



# Physicochemical properties of potential low-temperature drilling fluids for deep ice core drilling

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## ABSTRACT

Drilling fluids are added to deep ice boreholes to facilitate control pressure and remove chips. The drilling fluids currently in use are not intelligent choices for the future from safety, environmental, and technological standpoints. Two potential fluid types, namely, low-molecular weight dimethylsiloxane oils (DSOs) and low-molecular-weight fatty-acid esters (FAEs), were suggested to replace the drilling fluids currently in use. For this study, six types of liquids (DSO-3,0cs, KF96-2,0cs, ethyl butyrate, *n*-propyl propionate, *n*-butyl butyrate, and *n*-amyl butyrate) were selected because of their appropriate density-viscosity properties. These liquids were tested for properties such as electrical conductivity, thermal conductivity, and compatibility with plastics. The results indicated that the electrical conductivities of all the liquids were very small ( $<0.003 \mu\text{S}/\text{cm}$ ), and an electric field applied in the electromechanical drills was not sufficient to ionize the liquid. The thermal conductivities of all the tested liquids were considerably less than that of water. However, *n*-propyl propionate indicated the best performance in terms of the cooling ability at subzero temperatures. The effect of FAEs on O-rings swelling was stronger than that of the DSOs. The potential drilling fluids had absolutely no influence on polytetrafluoroethylene (PTFE) O-rings; hence, they could be considered as the ideal sealing material. Tests indicated that low-molecular-weight DSOs and FAEs were both applicable as drilling fluids for deep ice core drilling. It is suggested that the final decision should be confirmed by field-based and practical experiments in test boreholes.

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## 1. Introduction

Drilling fluid is one of the main components of deep ice core drilling technology. There are two basic functions of a drilling fluid (Talalay et al., 2014a). First, the presence of a density-balanced fluid in the hole prevents the hole from closing because of Newtonian-plastic deformations. Second, the circulation of the fluid in the borehole provides a mechanism for the transportation of cuttings from the drill head to the downhole chamber or to the surface. Past studies indicate several choices of low-temperature drilling fluids such as kerosene-based fluids, ethanol and *n*-butyl acetate. However, not all these fluids qualify as intelligent choices from the perspectives of safety, environment, and technology (Talalay et al., 2014b). Therefore, the selection of an appropriate drilling fluid for coring in deep ice is a pressing problem for future drilling projects.

Recently, aliphatic synthetic ester ESTISOL™ 140 was introduced as a good alternative to existing drilling fluids (Sheldon et al., 2014; Talalay et al., 2014b). ESTISOL™ 140 has appropriate density-viscosity properties and is not considered as hazardous. Over the last few years,

ESTISOL™ 140 was used at NEEM, Greenland (2012); Aurora Basin North, East Antarctica (2013–14); Summit, Greenland (2014); Renland Ice Cap, Greenland (2015); and more recently at the South Pole (2014–15 and 2015–16 seasons). Generally, ESTISOL™ 140 was as an acceptable drill liquid that consistently produced good quality ice cores. However, tests in Greenland conducted by researchers from the University of Wisconsin, Madison in the summer of 2014 revealed that the drilling fluid released strong vapors even at subzero temperatures. Furthermore, the drilling fluid had toxic and irritant effects (J. Johnson, pers. comm., 2014). The side effects experienced by personnel during drilling included headaches, lightheadedness, throat/lung irritation, eye irritation, skin dryness, and mild stomach aches. Similar toxic and irritant effects of ESTISOL™ 140 on drilling personnel were recorded at the South Pole (T. Kuhl, pers. comm., 2015).

Therefore, the identification of a non-toxic, non-flammable, density appropriate, hydrophobic, inexpensive, environmentally friendly, and readily available fluid with predictable performance characteristics is still a major challenge of the ice core drilling technology. Talalay (2007) and Xu et al. (2014) discussed two potential fluid types, namely low-molecular-weight dimethylsiloxane oils (DSOs) and low-molecular-weight fatty-acid esters (FAEs) in considerable detail. However, the final decision on the application of these fluids for ice core

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drilling depended on conducting additional lab tests and field experiments in a test borehole.

DSOs are clear, colorless, tasteless, odorless, hydrophobic, and essentially inert liquids that are stable in contact with water, air, oxygen, metals, wood, paper, and plastics. Although there are several DSOs, the low-viscosity grades ( $<5 \text{ mm}^2 \text{ s}^{-1}$ ) of silicones (e.g., KF96–1,5cs and KF96–2,0cs) are the closest match to the requirements for a drilling fluid (Triest and Alemany, 2014). Some of DSOs, namely PMX200 from Dow Xiameter, have exposure limits; however, most of DSOs have no specifications on the air contamination levels. Thus, there are no recommendations for the control of workplace contamination concentrations. Shin-Etsu Chemical Co., a DSOs manufacturer, reported on the potential hazard of DSOs to human health. Eye contact with low-molecular DSOs led to temporary irritations. However, no permanent harm to eyes was reported.

FAEs are another example of promising low-temperature drilling fluids. They are typically fragrant. FAEs with a sufficiently low molecular weight have appropriate volatility for application in fragrances. FAEs are often part of “essential oils” and pheromones. The chemically synthesized FAEs have found commercial applications in artificial flavorings, because they resemble certain flavorings (for example orange or pineapple juice) and within certain limitations are harmless to the human body if ingested. The following five non-HAP (i.e., not listed as hazardous air pollutants), low-molecular-weight FAEs could be considered for use as low-temperature drilling fluids for deep ice coring: ethyl butyrate, *n*-propyl propionate, *n*-butyl butyrate, *n*-amyl butyrate, and hexyl acetate. According to the available data, these FAEs are not hazardous to human health.

The density-viscosity tests (Talalay, 2007; Triest and Alemany, 2014; Xu et al., 2014) demonstrated that only a small number of DSOs and FAEs meet the ice-drilling requirements. Furthermore, some of the physicochemical properties of these liquids were unknown and require further clarification before conducting practical experiments in the test boreholes. The drilling fluid was required to exhibit low electrical conductivity in order to avoid interference with the operation of non-sealed electrical and electronic components such as slip rings, contacts, electric sensors, and motors. The drilling fluid should be non-aggressive to the drill components. This is especially applicable as O-rings and gaskets can swell, soften, or become tacky in fluid. Additionally, the thermal conductivity of the drilling fluid could influence the drilling process. For example, in “warm ice” (Augustin et al., 2007), liquids with high thermal conductivities could absorb the cutting heat produced by the drill head and improve drilling performance. This paper investigated electrical conductivities, thermal conductivities, and effect on plastics of DSOs and FAEs.

## 2. Electrical conductivity

Most ice core electromechanical drills have a number of non-sealed electrical and electronic components that considerably increase the ease of design and service. Many of the drill electronic sensors are designed to work directly in non-conductive or very poorly conductive drilling fluids. For example, drilling load is usually measured with simple linear displacement sensors located in the cable termination of the drills. Driven motors of some of the drills (e.g., KEMS drill) are not hidden in the pressure chamber and are immersed into the drilling fluid. Not all downhole electric connectors for signal and power communication appropriate for use in conductive fluids. Evidently, the electric conductivity of the drilling fluid can influence the operation capacity of the downhole drill components.

The electrical conductivity of fluid depends upon the number of ions per unit volume and the drift velocities of the ions. The drift velocity of an ion varies with the electric field intensity, the mass of the ion, and other factors. Thus, the electrical conductivities of different fluids can have a range of values. Electric conductivity is a factor of temperature,

and this affects ion mobility. In this regard, the conductivity of fluids generally decreases as temperature decreases.

According to the US National Fire Protection Association “Recommended Practice on Static Electricity” (NFPA 77, 2014), liquids having conductivities  $>10^{-4} \mu\text{S/cm}$  are classified as conductive. Liquids with conductivity  $<10^{-6} \mu\text{S/cm}$  are generally considered to be non-conductive. Liquids having conductivities between these values are classified as medium-conductive.

Kerosenes that were mostly used as bases of low-temperature drilling fluids in the past are medium-conductive liquids with conductivities of  $\sim 3 \times 10^{-6} \mu\text{S/cm}$  (Dey, 2004). Even conductive liquids like *n*-butyl acetate ( $0.02 \mu\text{S/cm}$  at room temperature; Flammability: A safety guide for users, 2013) were successfully used as drilling fluids because the electric fields in the drills were considerably small and, therefore, could not ionize the liquid. Thus, conductive liquids could also be used as drilling fluids up to a certain safety threshold. The estimation of the threshold requires additional tests on the applied electric field, temperature, impurities, and other factors. Water-based liquids (e.g., aqueous ethanol solutions) with conductivities  $>50\text{--}100 \mu\text{S/cm}$  cannot be used as drilling fluids with drills containing non-sealed electric components.

This study measured the electrical conductivities of six selected drilling fluid types (DSO-3,0cs produced at Shanghai Kaiping Resin Factory; KF96-2,0cs produced by Shin-Etsu Chemical Co.; ethyl butyrate, *n*-propyl propionate, *n*-butyl butyrate, and *n*-amyl butyrate) in a temperature range from  $-60^\circ\text{C}$  to  $0^\circ\text{C}$  with intervals of  $5^\circ\text{C}$ . General properties of selected fluids are listed in Table 1. Leici tester DDSJ-308F that could measure the conductivities of different mediums in the range of  $0.001\text{--}199.9 \mu\text{S/cm}$  with an error of  $\pm 0.5\%$  (Fig. 1) was used. A conductivity electrode DJS-0.01C with a narrower measuring range of  $0.001\text{--}2.0 \mu\text{S/cm}$  was used for the testing. The tested liquid was poured into the cup of a low-temperature thermostat of DC-6506 type produced by Fangrui Instrument Co Ltd., Shanghai. At subzero temperatures, the electric conductivities of all fluids were less than the tester sensitivity ( $10^{-3} \mu\text{S/cm}$ ). At positive temperatures ( $25^\circ\text{C}$ ), the electrical conductivities of only two liquids, namely ethyl butyrate and *n*-propyl propionate, were recorded as  $0.003 \mu\text{S/cm}$  and  $0.002 \mu\text{S/cm}$ , respectively.

Then, the electrical conductivity of the drilling fluid/ice-chips mixture was tested. The mixture was considered as a homogeneous fluid with mean physical properties that correctly characterized the real solid/liquid suspension. Ice chips were prepared by cooling water drops with an average volume of  $10\text{--}20 \text{ mm}^3$  in the drilling fluid to a temperature of  $-60^\circ\text{C}$  in a freezing chamber. Two sets of experiments were carried out with different concentration of ice chips. The experiment involved adding  $16 \text{ cm}^3$  and  $48 \text{ cm}^3$  of ice that was made into chips to  $350 \text{ ml}$  of the fluid, attaining ice volumetric contents of  $4.6\%$  and  $13.7\%$ , respectively. Then, the electrical conductivities of the drilling-fluid/ice-chips mixtures were measured in a temperature ranging from  $-60^\circ\text{C}$  to  $0^\circ\text{C}$  (Fig. 2).

At temperatures less than  $-15^\circ\text{C}$ , conductivities of all tested drilling-fluid/ice-chips mixtures were less than the sensitivity of the tester and were not affected by the ice content. At the temperature range from  $-15^\circ\text{C}$  to  $-5^\circ\text{C}$ , the electrical conductivities were potentially recorded because a liquid layer was developed on the surface of the ice chips and along the crystal boundaries. Temperature increases led to changes in the grain boundaries. The grain boundaries increased in width, were more disordered, and the amount of liquid water contained in the grain boundaries increased with an increase in temperature (Cuffey and Patterson, 2010). As a result, the electrical conductivities began to increase at a temperature of  $-5^\circ\text{C}$  and the electrical conductivities experienced a sharp jump at the phase-transition temperature ( $0^\circ\text{C}$ ).

The electrical conductivities of the DSO/ice-chips mixtures exceeded the electrical conductivities of the FAE/ice-chips mixtures. At  $0^\circ\text{C}$  and  $4.6\%$  ice content, the electrical conductivity of DSO-3,0cs was the

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