaxation time for such a disturbance of the solution temperature, from the experimental data in Figures 5 and 6, is 30 to 100 hr. Each drilling run takes 1 to 4 hr. Hence, a negligible amount of slush is formed by the vertical movement of the solution in the borehole with a positive temperature gradient.

4.8 Negative Temperature Gradient

A negative temperature gradient in a glacier is one reason for slush formation. The intensity of this process depends upon the gradient value and the mean ice temperature. Observations in a borehole of 567-m depth, when a negative gradient was present in its upper layer (Fig. 5), have shown that during the 12- to 14-hr drilling operation, approximately $20 \cdot 10^{-3}$ m^3 of slush formed in the borehole. The total volume of slush formed, without taking into account thermal flux into the ice, could be equal to about 1 m^3 during full-time drilling and about $8 \cdot 10^{-3}$ m^3 during one drilling run. That is much less than the observed value during the experiment. This can be explained by the above-mentioned phenomenon of an insufficient concentration of ethanol in the solution under its convective movement in the borehole when a negative temperature gradient exists (see estimations in Section 4.1).

5.0 DISCUSSION

The examples under review illustrate that the main physical characteristics of ethanol-water solutions satisfy the requirements for the liquids for filling boreholes. At the same time, some characteristics of these solutions, i.e., the ability to dissolve the ice, to form slush and to penetrate the ice core, as well as their high viscosity, look like insuperable obstacles for deep drilling in the central part of the Antarctic Ice Sheet.

5.1 Ice Core Dissolution

The problem of ice core dissolution is solved by choosing the correct technological regime for the drilling. This means that the ethanol concentration in the drilling solution must conform to the ice temperature at the given depth. Profiles in Figures 6 and 7 show that on the borehole kerf at the drilling moment, the solution temperature is 2 to 3°C higher than T_i. Approximately the same temperature difference is observed at T_i = -53°C. Thus, by measuring the solution temperature at the borehole kerf, one can evaluate the ice temperature with an accuracy of at least 1°C. Therefore, it is possible to maintain the equilibrium ethanol concentration even in cases where the temperature distribution through the glacier sequence is unknown, and has minimum (about 1-mm ply thickness) core dissolution.

5.2 Slush Formation

The heat transformations connected with drilling (Sections 4.2 to 4.4) result in slush formation. However, more detailed calculations (Section 4.5) have shown that the heat goes out from the borehole into the surrounding ice and only a few percent of one actually turn for dissolution of ice. From the above estimations, the main processes leading to formation of ice from the antifreeze solution in the hypothetical borehole are:

- energy losses due to cable electrical resistance (23 m^3);
- heat transfer by the drill and cable passage (13.1 m^3);
- solution heating by the drilling head (1.7 m^3).

From the examples in Sections 4.2 to 4.5, the absolute value of the borehole wall displacement is $1 \cdot 10^{-5}$ to $1 \cdot 10^{-3}$ mm. The practice of antifreeze thermal drilling (borehole depths of 570 to 720 m, ice temperatures of -8 to -15°C) shows that the intensity of the slush formation is 3 to 5 times higher than accounted for from the solution of equations 1 to 8 and it is 3 to 5% of the value from the solution of equations 1 to 5 and 5 to 9. It shows that a large percentage of heat from the borehole goes into the surrounding ice.

If the depth of drilling increases, the mass of slush increases also, especially during instrument passage. In this case, the number of runs N increases linearly, and the formed ice mass is proportional to the cubic power of N. The decrease of core length L results in an increase of $N = H_{bh}/L$ and ice mass proportionally 1/L. Decreasing both mass and heat capacity of the drill and cable results in a proportional decrease of the forming ice mass. Since only a small percentage of thermal energy is directed into dissolution, we can expect that no more than 2 m^3 of ice will be formed (that consists of 5% of the calculated slush volume without taking into account thermal flux in the surrounding ice).

Slush formation in a negative temperature gradient in glaciers does not cause significant difficulties during drilling. In Zagorodnov (1988b) the drilling regimen of the borehole at T_i = -8°C with a negative temperature gradient is described. In the range of depth from 125 to 185 m (Fig. 5), when drilling procedures had a technological disturbance, the T_c of the solution was 2°C higher than T_i. Herewith, slush was formed but did not cause a significant delay when lowering or raising the drill instruments, even after a cessation in drilling for 48 hrs. This is because slush forms and is bouyed slowly. At low ice temperature, the low density and high viscosity of the solution slows the concentration of slush at the top of the borehole. Thus, at low as well as at high ice temperatures, in case of a negative gradient and disturbance of the technological regimen, one has enough time to remove the surplus slush from the borehole or to add ethanol which will dissolve the slush and even the wall of the borehole, if necessary.

To reduce or to exclude completely the needle-shaped slush formed due to incomplete mixing of ethanol with melting water on a kerf, the ethanol temperature must be increased or a positive circulation of the drilling solution at the kerf must be maintained.

A special device on the drill allows the addition of ethanol during raising and lowering of the drill, thus there is no wasted time. In any case, dissolution of the slush in the borehole is preferable. Pumping of ethanol into the drill is faster than the removal of slush from it.

5.3 Ethanol Penetration into the Ice Core

Although the ability of ethanol to penetrate the ice may not be a unique property, it is related to ice core (specimen) quality – the number and depth of micro-cracks in it. In the above examples, the depth of penetration of kerosene or ethanol into the ice cores, which are obtained by thermal or mechanical drills, is approximately equal. Therefore, solving the problem of ice core pollution caused by drilling liquid lies in the improvement of drilling methods that will not cause ice cracking. In thermodrilling, improvement of ice core quality can only be achieved by decreasing the heat penetration into the core. Increasing the heating bit efficiency will also decrease the power consumption and losses, as well as the slush formation.

5.4 High Viscosity of Alcohol-Water Solutions

High viscosity of the ethanol solution slows the lowering and the raising of instruments in the borehole. In order to increase the speed of the drilling operation in a borehole, it is sufficient to increase the clearance between the core barrel and the hole wall, as is done with the French drill (Augustin *et al.*, 1988). Given that condition, the speed of lowering and raising the drill in the borehole will be in the range of 0.5 to 0.7 m/sec. Thermodrilling with a 6-m length of core barrel will yield about a 350 to 450 m/wk penetration rate.

5.5 Ethanol Requirements

If the temperature distribution in the glacier is known, it is not difficult to calculate the ethanol requirement for drilling the borehole. If the borehole has a volume of V_{bh}, the volume of ethanol is

$$V = V_{bh}/H_{bh} \int_0^{H_{bh}} X_c(z)dz/100,$$

where $X_c(z)$ is equilibrium concentration of ethanol at depth z. Taking into account linear dependencies of X_c and T, as well as T and z, one obtains

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

Using constant a, b, α, β, which were defined earlier, we get $V = 0.44\ V_{bh} = 16.3\ m^3$. In order to dissolve 2 m^3 of ice slush, it is necessary to put additional volume of ethanol into the borehole:

$$V = \frac{X_c}{100\text{-}X_c}\,\frac{\rho_i}{\rho_e}V_i,$$

where X_c is an equilibrium concentration of ethanol on the surface, ρ_i , ρ_e are densities of ice and ethanol, accordingly. If X_c = 76% (Fig. 1), then the needed volume of ethanol $V = 0.19V_{bh} = 7.35\ m^3$. The total amount of ethanol needed for drilling a 3700-m borehole is $V = 0.64V_{bh} = 23.6\ m^3$.

During uplift of the drill from a 500-m depth, at velocity 0.8 m/s, about $3 \cdot 10^{-3}$ m^3 of the antifreeze solution is extracted from the borehole on the surface of the cable. Only as a first approximation is the amount of liquid independent of the cable type, speed of uplift, viscosity of the solution or its level in the borehole. In this case, the amount of solution extracted from the hole is proportional only to the time of uplift of the instruments. In practice, when taking into consideration the depth of the borehole and the number of runs, about 7 m^3 of solution will be removed. Therefore, adding 7.35 m^3 of ethanol into the borehole will compensate for loss of antifreeze solution by extracting it with cable.

So, overcoming problems connected with the specific properties of ethanol-water solutions at low temperatures lies in improving drill design and in keeping to an optimum technological regimen (ratio of ethanol and water). For more exact estimations of the ethanol consumption for drilling deep holes in low temperature glaciers, it is necessary to carry out theoretical, laboratory and field investigations of the heat- and the mass-exchange processes in a borehole filled with an ethanol-water solution.

6.0 CONCLUSIONS

1. The use of ethanol for filling boreholes in glaciers maintains ecological integrity.

2. The volume of ethanol delivered to a glacier for this practice of drilling is less than the volume of the borehole (approximately half).

3. Ethanol-water solutions in the borehole possess a positive density gradient and a comparatively high viscosity that prevent convective movement in the

borehole. The temperature of the solution in the borehole approaches the temperature of the surrounding ice rather quickly for approximately 100 hr.

4. As the experimental and theoretical data have shown, the small radial thermal gradient in the borehole took place during drilling and is connected with cable heating, instrument passage and other factors. In this case, inner and outer thermal fluxes on the borehole wall almost coincided and a marked dissolution of the borehole wall was not caused. Thus, surplus of the borehole heat goes out from the borehole into the surrounding ice.

5. There can be expected a volume of ice slush of no more than 2 m^3 during 3,700-m drilling in the central Antarctica Ice Sheet. Its dissolution is carried out during the lowering and the raising of the drill, thus additional time is not required.

6. Ethanol viscosity at low temperatures is rather high. However, structure of the thermodrill to allow an increased clearance between it and the borehole wall will achieve the lowering-raising speed of nearly 0.5 m/s. There is to be expected 350 to 450 m/wk penetration rate at 2,000- to 4,000-m borehole depth.

7. With suitable concentration of ethanol in the borehole solution, about 1-mm ply of ice core will be dissolved during drilling procedures.

8. Increasing thermal drill heating bit efficiency will decrease thermal elastic stresses in the ice core and penetration depth of ethanol into the ice core.

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8.0 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_c	temperature of crystallization
T_i	temperature of the ice
V	volume of ethanol
V_{bh}	volume of the borehole
V_i	formed volume of ice

X_c, X_c^1	initial and new concentration of ethanol in the solution
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
υ	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