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DRILLING FLUID FOR DOME F PROJECT IN ANTARCTICA

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Abstract: At Dome F, one of the summits of the East Antarctic Ice Sheet, a very deep ice-coring operation is to be carried out by the Japanese Antarctic Research Expedition from 1995. Since it will take two years to complete the coring up to about 3000 m depth, the borehole should be filled with proper drilling fluid to prevent borehole closure during the operation. This paper is a report on our investigations for searching for the proper drilling fluid which can be used in the very cold environment at Dome F. Although the investigations are still in progress, three kinds of fluid were chosen as drilling fluid candidates. They are: 1) n-butyl acetate, 2) "IP-solvent" with densifier and 3) Silicone Oil. Their properties were investigated and compared in terms of density and viscosity, which are essential requirements for a drilling fluid. As a result, it was shown that n-butyl acetate and IP-solvent with densifier can be used as the drilling fluid. However, the use of n-butyl acetate is impossible without sufficient ventilation at the coring site or other action to dispose of its vapor. When the use of IP-solvent with densifier is considered, the choice of proper densifier is also a problem.

1. Introduction

The Japanese Antarctic Research Expedition (JARE) has a plan for ice-coring at Dome F, one of the summits of the East Antarctic Ice Sheet (77°22'S, 39°37'E, 3807 m a.s.l. (AGETA *et al.*, 1989)). This plan is called the Dome F Project. It is planned to take two years from 1995 for the coring operation to reach the bottom of the ice sheet, which is at depth between 2800 m and 3000 m. In order to prevent borehole closure during the coring operation, the borehole should be filled with a proper drilling fluid. So far, various kinds of drilling fluid have been used for ice-coring of glaciers and ice sheets. Some reports have been published (*e. g.* GOSINK *et al.*, 1991). However, since the annual mean temperature at Dome F is about –58°C (AGETA *et al.*, 1989), a drilling fluid that can be used in such a cold environment is required for the project. Considering the viscosities at temperatures up to –58°C, only a few kinds of fluid can be used at Dome F.

The fundamental requirements for the drilling fluid are as follows:

1) Physical properties
   a. The density should be comparatively the same as ice in the ice sheet between about 940 (kg/m^3) and about 960 (kg/m^3).
   b. The viscosity should be smaller than 10 (cp).
2) Effect on the ice core qualities

The fluid should not spoil ice core quality.

3) Effect on the coring equipment

The fluid must be one which is compatible with the coring equipment.

4) Effect on human health

The fluid must not cause health hazards for the people who work at the coring site.

5) Low cost

6) No danger on flammability and volatility

There is no fluid which satisfies all of the stated requirements completely. Some liquids remained as candidates after careful investigations. They are as follows.

1) N-butyl acetate

2) A solvent identified as "IP-solvent, 1620" with a densifier. "IP-solvent, 1620" is manufactured by Idemitsu, a company which manufactures petrochemical products. The manufacturer suggested that the IP-solvent can also be used as a fuel oil. It has similar components and properties as the fuel oil "Exxon D60". The densifier candidates are CFC11 or CFC113. Here CFC is the abbreviation of Chloro Fluoro Carbon.

3) Silicone oil (KF96-1.5 cs) manufactured by Shin-Etsu, a company which manufactures silicone products.

Among these three candidates, a detailed report about n-butyl acetate as the drilling fluid for deep drilling was given by GOSINK *et al.* (1991). The advantages and disadvantages of these three are summarized as follows. One of the advantages of n-butyl acetate is that the viscosity is very small (below 4 cp at temperatures above –60°C). Thus the total period of time for the coring operation can be minimized. In addition, no densifier is necessary. It cannot be used without sufficient ventilation to minimize air pollution. The viscosity of the IP-solvent with densifier is larger than that of n-butyl acetate but is still acceptable. However, it is not certain yet whether CFC113 and CFC11 can be used as the densifier. A problem remains because the freezing point of CFC113 is –35°C and the vapor pressure of each CFC is very high. Silicone Oil has the advantage of safety for human health. However, it has a higher viscosity than the other two candidates and it is expensive (about 5000 yen/kg). It can be used only when relatively high viscosity is acceptable for the coring operation.

In this paper we first show the temperature and pressure conditions in the ice sheet at Dome F. Second, the properties of these three candidates are compared in terms of density and viscosity because they are essential conditions required for the drilling fluid. Finally, some problems that still remain unsolved are summarized.

2. Environment in the Ice Sheet at Dome F

The drilling fluid should be one which can be used in the environment described below. At Dome F, the annual mean temperature is expected to be –58 °C. This was deduced from the 10 m snow temperature there observed by AGETA *et al.* (1989). NISHIO (personal communication) calculated the possible depth-temperature profile. In the calculation, steady state and accumulation rates between 2 and 5 cm/a (ice equivalent) were assumed. Based on the calculated result when the accumulation rate was assumed to be 5 cm/a, the temperature-pressure (T-P) profile in the ice sheet was estimated. It is shown as Fig. 1. It is seen that both the temperature and the internal hydrostatic pressure increase in

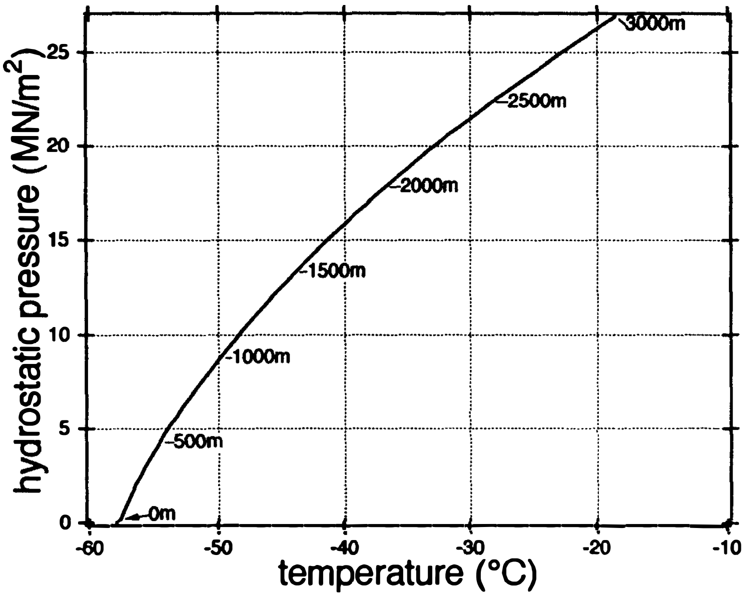

Fig. 1. Estimated temperature-pressure (T-P) profile in the ice sheet at Dome F. The temperature profile was calculated by Dr. F. Nishio (personal communication). Boundary conditions for the calculation are as follows: the surface flow velocity (u_s) is zero; surface slope (α) is zero; surface temperature is −58°C; accumulation rate is 5 cm/a; geothermal heat flux is 1 (HFU). The assumed accumulation rate is one which makes the calculated temperature colder. This value was selected to give the most conservative estimate.

deeper layers.

3. Density

Density is one of the most essential requirements for the drilling fluid. When the hydrostatic pressure in the borehole that is filled with the drilling fluid is smaller than that in the surrounding ice sheet, the diameter of the borehole becomes smaller. Conversely, when the hydrostatic pressure in the borehole is larger than that in the ice sheet, the diameter of the borehole expands. In this section, we first compare the density of the three drilling fluid candidates. Second, the difference in the hydrostatic pressure between the borehole and the surrounding ice sheet is estimated based on the density data. And finally, the annual strain rate of the borehole diameter is calculated. Based on these estimates, we will show that a density between about 940 (kg/m^3) and about 960 (kg/m^3) is desirable and that three candidates can satisfy this requirement.

3.1. Density of the fluid

First of all, the density of the drilling fluid candidates are shown in Fig. 2. The density of ice is also shown for comparison. For the IP-solvent with densifier, CFC11 is assumed as the densifier. Three cases of the volume fraction between the volume of IP-solvent and CFC11 were investigated. In the figure, pressure dependence is not considered except [e2] although the actual drilling fluid is to be subject to a hydrostatic pressure up to 27 (MN/m^2) in the ice sheet. Gosink *et al.* (1991) described that the density of n-butyl acetate increases nearly 3% at 3000 m depth. In contrast, since the bulk modulus of ice is about 10×10^9 (N/m^2) at –10°C (FLETCHER, 1970), it results in a density increase of about 0.27% at 3000 m depth. However, these effects were not considered in the data in Fig. 2.

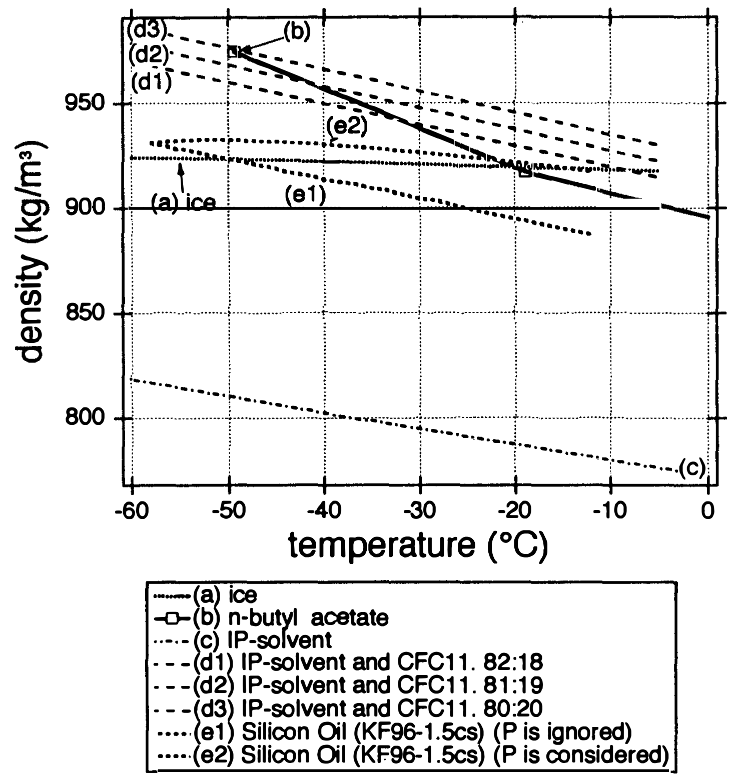

Fig. 2. Density of the drilling fluid candidates versus temperature. (a) is the density of ice when hydrostatic pressure is not considered. (b) is the density of n-butyl acetate (GOSINK et al., 1991). (c) is the density of IP-solvent itself without the densifier. The data was from the manufacturer of IP-solvent. (d1)~(d3) are the density of the IP-solvent with densifier. Three cases of volume fraction were considered. The densities are simple averages of both fluids. Increase in the density when the fluids are mixed is not considered. (e1) is the density of Silicone Oil when hydrostatic pressure is ignored. (e2) is that when hydrostatic pressure is considered. The data on Silicon Oil were given by the manufacturer.

3.2. Difference in the hydrostatic pressure between the borehole and the ice sheet

Based on the data in Fig. 2, the difference in the hydrostatic pressure between the borehole and the ice sheet (ΔP, (MN/m^2)) was calculated assuming that the borehole is filled with drilling fluid at depths below 100 m. At depth above 100 m, the borehole cannot be filled with the fluid because the ice sheet is expected to be firn there. Figure 3 shows ΔP *versus* depth. In the figure, in addition to the case of a real fluid, there are also included cases in which the borehole is filled with imaginary fluids which have various densities between 920 (kg/m^3) and 1000 (kg/m^3). At shallow depths, the hydrostatic pressure in the ice sheet is always larger than that in the borehole because the upper surface of the drilling fluid is at 100 m depth. Only when fluid with density larger than about 920 (kg/m^3) is used, ΔP increases with depth. In addition, only when fluid with density larger than about 950 (kg/m³) is used, ΔP becomes positive in deeper layers; *i.e.* the hydrostatic pressure in the borehole is larger than that in the surrounding ice sheet there.

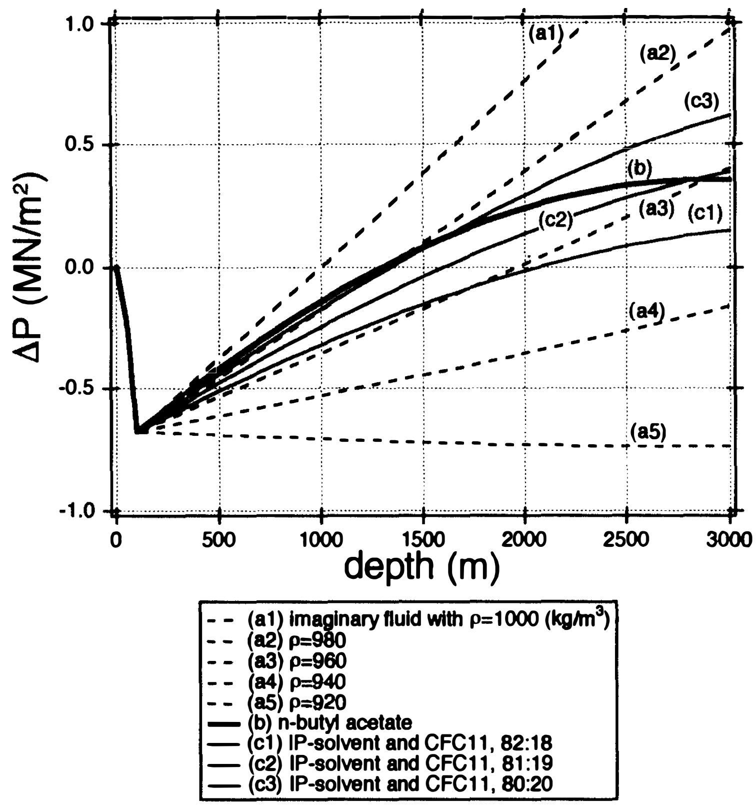

Fig. 3. The difference in the hydrostatic pressure between the borehole and the ice sheet for various drilling fluids. Positive value means that the hydrostatic pressure in the borehole is larger than that in the ice sheet. (a1)~(a5) are imaginary fluids of density between 1000 (kg/m³) and 920 (kg/m³). (b) is for n-butyl acetate. (c1)~(c3) is for IP-solvent with densifier. Three volume fractions were considered. These estimates are based on the data in Fig. 2.

3.3. Strain rate of the borehole

Based on Fig. 3, the annual strain rate of the borehole diameter was estimated. The results are shown in Fig. 4. For the estimation, it was assumed that a borehole was made at a time, and the strain after one year was calculated. To calculate the strain rate, the relation between stress and strain rate observed at Mizuho Station (NARUSE *et al.*, 1988) was used. The activation energy of the creep of ice given by PATERSON (1977) was also used. It is expressed as follows.

$$\dot{\varepsilon}=A \exp\left(\frac{Q}{RT_k}\right) \tau^n. \quad (1)$$

$\dot{\varepsilon}$: effective shear strain rate
τ: effective shear stress (MN/m²)
A=4529

n=2.87

Q=54 (kJ/mol): activation energy obtained by PATERSON (1977)

R: gas constant

T_k: temperature in degrees Kelvin

Using the planned diameter of the borehole at Dome F, 13.5 (cm), changes in the diameter of the borehole were calculated. Figure 4 indicates that when the density is between 940 (kg/m^3) and 960 (kg/m^3), the annual changes in the diameter are smaller than 0.5 mm. N-butyl acetate and IP-solvent with densifier can satisfy this condition. Although the case of Silicone Oil was not included in this figure, it will be between (a4) and (a5).

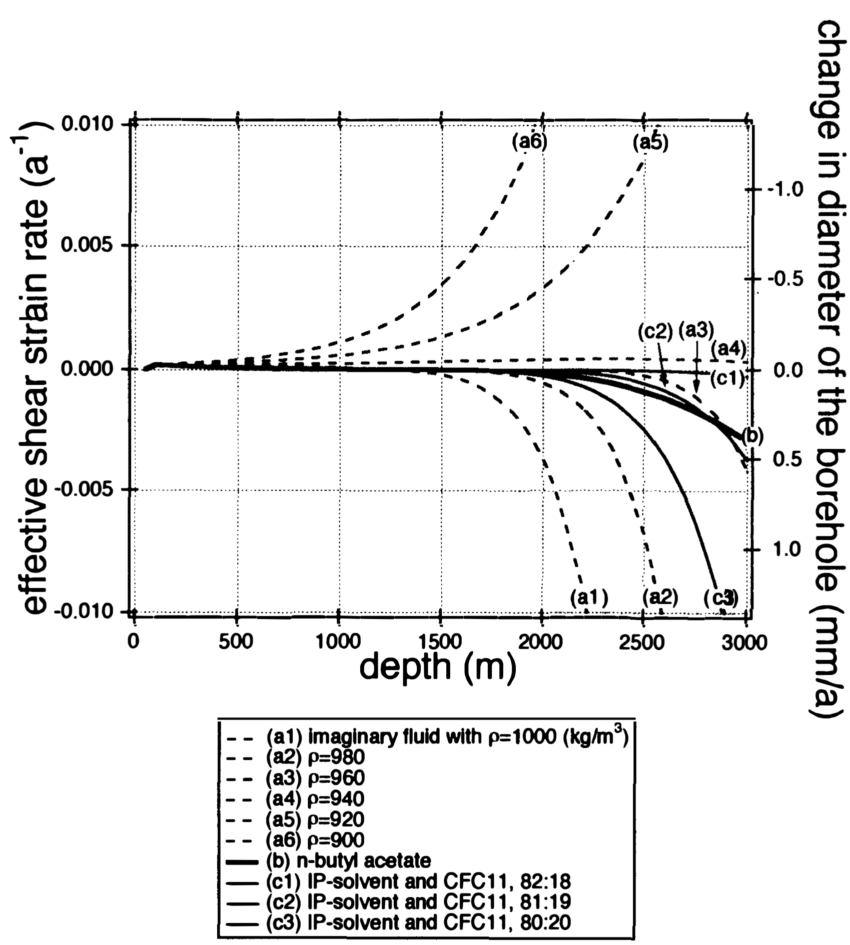

Fig. 4. The calculated annual strain rates and changes in the borehole diameter. Strain occurs due to the difference in the hydrostatic pressure between the borehole and the ice sheet shown in Fig. 3. (a1)~(a6) are the cases of the imaginary fluid that have density between 1000 (kg/m3) and 900 (kg/m³). (b) is the case when n-butyl acetate is used. (c1)~(c3) are cases when IP-solvent with densifier is used.

4. Viscosity

Low viscosity is also one of the essential requirements for the drilling fluid. Since the viscosity determines the drill's lowering velocity and pull-up velocity, total period of time to complete the coring operation will be determined by it. Although it is difficult to estimate the exact viscosity of the drilling fluid under high pressure in the borehole, we experimentally confirmed that the IP-solvent and n-butyl acetate exist as fluid under pressure up to 50 (MN/m^2) and at temperatures typical of the ice sheet of Dome F. In this section, we first describe this experiment. Second, the viscosity of the drilling fluid candidates under atmospheric pressure are compared. Finally, based on these data, the total period of time to complete the 3000-m coring is estimated.

4.1. The fluid under high pressure

First of all, we briefly describe the experiment by which we confirmed that the drilling fluid will not freeze under pressures up to 27 (MN/m^2) and at temperatures up to –58 (°C) at Dome F. The fluid was compressed in a cylindrical high-pressure cell together with a small iron ball. The inner size of the cell was 15 mm in diameter and 7 mm in width. The diameter of the iron ball was about 2 mm. The pressure was varied between 0 and 100 (MN/m^2) at temperatures between –20°C and –60°C. We confirmed that the fluid exists as fluid by shaking the cell and by observing the iron ball to roll. In the experiment, pressure was detected with a load-cell and the temperature was controlled with nitrogen gas. The temperatures and the pressures at which the rolling of the iron ball was observed are shown in Fig. 5. In the figure, the T-P profile at Dome F (in Fig. 1) is also shown for reference. As for the n-butyl acetate and IP-solvent, we observed that under a pressure as low as below 50 (MN/m^2) the fluid did not freeze and the steel ball rolled when the cell was shaken.

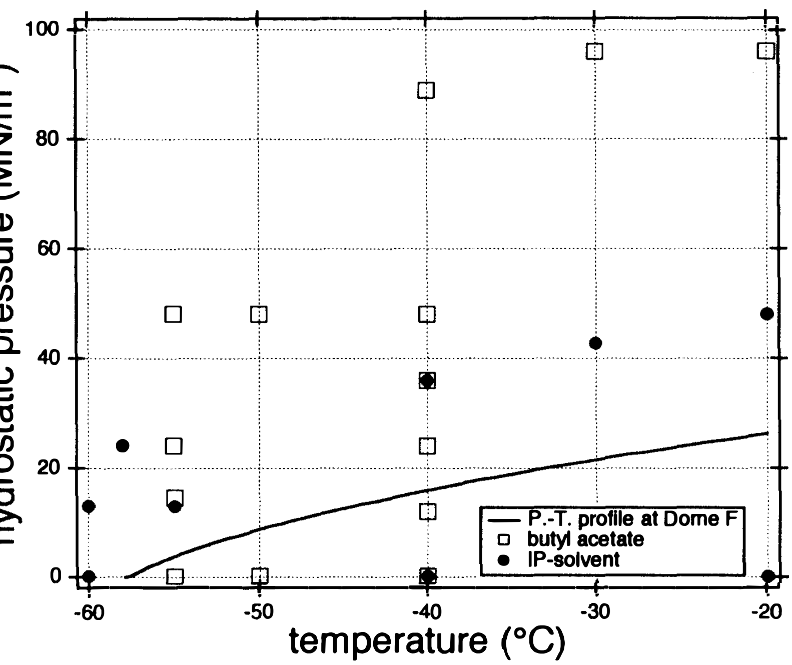

Fig. 5. Temperatures and pressures at which rolling of the iron ball was observed in the high-pressure cell. Open squares are the results for n-butyl acetate. Solid circles are the results for IP-solvent (without densifier). P-T profile at Dome F (in Fig. 1) is also shown for reference.

4.2. Viscosity

The viscosity of each drilling fluid candidate is shown together in Fig. 6 as a function of temperature. The effect of hydrostatic pressure is not considered except in the case of Silicone Oil ((d2) in the figure). As for the IP-solvent with densifier, the viscosity of the IP-solvent itself and that of CFC11 itself are also shown. Since the viscosity of the CFC11 is much smaller than that of IP-solvent, the calculated viscosity of the mixture of the two is smaller than that of IP-solvent. Among the three candidates, the viscosity of n-butyl acetate is the smallest. That of Silicone Oil is the largest.

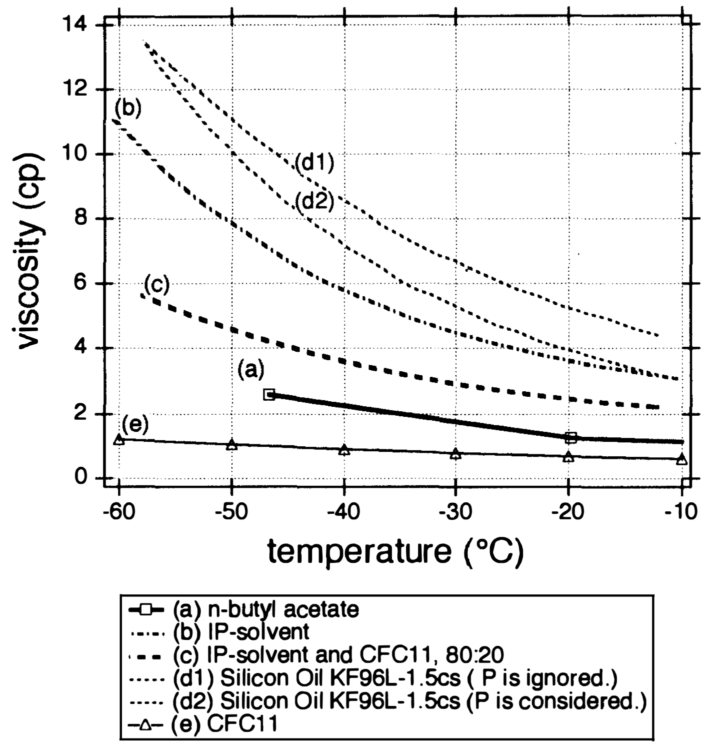

Fig. 6. The viscosity of the drilling fluid candidates. (a) is that of n-butyl acetate (GOSINK et al. 1991). (b) is that of IP-solvent measured by the authors. (c) is that of the mixture of IP-solvent and CFC11. These are calculated values based on (b) and (e). (d1) and (d2) are those of Silicone Oil, without and with the effect of hydrostatic pressure, respectively. (e) is that of CFC11.

4.3. Total period of time for the coring operation as a function of viscosity

Based on the viscosity in Fig. 6, the total period of time to complete the 3000 m coring was estimated. The total period is determined by the drill's lowering and pull-up velocity and the stationary time of the drill at the top and at the bottom of the borehole in each "drill run". In order to determine the relation between the viscosity of the drilling fluid and the velocity of the drill which was developed for the coring at Dome F, an experiment was carried out at the test site for ice-coring at Rikubetsu in Hokkaido in February, 1993. As a result, a free-fall velocity of 0.7 m/sec, was obtained in a borehole filled with fluid of viscosity 2.7 cp. The clearance between the borehole wall and the drill was 5.5 mm.

Based on this relation, total hours to complete the arbitrary depths were calculated for

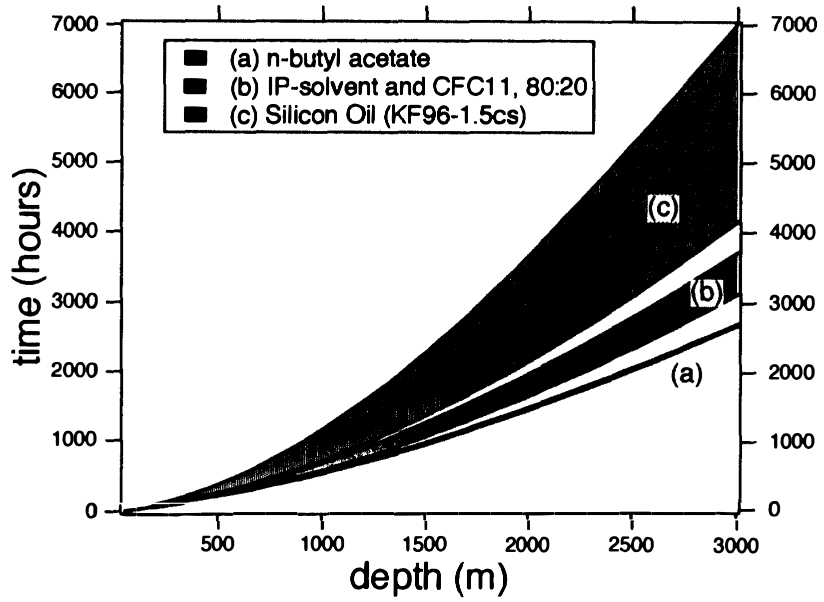

Fig. 7. Total period of time (hours) of ice coring to reach the arbitrary depth. (a) is the case when the n-butyl acetate is used as the drilling fluid. (b) is the case when IP-solvent with densifier is used. (c) is the case when Silicone Oil is used. For the calculation, the lowering velocity of the drill in the borehole was calculated using eqs. (2) and (3). The pull-up velocity was assumed to be 1.2 times the lowering velocity. The stationary time of the drill at the top and the bottom of the borehole at each "drill run" was assumed to be 40 minutes. It was assumed that lowering velocity larger than 1 (m/s) is impossible.

each fluid. The results are shown in Fig. 7. For the calculation, the following relations were assumed between the viscosity (η) and the lowering velocity (v).

$$v \cdot \eta = 1.9, \tag{2}$$
$$v^2 \cdot \eta = 1.3. \tag{3}$$

The constants 1.9 and 1.3 were based on the experimental result at Rikubetsu. Equation (2) is a model which holds when the friction drag due to the drill is dominated by the shear friction of the fluid in the laminar flow between the borehole wall and the drill. In this case, eq. (2) holds because the friction drag is proportional to the drill velocity and the viscosity, and because the only driving force of the drill's lowering, the weight of the drill, is always constant. Free fall velocity is always attained when the two are equal. On the other hand, eq. (3) is a model which holds when the friction drag by the turbulent flow in the fluid between the borehole wall and the drill is dominant and when the drag due to the collision between the fluid and the drill at the front of the drill is dominant. In this case, the friction drag is proportional to the square of v, and we assume that the friction drag is still proportional to η. Since the friction drag is constant when the free fall velocity is attained, eq. (3) holds. The actual relation between v and η must have components expressed by eqs. (2) and (3). Thus, v for fluids which have various viscosity values was calculated with both of the equations as two extreme cases. The other conditions used for the calculations are described in the figure caption.

In Fig. 7, it can be seen that it takes about 2700 hours to complete 3000 m coring when n-butyl acetate is used. It takes about 3200~3700 hours when IP-solvent with densifier is used. It takes more than 4100 hours when Silicone Oil is used. If it is assumed that 4000 hours is the upper limit for coring in the two years coring operation, only n-butyl acetate and IP-solvent with densifier are acceptable.

5. Unsolved Problems

Based on the above estimates, n-butyl acetate and IP-solvent with densifier can remain as the drilling fluid candidates for use at Dome F. Silicone oil can remain only when relatively high viscosity is acceptable. However, some problems which must be solved urgently still remain before n-butyl acetate and IP-solvent with densifier can be used. Before the final determination, the proper solutions to the problems below must be given.

5.1. N-butyl acetate

One of the problems is the high vapor pressure. When the drilling site at Dome F is assumed to be kept at –20°C, the possible air concentration of n-butyl acetate vapor is approximately 1300 ppm (GOSINK *et al.*, 1991). The vapor pressure at –20°C is about 0.8 mmHg (extrapolated from Fig. 6 in GOSINK *et al.*, 1991). Although the fire-safety questions and answers are discussed in GOSINK *et al.* (1991), there still remains the problems with respect to the physical and mental health of the people who work at the coring site. Since the Occupational Health and Safety Administration (OSHA) limit is 150 ppm, it is impossible to use n-butyl acetate without sufficient ventilation and/or without some means of removing the n-butyl acetate vapor.

5.2. IP-solvent with densifier

CFC11 and CFC113 are the densifier candidates. One of the problems in using CFC11 is its high vapor pressure. The boiling point of CFC11 under 1013 hPa is 23.8°C. Under 600 hPa; this is the anticipated approximate pressure at Dome F; it is about 9°C. We have not confirmed yet that it can be used at –20°C at which the vapor pressure of CFC11 is about 120 mmHg. Vapor pressure is about 12 mmHg at –58°C, the 10 m snow temperature at Dome F.

As for CFC113, one of the problems is its freezing point at –35°C. We have not confirmed yet whether sediment appears in the mixture of IP-solvent and CFC113 at temperatures below –35°C. The boiling point of CFC113 under 1013 hPa is 47.57°C. Under 600 hPa, it is about 33°C. At –20°C, the vapor pressure is about 39 mmHg.

It should also be noted that HCFC (Hydro Chloro Fluoro Carbon) was developed for use in place of CFC because CFC is a substance which harms the ozone layer of the atmosphere. The allowable exposure limits (AEL) set by the manufacturer of HCFC are 10 ppm and 100 ppm for HCFC123 and HCFC141b, respectively, whereas that of CFC11 and CFC113 is 1000 ppm. In addition, HCFC has the same problem as CFC has, as described above. Moreover, recently it has become clear that at least HCFC141b also harms the ozone layer. Thus, there seems to be no merit in using these HCFCs in place of CFC as the densifier.

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References

AGETA, Y., KAMIYAMA, K., OKUHIRA, F. and FUJII, Y. (1989): Geomorphological and glaciological aspects around the highest dome in Queen Maud Land, East Antarctica. Proc. NIPR Symp. Polar Meteorol. Glaciol., **2**, 88–96.

FLETCHER, N.H. (1970): The Chemical Physics of Ice. Cambridge, Cambridge University Press.

GOSINK, T.A., KELLEY, J.J., KOCI, B.R. and BURTON, T.W. (1991): Butyl acetate, an alternative drilling fluid for deep ice-coring projects. J. Glaciol., **37**, 170–176.

NARUSE, R., OKUHIRA, K., OHMAE, H., KAWADA, K. and NAKAWO, M. (1988): Closure rate of a 700 m deep bore hole at Mizuho Station, East Antarctica. Ann. Glaciol., **11**, 100–103.

PATERSON, W.S.B. (1977): Secondary and tertiary creep of Glacier ice as measured by borehole closure rate. Rev. Geophys. Space Phys., **15**, 47–55.

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