

Dimethyl siloxane oils as an alternative borehole fluid

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ABSTRACT. Finding a new safe and ecologically friendly borehole fluid is one of the most pressing problems for forthcoming ice-drilling projects. Not all recent borehole fluids qualify as intelligent choices from safety, environmental and other technological standpoints. We propose the use of silicone oils as the borehole fluid. The most suitable type of silicone oils for deep ice drilling are low-molecular (or volatile) dimethyl siloxane oils (DSOs). Low-molecular DSOs are clear, water-white, tasteless, odorless, neutral liquids. They are hydrophobic and inert substances that are stable to water, air, oxygen, metals, wood, paper, plastics, etc. Of the DSOs, class 2 grades of KF96-1.5cs and KF96-2.0cs most fully fit our criteria for choice as borehole fluids. The final conclusion as to the suitability of DSOs for ice deep drilling will be made after the experiments in a test borehole.

INTRODUCTION

One of the main ice properties that have a major influence on drilling technology is the ice creep that causes borehole deformation under conditions of negative pressure difference on the hole walls. To compensate ice-overburden pressure, drilling in glacial ice requires the use of a borehole fluid that prevents borehole closure.

The ideal borehole fluid will meet the following criteria: (1) fluid density is approximately equal to or a little higher than the ice density; (2) fluid viscosity does not adversely affect the drill's optimal lowering/hoisting rate; (3) fluid freezing point is lower than not only the minimal temperature in the borehole but also the minimum temperature of the air outside the drilling shelter (where the fluid is usually stored); (4) fluid is not aggressive to the ice core, borehole walls, drill and cable components; (5) fluid does not change its chemical or physical properties during storage, transportation and use in borehole; (6) fluid is non-flammable and non-explosive; (7) fluid is non-toxic to humans, biodegradable and has no other environmental effects; (8) fluid is inexpensive and readily available from markets.

In the practice of deep ice drilling, only three types of borehole fluid have been used: (1) petroleum-based products (e.g. kerosene) with added densifier; (2) aqueous glycol or ethanol solutions; and (3) *n*-butyl acetate. All of these are far from ideal for use as a borehole fluid because of safety, environmental and other issues (Talalay and Gundestrup, 2002a).

The borehole fluids of the first category – two-component systems based on petroleum products – impose a high environmental risk since, in the event of a spill, they have a long resistance time, particularly in a cold environment. Even at very low concentrations in the water environment ($<1 \text{ mg m}^{-3}$), petroleum fluids can poison microorganisms. The materials used as densifiers in these two-component systems (CFC-11, CFC-113, HCFC-141b) cause depletion of the ozone layer when released into the atmosphere and their use has been limited or banned by the Montreal Protocol.

The borehole fluids of the second category – aqueous glycol or ethanol solutions – have generally low environmental hazard potential. From the technological standpoint, these hydrophilic liquids have two major disadvantages that limit their use as borehole fluids. First, they continuously

dissolve the borehole walls, the core and chips until slush plugs are formed in the borehole, resulting in a high risk of equipment loss down the hole. Second, they are extremely viscous at temperatures below 0°C .

The use of the third borehole fluid – *n*-butyl acetate – was proposed and introduced by the Polar Ice Coring Office (PICO), University of Alaska Fairbanks, USA. They conducted a chemical literature survey in an effort to identify a borehole fluid (1) with the necessary viscosity and density characteristics to minimize health and safety risks for drillers, (2) which would cause minimal environmental impact, and (3) which would not compromise the scientific integrity of the ice core. Of nearly 250 000 compounds electronically surveyed, 11 potential drilling fluids were identified: anisole, hexanol, heptanol, octanol, *p*-cymene, *s*-butyl benzene, pseudocumene, propyl, *n*-butyl acetate, amyl acetate and propyl propionate. PICO concluded that of these 11, only *n*-butyl acetate met their requirements (Gosink, 1989; Gosink and others, 1989).

n-butyl acetate was subsequently used as the borehole fluid on the GISP2 project in Greenland (Gosink and others, 1994), and at Dome Fuji, Antarctica (Fujii and others, 2002). The main problem with its use is the hazard posed to the health of the people working at the coring site. The recommended exposure limit to *n*-butyl acetate adopted in various countries varies from 40 to 200 ppm (Talalay and Gundestrup, 2002a). The safety and health hazards associated with *n*-butyl acetate now cause us to exclude it from the list of desirable borehole fluids.

The search for safe and ecologically friendly borehole fluids is now a major concern for forthcoming ice-drilling projects. The latest investigations for such a fluid were carried out by Ice Coring and Drilling Services (ICDS), University of Wisconsin, USA, (Gerasimoff, 2003) and the Department of Geophysics, University of Copenhagen, Denmark (personal communication from J.P. Steffensen, 2006).

ICDS tested a two-compound fluid consisting of Isopar-K and hydrofluoroether HFE-7100 as densifier. Isopar-K is a high-purity isoparaffinic solvent with low odor and low skin irritation. The properties of Isopar-type solvents are similar to the properties of solvents of the Exxsol D family used previously at the North Greenland Icecore Project (NorthGRIP), European Project for Ice Coring in Antarctica (EPICA) Dome C and Dronning Maud Land (DML, Antarctica), ice-drilling

projects. To increase the density of the borehole fluid, Isopar-K was blended with the segregated hydrofluoroether, HFE-7100, produced by 3M Corporation. Ordinarily the segregated HFEs have zero ozone depletion potential, but they exhibit extremely high (low hundreds to about 15 000) global warming potential. The segregated HFEs have low viscosity, low toxicity and no flash point. The density of HFE-7100 is 1520 kg m^{-3} (at 25°C). Tests show that the mixture of Isopar-K with HFE-7100 separates into two phases over a limited temperature range of -29 to -37°C which makes it impractical to use in the drillholes.

The University of Copenhagen investigators chose a mixture of Haltermann ESTISOL 240 and Haltermann COASOL for the laboratory and field tests. These products are di-esters of biological fatty acids. By varying the mixing ratio of these two fluids, densities between 860 and 965 kg m^{-3} can be obtained. These fluids are characterized by low vapor pressure, almost no odor, low toxicity and good biodegradable properties. The main disadvantage of this mixture is its very high viscosity ($\sim 20 \text{ cS}$ at -25°C and $\sim 30 \text{ cS}$ at -35°C ($1 \text{ cS} = 10^{-6} \text{ m}^2 \text{ s}^{-1}$)). To achieve the drill's optimal lowering/hoisting rate, a borehole with a larger clearance between the drill and the borehole wall may be required. This will lead to a significant increase in the number of cuttings, shortening of run penetration, decrease of ice production rate and so on.

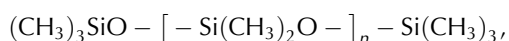
The field tests revealed another disadvantage of the Haltermann ESTISOL 240 and Haltermann COASOL mixture: although considered a non-hazardous material with very simple handling procedures, the mixture spilled on the floor of the drilling shelter, destroying rubber-soled shoes. It is difficult to consider a fluid with such aggressive properties as a safe and ecologically friendly material.

The foregoing short review indicates that there are no known new alternative fluids suitable for use as drilling fluid. We suggest once again that the low-temperature silicone oils might be considered one of the most promising types of drilling fluid.

GENERAL DESCRIPTION

The silicone oils are specified as any of a number of polymers containing silicon atoms connected with carbon atoms over atoms of other elements (oxygen, nitrogen, sulfur, etc.). The silicone oils are hydrophobic and inert substances that are stable to water, air, oxygen, metals, wood, paper and plastics. The use of silicone oil as a drilling fluid was first suggested by Fujita and others (1994) who, however, noted that 'it has a higher viscosity than other candidates and it is expensive'. Japanese drillers therefore chose to use *n*-butyl acetate as their borehole fluid.

The most suitable kind of silicone oils for deep ice drilling are the low-molecular (or volatile) dimethyl siloxane oils (DSOs). These differ from other silicone, mineral and synthetic oils in that they have the smallest viscosity changes with temperature variation and also in their volatility properties. The common chemical structure of DSOs is:



where n is the average rate of polymerization (low-molecular DSOs have $n \leq 8$).

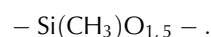
DSOs are used in industry as hydraulic liquids, lubricants, anti-adhesion coverings, foam breakers, cooling agents, dielectrics, etc. They are also often used as the temperature

control fluid in laboratory ice deformation tests (personal communication from T.H. Jacka, 2008).

Companies that manufacture DSOs use different trade names:

- DC-200 by Dow Corning Corp. (USA);
- KF96 by Shin-Etsu Chemical Co. (Japan);
- MS-200 by Midland Silicones (United Kingdom);
- Si by Siss (France);
- AK by Bayer (Germany);
- Lukosil M by Synthesia Kolin (Czech Republic);
- PMS by State Institute of Applied Chemistry (Russia).

For distribution purposes, DSOs are subdivided according to their viscosity (usually in centistokes at 20 or 25°C), which is considered to be the main working characteristic of the silicone oils. In Russia, DSOs are subdivided additionally into two classes due to content of the branching links expressed by the chemical formula:



These two classes are (1) DSOs with a linear structure (without branching links) and (2) DSOs with a branched structure (containing different amounts of branching links).

DSOs with a branched structure are either not manufactured or not distinguished in other countries. In Russia, DSOs with a branched structure have an additional letter 'r' at the end of their trade name (in Cyrillic transliteration the letter 'p' from the Russian word *razvletvlyenniy* which in English means 'branching').

The characteristics of DSOs with the linear and branched structures are very similar, and the main differences between oils of these two classes are their low-temperature properties. DSOs with the branched structure do not tend to crystallize at low temperatures down to -110°C due to the presence of branching links. These silicone oils are used as cooling and damping agents in space apparatuses.

Low-molecular DSOs are clear, water-white, tasteless, odorless and neutral liquids. The properties of low-molecular DSOs with the same structures are slightly different from manufacturer to manufacturer (Tables 1 and 2). Moreover, physical and working characteristics of silicone oils can vary in the range specified by manufacturers. For example, Shin-Etsu Chemical Co. (unpublished information) specifies the viscosity variability in the ranges (at temperature of 25°C) $1.5 \pm 0.15 \text{ cS}$ for KF96-1.5cs and $2.0 \pm 0.2 \text{ cS}$ for KF96-2.0cs.

DENSITY-VISCOSITY PROPERTIES

The expansion coefficient of low-molecular DSOs is in the range $(1.0-1.1) \times 10^{-3} \text{ K}^{-1}$. Typical values of density, ρ (kg m^{-3}), and viscosity, ν (cS), as a function of temperature, t ($^\circ\text{C}$), for some low-molecular DSOs are given in Table 3. The density-temperature relationship of KF96-1.5cS has a linear shape at atmospheric pressure. Our processing of the curve published by Fujita and others (1994) results, for KF96-1.5cs, in the equation

$$\rho = -t + 874.2. \quad (1)$$

The experiments carried out at the University of Copenhagen found a similar density-temperature relationship for

Table 1. Chemical structure and main properties of low-molecular DSOs with viscosity grade of 1.5 cS (Shin-Etsu Chemical Co. data; Alekseev and others, 1997)

Industrial label	KF96-1.5cs (Shin Etsu Chemical Co.)	PMS-1.5 (Russia)	PMS-1.5r (Russia)
Name	Decamethyl tetrasiloxane		–
Formula index	$(\text{CH}_3)_{10}\text{Si}_4\text{O}_3$		–
Chemical structure	$(\text{CH}_3)_3\text{Si} - \text{O} - \left(\begin{array}{c} \text{CH}_3 \\ \\ \text{Si} - \text{O} \\ \\ \text{CH}_3 \end{array} \right)_2 - \text{Si}(\text{CH}_3)_3$		–
CAS RN*	141-62-8	–	–
Molecular weight	310.7	260–300	320–440
Density (kg m^{-3})	850–855 @ 25°C	853.6 @ 20°C	850 @ 20°C
Viscosity (cS)	1.53 @ 25°C	1.53 @ 25°C	1.5 @ 20°C
Pour point (°C)	–76	–76	–150
Flash point (°C)	38	40	50
Autoignition temperature (°C)	–	340	340

*CAS RN is the register number assigned by the Chemical Abstracts Service (CAS) as a unique identifier for the compound.

Table 2. Chemical structure and main properties of low-molecular DSOs with viscosity grade of 2.0 cS (Shin-Etsu Chemical Co. data; Alekseev and others, 1997)

Industrial label	KF96-2.0cs (Shin Etsu Chemical Co.)	PMS-2.0 (Russia)	PMS-2.0r (Russia)
Name	Dodecamethyl pentasiloxane		–
Formula index	$(\text{CH}_3)_{12}\text{Si}_5\text{O}_4$		–
Chemical structure	$(\text{CH}_3)_3\text{Si} - \text{O} - \left(\begin{array}{c} \text{CH}_3 \\ \\ \text{Si} - \text{O} \\ \\ \text{CH}_3 \end{array} \right)_3 - \text{Si}(\text{CH}_3)_3$		–
CAS RN	141-63-9	–	–
Molecular weight	384.9	340–370	400–450
Density (kg m^{-3})	870–875 @ 25°C	875.5 @ 20°C	870 @ 20°C
Viscosity (cS)	2.07 @ 25°C	2.07 @ 25°C	2.0 @ 20°C
Pour point (°C)	–84	–84	–113
Flash point (°C)	75	56	70
Autoignition temperature (°C)	–	–	305

Table 3. Density, ρ (kg m^{-3}), and viscosity, ν (cS), of low-molecular DSOs at atmospheric pressure (Shin-Etsu Chemical Co. data; Alekseev and others, 1997)

Temp. °C	KF96-1.5cs		PMS-1.5		PMS-1.5r		KF96-2.0cs		PMS-2.0		PMS-2.0r	
	ρ	ν	ρ	ν	ρ	ν	ρ	ν	ρ	ν	ρ	ν
–93	–	–	–	–	966	31.3	–	–	–	–	985	32.5
–73	–	–	944	22.2	946	15.0	–	–	960	20.0	965	15.4
–53	–	–	924	9.24	926	7.77	–	–	941	10.1	945	9.11
–33	–	–	904	4.94	907	4.28	–	–	922	5.65	926	5.52
–30	902	3.9	–	–	–	–	924	5.8	–	–	–	–
–13	–	–	883	2.98	887	2.76	–	–	903	3.50	906	3.63
7	–	–	863	2.01	867	1.93	–	–	884	2.45	887	2.53
27	–	–	843	1.43	848	1.44	–	–	865	1.81	867	1.87

Table 4. Compressibility of PMS-2.0 at room temperature (Sobolevsky and others, 1985)

Pressure MPa	Relative volume change %
50	4.8
100	8.2
200	12.7
500	20.1
2000	31.5

KF96-2.0cs in the temperature range -58 to 23°C (Fig. 1):

$$\rho = -0.968t + 894.2. \quad (2)$$

The densities of these oils are equal to the ice density at -45°C for KF96-1.5cs and at -27°C for KF96-2.0cs.

The compressibility of DSOs is high (Table 4). Thus, it is necessary to account for changes in DSO density under hydrostatic pressure in the hole. Processing of the experimental data (personal communication from M. Hazu, 1998) gives the density–temperature–pressure relationship of KF96-2.0cs:

$$\rho = \frac{891.6 - 1.08t}{1 - 10^{-5}t[0.52(P - P_0) + 6.1] - 10^{-3}(P - P_0) - 2.05 \times 10^{-3}t} \quad (3)$$

where $-50 \leq t \leq 25^{\circ}\text{C}$, P is the absolute pressure (MPa; $0.1 \leq P \leq 35$ MPa) and P_0 is the atmospheric pressure ($P_0 = 0.1$ MPa).

Knowing the density–temperature–pressure relationship, it is possible to estimate precisely the difference between the hydrostatic pressure of the fluid and the overburden pressure of ice in order to predict the borehole deformation (Talalay and Gundestrup, 2002b). The pressure difference estimated theoretically in the borehole filled with type KF96-2.0cs DSO under the temperature and pressure conditions at NorthGRIP and at Vostok station, Antarctica, does not exceed 0.2 MPa at the most critical depths below 2000 m. This is sufficient to prevent borehole closure (Fig. 2). The fluid level is to 60 m at NorthGRIP and 100 m at Vostok. Due to the high compressibility of KF96-2.0cs,

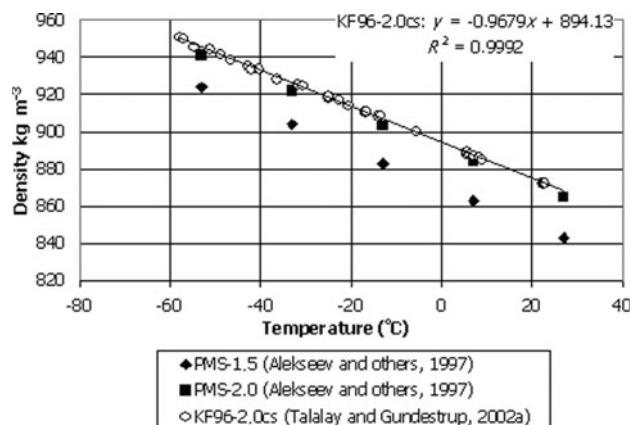


Fig. 1. Density of low-molecular DSOs vs temperature.

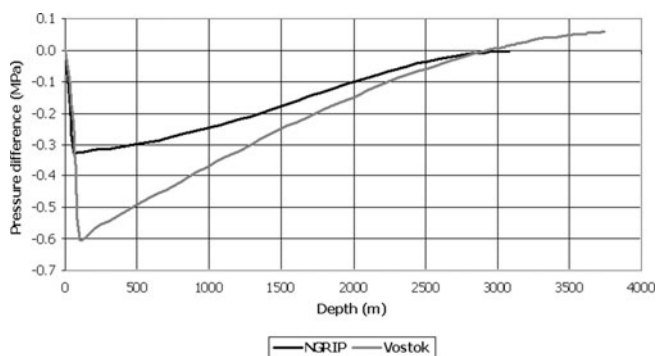


Fig. 2. Estimated pressure difference in holes filled with KF96-2.0cs type DSO for temperature and pressure conditions at NorthGRIP, Greenland, and Vostok station, Antarctica (liquid level is at 60 m for NorthGRIP and 100 m for Vostok).

the pressure difference rapidly decreases with depth, and pressure equilibrium is achieved near the borehole bottom. This prognosis confirms the value, from an ice-stress compensation point of view, of using KF96-2.0cs for deep ice drilling.

The viscosity–temperature relationship of low-molecular DSOs is not linear (Fig. 3). The viscosity of KF96-1.5cs and KF96-2.0cs is about 10 cSt at -50°C , decreasing to near 5 cSt at -30°C .

The viscosity, ν (cSt), of low-molecular KF96-1.5cs type DSOs in the temperature range -58 to -10°C can be estimated by the equation (from our processing of the curve published by Fujita and others, 1994), as

$$\nu = 10^{[785.6/(273.1+t)] - 2.51}. \quad (4)$$

The tests carried out with KF96-2.0cs type DSO gave a similar approximation in the temperature range -51 to 25°C (Talalay and Gundestrup, 2002a):

$$\nu = 10^{[582.2/(273.1+t)] - 1.65}. \quad (5)$$

Due to the long chains, the viscosity of DSOs is highly dependent on pressure, and increases with time. Each 1 MPa of overpressure results in a $\sim 1\%$ increase in the viscosity of the low-molecular DSOs (Sobolevsky, 1985). Nevertheless, the fluidity of low-molecular DSOs is maintained, even at very high pressures up to 800 MPa (Fig. 4).

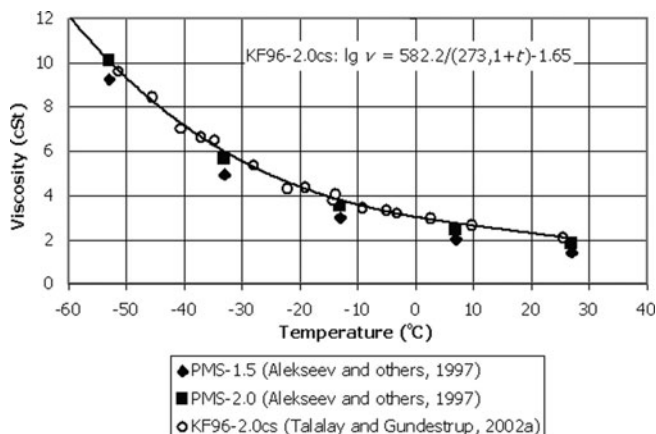


Fig. 3. Viscosity of low-molecular DSOs vs temperature.

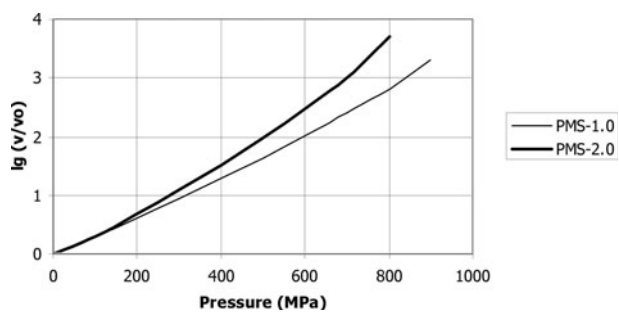


Fig. 4. Relative change of viscosity of low-molecular DSOs vs pressure (Sobolevsky, 1985).

The viscosity of KF96-2.0cs predicted for the boreholes under the temperature and pressure conditions of NorthGRIP and Vostok is high (Fig. 5) when compared to that for other drill fluids.

While the fluid viscosity determines the travel time of the drill string and, consequently, the total time for drilling, the adverse effects of the higher viscosity of DSOs might be lessened by changing some of the other parameters of the drill's design. For example, for a hole with a final depth of 3000 m, the optimum range of the drill's lowering/hoisting rate might be $0.8\text{--}1.0\text{ m s}^{-1}$ (Bobin and others, 1988). To achieve the desired lowering rate in the more viscous fluid, the clearance between the drill and the borehole wall could be increased. Assuming a borehole with a diameter of 0.13 m, a drill length of 11 m, a drill mass of 130 kg and a fluid density of 930 kg m^{-3} , calculation of the lowering rate for various clearances and fluid viscosities using the methods of Ohishin and others (1990) yields a set of curves (Fig. 6). In this case, a clearance of 8–9 mm would provide a lowering rate adequate for Vostok or NorthGRIP.

The effects of higher-viscosity drill fluids on ice-cutting transport, and also the ability of screens to separate ice cuttings, need examination.

REACTIVITY, MISCIBILITY AND VOLATILITY

DSOs are inert to ice. This has been confirmed by experiments in which ice samples lost no weight over a period of 1 week in contact with KF96-2.0cs (Talalay and Gundestrup, 2002a). In addition, DSOs do not corrode metals (steel, aluminum, zinc, copper, etc.) or other substances.

DSOs are compatible with most plastics and elastomers. Low-molecular DSOs can extract the plasticizers contained in some types of rubber and plastic, and cause weight and volume loss, with some odor. I have carried out experiments which revealed no visible changes in O-rings and gaskets (ethylene-propylene-diene monomer (EPDM) and nitrile rubber (NBR)) after immersion in KF96-2.0cs for a period of 1 week.

DSOs belong to the typical hydrophobic liquids in which the water wets a liquid/air boundary surface to some extent and, after mixing, the water and the liquid form an emulsion. DSOs are insoluble not only in the water but also in the so-called polar solvents (methanol, ethanol, glycol and glycerine). DSOs are perfectly soluble in the non-polar solvents such as hydrocarbons (gasoline, benzene, toluene), chlorinated hydrocarbons, ethers, esters, and higher alcohols from butanol onward.

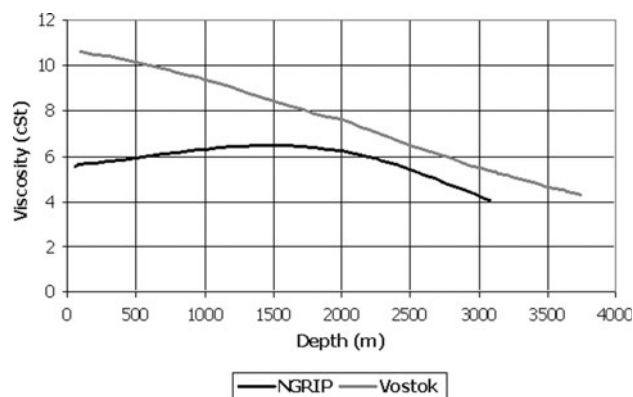


Fig. 5. Viscosity of KF96-2.0cs predicted for the boreholes under temperature and pressure conditions at NorthGRIP and Vostok station (liquid level is at 60 m for NorthGRIP and 100 m for Vostok).

DSOs of the different grades can be easily mixed together; this gives additional options to create a borehole fluid with the required density and viscosity properties by the blending of two available standard grades (US Patent 6942820 issued to T. Ihara and others, 13 September 2005).

Low-molecular DSOs evaporate cleanly. DSOs' use however, does require longer clean-up times than for other borehole fluids. Experiments show that the vaporization rate of KF96-2.0cs is three to four times lower than the rate for solvent Exxsol D60, used as the base fluid at NorthGRIP (Fig. 7). Samples of liquids (10 mL) were poured into a cylindrical glass plate with inner diameter 56 mm (area of free surface 24.6 cm^2) at room temperature (22.5°C). The mass loss of the samples was periodically measured with an accuracy of 0.1 g.

In the field environment it should not be a problem to wait for the complete evaporation of low-molecular DSOs from the ice-core surface. To shorten clean-up time the contaminated surface can be machined away. Additional testing of DSO compatibility with analytical systems should be completed, but the fact that low-molecular DSOs do not form a film suggests that the core can be processed easily and analyzed with mass spectrometry.

ENVIRONMENTAL AND TOXICOLOGICAL PROPERTIES

Over the past several years, safety and environmental criteria have become more important in the selection of a suitable borehole fluid. Although drilling sites may be outside national boundaries, users should follow recognized standards and recommendations to avoid environmental damage and to maintain a healthy and safe working environment.

A first strategy for environmental control was set out in the Declaration of the United Nations Conference on the Human Environment in Stockholm, Sweden, in 1972. This was confirmed by the Antarctic Treaty Protocol on Environmental Protection, which entered into force on 14 January 1998 following ratification by all Antarctic Treaty Consultative Parties. Article 3 of the protocol declared, 'The protection of the Antarctic environment and dependent and associated ecosystems... shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area.' The same environmental requirements were established for the Greenland ice sheet, the

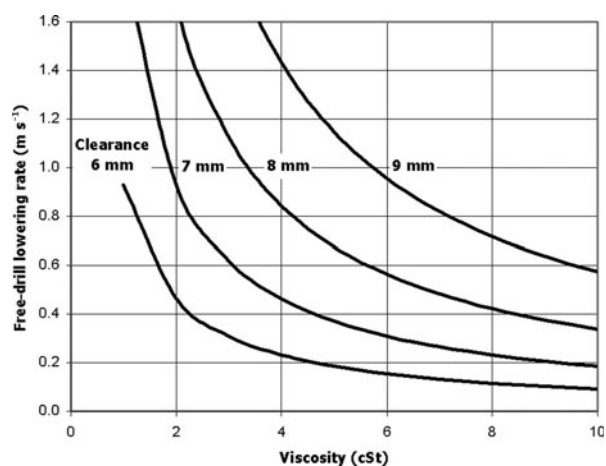


Fig. 6. Free drill lowering rate vs viscosity at different clearances between drill and hole walls.

northern and northeast parts of which form the largest national park in the world, more than 700 000 km² in area.

All the recent borehole fluids and their components (Exxsol D-series solvents, fluorocarbons, *n*-butyl acetate) are high-environmental-risk and/or human-hazardous materials (Talalay and Gundestrup, 2002a). It is difficult to find a chemical that completely meets the technological requirements mentioned above and is harmless to the environment and to human health. Of the millions of existing chemical compounds, the silicone oils are one of the safest and most ecologically friendly materials.

The inertness of DSOs renders these fluids acceptable for use as ingredients in cosmetics, for preventing human skin from chafing and as defoamers for food and beverages. There are no adopted workplace air DSO contaminant levels, specified for a normal 8 hour working day or 40 hour working week, to which all workers may be exposed repeatedly without adverse effect. As a result, there are no recommendations for the control of workplace contaminant concentrations. For example, the US Department of Transportation gives the following certification of DSO health hazards:

Personal protective equipment: Safety goggles.

Symptoms following exposure: Contact of liquid with eyes may cause temporary discomfort. Does not irritate skin. Harmless when ingested.

Treatment of exposure: Except for eye contact, exposures generally do not require treatment. Eyes: flush with water.

TLV-TWA (threshold limit value–time-weighted average): Not listed.

TLV-STEL (TLV–short-term exposure limit): Not listed.

TLV ceiling: Not listed.

Toxicity by ingestion: Currently not available.

Toxicity by inhalation: Currently not available.

Chronic toxicity: None.

Vapor (gas) irritant characteristics: Currently not available.

Liquid or solid characteristics: Currently not available.

Odor threshold: Currently not available.

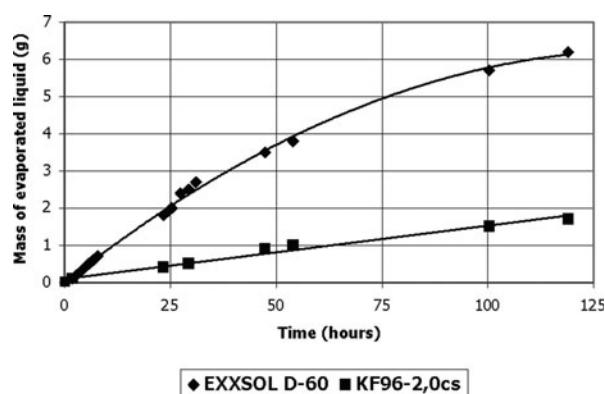


Fig. 7. Vaporization rate of solvent Exxsol D-60 and low-molecular KF96-2.0cs type DSO at room temperature.

IDLH (immediately dangerous to life and health) *value:* Not listed.

OSHA PEL-TWA (US Occupational Safety and Health Administration permissible exposure limits–TWA): Not listed.

OSHA PEL-STEL: Not listed.

OSHA PEL ceiling: Not listed.

EPA AEGL (US Environmental Protection Agency acute exposure guideline): Not listed.

Shin-Etsu Chemical Co., one of the DSOs, manufacturers, notes only one potential hazard to human health: in contact with eyes, low-molecular DSOs cause temporary irritation but without permanent harm.

Nashua Corp. indicates that low-molecular DSOs are a questionable carcinogen with experimental neoplastigenic data, and that repeated skin contact may lead to development of dermatitis (Gerasimoff, 2003). There is little documentary evidence of the effect of DSOs on the environment. When low-molecular DSOs are discharged in large quantities, aquatic life may be harmed. For bluegill and rainbow trout species, the LC50 (exposure level used in toxicology as a lethal concentration (LC), with the death of 50% of an entire defined experimental animal population) is 10 g L⁻¹.

Ordinary industrial hygiene and satisfactory environmental protection (ventilation of working areas, safety goggles, protection of the open skin, proper organization of the system for fluid storage and dumping, etc.) should easily solve all safety and ecological problems.

COST

The final choice of the borehole fluid depends on the rational correlation between its cost and other properties. Of the recent and potential borehole fluids, *n*-butyl acetate is the least expensive (Table 5) and this was one of the main considerations behind its use by US specialists at GISP2 and by Japanese drillers at Dome Fuji in spite of rather high health hazards.

Several researchers are mistaken about the cost of low-molecular DSOs. Gerasimoff (2003) remarked that one of the main disadvantages of using silicone oils is that 'they are very expensive'. However, the cost of low-molecular DSOs is comparable with the cost of other recent and potential borehole fluids. Whereas the cost of the densifier

Table 5. Cost of recent and potential borehole fluids

Type of borehole fluid	Approximate price US\$ L ⁻¹
Exxsol D-60 + 32% HCFC 141b	~12
<i>n</i> -butyl acetate	0.8
Isopar-K + 25% HFE-7100	14.5
Lusolvan FBH	3.6
Haltermann ESTISOL 240 + Haltermann COASOL	~25
KF96-2.0cs	6.5

HCFC-141b has jumped several times during the last few years because of limited stocks, the cost of low-molecular DSOs has decreased over time. For example, the cost of KF96-1.5cs was about US\$36 L⁻¹ in 1993 and about US\$6.5 L⁻¹ 13 years later.

CONCLUSIONS

The properties of low-molecular DSOs satisfy all the criteria for use as a deep ice-drilling borehole fluid. DSOs are therefore a very promising candidate for future deep ice-coring operations. The advantages are:

The density of DSOs is right for the compensation of the ice-overburden pressure, and the viscosity is suitable for the output of pumps and for the performance of drill-lowering/hoisting operations.

DSOs are inert to ice, metals and most plastics and elastomers, and have satisfactory volatile properties.

They have no odor and have low toxicity. DSOs are easy to handle, and only the usual commonsense protection is required in the working environment.

Low-molecular DSOs have never been used in ice-core drilling projects. Therefore, any final conclusion as to their suitability for ice deep drilling can only be made after field experiments and after a test borehole has been drilled.

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