A Case for n-Butyl Acetate
a
Safe, Auto-Dense Ice Core Drilling Fluid

Thomas A. Gosink, Ph.D.
Research Associate, UAF
Environmental Analytical Chemist

Mark A. Tumeo, P.E., Ph.D.
Assistant Professor, UAF
Civil and Environmental Quality Engineering

Bruce R. Koci
PICO Senior Engineer

and
Tyler W. Burton
PICO Drill Technician

POLAR ICE CORING OFFICE (PICO)*
University of Alaska
Fairbanks, Alaska 99775

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PREFACE

The Polar Ice Coring Office's contractual obligations to develop a deep ice coring capability, including operations in a fluid-filled hole, necessitated an investigation of available fluids which meet various technical constraints and have low risk to the environment and human health. An initial literature search was conducted (PICO-TR-89-2, 1989) which yielded eleven fluids, of which two (butyl acetate and anisole) seemed to meet the desired conditions for a safe and technically acceptable drilling fluid.

A follow-up study was conducted on butyl acetate and anisole to investigate in as much detail as possible the applicability of these fluids in the deep ice coring process.

John J. Kelley
Director

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INTRODUCTION

Because of the potential health, safety and environmental risks associated with the use of compounds currently used as drilling fluids, the Polar Ice Coring Office (PICO) conducted a chemical literature survey in an effort to identify a drilling fluid with the necessary viscosity and density characteristics that would minimize health and safety risks for workers, cause minimal environmental impact, and not compromise the scientific integrity of the ice core sample. The results were published in a PICO Technical Report 89-2 (Gosink, 1989— PICO TR 89-2). Of nearly 250,000 compounds electronically surveyed, 11† potential drilling fluids were identified. Of these eleven, only two fully meet the constraints imposed by technical, scientific, health, safety and environmental concerns. This report briefly reviews the past report, and presents the case for butyl acetate, and to a lesser extent for anisole.

Recent practice has been to use various types of fuel oils as the drill fluid, with a densifier such as PER (perchloroethylene) or TCE (trichloroethylene). The drill fluid projected for use during the the 1990 drilling season at the GISP-2‡ site is "permoil," or "bromoil"*, a dilute solution of PBBE (polybrominated biphenyl ether) in a more refined hydrocarbon known as LVT-200.** It should be noted that bromoil was developed for *high temperature* well boring, and not low temperature ice coring. LVT-200 appears, by gas chromatography-mass spectrometry, to be a mixture of saturated branch chain compounds. The selection of LVT-200 is indeed a laudable improvement over fuel oils with the latter's aromatic components. However, LVT-200 still is not dense enough, and its viscosity far too high to meet earlier specifications (e.g. PICO TR 89-2). Furthermore, the planned use of PBBE as the densifier is less acceptable than the use of PER or TCE, all of which are hazardous to health and the environment.

PER and TCE pose significant health safety and environmental risks. PER and TCE have known and suspected carcinogenic properties (PICO TR 89-2 and references therein), and add to the already undesirable load of atmospheric organic chlorides. PBBE is a viscous semi-solid material (Brackenridge and McKinzie, 1988), and is on the Environmental Protection Agency's (EPA) list of "Extremely Hazardous Substances" and falls under the EPA's "Community Right to Know" as promulgated under the Superfund Amendments and Reauthorization Act (SARA) Title III (Sax and Lewis, 1989). Moreover, the brominated components are resistant to biodegradation as are DDT, PCB (polychlorinated biphenyl) and PBB (polybrominated biphenyls), all of which have been shown to concentrate in the food chain, and to have deleterious long-term effects on the health of individuals who have been exposed to relatively low levels (e.g. Watanabe et al., 1987, Mulligan et. al., 1980, Sundström and Hutzinger, 1976) and are potent inducers of xenobiotic metabolism (Carlson, 1980 a, b).

This report discusses the chemical and physical characteristics of butyl acetate and anisole with respect to their use as a drilling fluid, and presents some important technical considerations with respect to health, safety and the environment surrounding the use of these compounds. The report shows that butyl acetate alone is dense enough at lower temperatures (-20 to -78°C) to meet the desired specifications (PICO TR 89-2). Moreover

† The eleven candidates were: anisole, 1-hexanol, 1-heptanol, 2-octanol, p-cymene, s-butyl benzene, pseudocumene, propyl, butyl and amyl acetates and propyl proprionate.

‡ GISP— Greenland Ice Sheet Project, University of New Hampshire, Durham.

* "Bromoil," a trade name of OSCA, Lafayette, La.; a mixture of LVT-200 and PBBE.

** "LVT-200," a CONOCO acronym/trade name.

the viscosity of butyl acetate (or 10% anisole in butyl acetate) at lower temperatures is well below the desired upper limit, and far below that of LVT-200 or bromoil. In addition, the cost is considerably lower than bromoil. Both butyl acetate and anisole are totally synthetic, i.e. derived from petroleum products, thus presenting no carbon-14 complications.

From an environmental aspect, butyl acetate (and anisole) is a single, easily biodegradable compound as opposed to the mixture of components in fuel oil, LVT-200 or PBBE. The various properties of butyl acetate are shown in Table 1, in the same format as our earlier report. Anisole's properties were tabulated in our prior report (PICO TR 89-2).* The chemical structures of butyl acetate and anisole are shown in Figure 1.

The reason some of the other potential fluids, such as higher molecular weight alcohols (PICO TR 89-2) are not recommended is that their viscosities exceed 5 cp at at temperature ≤0°C. For example, the viscosity of butyl alcohol is 5.2 cp at 0°C; 36 cp at -50°C. Octyl alcohol is 10.6 cp at 15°C. Likewise, AMSOIL's offer of a lubricating ester (A-1312) of unknown structure has a viscosity over 500 cp at -40°C. The alkyl aromatics were rejected for cost and various safety considerations. Recommendation of butyl actate is also based on the facts that even numbered carbon chains (e.g. butyl—4) are less toxic (narcotic) than the odd numbered (e.g. propyl—3 or amyl—5), and it is more readily available. This leaves only n-butyl acetate and anisole on the list of potential drill fluids.

The Case for Butyl Acetate

CHEMICAL/PHYSICAL CHARACTERISTICS

DENSITY

The hydrostatic pressure, which is a function of density and depth, is of major importance in the selection of ice core drilling fluids. There is a pressure sensor on the drill string, the depth is known, and thus drill fluid is added to maintain an adequate pressure for the depth, assuming an ice density of 0.920. The density of butyl acetate rapidly increases with decreasing temperature (see Figures 2a, b).†‡ The density of butyl acetate at temperatures below -15°C alone is sufficient, being greater than the firn-ice-layer density of 0.90 (Patterson, 1981). At -30°C the density of butyl acetate is the same as 0.91 density bromoil (Figure 2a) both of which are then more dense than pure ice (Ashton, 1986). Glacier ice with its occluded air is always slightly less dense than pure ice. A 10% mixture of anisole in butyl acetate is as dense as pure ice at -15°C, and essentially as dense as 0.91 bromoil (Figure 2a), with a similar slope, and is more dense (desirable) at very cold temperatures.** Typically, in other deep cores, the top of the fluid level is about 100 meters below the ice surface to balance the ice matrix pressure. Given an average bore hole temperature of -20°C, butyl acetate will *not* require any dense fluid additive to maintain the desired pressure in the lower portions of the bore hole. Since the average internal temperature in the Greenland glaciers has been observed to be -31°C, and is expected to be significantly colder in Antarctica, an

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* Anisole: Yellow liquid with a sweet anise-like odor. Used in perfumery, and as solvent in a variety of other uses. Oral LD_{50}– 3700 mg/kg (in rats); skin 500mg/24hr (moderate irritation in rabbits).

† Viscosity data acquired with a falling ball type viscometer. Centistokes (cs) and centipoise (cp) differ by the density factor according to the equation $cp = cs \times den$.

‡ The density of amyl acetate (not shown in Fig. 1) is slightly less than butyl acetate, and does not become as dense as the latter at very low temperatures.

** Anisole solidifies at -38°C. No crystals were observed in the 10% anisole in butyl acetate mixture at -49°C. Likewise, the semi-solid PBBE did not come out of solution at -48°C in 0.91 permoil.

added densifier definitely will *not* be required. If a densifier is required for more temperate glacier drilling operations, anisole is much more desirable than PCE, TCE or bromoil, with respect to water pollution, human toxicity and air pollution.

VISCOSITY

The viscosity of the fluid is very important to the travel time of the drill string, particularly at greater depths, and thus to the overall cost of the project. Either a low viscosity fluid must be employed, or alternatively, larger diameter (more expenditure of time and energy) holes must be bored to accommodate the high viscosity fluids such as bromoil. Figure 3 shows the effect of drill fluid viscosity on velocity of the fall of the 1250 lb drill string. At 10 cp it is about 4 seconds per meter; at 2 cp about 1 second per meter, thus butyl acetate will cut this major portion of the operation time by a factor of 4 compared to other dense fluids. The time savings is eight times compared to bromoil with a viscosity of ca. 15 cp at the observed average internal glacier temperature of -31°C. Figure 4 shows the round trip time for the drill string going to 1000 m depth. It is calculated to be about 10 minutes with butyl acetate, but nearly an hour and a half with bromoil with its viscosity of about 15 cp at -30°C. Depths of 3000 meters are anticipated.

The original specifications (PICO 89-2) of the drill fluid were that the viscosity be less than 5 cs (nearly 5 cp— see footnote p. 2). As can be seen in Figures 5a, b, the viscosity of butyl acetate (and the 10% anisole mixture) remains well below 3 cp, even at -50°C, whereas the viscosity of 0.91 bromoil is substantially above 10 cp at anticipated ice temperatures. With the exception of the three points labeled "Lit.," all of the data in Figure 5 were determined in this laboratory. The viscosity reported by CONOCO for LVT-200 at -40°C is shown in Figure 5a, and fits well with our experimental data. It can also be seen that the addition of a small quantity of PBBE to LVT-200 in the formulation of bromoil raises the viscosity even higher.

VOLATILITY/FLAMMABILITY

The greater volatility of butyl acetate raises fire safety questions, but it is unlikely that under the conditions experienced in ice-core work that this will be a problem. In Figure 6 the handbook vapor pressure of s-butyl acetate is plotted against temperature. The curve for n-butyl acetate is reasonably estimated from the fact that the boiling point of the n-butyl isomer is 2% higher, on the absolute temperature scale, than that of the s-butyl isomer. The published safety sheets state that the lower flame limit concentration of n-butyl acetate in air is 1.7%. This corresponds to a vapor pressure of 12.9 mm Hg, achievable only in an unventilated closed room or container at 24°C (75°F). It is doubtful that the air temperature even in the living quarters at the drill site will reach 24°C. At -20°C (-4°F), an average to cool day on the drill site, the maximum possible air concentration of butyl acetate in an unventilated area would be approximately 1300 ppm (0.13%), well below the lowest published (1988-89 CRC handbook) lower flame limit of 1.4% (Figure 6). Figure 6 further indicates that at the higher altitudes where the drilling operation will occur, the lower flame limit is still in the +15 to 18°C range.† The warmest part of the drill site days, according to temperature records from past sites, gets to be about 0°C. Odor detection and irritation both occur below the permissible exposure limit (150 ppm), and thus provide both adequate physiological and fire warning properties.‡

† Calculated on an air pressure at 2300 m altitude (7000 ft) of 575 mm Hg.

‡ There is confusion in the technical literature on the flash point of butyl acetate. *(cont'd next page)*

This theory was tested by applying a lit paper match to a small beaker of butyl acetate at laboratory temperature (ca 24°C). The butyl acetate ignited *only* by briefly touching the flame to the surface, but it went out as the match was immediately withdrawn. The same beaker of wet butyl acetate was placed outside for a few minutes where the temperature was approximately 4°C. The butyl acetate would not ignite, and in fact, extinguished the match. The experiment was repeated with fresh dry butyl acetate when the air temperature was about 1°C. Again there was a slight flare as the glowing match head touched the surface, but all of the flame was extinguished as the match was plunged below the liquid surface.

Side benefits of the greater volatility of butyl acetate are:

1) No residual odor or oily residue will remain on work-clothes between shifts (see Figure 7.);

2) The probable elimination of problems in the "slime" and the science pits in that (a) the residual solvent is not expected to pose serious emulsion problems (to be tested this winter) since it will evaporate in hours even at -20°C (Figure 7); (b) the core will be much less "greasy" to handle and (c) cleaning of the chips in the screen is expected to be easier with only a small fraction of the chips having to be melted in order to free them of the associated butyl acetate;

3) The existing drill fluids pose another safety hazard by causing the drillers deck to become very slippery. Butyl acetate, with its lower viscosity and higher volatility should pose less of a hazard.

SOLUBILITY

Several experiments in which a 20 gram cube of ice was placed in a covered beaker with about 100 ml of solvent. The published solubility of butyl acetate in water (Table 1) is about an order of magnitude lower than ethyl acetate, and is essentially the same as that for PER, about 0.7%, and the solubility of water in butyl acetate, 1.6%. Note that the weight loss of ice in *wet* butyl acetate was not noticeable in seven hours contact time. It has been reported that Soviet drillers have utilized alcohol at their drill sites. However, experiments show that pure alcohol causes a rapid solution of the ice (Figure 8). No attempt was made to study 50% ethanol-water mixtures because even if there were no appreciable weight loss, it is anticipated that the water exchange would be unacceptable.

SOLVENT EFFECT ON POLYMERS

The effect of butyl acetate and several other solvents on a variety of polymers is shown in Table 2. Both butyl acetate and anisole have no effect on the various polymeric materials employed in the drill string. The wires in the electric motor, even at temperatures of 125°C, were not affected by either butyl acetate or the 10% mixture of anisole. Furthermore, the tensile strength of the cable is not affected by butyl acetate. This is according to a recent report from the manufacturer, Cortland Cable Co. (Koci, personal communication, 10/89)

COST AND AVAILABILITY

The carload cost of butyl acetate East of the Rockies is 43¢/lb (about $3.16/gal). For 98% purity material in 55 gallon drums, a price was quoted by Eastman-Kodak as 53¢/lb, delivered. Thus the cost for 20,000 gallons delivered in 55 gallon drums to the East coast

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(cont'd from previous page) Sax and Lewis (1989) report 72°F; 92°F on a bottle of high quality butyl acetate, suggesting a common error of "7" for a "9," and the Merck Index (1976) quotes 38°C (100°F). Determination of the flash point by a local independent testing laboratory indicated 85°F (29.4°C), in keeping with our observations *(vide supra)*.

port of choice would be $77,900, a savings of over $60,000 on the projected cost of bromoil (in addition to the real dollar savings in time— p. 3).

A recent analysis of a grade ≥99.5% of butyl acetate indicated contaminant concentrations of: <0.01% water, 0.07% butanol and 0.01% acetic acid. An analysis based on a 1:1 water extraction was reported as: chloride, <0.5 ppm; sulfate <0.1 ppm, i.e. below the routine detection limits of the analyzer.*

The cost of anisole is estimated to be $2+/kg (ca. $8/gal) in 55 gal drums. Distributor costs for one drum are high: $9.20/kg, or about $35/gal. Eastman has an excess inventory now (Oct/89) and said they would sell PICO abut 3000 lb at $1/lb. However, it is again emphasized that the addition of a densifier will *not* be required.

MANUFACTURERS/ SUPPLIERS

Eastman Chemical Products, Inc., Kingsport, TN (800) 377 8626

Union Carbide, Longbeach, CA (213) 493 6573

BASF, Newark, NJ (201) 316 4703

Hoechst Celanese, Corpus Christi, TX (214) 689 4000

SAFETY AND HEALTH CONCERNS

Indoor Ambient Air Quality

Butyl acetate odors are detectable at 10 ppm. At approximately 100 ppm ambient concentration, some nasal irritation may be noticed. This is well below the Occupational Health and Safety Administration's (OSHA) limit of 150 ppm (710 mg/m^{-3}). Therefore, before any significant health hazard would be present, odors would be noticeable and irritating.

Potential problems of excessive butyl acetate concentrations in the air can be eliminated by proper design and use of ventilation systems in the drill enclosure, relaxation pit and science trench. Fans to keep the interior of the science hut cold are already part of the design. It is further recommended that small, battery operated gas detectors be placed in each segment (drill enclosure, relaxation pit, and science trench) which would sound an alarm should an ambient concentration of 100 ppm be exceeded. Several such inexpensive alarms are available on the market. Additionally, PICO should develop plans of action in the event of excessive vapors being detected, spills, fire, or other emergencies.

Anisole odors are detectable at 0.2 ppm, but no OSHA standards have been set. Given that anisole, if used, will be used in such low amounts, no special precautions will be necessary above those which should be instituted for butyl acetate.

Health Hazards

Butyl acetate has an NFPA code of blue, which designates a compound that is slightly hazardous to health. The compound has been shown to be a mammalian reproductive toxin. The main risk comes from inhaling vapors in excessive concentrations. Therefore, the precautions discussed in the ambient air quality section (detectors, proper ventilation) should be sufficient to protect the health of workers. Special attention must be paid to ventilation for areas that may be lower than the drill enclosure area. Since butyl acetate fumes are heavier than air (den.=4.0), the fumes will tend to flow towards the lowest area and accumulate. Significant increases in butyl acetate vapors may occur indoors of scientific areas if ventilation is not adequate.

Anisole has no specified health hazards and is not a mammalian reproductive toxin. Neither butyl acetate nor anisole is listed as a carcinogen.

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* No data is available on the residual trace inorganic pollutants in fluids such as fuel oil, LVT-200 or PBBE etc.

During drilling operations, workers' clothing may become soaked with the drilling fluid. Such soaking does not represent a significant health hazard if: 1) exposure is not prolonged and 2) the worker does not have to go outside before removing soaked clothing. Due to the relatively high volatility of butyl acetate, workers should not venture out into cold and/or wind with the substance on their skin. The cooling effect of evaporation could result in rapid frostbite or other cold-related complications. For this reason, it is strongly recommended that a shower area be provided immediately off the drill enclosure area, which could be used by workers who become soaked with drilling fluid. It should be standard operating procedure for drill operators to change into and out of work clothes in the shower area. The shower area must be heated to some extent, have an area for the airing and drying of soaked clothing, provide storage area for workers' clothes, and must be properly ventilated.

Fire Hazards

The volatility and relatively high vapor pressure of butyl acetate does necessitate that proper precautions be taken to avoid fire hazards in heated areas. As temperatures should be relatively low inside the buildings where butyl acetate is present, fire hazards should be reduced. The ventilation and ambient air quality protection measures discussed above will also greatly further reduce the risk of any potential fire hazard. Since it is current policy to prohibit smoking in the drill enclosure, relaxation pit, and science trench, fire hazards from accidental ignition will be minimal. (Recall the earlier flammability discussion on pp. 3 and 4.) Prudence warrants the recommendation that a portable fire extinguisher be located by each exit in the drill enclosure in case of an emergency. A common ABC dry chemical extinguisher is recommended.

ENVIRONMENTAL CHARACTERISTICS

Both fuel oils and LVT-200 pose higher environmental risks since, in the event of a spill (or the long-term eventual release of residual material left in the glacier), they have a long residence time, particularly in a cold environment (Figure 7). In a worst case scenario, if all the butyl acetate leaked out the bottom and flowed into a fjord, most it should evaporate in 1 to 3 days. An additional small amount would disperse in the water column, where it would be rapidly biodegraded. Butyl acetate will, contrary to all the other fluids proposed or in use, totally clean itself up in a matter of days, even in a cold climate. Anisole would behave similarly. LVT-200, on the other hand, is not readily biodegradable, and would not evaporate appreciably, not even as well as fuel oil (Figure 7). A portion of LVT-200 is not expected to disperse in the water column as would fuel oil because of the lack of the aromatic fraction, which is advantageous. Thus, virtually *all* of it would have to be physically removed from the water surface, *particularly* in view of the toxic densifier materials, whether it be PBBE or TCE etc.

Anisole is not as biodegradable as butyl acetate, but should not have an extremely high environmental residence time. If the use of a densifier is required in temperate glaciers (average internal temperature $\geq$-20°C), anisole should be acceptable in comparison to other commonly used densifiers from an environmental standpoint.

SUMMARY/CONCLUSIONS

A comparison of butyl acetate to presently used drilling fluids reveals that in all areas of technical importance (density, viscosity, solubility and reactivity), butyl acetate performs as well or better than fuel oil, bromoil, or LVT-200. Other potential drilling fluids such as higher molecular weight alcohols (PICO TR 89-2) are not recommended because their viscosities exceed 5 cp at 0°C. Amyl acetate, propyl propionate and other longer odd numbered chain hydrocarbons tend to be more toxic than butyl acetate, and are typically less available. Amyl acetate is also slightly less dense than butyl acetate and does not become as dense at very low temperatures.

Butyl acetate represents a significantly lower risk to the environment than bromoil, LVT-200, or fuel oil. Both fuel oil and LVT-200 are resistant to environmental degradation and subsequently have long residence times in the environment. Persistence of these compounds is increased in cold temperatures. In the event of a spill, or in the inevitable long- term release of residual material left in the glacier, the persistence of these compounds will represent a grave environmental hazard. In contrast, butyl acetate is relatively easily degraded in the environment. Any unexpected releases or spills should evaporate quickly and present little environmental or safety hazard. The fire hazard of butyl acetate is very low at temperatures below about 0 to 10°C and thus does not pose any inordinate danger.

Commonly used densifiers are of even more environmental concern. Brominated biphenyl ether is on the EPA's list of "extremely hazardous substances". Chemically similar compounds such as DDT, PCB (polychlorinated biphenyl) and PBB (polybrominated biphenyl) have been shown to concentrate in the food chain and are highly resistant to biodegradation. PER and TCE pose significant health, safety and environmental risks. They have known and suspected carcinogenic properties, are relatively toxic (TR 89-2 and references therein), and add to the already undesirable load of atmospheric organic chlorides. Butyl acetate is more than dense enough at temperatures $\leq$-20°C so that the addition of a dense fluid should *not* be required.

RECOMMENDATIONS

The following actions are recommended with regards to the GISP-2 project:

1) Butyl acetate alone be used as the drilling fluid;

2) Special attention must be paid to the design of the drilling enclosure, relaxation pit, and science trench to provide proper ventilation;

3) A shower and change room facility should be provided immediately off the drill enclosure;

4) Small, battery operated gas detectors should be located in every segment of the drill/science trench area;

5) Portable, dry chemical fire extinguishers should be located at each exit of the drill enclosure area. Fire blankets should be located in heated areas;

6) PICO should develope and circulate an emergency plan in case of spills, fire, injury and other emergencies.

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Table 1. **Properties of n-Butyl Acetate**

Name of Compound:	n-Butyl Acetate
Synonyms:	1-Butyl Acetate, or Butyl Ethanoate, or Acetic acid, Butyl Ester or simply Butyl Acetate.
CAS Number:	123-86-4
Reg. Toxic Number:	AF7350000
Chemical Formula:	$C_6H_{12}O_2$
General Description:	Colorless liquid with a fruity odor.
Solubility (water):	0.68 g/100g H_2O
Freezing Point:	-78°C
Spec. Gravity:	0.882g/cc at 20°C; $\geq$0.92 at $\leq$-20°C (See Figures 2a, b)
	vapor density: 4.0
CERCLA Hazard Ratings:	
Toxicity	1
Ignitability	3 (Flash Point: ca. 30°C) (see text and footnote p.3)
Persistence	0
Toxicology:	
Permissible Exposure:	150 ppm OSHA ‡
Dangerous Exposure:	10,000 ppm OSHA/NIOSH
Short Term Limit:	200 ppm
IHL-HMN TCLo	200 ppm
IHL-RAT LC50	2000 ppm/4hr
IHL-GPG LCLo	67000mg m^3/4hr (ca. 13,000 ppm)
ORL-RAT	14,000 mg/kg
ORL-GPG LDLo	4700 mg/kg
SKN-RBT	500mg/24hr; moderate irritation
Aquatic Toxicity Rating:	2

Remarks:

ALTERNATIVE, AUTO-DENSE, SAFE DRILL FLUID.

Pleasant fruity odor, used as a solvent in the lacquer and plastics industries. A component of apple odor. Mildly toxic by inhalation. A mild allergen. High concentrations irritating to eyes and respiratory tract and cause narcosis. No chronic systemic effects have been reported in humans.

‡Odor detection and irritation both occur below permissible exposure limit (150ppm), and provide adequate warning properties.

Reportable quantity: 5000 lb.

Table 2. **SOLVENT EFFECT ON POLYMERS** (24±3Hrs)

Plastic	No. 1 Fuel Oil	0.91 Bromoil	PER	LVT-200	Anisole	n-Butyl Acetate
Black Rubber	ss−	ss+	ss+	ss+	se	se
Polypropylene	ss−	ss	ne	se	ne	ne−
Teflon	ne	ne	ne	ne	ne	ne
Viton	ne	ne	ne	ne	ne	ne
Elec. Insul.*		ne	ne		ne	ne
Elec. Insul.†						ne
Polyethylene						ne
Kevlar						ne
Nylon						ne

se = slight effect   ss = soften and/or swell

+ = more;   − = less— i.e. a very slight effect or softening.

ne = no effect (did not swell, soften or become tacky)

* Lacquer on wire, 125°C FOR 2hrs.

†Plastic jacket on wire.

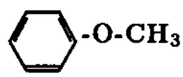
A blank area indicates no data.

Table 1 in the paper

Figure 1. **Chemical structures for butyl acetate and anisole.**

$$CH_3\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}O\text{-}\overset{O}{\overset{\|}{C}}\text{-}CH_3$$

n-Butyl Acetate (or BuOAc)



Anisole

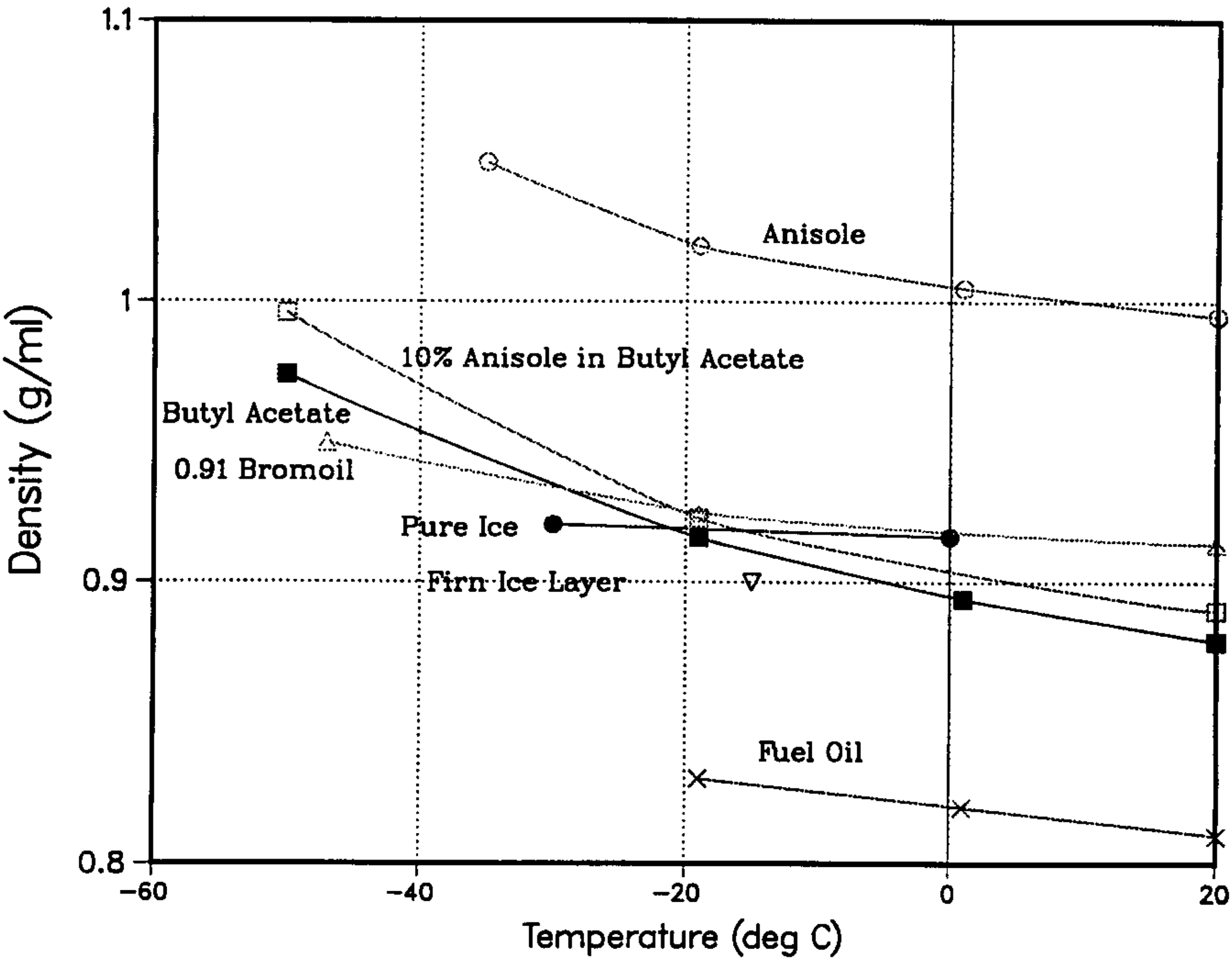


Figure 2a. **Density (g/ml) of potential ice drilling fluids versus temperature (°C). Fuel oil(×); pure ice(•); 0.91 bromoil(△); butyl acetate(▪); 10% anisole in butyl acetate(▫); anisole(○).**

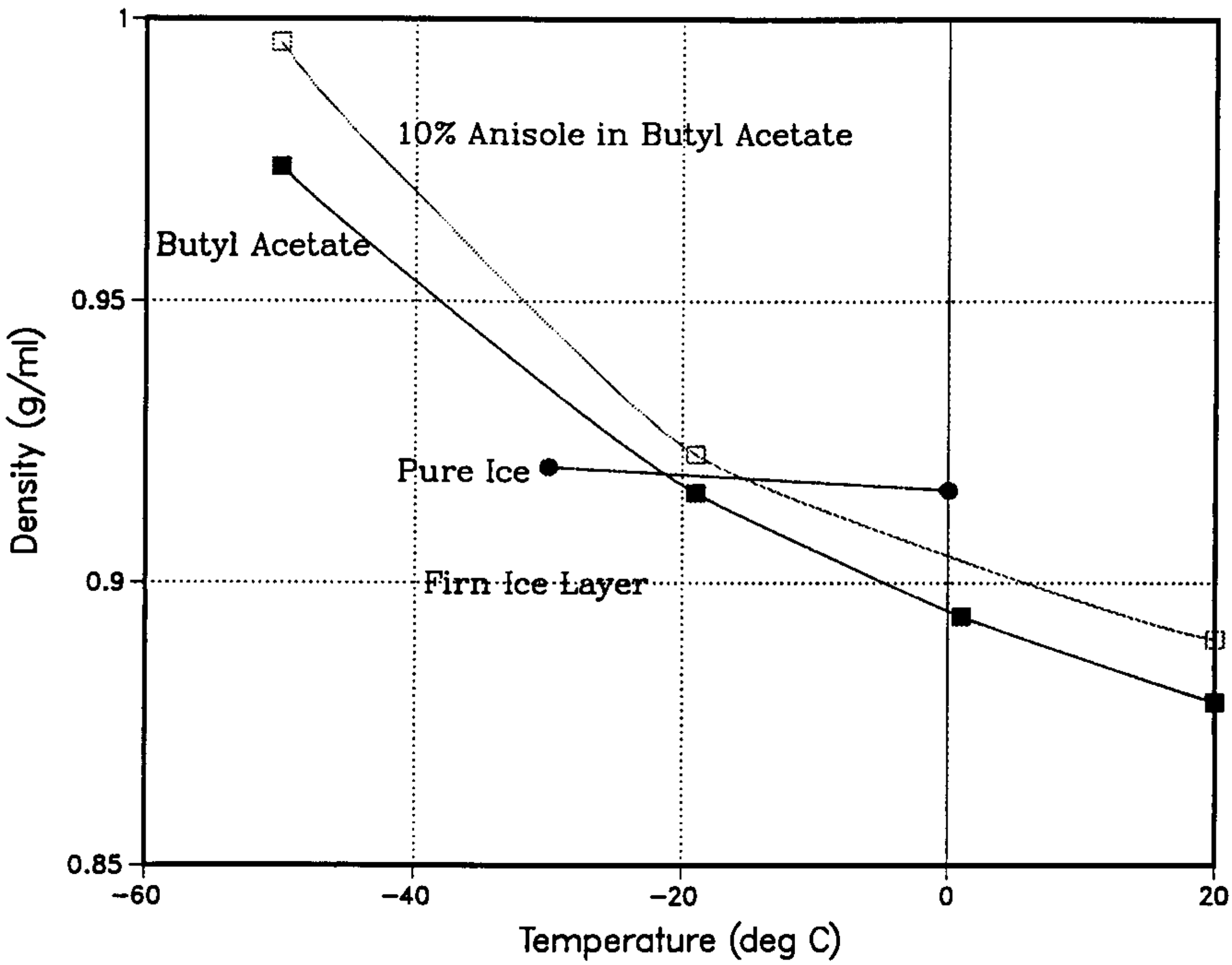


Figure 2b. **Greater detail— Density of butyl acetate and 10% anisole in butyl acetate versus temperature.**

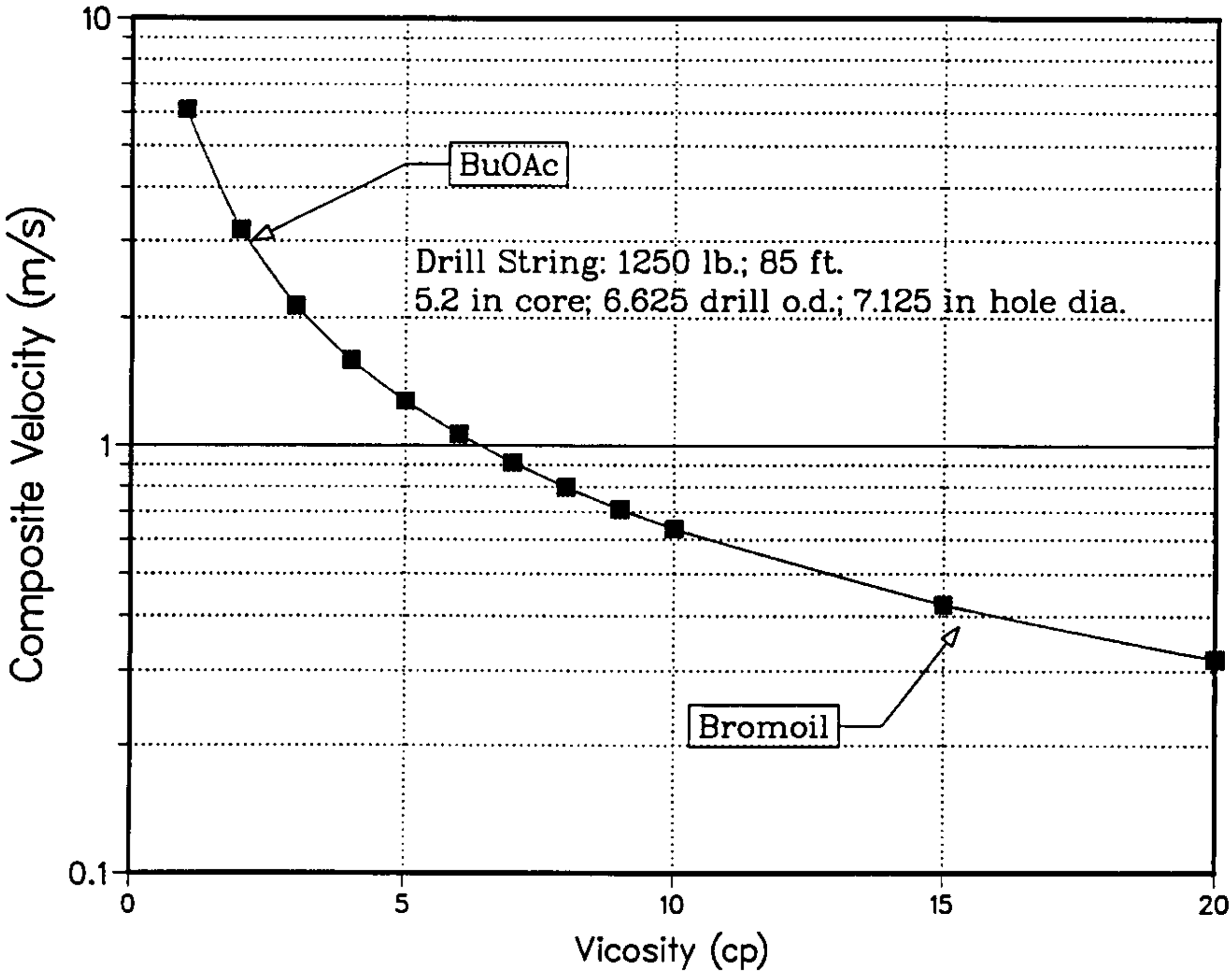


Figure 3. **Drill string fall velocity as a function of the drill fluid viscosity.**

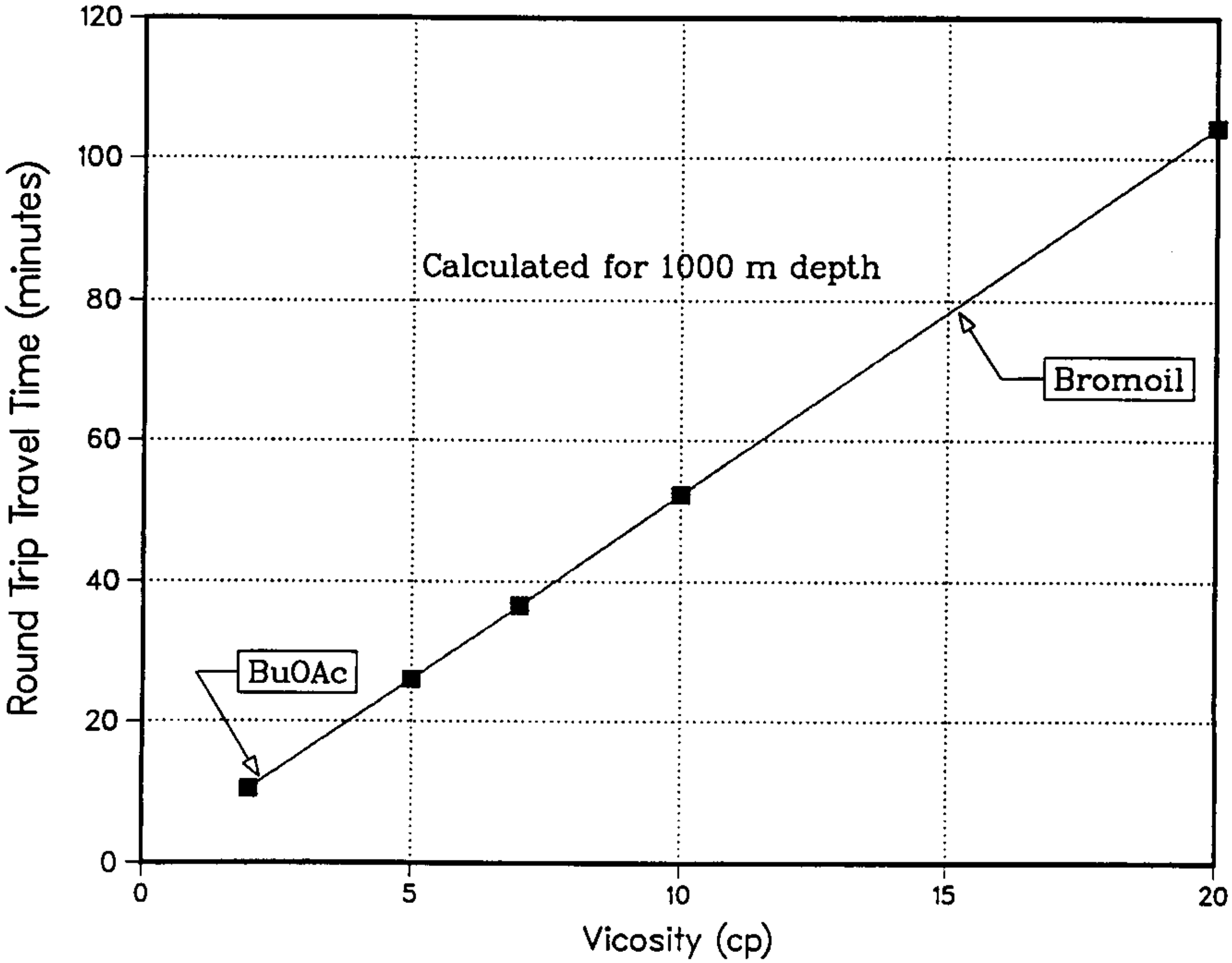


Figure 4. **Drill string round trip travel time as a function of drill fluid viscosity.**

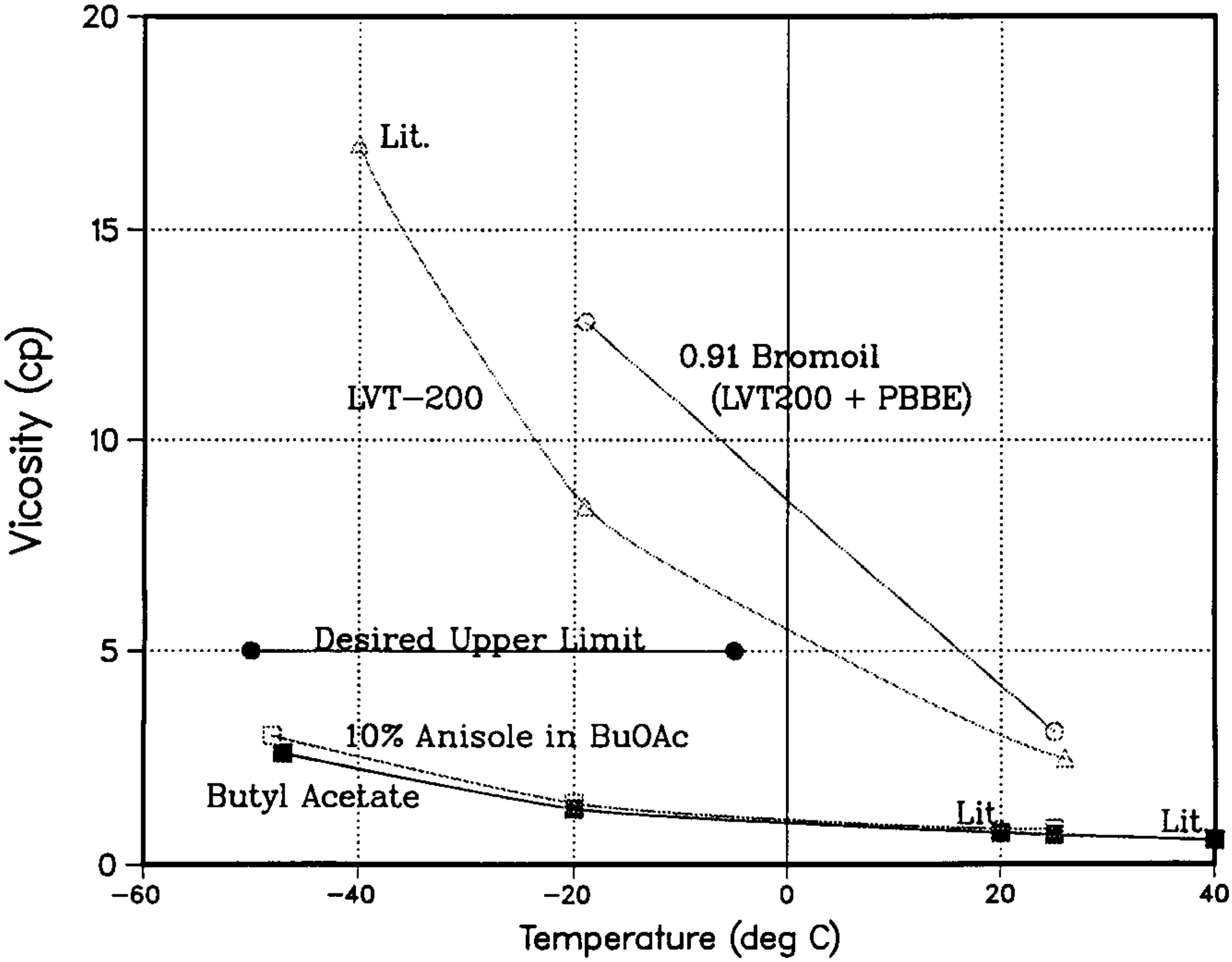


Figure 5a. **Viscosity (cp) of potential ice drilling fluids versus temperature (°C). Butyl acetate(■); 0.91 bromoil(○); 10% anisole in butyl acetate(□); LVT-200 (△). "Lit."= literature data points.**

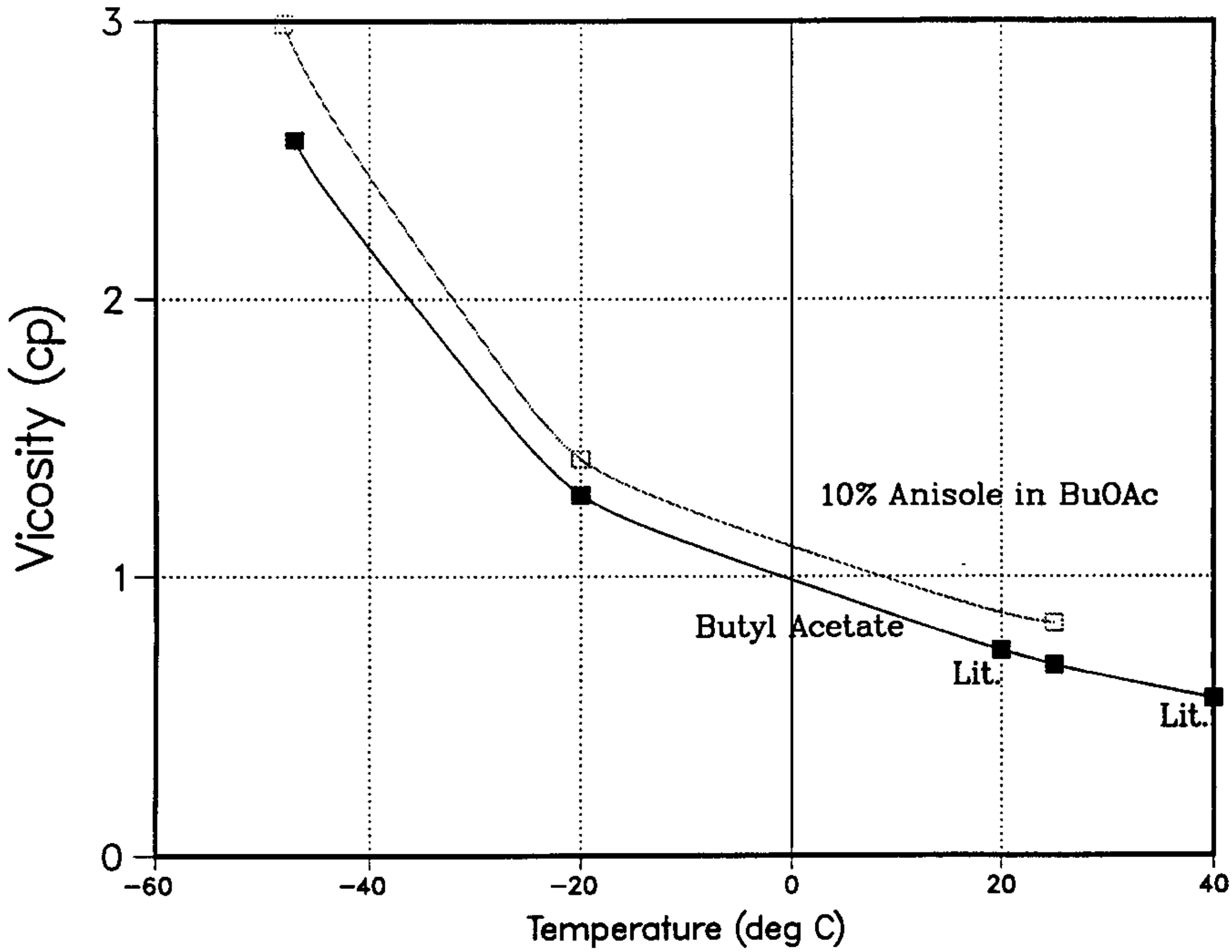


Figure 5b. **Greater detail— Viscosity of butyl acetate and 10% anisole in butyl acetate versus temperature.**

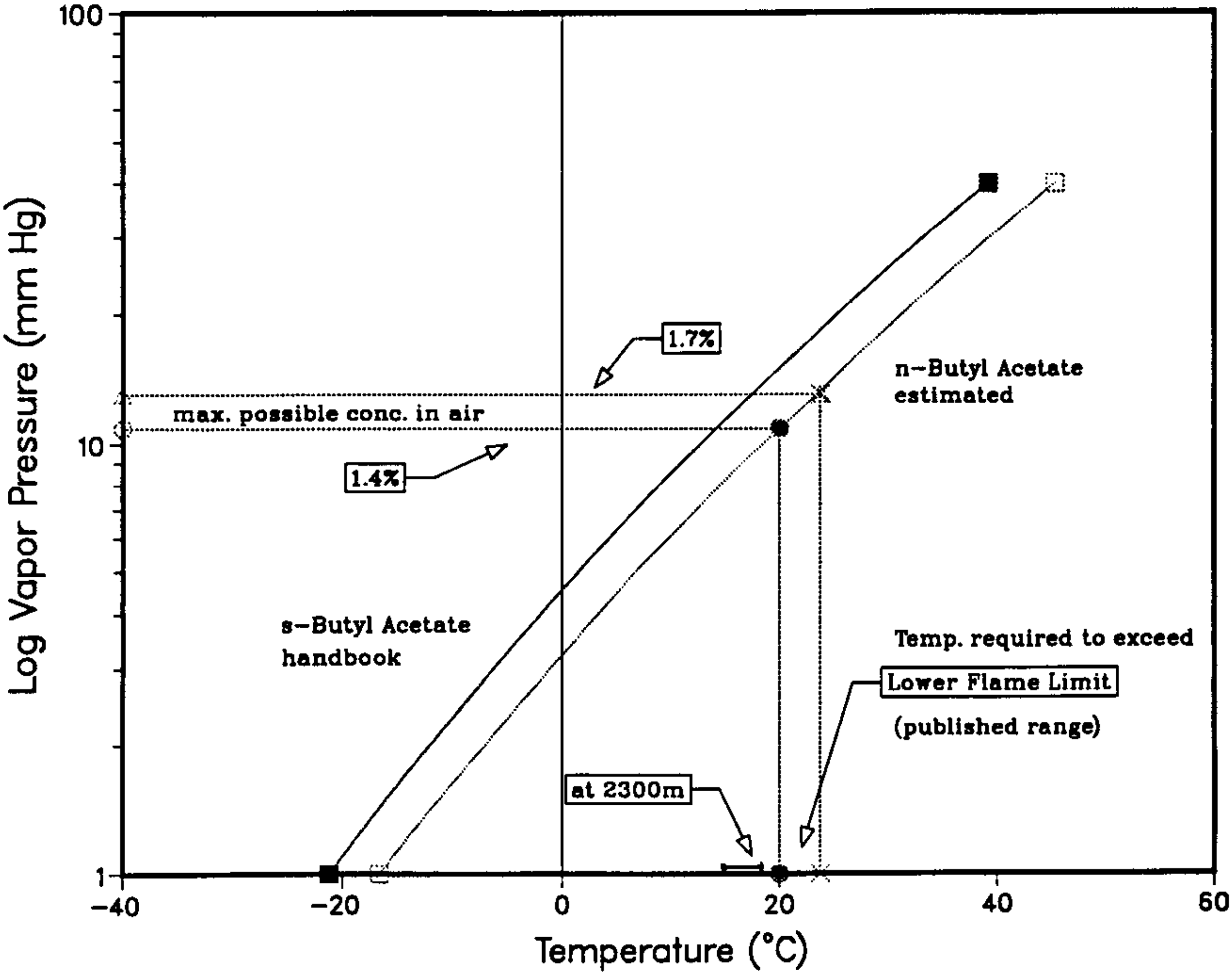


Figure 6. **Vapor Pressure versus temperature of butyl acetate, indicating the temperature required to exceed the lower flame pressure/concentration at sea level and at 2300 m (7000 ft) altitudes.**

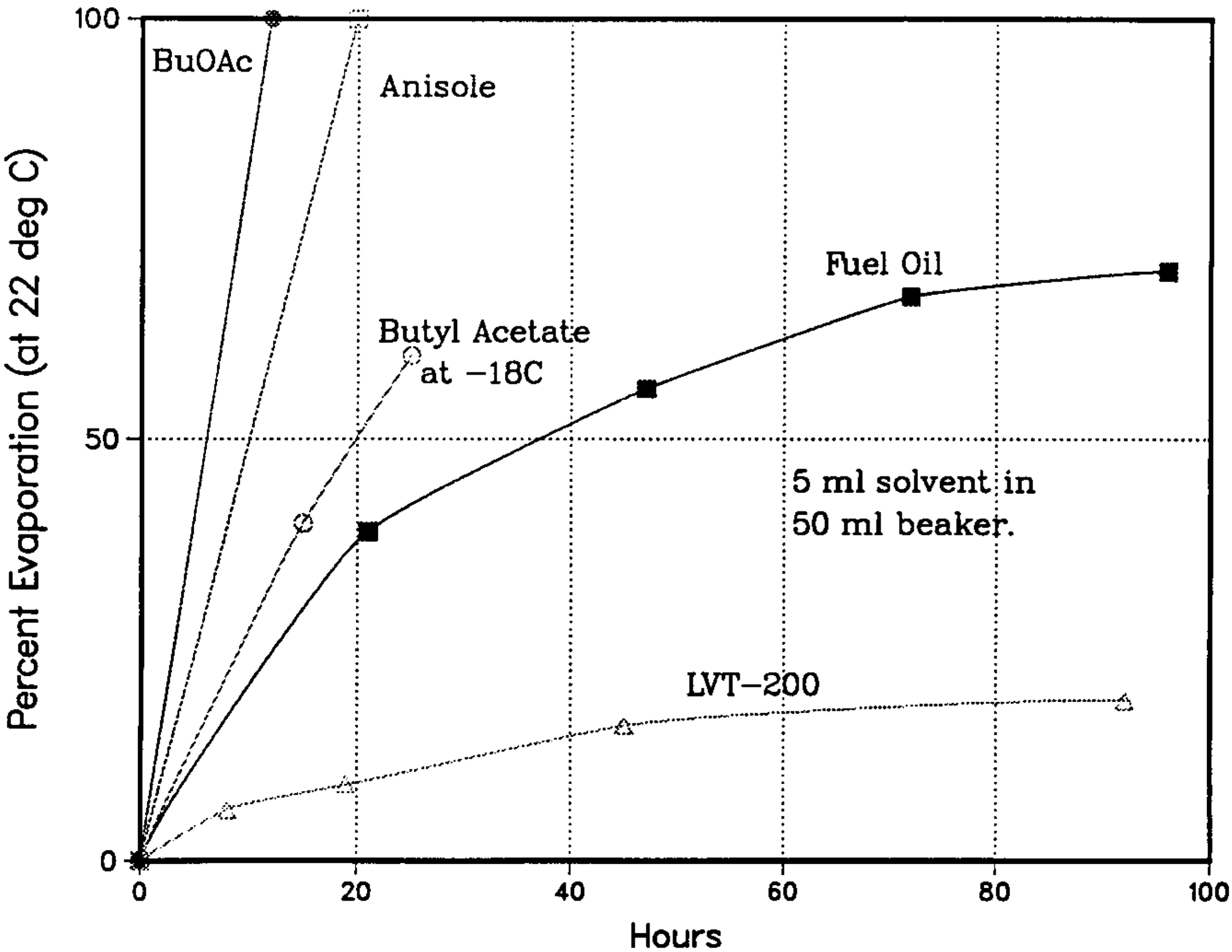


Figure 7. **Percent evaporation of potential drilling fluids (at ca. 22°C) versus time (hours). (5ml of solvent in a 50ml beaker.)**

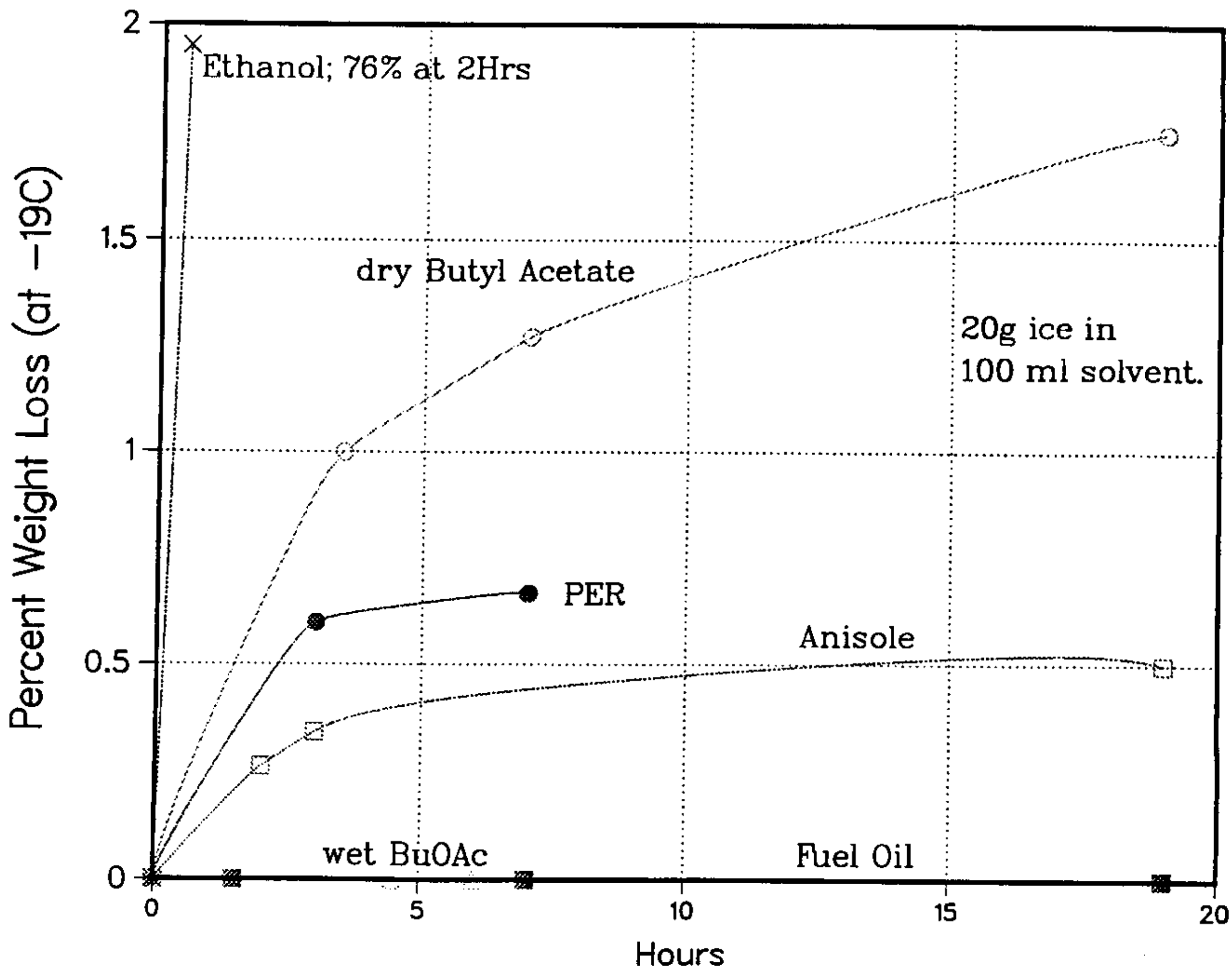


Figure 8. **Percent weight loss of ice in potential ice drilling fluids (at -19°C). (Approximately 20 g of ice in ca. 100 ml of solvent.)**