Mem. Natl Inst. Polar Res., Spec. Issue, **56**, 171-180, 2002

Hydrostatic pressure and fluid density profile in deep ice bore-holes

P.G. Talalay[1,2] and N.S. Gundestrup[2]

[1] *St.-Petersburg State Mining Institute, 21 Line, 2 St.-Petersburg 199026, Russia*
[2] *University of Copenhagen, Department of Geophysics, Juliane Maries Vej 30, DK-2100 Copenhagen OE, Denmark*

Abstract: The drilling of deep bore-holes in ice requires that the hole is filled by a liquid to compensate the ice-overburden pressure. Moreover, the hydrostatic pressure of the fluid should be exactly known in order to estimate the hole closure.

The estimation of the hydrostatic pressure in the bore-hole can be made in two different ways. The first is the *in situ* measurements using pressure sensor, and the second is calculation of the pressure using the sampling of drilling fluid from different depths. The second method can be used also for prognosis of the hydrostatic pressure when the necessary density of the hole liquid is chosen.

The paper includes the necessary equations for the calculation of hydrostatic pressure for one and two-compound liquids based on the pressure and temperature in the bore-hole.

The measured and calculated densities are compared for the GISP2 bore-hole at Summit, Greenland, and it shows a high correlation. The difference between measured pressure and calculated pressure along most of the hole length doesn't exceed 0.12%.

1. Introduction

One of the main functions of the bore-hole fluid is to prevent or at least minimize the bore-hole closure. In order to prevent hole closure, the hydrostatic pressure difference between the ice and the bore-hole liquid should ideally be equal to zero at any depth. It is not sufficient to have a high pressure in the bore-hole because then the bore-hole will expand. Lowering the stand of the liquid and thereby creating a low hydrostatic pressure at the top of the fluid column leads to bore-hole closure.

Bore-hole closure has several times caused a drill to stick. As an example, bore-hole 5 G at Vostok station, Central Antarctica, was started in 1990. In December 1991, when the drilling had reached a depth 2502 m, the thermal drill was stuck at a depth of 2250 m during hoisting. The drilling fluid was a mixture of TS-1 (low-temperature aircraft fuel), and about 2% by mass of densifier (trichlorofluoromethan-CFC 11) with resulting density of 860 kg/m^3 at -50°C. During the drilling operations, the top of the fluid was between 150 and 250 m below the surface with an average value of 200 m. This resulted in a pressure difference between fluid and ice of about 2.7 MPa.

According to Tchistiakov *et al.* (1994) at a depth of 2250 m and a temperature -32°C the closure rate will be 16.1 mm/a assuming a pressure difference between fluid and ice of

Table 1. The rate of the bore-hole closure at Vostok Station (depth 2250 m).

Pressure difference, MPa	0.5	1.0	1.5	2.0	2.5	2.7	3.0
The rate of bore-hole closure, mm/a	0.1	0.8	2.7	6.5	12.8	16.1	22.1

2.7 MPa (Table 1).

In 1996 at Dome Fuji, Antarctica, the same accident happened with the Japanese electromechanical drill at the depth of 2250 m, when the top of the fluid (*n*-butyl acetate) was lowered to 722 m below the surface (Fujii *et al*., 1999).

Therefore, knowledge of the exact pressure difference in the bore-hole is considered to be one of the most important parts of ice deep drilling technology.

2. Calculation of hydrostatic pressure

The pressure P (Pa) in a bore-hole fluid at rest follows from the hydrostatic equation:

$$\frac{dP}{dz} = -g\rho, \tag{1}$$

where z is the height, m; g is the acceleration of gravity, m/s^2; ρ is the density, kg/m^3.

In practice the density varies with depth, and the hydrostatic pressure $P_{fl}(z)$ at the depth H (m) can be found by integration of eq. (1):

$$P_{fl}(z) = -g\int_{H_0}^{H} \rho_{fl}(z)dz, \tag{2}$$

where $\rho_{fl}(z)$ is the fluid density profile in bore-hole; H_0 is the fluid top below surface (Fig. 1).

The fluid density $\rho_{fl}(z)$ depends both on the temperature and the pressure in the bore-hole. With increasing temperature the density decreases and with increasing pressure the density increases.

The fluid compressibility is neglected frequently, possibly because it is difficult to measure. Neglecting compressibility the fluid density $\rho'_{fl}(z)$ at the temperature t (°C) is determined using the thermal expansion coefficient k_t (K^{-1}):

$$\rho'_{fl}(z) = \frac{\rho_0}{1 + k_t(t - t_0)}, \tag{3}$$

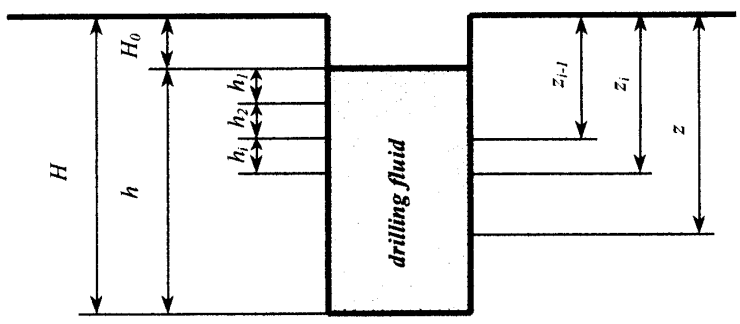

Fig. 1. Naming of bore-hole distances.

where ρ_0 is the density of the fluid at temperature t_0.

Equation (3) is inconvenient because the thermal expansion coefficient k_t isn't constant and changes with temperature. For a limited range of temperatures the density can be approximated with a linear equation and may be defined by Mendeleeff's formula:

$$\rho_{fl}^{t}(z)=a_t\ (t-t_0)+\rho_0, \qquad (4)$$

or

$$\rho_{fl}^{t}(z)=a_t t+b, \qquad (5)$$

where a_t is the thermal coefficient, kg/(m³·°C); b is the density of fluid at 0°C.

A summary of the equations for the density *versus* temperature of actually used or potential fluids for ice core drilling can be found in the paper of Talalay and Gundestrup (2002).

In order to calculate the hydrostatic pressure, we first need to estimate the temperature profile at the drilling site. Then using the temperature profile the density versus depth is calculated, and the hydrostatic pressure can be found using the approximate integration method of trapezium:

$$P_{fl}^{t}(z)=g\sum\frac{\rho_{fl}^{t}(z_{i-1})+\rho_{fl}^{t}(z_i)}{2}h_i, \qquad (6)$$

where h_i is the depth interval.

For shallow and intermediate drillings, eq. (6) gives satisfactory results. For deep drillings, however, neglecting of the fluid compressibility leads to significant errors. Kuksov *et al.* (1992), for example, found a pressure error of about 6% in an oil well when the compressibility is ignored. For the GISP bore-hole, using the *n*-butyl acetate, Gosink *et al.* (1991) found the density to increase 3% at the bottom of the 3-km bore-hole due to the pressure.

There are several methods to estimate the hydrostatic pressure in a compressible fluid. The most widespread equation is (Kuksov *et al.*, 1992)

$$P_{fl}^{P,t}(z)=kP_{fl}^{t}(z), \qquad (7)$$

where $P_{fl}^{P,t}(z)$ is the hydrostatic pressure corrected for both thermal expansion and compressibility of the fluid; k is the coefficient for compressibility of the fluid.

According to eq. (7) we can't calculate the hydrostatic pressure exactly because the value of the coefficient k isn't constant, it depends on the type of the bore-hole fluid, pressure and temperature.

At constant temperature and changing pressure P the density is

$$\rho_{fl}^{P}=\frac{\rho_0}{1-k_P(P-P_0)}, \qquad (8)$$

where k_P is the compressibility of the fluid, Pa^{-1}; ρ_0 is the density of the fluid under the pressure P_0.

The calculation of the real fluid density profile may be done in two stages (Menshikov and Talalay, 1993). The first stage includes the calculation of the density $\rho_{fl}^{t}(z)$ at real temperatures in a bore-hole and standard atmospheric pressure using eqs. (3), (4), or (5). Next the density is corrected for the real pressures in bore-hole:

$$\rho_{fl}^{P,t}(z)=\frac{\rho_{fl}^{t}(z)}{1-k_P P_{fl}(z)}. \tag{9}$$

In this case the hydrostatic pressure of the fluid at depth z is calculated step by step using the approximate integration method of rectangle:

$$P_{fl}^{P,t}(z)=g\sum\rho_{fl}^{P,t}(z_{i-1})h_i. \tag{10}$$

Here we can't use the more correct method of trapezium because the density at the depth z_i depends on the pressure itself and is unknown.

For the correct calculation according to eqs. (9)-(10) it is necessary to know the exact value of the fluid compressibility k_P, which significantly depends on the temperature and pressure. For solids values of compressibility are typically of the order 10^{-11} Pa^{-1}, and for liquids 10^{-9} Pa^{-1} (Table 2). With increasing pressure and lowering temperature of the liquid compressibility approaches the values for solids.

Table 2. Fluids compressibility versus temperature (°C).

Name	Compressibility, Pa^{-1}	Interval of absolute pressure, MPa	References
Aircraft fuel TS-1	$k_P=(0.0106t+0.7093)\cdot10^{-9}$	0.1-10	Dubovkin *et al.* (1985)
Trichlorofluoromethane CFC 11	$k_P=(0.0082t+1.331)\cdot10^{-9}$	0.1-20	Bogdanov *et al.* (1976)
n-Butyl acetate	$k_P=(-4.72t+1091.7)^{-1}\cdot10^{-6}$	0.1-30	Letter from Eastman Chemical Co. (1990)

3. Hydrostatic pressure and density profile of two-compound fluid

Kerosene type hydrocarbons, mostly used as drilling fluid, have a density of about 800 kg/m^3 compared to 920 kg/m^3 for ice. Therefore, usually they are made denser by addition of various densifiers.

It is assumed that the two components in the fluid don't react neither chemically nor physically.

The density of a mixture at atmospheric pressure is:

$$\rho_{fl}=\frac{\rho_1}{1-\dfrac{C_M(\rho_2-\rho_1)}{100\rho_2}}, \tag{11}$$

where C_M is the mass concentration of densifier, %; ρ_1 and ρ_2 are the densities of the base fluid and the densifier respectively, kg/m^3.

Based on this equation the change of density with temperature and pressure can be calculated knowing how the density of the two components change. Equation (11) leads to the following density profile of two-compound fluid:

$$\rho_{fl}^{P,t}(z)=\frac{\rho_1^{P,t}(z)}{1-\dfrac{C_M[\rho_2^{P,t}(z)-\rho_1^{P,t}(z)]}{100\rho_2^{P,t}(z)}}. \tag{12}$$

Then the hydrostatic pressure of the fluid $P_{fl}^{p,t}(z)$ is calculated using eq. (10).

The condition for no-reaction between the two components is verified for a mixture of TS-1 (base fluid) with trichlorofluoromethane (CFC 11) as densifier. The density of the fuel TS-1 $\rho_1^t(z)$ and the density of the densifier CFC 11 $\rho_2^t(z)$ *versus* temperature are (Litvinenko *et al.*, 1996):

$$\rho_1^t(z) = -0.749t + 810.2; \tag{13}$$

$$\rho_2^t(z) = -2.202t + 1534.4. \tag{14}$$

Equations (13) and (14) are substituted in eq. (12), and the density of the mixture is obtained:

$$\rho_{fl} = \frac{810.2 - 0.749t}{1 - \dfrac{C_M(724.2 - 1.453t)}{100(1534.4 - 2.202t)}}. \tag{15}$$

The results are compared with experimental data (Table 3). The difference between measured and calculated densities of isn't more than 0.5%. Thus, we can conclude that for this mixture the two components don't react and the density can be calculated using the densities of the compounds.

In practice it is difficult to mix the two components with sufficient accuracy, and *in situ* measurements are needed to verify the density profile. One possibility is to take samples from different depths of the bore-hole. At the surface the density of the sample is measured under atmospheric pressure at fixed temperature and the mass concentration of densifier in the sample from the depth z is calculated:

$$C_M = 100 \frac{\rho_2^t(z)[\rho_{fl}^t(z) - \rho_1^t(z)]}{\rho_{fl}^t(z)[\rho_2^t(z) - \rho_1^t(z)]}. \tag{16}$$

Then the real density according to eq. (12) can be found.

Table 3. Density (kg/m³) versus temperature (°C) of fuel TS-1 with densifier CFC 11.

Mass concentration C_M, %	Experimental equations (V. Lipenkov, unpublished)	Theoretical equations	Maximal difference in the range from −50 to 0°C, %
2	$\rho_{fl} = -0.768t + 818.3$	$\rho_{fl} = -0.761t + 817.9$	0.09
4	$\rho_{fl} = -0.824t + 824.2$	$\rho_{fl} = -0.772t + 825.8$	0.19
6	$\rho_{fl} = -0.831t + 832.4$	$\rho_{fl} = -0.784t + 833.8$	0.17
10	$\rho_{fl} = -0.835t + 847.1$	$\rho_{fl} = -0.810t + 850.3$	0.38
14	$\rho_{fl} = -0.901t + 865.1$	$\rho_{fl} = -0.836t + 867.5$	0.28
18	$\rho_{fl} = -0.924t + 882.5$	$\rho_{fl} = -0.865t + 885.4$	0.33
22	$\rho_{fl} = -0.938t + 901.6$	$\rho_{fl} = -0.894t + 904.1$	0.27
26	$\rho_{fl} = -0.999t + 919.5$	$\rho_{fl} = -0.926t + 923.5$	0.43
30	$\rho_{fl} = -1.060t + 939.3$	$\rho_{fl} = -0.960t + 943.8$	0.48

4. Hydrostatic pressure and density profile in GISP2 bore-hole at Summit, Greenland

In 1990–1993 the deepest bore-hole through the Greenland Ice Cap was drilled at Summit by PICO in support of the GISP2 Project, Greenland Ice Sheet Program II (Kelley *et al.*, 1994). Geophysical measurements carried out in 1995 showed that due to the inclined nature of the GISP2 bore-hole, the total GISP2 bore-hole length of 3056.4 m is 8.6 m longer than the true vertical depth (Clow and Gundestrup, 2000).

n-Butyl acetate was used as a drilling fluid and the density calculated using parabolic relation (Gosink *et al.*, 1991):

$$\rho'_{fl} = 0.0116t^2 - 0.982t + 895. \qquad (17)$$

n-Butyl acetate dissolves ice slightly. The water solubility in *n*-butyl acetate is 2.88% by mass at temperature 25°C and decreases at lower temperature (Industrial Solvents Handbook, 1991). A 20 g cube of ice lost in 1 hour 1% of its mass in *n*-butyl acetate at −19°C (Gosink *et al.*, 1991). That *n*-butyl acetate to some degree can dissolve ice is ignored in the following calculations.

The value of *n*-butyl acetate compressibility can be estimated from the bulk modulus. Fluids, as well as solids, have bulk modulus, and compressibility is reciprocal to the bulk modulus. According to letter from J.J. Harris (12 July 1990, Eastman Chemical Co.) the bulk modulus of *n*-butyl acetate is equal to 1238.15 MPa at temperature −31°C and 1068.13 MPa at 5°C. The compressibility of *n*-butyl acetate versus temperature was approximated according to the linear relationship (Table 2).

In August of 1995 the GISP2 bore-hole logging with UCPH logger included the

Table 4. Measured and calculated hydrostatic pressure (MPa) in GISP2 bore-hole according to linear density-temperature relation of n-butyl acetate.

Depth m	Measured hydrostatic pressure (1995)	Calculated hydrostatic pressure based on temperature	Calculated hydrostatic pressure based on temperature and compressibility
102.2	0.233	0.234	0.234
254.7	1.625	1.629	1.630
502.9	3.898	3.899	3.905
753.7	6.205	6.192	6.207
1003.8	8.504	8.480	8.508
1254.0	10.811	9.255	10.815
1503.4	13.118	13.051	13.119
1747.5	15.372	15.285	15.378
2001.8	17.727	17.210	17.733
2252.8	20.049	19.898	20.057
2500.5	22.332	22.147	22.345
2749.7	24.623	24.397	24.639
2999.0	26.903	26.633	26.926
3046.6	27.330	27.059	27.360

measurements of the temperature and the absolute pressure (at Table 4 the measured absolute pressure is converted to hydrostatic pressure subtracting the atmospheric pressure of 0.066 MPa).

The temperature versus depth z(m) in GISP2 bore-hole can be fitted by a polynomial:

$$t = -31.46 + 2.9257\cdot 10^{-3}z - 5.6474\cdot 10^{-6}z^2 + 2.3451\cdot 10^{-9}z^3. \tag{18}$$

At the GISP2 site the acceleration of gravity increases with depth (K. Keller, personal communication):

$$g = 9.817953 + 2.31467\cdot 10^{-6}z. \tag{19}$$

Using eqs. (6), (9) and (17) the hydrostatic pressure is calculated in 25 m steps (the fluid top $H_0 = 76.6$ m). This was done for two cases: first the hydrostatic pressure is corrected for temperature (Fig. 2, thin green line), second the hydrostatic pressure is

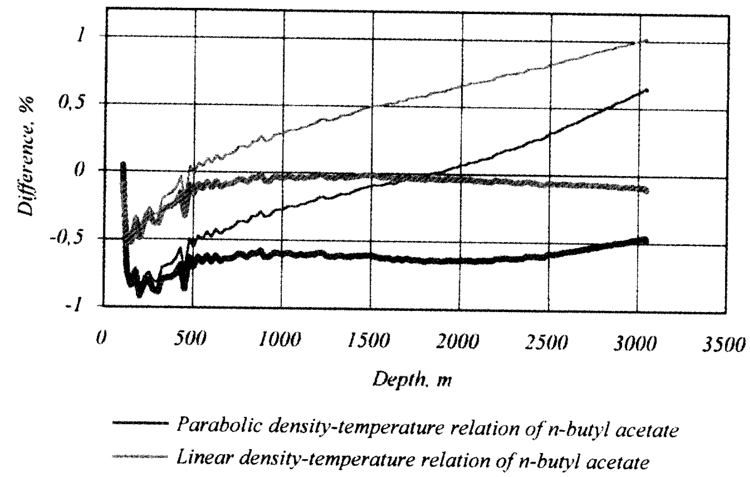

Fig. 2. *Difference between measured and calculated pressure. (thin lines-based on temperature; thickened lines-based on temperature and compressibility).*

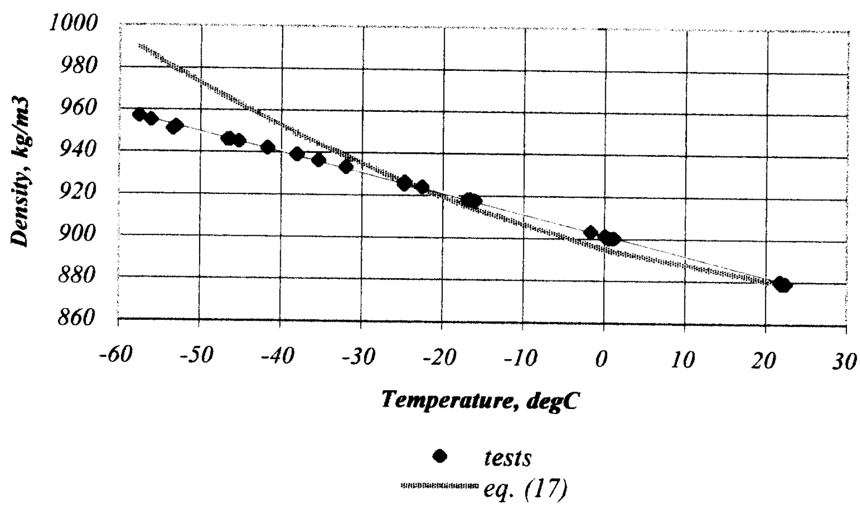

Fig. 3. *Density of n-butyl acetate versus temperature.*

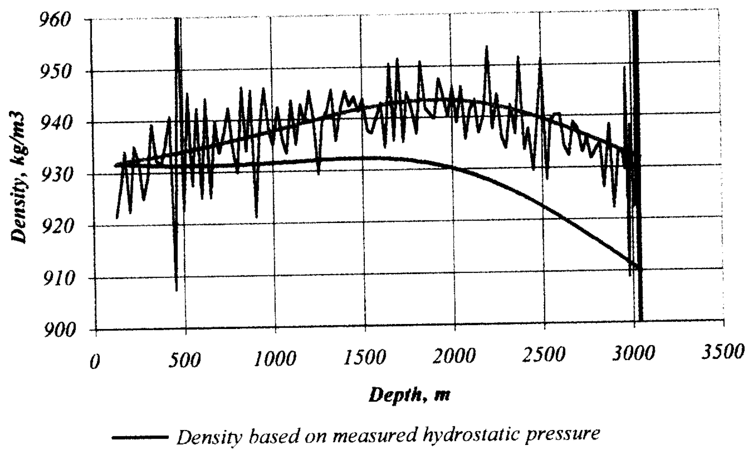

Fig. 4. Density profile in GISP2 bore-hole.

corrected for temperature and compressibility (Fig. 2, thickened green line).

We see that the difference between measured and calculated pressure in both cases is high. In the second case, when compressibility is accounted for, the difference is nearly 0.6% independent on depths, indicating that the compressibility is correct. Therefore, we decided to check eq. (17). Experiments carried out in Copenhagen University showed a linear density-temperature relation of *n*-butyl acetate at $-57.6°C < t < 22.4°C$ (Fig. 3):

$$\rho^t_{fl} = -0.97t + 901.2. \tag{20}$$

Then the calculations were repeated (Table 4) and now the difference between measured and calculated pressure, based on temperature and compressibility, is less than 0.12% in most of the bore-hole (Fig. 2, thickened red line). At the bottom of the GISP2 bore-hole the difference is only 0.03 MPa. At the upper part of the GISP2 bore-hole the difference between measured and calculated pressure is about 0.5%, probably because the fluid contains some amount of ice chips.

The difference between the measured pressure and the pressure, based on temperature only, increases with depth and at the bottom of the bore-hole it is 0.27 MPa or 1%.

Measurements of hydrostatic pressure and vertical depth make it possible to calculate the average density of drilling fluid over given depth intervals, but if the interval h_i is small, the average density at this interval is approximately equal to the real density at the depth z_i:

$$\rho^{P,t}_{fl}(z_i) \approx \frac{P^m_{fl}(z_i) - P^m_{fl}(z_{i-1})}{gh_i}, \tag{21}$$

where $P^m_{fl}(z_i)$ and $P^m_{fl}(z_{i-1})$ are measured hydrostatic pressure at the vertical depths z_i and z_{i-1}, respectively.

The fluid density in the GISP2 bore-hole is calculated according to eq. (21) with h_i 25 m (Fig. 4). The curve has parabolic shape with high frequency errors in the order of 5 kg/m^3 due to the limited resolution of the pressure sensor. The theoretical density profiles in the GISP2 bore-hole are also shown. The calculated density profile based on temperature and pressure is in a good agreement with the bore-hole measurements.

5. Conclusions

Deep ice core drillings are only possible if the hydrostatic pressure in the bore-hole is near equilibrium with overburden pressure. Therefore, the bore hole liquid must have a density close to the density of ice for the actual pressure and temperature in the bore-hole. At any depth, and especially at the warmer, deeper, part of the bore-hole the pressure must be correct within about 0.1 MPa. If the pressure difference is too high, the bore-hole will deform and prevent further drilling.

Therefore, the choice of the fluid density is directly connected with estimation of the hydrostatic pressure in order to prevent bore-hole closure and accidents connected with this complication.

The foregoing method of hydrostatic pressure calculation allows for the choice of the correct fluid density for a specific drilling site. This method is suitable both for one and two-compound fluids. To estimate the hydrostatic pressure it is necessary to know: (a) the hole temperature *versus* depth; (b) the value of acceleration gravity; (c) density-temperature relation of drilling fluid; (d) compressibility of drilling fluid.

The correctness of the hydrostatic pressure during and after the drilling can be made in two different ways. The first is the *in situ* measurements using pressure sensor with high resolution, and the second is calculation of the pressure using the sampling of drilling fluid from different depths.

The theoretical method was compared with pressure measurements in the GISP2 bore-hole. The very high correlation between measured hydrostatic pressure and calculated pressure corrected for thermal expansion and compressibility of the fluid confirms this method.

For GISP2, the ice pressure at the bottom of the hole is estimated to 27.30 MPa compared to 27.36 MPa calculated and 27.33 MPa measured bore-hole pressure. Therefore, the GISP2 bore-hole is close to the pressure equilibrium.

Density of *n*-butyl acetate in GISP2 bore-hole smoothly increases from 931.7 kg/m^3 at the fluid top to 943.4 kg/m^3 at the depth of 2000 m. Then it decreases to 932.0 kg/m^3 at the bottom of the bore-hole.

Acknowledgments

The estimations of drilling fluid properties and the hydrostatic pressure in bore-hole has been supported by grant of Danish Rectors Scholarship StudID No 4555.

References

Bogdanov, S.N., Ivanov, O.P. and Kupriyanova, A.V. (1976): Refrigeration engineering. Characteristics of substances: Handbook. Leningrad, Mashinostroeniye, 1-168 (in Russian).

Clow, G.R. and Gundestrup, N.S. (2000): Geophysical measurements in the deep boreholes at GISP2 and GRIP, Greenland. J. Geophys. Res. (in press)

Dubovkin, N.F., Malanicheva, V.G., Massur, Yu. P. *et al.* (1985): Physical-chemical and operating characteristics of jet fuels. Moscow, Himiya, 1–240 (in Russian).

Fujii, Y., Azuma, N., Tanaka, Y. *et al.* (1999): Deep Ice Coring on Dome Fuji Station, Antarctica. Nankyoku Shiryô (Antarct. Rec.), **43**, 162–210 (in Japanese with English abstract).

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

Industrial Solvents Handbook (1991): 4th ed., ed. by E.W. Flick. Noyes Data Corporation. Park Ridge, New Jersey, USA, 1–930.

Kelley, J.J., Stanford, K., Koci, B., Wumkes, M. and Zagorodnov, V. (1994): Ice coring and drilling technologies developed by the Polar Ice Coring Office. Mem. Natl Inst. Polar Res., Spec. Issue, **49**, 24–40.

Kuksov, A.K., Babayan, E.V. and Shevtsov, V.D. (1992): Prevention and liquidation of the oil and gas revealing. Moscow, Nedra, 1–251 (in Russian).

Litvinenko, V.S., Talalay, P.G. and Chistyakov, V.K. (1996): Fluids for the drilling in permafrost and glaciers. St.-Petersburg State Mining Institute, 1–69 (in Russian).

Menshikov, N.G. and Talalay, P.G. (1993): Tests of the drilling fluid for deep ice drilling. Methods and Technique of Prospecting, **3**(141), 115–119 (in Russian).

Talalay, P.G. and Gundestrup, N.S. (2002): Hole fluids for deep ice core drilling. Mem. Natl Inst. Polar Res., Spec. Issue, **56**, 148–170.

Tchistyakov, V.K., Kracilev, A., Lipenkov, V.Ya., Balestrieri, J.Ph., Rado, C. and Petit, J.R. (1994): Behavior of a deep hole drilled in ice at Vostok Station. Mem. Natl Inst. Polar Res., Spec. Issue, **49**, 247–255.

(Received March 5, 2001; Revised manuscript accepted June 22, 2001)