

CHARACTERISTICS AND RECOVERY METHOD OF SPILLED OIL UNDER ICE FLOES

N. Ohtsuka¹, K. Ohshima², N. Usami², S. Takahashi³, Y. Watanabe², H. Saeki²

¹Norh Japan Port Consultants Co.,Ltd., Sapporo, Japan

²Hokkaido University, Sapporo, Japan

³Nishimura Gumi Co.,Ltd., Yubetu, Japan

ABSTRACT

Development of oil and natural gas deposits off Sakhalin's northern coast in the Sea of Okhotsk are currently under way. An accident involving a spill of crude oil or other effluents during the current development of the oil and natural gas deposits off the eastern coast of northern Sakhalin could be expected to affect the environment and economy of the Hokkaido's Okhotsk and Pacific coast. This paper describes a recovery method for spilled oil under the ice floes established through systematic experiment.

1. INTRODUCTION

Oil spilled in cold waters such as the Sea of Okhotsk behaves differently from that spilled in normal temperature waters. Oil spilled in the former, beneath the ice sheet, is thought not to degrade because even high waves are rendered to long waves with small amplitude. Also, such oil is said to be very unlikely to volatilize, alternate, or biodegrade because of its location beneath the ice sheet. As a result, cold waters would be subjected to the effects of toxic, volatile components of oil. In addition, seawater beneath an oil layer trapped under an ice sheet may freeze, sandwiching the oil between an upper and lower ice. Thus, it is important to develop methods which enable quick recovery of spilled oil, so as to minimize damage.

Current oil and gas exploration in frozen waters includes that in the Cook Inlet of Alaska; the Beaufort Sea of the Arctic Ocean; and the Barents Sea off the northern part of the Scandinavian Peninsula. It is said that small-scale oil spills have occurred quite often at these sites. Exploration off of Sakhalin, which lies close to a zone where earthquakes occur frequently and is affected by rapid ocean currents that propel ice floes, can exert great environmental and economic impact on the Okhotsk coast of Hokkaido. Oil that spills off of Sakhalin can be carried rapidly southward along with ice floes by the East Sakhalin Current and winter winds, to reach the coast.

Given the above, this paper aims to identify the fundamental characteristics of oil beneath ice sheets and to describe our basic research to develop recovery methods of oil spilled and trapped under ice floes.

2. STUDY ON TEST ALTERNATIVES TO CRUDE OIL

Iranian Light oil was used for our experiments because of its similarity in properties to Sakhalin oil. However, more than 30% of the Iranian oil is volatile components, making the oil toxic and dangerous to handle. Also, its toxicity changes over time. Consequently, alternative materials to the crude oil (hereafter alternative oils), four types of gear oil with

different ISO viscosity (grades 10, 32, 100 and 460) were also used to ensure that more systematic experiments could be made with higher levels of safety.

2.1 Measurement of density and viscosity

2.1.1 Measurement methods

A petroleum densitometer was used to measure the density of the oil and the alternative oils. Also, a viscotester (rotary drum viscosity meter with measurement range of 0.002 to 400 Pa·s) was used to measure viscosity. Both of these measurements were carried out at a room temperature range of -2 to 10°C, a typical temperature band of seawater during the ice-floe season.

2.1.2 Results of the experiments

The relationship between the density and the temperature of the Iranian oil was studied. The results (Figure-1) indicate that the density of the Iranian oil drops as its temperature rises. Table 1 shows the density ρ and the viscosity η of the Iranian oil and of the alternative oils. It indicates that at the water temperature of -2°C, a typical seawater temperature during the ice-floe season, ISO 32-grade alternative oil is most similar in properties to the Iranian oil.

Table 1: Density ρ and viscosity η of the Iranian oil and the alternative oils.

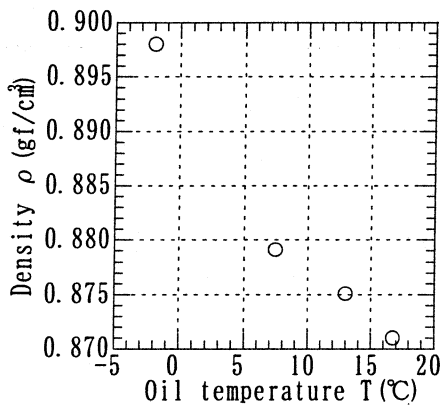


Figure-1: The relationship between temperature T and density ρ of the Iranian oil.

ISO viscosity grade	Mean density ρ (gf/cm ³)		Mean viscosity η (dPa · s)	
	T=-2°C	T=10°C	T=-2°C	T=10°C
10	0.874	0.867	0.81	0.272
32	0.878	0.873	4.1	2.84
100	0.895	0.892	20	6.95
460	0.912	0.906	190	35
Crude oil	0.898	0.879	4.9	0.53

2.2 Measurement of contact and tilt angles

2.2.1 Measurement methods

Characteristics of the Iranian oil's and alternative oils adhesion to a sheet of frozen seawater were systematically studied by the following two methods. In the first experiment, the angle of contact between a frozen seawater sheet floating on seawater and the Iranian and alternative oils beneath the ice sheet was measured. This angle indicates adhesion caused by surface-active energy generated between the ice sheet and the oils.

In the second experiment, a rectangular ice sheet floating on seawater was tilted gently and just enough to cause the oils trapped underneath to move. This angle corresponds to the coefficient of static friction between the ice sheet and the oils.

To measure the angle of contact, a tank (30cm wide \times 60cm long \times 35cm high) was filled with seawater on which was floated a sheet of frozen seawater (20cm wide \times 30cm long \times 5 to 13cm thick). Then, with the ice sheet secured in position with two point gauges, the oils were placed underneath the ice sheet. Finally, photographs were taken for side view analysis (Figure-2).

Following the contact angle experiment described above and with one of the point gauges fixed, the other was lowered gently to tilt the ice sheet until the oil and alternative oils moved. This tilt angle and the corresponding static friction coefficient were then calculated by measuring the extended length of the latter gauge and the distance between the two gauges (Figure-3).

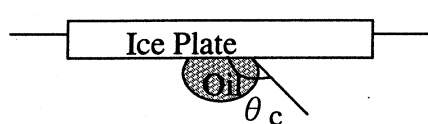


Figure-2: Contact angle

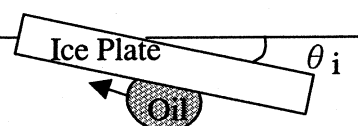


Figure-3: Tilt angle

2.2.2 Results of the experiments

Based on the results of these experiments, the average contact and tilt angles and the average friction coefficient of the oil and alternative materials are summarized in Table 2.

Table 2: Average contact angle (θ_c), average tilt angle (θ_i) and average friction coefficient (μ) of the oil and alternative materials.

ISO viscosity grade	Mean friction factor μ	Mean inclination angle θ_i (deg)	Mean contact angle θ_c (deg)
10	0.033	1.86	153
32	0.055	3.15	153
100	0.055	3.17	151
460	0.056	3.13	148
Crude oil	0.065	3.72	146

Based on the results of the above experiments on contact and tilt angles (Table 2) and the measurement of viscosity and density, the gear oil of ISO viscosity grade 32 was chosen as being most similar in properties to the Iranian oil.

3. EXPERIMENT ON OIL RECOVERY

Liukkonen et al (1997) are proposing the use of an oil recovery method in which holes are drilled in ice sheets and then spilled oil and seawater are pumped out simultaneously for subsequent separation. However, it is difficult to recover oil with this method when ice sheets are of various thicknesses or, as in the case of the Sea of Okhotsk, ice sheets vary in both thickness and size. The authors and our study team carried out two experiments on the separation of oil from ice sheets:

One of these experiments relies on the relative velocity between ice sheets and the seawater beneath them to separate oil from the ice sheet; the other uses compressed air blown from a compressor sunk under the sea to impart relative velocity to ice sheets and seawater so as to subsequently separate trapped oil from ice sheet. The latter method not only makes it easier for oil to be separated from the ice sheet, but prevents oil from being sandwiched between ice sheets.

The size of the drift ice of the Sea of Okhotsk is about 3m and thickness is about 0.5m (in the near shore), and ice concentration is not so high, so that to remove those drift ice is comparatively easy. Therefore, if relative movement is not generated between ice sheet and sea water, two small icebreakers are used to trail an ice boom, thereby imparting relative velocity. The tensile force generated in the ice boom can be calculated by the method which reported from the experimental research and the field observation of the ice boom, which installed in Saroma Lagoon that faces the Sea of Okhotsk, by Enoki et al (1992). Figure-4 outlines the oil recovery operation.

Two types of experiment were carried out: In one, an ice sheet floating on seawater was moved, and the velocity at which the ice sheet separates from oil trapped underneath was measured; in the other, air was blown beneath an ice sheet, and with the air trapped between the ice sheet and oil underneath it, the ice sheet was pulled away from the oil. In these experiments, the gear oil of ISO viscosity grade 32 was used as an alternative to the Iranian oil. The gear oils of other grades were also used for comparison with the grade 32 oil.

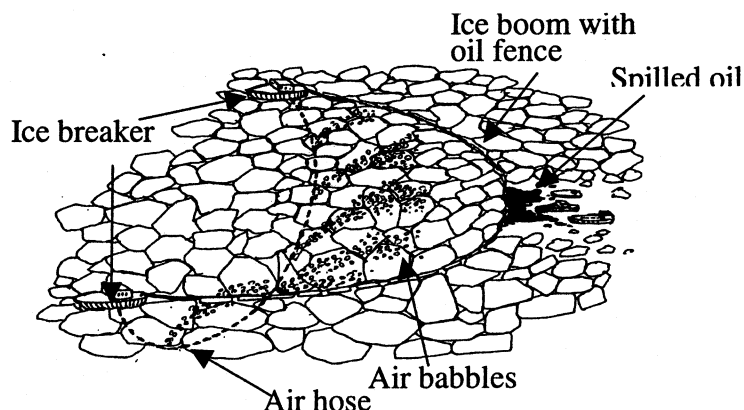


Figure-4: Schematic drawing of oil recovery operation

3.1 Measurement of coefficient of shear resistance (Cos) between oil and seawater

3.1.1 Measuring experiments of coefficient of shear resistance between oil and seawater

To establish the coefficient of shear resistance between oil and seawater, three timber frames (90cm, 180cm and 270cm long \times 30cm wide \times 1.5cm high) filled with gear oil were trailed at various velocities, and corresponding loads were measured (Figure-5). As an example of the results, Figure-6 shows the relationship between the velocity and the load when the gear oil of ISO viscosity grade 32 was used. It indicates that the resistance of oil increases in direct proportion to the length of the timber frame.

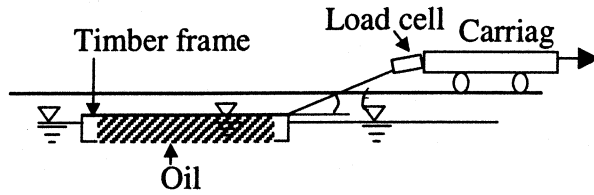


Figure-5: Measurement of shear resistance coefficient.

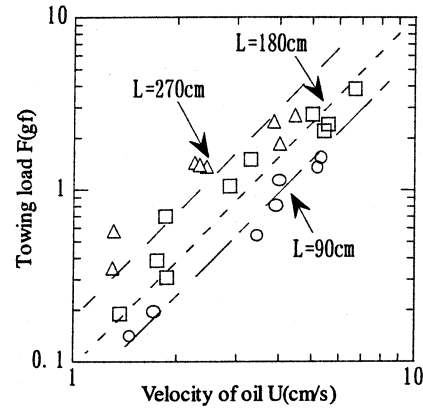


Figure-6: Relationship between velocity U (cm/s) and load F (kgf).
(The gear oil of ISO viscosity grade 32 was used.)

3.1.2 Calculation of shear resistance coefficient between oil and seawater

Based on the results of the above experiment, the profile drag coefficient (C_d) of the timber frames and the shear resistance coefficient (C_{os}) of the oil were calculated. To this end, the relationship between the velocity U , load F and frame length L was established (Figure-7), based on Figure-6. In Figure-7, the load which results when $L = 0$ corresponds to the profile drag F_d . The shear resistance F_s can then be obtained based on this profile drag F_d and the following the formula of resistance eq (1).

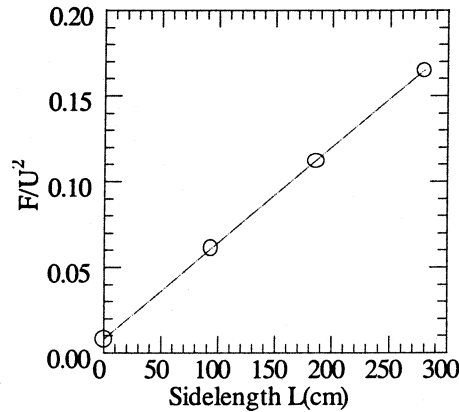


Figure-7: Relationship between the load and the timber frame length at different velocities.

$$F = F_d + F_s \quad (1)$$

$$F_d = \frac{w}{2g} C_d B h U^2 \quad (2)$$

$$F_s = \frac{w}{g} C_{os} B L U^2 \quad (3)$$

Where:

w = water weight per unit volume (gf/cm^3), B = width (cm),
 L = length (cm), and U = velocity (cm/s).

Using the above formulas, the profile drag coefficient (C_d) was calculated to be 0.6. Then, using this value, the shear resistance coefficient (C_{os}) was calculated for each gear oil. The resultant values ranged from 0.0183 to 0.0215. Thus, for the analyses that follow, the mean value of 0.0196 is used as the shear resistance coefficient.

3.2 Travel speed of oil under ice sheet

This experiment was carried out to determine how fast gear oil trapped under an ice sheet travels when the ice sheet is moved at various velocities. An ice sheet (50cm long \times 40cm wide \times 7cm thick) was floated in a tank filled with seawater, and four types of gear oil (ISO viscosity grades 10, 32, 100 and 460) were trapped beneath.

An example of the test results is shown in Figure-8 (for which the gear oil of ISO viscosity grade 32 was used). It indicates that when the velocity of the ice sheet is about 13cm/s or slower, the oil does not travel relative to the ice sheet; in other words, it travels together with the ice sheet. This phenomenon was also observed with the oils of other grades. Based on the data obtained from this experiment, the velocity of ice sheet at which oil starts to move (V_{i0}) is summarized in Table 3. And the following relationship between the velocity of ice sheet (V_{i0}) and the viscosity of the oil was obtained from the results of the present experiments (shown in Figure-9):

$$V_{i0} = 4.982 + 10.503 \log(\eta) \quad (4)$$

Thus, spilled oil under the ice sheet can be separated from and left behind the ice sheet for recovery by an ice boom trailed over the ice sheet faster than V_{i0} described above, but slower than 60 to 70 cm/s to prevent the ice boom from overturning of the ice sheet (Enoki et al, 1992).

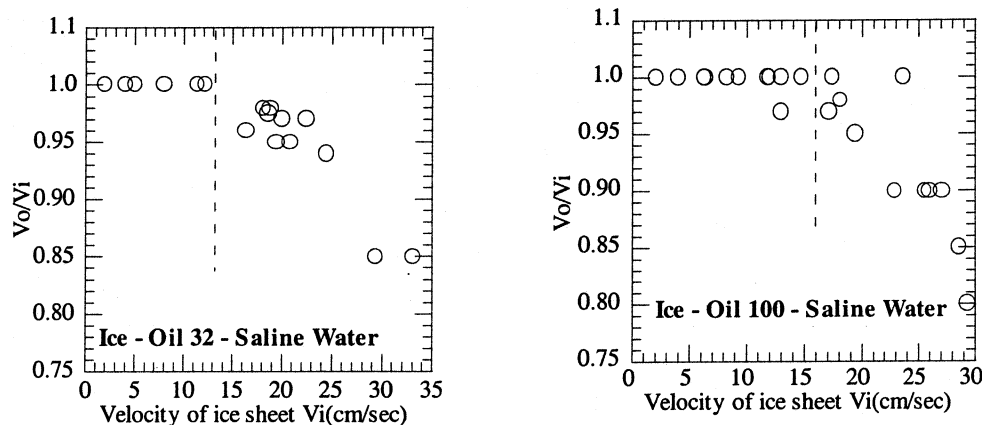


Figure-8: Relationship between travel speed of ice sheet (V_i) and that of oil (V_o).

Table 3: Velocity of ice sheet (V_{io}) at which oil starts to move.

ISO viscosity Grade	Velocity of ice plate V_{io} (cm/s)
10	4
32	13
100	16
460	30

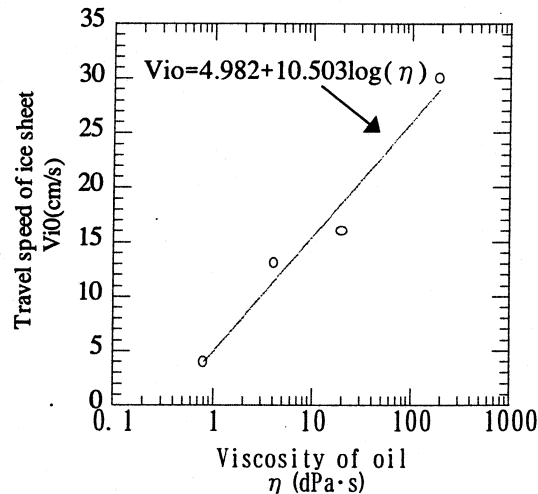


Figure-9: Relationship between Velocity of ice sheet (V_{io}) at which oil starts to move and the viscosity of the oil

3.3 Measuring experiments on the thickness of oil trapped under ice sheet

Thickness of spilled oil left under an ice sheet for a long time was measured. Sheets of frozen seawater (20cm wide x 30cm long x 5 to 13cm thick) were placed in a tank (30cm wide x 60cm long x 35cm high) filled with seawater, and a fixed amount (about 50ml) each of the Iranian oil and the four gear oils were trapped under these ice sheets. After 30 minutes to several hours, average oil thickness was calculated (Table 4) based on the area to which the oils had spread. These values were used later when we studied the force applied to oil.

Table 4: Thickness h (cm) of the Iranian oil and gear oils

ISO viscosity grade	Mean thickness(cm)
0	0.57
32	0.71
100	0.68
460	0.49
Crude oil	0.84

3.4 Calculation of coefficient of shear resistance (C_{io}) between oil and sheet of frozen seawater

When an ice sheet is traveling at V_i , oil trapped beneath it receives static friction (F_u), shear resistance between ice and oil (F_{io}), and shear resistance between ice and seawater or between water and oil (F_{os}) (Figure-9). Also, the force per unit width of oil can be expressed by the following formulas eq (4):

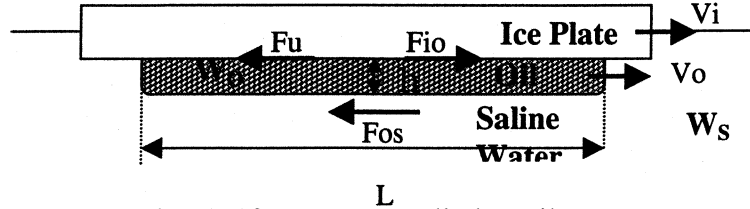


Figure-10: Force applied to oil.

$$F = F_{io} - F_u - F_{os} \quad (5)$$

$$F = m \cdot \frac{dV_o}{dt} = \rho \cdot h \cdot L \cdot \frac{dV_o}{dt} \quad F_{io} = \frac{W_o}{2g} \cdot C_{io} (V_i - V_o)^2 \cdot L$$

$$F_u = h \cdot L \cdot (W_s - W_o) \cdot \mu \quad F_{os} = \frac{W_s}{2g} \cdot C_{os} \cdot V_o^2 \cdot L$$

Where:

h = oil thickness (cm)

L = oil width (cm)

μ = friction coefficient of oil

ρ = oil density (g/cm^3)

W_s = weight per unit volume (g/cm^3) of seawater

W_o = weight per unit volume (g/cm^3) of oil

C_{os} = coefficient of shear resistance between oil and seawater (obtained in Section 3.1.2)

V_i = travel speed of ice sheet (cm/s)

V_o = travel speed of oil (cm/s)

Also, when relative travel speed between ice sheet and oil is specified as $V = V_i - V_o$, the constant travel speed of ice sheet (V_i) at which oil starts to move can be expressed by the following formula.

$$\frac{dV}{dt} = - \frac{dV_o}{dt} \quad (6)$$

Based on formulas eq (5) and eq (6), the travel speed of ice sheet (V_i) at which oil trapped under the ice sheet starts to separate from it can be expressed by the following formula.

$$V_i^2 \geq \frac{2gh \left(\frac{W_s}{W_o} - 1 \right) \cdot \mu}{\frac{W_s}{W_o}} \left(\frac{W_s}{W_o} \cdot \frac{1}{C_{io}} - \frac{1}{C_{os}} \right) \quad (7)$$

The coefficient of shear resistance between each type of oil and sheets of frozen seawater (C_{io}) can then be determined by substituting V_{io} (obtained in Section 3.2), $C_{os} = 0.0196$ (coefficient of shear resistance between oil and seawater), h , μ , W_s and W_o in the above formula.

Accordingly, the coefficient of shear resistance between oil and sheets of frozen seawater (C_{io}) was found to be in the range of 0.011 and 0.016.

3.5 Travel speed of oil trapped under ice sheet with air caught in-between

In this experiment, the travel speed of oil trapped under ice sheet with air caught between oil and ice sheet was measured. Wooden plate was used instead of ice sheet. Four types of gear oil (ISO viscosity grades 10, 32, 100 and 460) mixed with air were trapped beneath the wooden plate, which was then trailed to measure the travel speed of the gear oils.

An example of the test results is shown in Figure-10. It indicates that when air exists under ice sheets, the corresponding shear resistance coefficient is extremely small, which means that ice sheets can be moved at much lower speed than that there is no air trapped under the ice sheet.

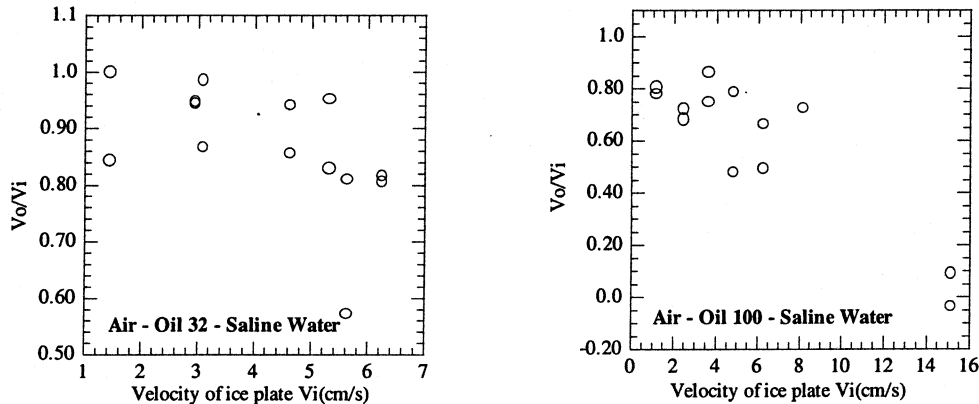


Figure-10: Relationship between travel speed of ice (V_i) and that of oil (V_o) when air is caught beneath the ice sheet.

4. CONCLUSIONS

- (1) The viscosity and density at about -2.0°C were determined for various materials (Table 1). It was found that the Iranian oil seems similar in properties to the gear oil of ISO viscosity grade 32. Thus, this gear oil can substitute for the Iranian oil in experiments in which viscosity and density play a major role.
- (2) A sheet of frozen seawater was tilted slowly in a tank of seawater until oil trapped beneath the ice sheet started to move. Accordingly, this tilt angle (θ) and the corresponding static friction coefficient (μ) were determined for various types of oil (Table 2). The Iranian oil trapped beneath an ice sheet floating on seawater starts to move when the ice sheet's tilt angle reaches 3.72 degrees. The corresponding friction coefficient at that time was determined to be 0.065. Thus, in experiments that rely on the difference in relative speed between ice sheets and seawater to separate oil from ice sheets, materials should be used whose friction coefficient is as close to 0.065 as possible.
- (3) An ice sheet was placed on stationary, seawater surface, and gear oil was trapped under the ice sheet. Then, the ice sheet was moved. This process was repeated for various types of

gear oil. Consequently, it was found that the gear oil of ISO viscosity grade 32 separated from the ice sheet when the travel speed of the ice sheet exceeded about 13cm/s, and that the higher the friction coefficient, the more difficult it was for the oil to separate from the ice sheet.

- (4) Various types of gear oil were tested again using a process similar to that described in (3) above, but this time air bubbles were blown in to create a layer of air between the ice sheet and materials. As a result, all the materials used separated from the ice sheet even when the ice sheet was moved at much slower speeds.

The above findings indicate that level ice and oil can be separated using two icebreakers, each trailing an ice boom at either end at a speed of about 1 knot. Also, it is possible to separate oil from ice sheets easily at trailing speeds of as low as 2 to 3 cm/s when air has been blown between ice sheet and trapped oil. Separating oil from a mass of ice sheets of various thickness can also be facilitated by blowing air underneath the ice sheets and thereby creating a uniform layer of air.

Moreover, a layer of air formed by the air blowing will help reduce the mount of volatile components in trapped oil by absorbing such components when they vaporize, part of which may find its way into the atmosphere through the gap between the ice sheets.

5. REFERENCES

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