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(Résumé en français)

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WATER RESOURCES BRANCH,
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Behaviour of Oil Spilled in Ice-Covered Rivers

E. C. Chen, B. E. Keevil and R. O. Ramseier

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Abstract

Experiments were carried out in a cold room at -15°C to investigate the behaviour of Norman Wells crude oil spilled under freshwater ice. The oil, when released in water under ice, separates into droplets and rises to the ice-water interface where the oil drops coalesce to form a slick. The spreading of oil under ice is complicated by the coalescence of oil drops at the interface. In calm waters, the radius of the oil slick under ice is approximately proportional to 0.25 power of the elapsed time. In turbulent waters, however, the oil drops travel some distance, following the flow direction of water, before reaching the interface. Some of the small drops are suspended and dispersed in the water column. The slick formed at the ice-water interface does not adhere to the ice and contains some water-in-oil emulsions. If the oil is spilled under the ice and the ice continues to grow, the oil will be sandwiched between the ice layers. An oil lens trapped between the ice layers acts as an insulator and increases the temperature drop across the ice.

The behaviour of accidental oil spills in Canadian rivers was surveyed and analyzed. Observations of these accidental spills show that the oil, when spilled in a river, is quickly dispersed downstream.

Résumé

On a réalisé des expériences en chambre froide, à -15 °C, pour étudier le comportement du pétrole brut de Norman Wells déversé sous la glace formée à partir d'eau douce. Lorsque le pétrole se répand dans l'eau au-dessous de la glace, il se sépare en gouttelettes qui remontent à l'interface glace-eau pour former une couche de pétrole par coalescence de ces gouttelettes. L'étalement du pétrole sous la glace est complexe, en raison de la coalescence des gouttelettes de pétrole à l'interface glace-eau. Dans les eaux calmes, le rayon de la nappe de pétrole qui se forme sous la glace est approximativement proportionnel à la puissance 0.25 du temps écoulé. Dans les eaux troubles, cependant, les gouttelettes parcourent une certaine distance dans le sens d'écoulement de l'eau, avant d'atteindre l'interface. Quelques-unes d'entre elles se trouvent en suspension et sont dispersées dans la colonne d'eau. La nappe formée à l'interface glace-eau n'adhère pas à la glace et contient des émulsions «d'eau-dans-le pétrole». Le pétrole qui se répand au-dessous d'une couche de glace dont l'épaisseur continue d'augmenter se trouve pris entre les couches de glace. Une lentille de pétrole intercalée entre des couches de glace se comporte comme un isolant et favorise l'abaissement de la température des couches de glace.

On a étudié et analysé le comportement du pétrole répandu accidentellement dans des cours d'eau canadiens. Les observations effectuées au sujet des déversements accidentels ont révélé que le pétrole répandu dans un cours d'eau se disperse rapidement en aval.

List of Symbols

A — area of oil slick, cm
c — constant, dimensionless
d — droplet diameter, cm
D — diffusion coefficient, cm^2/s
D_n — nozzle diameter, cm
F_b — buoyancy force, $dynes/cm^3$
F_p — outward pressure force, $dynes/cm^3$
F_v — viscous force, $dynes/cm^3$
g — gravitational constant, 980 cm/s^2
h — thickness of oil slick or oil lens, cm
k — mass-transfer coefficient, $g/(s)\text{-}(cm^2)\text{-}(g/cm^3)$
K_i — thermal conductivity of ice, cal/s-cm-°C
K_o — thermal conductivity of oil, cal/s-cm-°C
L_1 — thickness of ice layer above the oil lens, cm
L_2 — thickness of ice layer below the oil lens, cm
N_{Re} — Reynolds number, $(d\, v_t \rho_w)/\mu_w$, dimensionless
N_{Sc} — Schmidt number, $\mu_w/(\rho_w D)$, dimensionless
N_{Sh} — Sherwood number, $k/(d\,D)$, dimensionless
Q — oil spilling rate, cm^3/s
Q_i — amount of heat transferred through the clean ice, cal/cm^2-hr
Q_{io} — amount of heat transferred through the ice with an oil lens, cal/cm^2-hr
R — radius of oil slick, cm
t — elapsed time, s
T_{ia} — temperature at the ice-air interface, °C
T_{iao} — temperature at the ice-air interface above the oil lens, °C
T_1 — temperature at the top of the oil lens, °C
T_2 — temperature at the bottom of the oil lens, °C
u — velocity of spreading, cm/s
v_n — nozzle velocity, cm/sec
v_t — drop terminal velocity, cm/s
V — oil volume, cm^3
δ — thickness of water film under the oil so set into motion by the viscous force, cm
μ — viscosity of oil, poise
μ_w — viscosity of water, poise
π — 3.1416
ρ_d — density of dispersed phase, i.e., density of crude oil, g/cm^3
ρ_w — density of water, g/cm^3
σ — interfacial tension, dynes/cm
τ — shear stress, $dynes/cm^2$

Behaviour of Oil Spilled in Ice-Covered Rivers

E. C. Chen, B. E. Keevil and R. O. Ramseier

INTRODUCTION

The discovery of oil in commercial quantities in northern Canada could lead to the construction of oil pipelines to southern markets. These pipelines would cross many rivers and streams that are subjected to ice conditions of varying seasonal length. It is conceivable that oil spills in ice-covered rivers would result from such pipeline crossings. The spills could be large, e.g., caused by a major pipeline fracture, or small, e.g., developing through holes in the pipe. In addition, accidents involving oil tankers, storage tanks and tank trucks could also result in oil spills in rivers.

Although results of oil pollution research are being published in an increasing number, available information on the behaviour of oil spilled in ice-covered rivers is limited. The only systematic study reported in the literature is by Wolfe and Hoult (1), who investigated the effect of crude and diesel oils on the porous substructure of Arctic Sea ice. The apparatus used consisted of an insulated Plexiglas tank, 30.4 cm square in cross section and 106 cm deep, topped by a square, stainless steel cold plate. The authors reported that

1) the oil, when injected under the ice, was pocketed below the ice surface and as freezing continued more ice formed beneath the oil,
2) the oil acted as an insulating layer impeding the flow of heat, and
3) a crude oil spill under first-year sea ice would spread to a mean thickness of 0.7 cm.

In field experiments, Glaeser and Vance (2) found that North Slope crude oil released under multi-year sea ice did not disperse, but rose to the ice-water interface and pocketed in holes. In one instance, a drum (55 gal or 250 l) of oil released under a fairly flat subsurface was pocketed in numerous small holes; there was no current in the area and one day later the oil had spread to a slightly larger area. It was concluded that crude oil, if given the opportunity, would flow under multi-year sea ice because of hydrostatic conditions.

In a discussion on the possible fate of oil in the Arctic basin, Ramseier (3) suggested that the diffusion or spreading of oil under ice would take a very complex form, contaminating vast areas over a period of years, and estimated that owing to current, the rate of movement of oil under the ice near the North Pole would be around 800 cm per day. Furthermore, no ageing of oil would occur under ice.

Observations reported from accidental spills of oil under ice are also very limited. At the Arrow spill in Chedabucto Bay (4), oil drops were observed in the bottom 5 cm of a 20-cm ice cover, and the distribution suggested that the oil was migrating through the ice; whereas in the Deception Bay spill (5), the oil was found to follow the vertical tidal movement with the ice and also was displaced by the horizontal movement of ice from one spot to another.

To assess the effect of oil spilled in ice-covered rivers and to assist in developing clean-up techniques for such an oil spill, more must be understood about the behaviour of oil spilled under ice. This report investigates the behaviour of oil spilled under ice and surveys the behaviour of accidental oil spills in Canadian rivers.

EXPERIMENTAL

Equipment

A circular aluminum basin, inner diameter 150 cm and 70 cm deep, was installed in a cold room where the air temperature was maintained at -15° ±3°C (Fig. 1). The cold room was equipped with a fan to ensure uniform air flow and heat transfer in the basin. Heating tapes were glued to the outside wall of the tank and covered with polystyrene insulation 10 cm thick. The heating tapes were connected to Variacs set at very low power to cancel out the bottom and side heat losses. This combination of heating tapes and insulation allowed one-dimensional freezing in the basin and effectively simulated the growth of natural ice similar to the type found in lakes, reservoirs and rivers with low flow velocities.

The ice thickness was measured with ice thickness gauges (6). The gauge was a small steel cylinder suspended by a wire under the ice. To measure the thickness the cylinder was raised to the ice-water interface, and the distance from the ice-air interface was measured and subtracted from the total wire length.

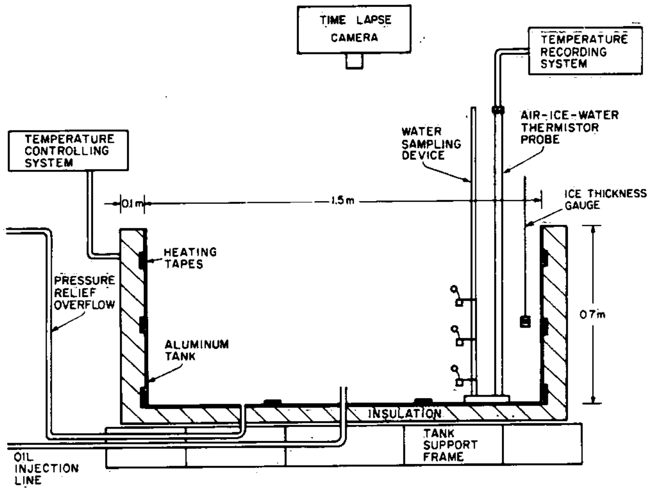

Figure 1. Schematic diagram of the circular basin.

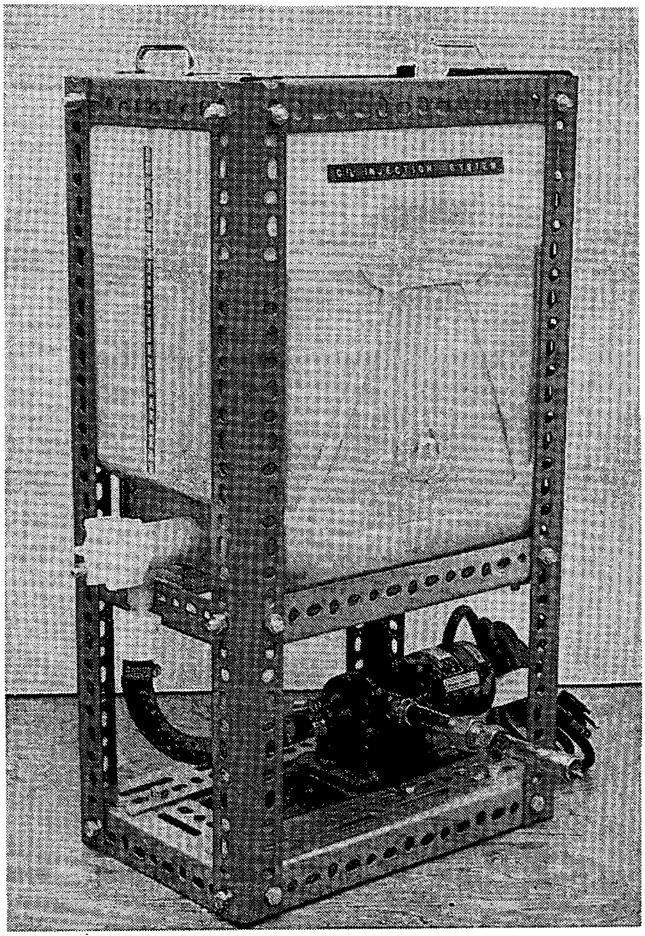

Figure 2. Oil injection system.

An air-ice-water thermistor probe obtained a temperature profile with relative accuracy of ±0.2°C. The probe contained 19 precision thermistors, manufactured by Yellow Springs Instruments (YSI No. 44033), mounted in a PVC rod at a separation of 1 cm in the ice and 5 cm in the air and water. Each thermistor solder joint and wire was waterproofed with epoxy resin. A multiconductor plug was installed at the top of the probe for connection of the bridge circuit. A rotary switch enabled each thermistor to be switched into the bridge, to be balanced, and to record resistance.

Most oil spilled under the ice is initially hot because the transit temperatures of the well head, tanker and pipeline are about 60°C. The crude, however, was injected at a room temperature of about 20°C, as heating of oil in the laboratory is dangerous. The oil injection system was a 25-litre plastic tank and gravity-fed electric pump (Fig. 2). The system is portable and can easily be carried into the cold room and connected to the oil injection pipe.

Procedure

The typical test procedure was as follows. The basin was filled with water to a height of 60 cm at a room

Table 1a. Properties of Norman Wells Crude Oil

Pour point: -50°C	Colour: dark green
Degree API at 15°C: 38.4	Specific gravity at 15°C: 0.833
Surface tension at 24°C: 27.8 dynes/cm	Interface tension (with water) at 24°C: 21.0 dynes/cm

Table 1b. Components of Norman Wells Crude Oil

Components	Percent by volume (approx.)
Light gasoline	10.5
Total gasoline and naphtha	35.6
Kerosene distillate	5.7
Gas oil	19.5
Nonviscous distillate	8.1
Medium distillate	5.7
Viscous distillate	2.9
Residuum	21.5
Distillation loss	1.0

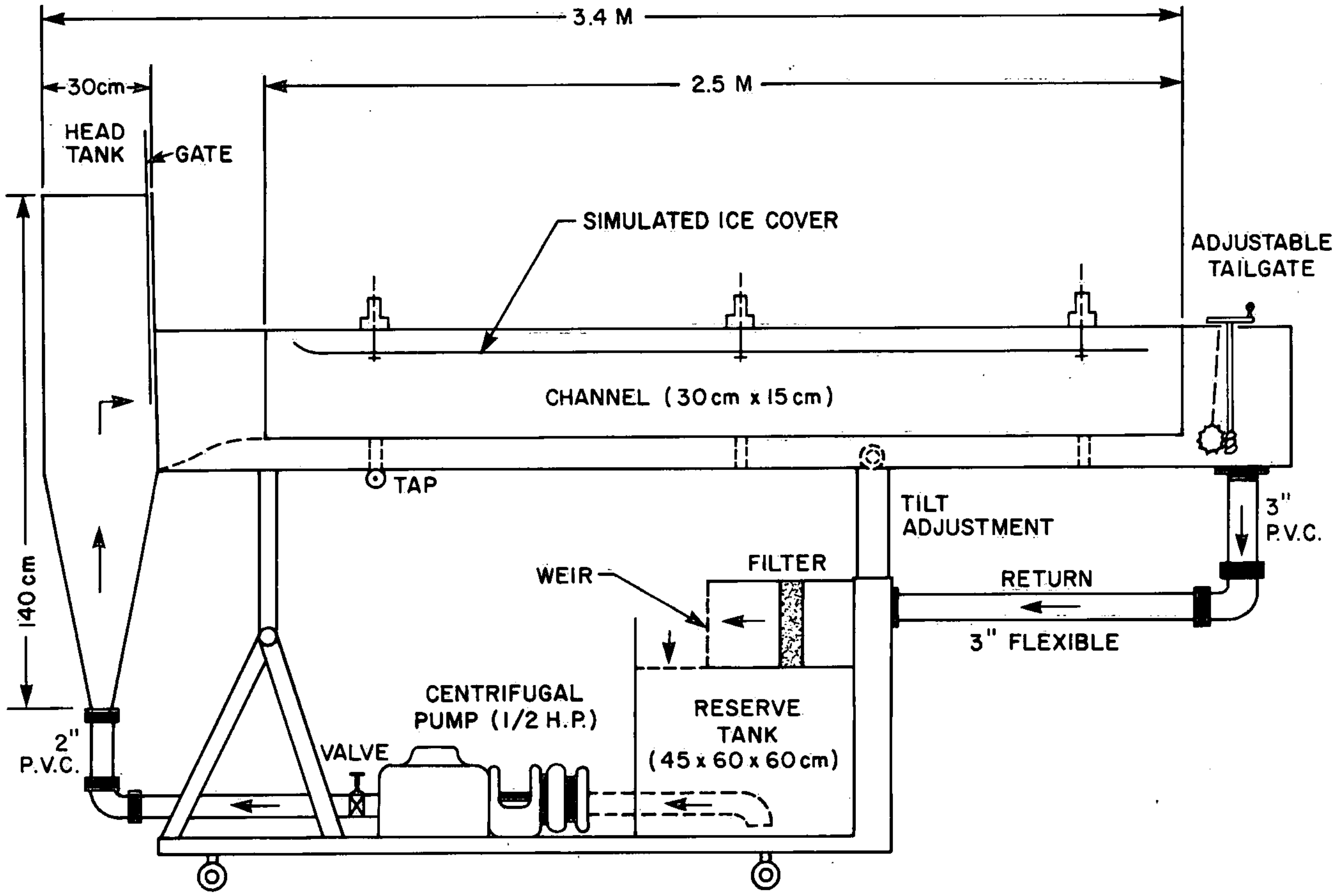

Figure 3. Schematic diagram of the recirculating flume.

temperature of -15°C. Two days later, a primary ice layer began to form. Its growth was predominantly in the horizontal plane, forming a very thin ice layer. The secondary ice grew parallel to the heat flow, perpendicular to the water surface and reached the desired thickness three days later. The crude oil (5 l at 20°C) was pumped for about 70 s through a 1.27-cm pipe and released 30 cm below the ice-water interface in the centre of the basin.

For some experiments carried out under a circular current, an electric outboard motor was mounted on the side of the basin, and a circular oil boom was installed to prevent the oil from rising up the tank walls and spreading over the ice surface. The outboard motor was turned on when the basin was filled with water and left running for the duration of the test. A detailed velocity profile across the basin was not obtained. A small current meter, however, indicated an average velocity of about 10 cm/s.

A few tests were made in a simulated ice-covered flume with water flowing in one direction. The recirculating flume was 250 cm long, 15 cm wide and 30 cm deep (Fig. 3). A screw-type valve controlled the flow from the circulation system into the flume, and the depth of flow was established by adjusting the tailgate setting. The average current in the flume was around 15 cm/s. The flume was filled with water of 6°C and the centrifugal pump maintained a continuous flow of water. Two litres of crude oil of 20°C was injected under the Plexiglas cover from a pipe 1.27 cm in diameter.

Norman Wells crude oil was used in this investigation; its properties are given in Table 1.

BEHAVIOUR OF OIL UNDER ICE

Droplet Formation

When crude oil is injected under ice in water, being the same as dispersing a liquid in an immiscible liquid medium, oil droplets will be formed. The drop size is a function of the properties of both the liquids and the geometry of the injector. Generally speaking, the drop size is increased by increased interfacial tension, decreased difference in density between the two liquids, increased viscosity of the aqueous phase, and by increased opening of the injection nozzle; it is practically unaffected by viscosity of the dispersed phase.

The formation of a droplet depends also on the flow rate of oil. At low flows, drops will form individually at the nozzle tip and grow in size until the buoyancy force overcomes the interfacial tension force and the drop is released. At increased flow rate, a point will be reached where a continuous liquid jet exists between the nozzle tip and the point of drop detachment. Additional increase in the flow rate will rapidly lengthen the jet until a maximum value is attained while the jet takes on a ruffled appearance at its outer end and the drops formed become less uniform. Increasing the flow rate more will decrease the jet length and increase drop nonuniformity until the jet breakup point retreats to the nozzle tip, where a nonuniform spray of rather small drops results.

The drop sizes in a liquid-liquid system can be estimated by known methods. Hayworth and Treybal (7) found that drop size is uniform and increases with nozzle velocity, i.e., the flow rate divided by the cross-sectional area of the nozzle, up to 10 cm/s, decreases and becomes less uniform from 10 cm/s to 30 cm/s and is erratic and unreproducible at higher nozzle velocity. By considering the forces acting upon the drop during formation, a semi-theoretical equation was derived, and a chart was prepared from which the droplet diameter could be calculated for a nozzle velocity up to 30 cm/s. Null and Johnson (8) developed a method for predicting the drop diameter for flow rate in the range of

$$0 \leq \left(D_n v_n^2 \ \rho_d/\sigma\right)^{0.5} \leq 1.4$$

where D_n is the nozzle diameter, v_n is the nozzle velocity, ρ_d is the density of the dispersed phase, and σ is the interfacial tension. From knowledge of the physical properties of the system, the drop size may be computed from a series of charts given by them.

In this investigation, the crude oil was injected through a pipe, 1.27 cm (0.5 in.) in diameter, 30 cm below the ice-water interface with a flow rate of 70 ml/s. The nozzle velocity, v_n, and $(D_n v_n^2 \ \rho_d/\sigma)^{0.5}$ were calculated to be 13.8 cm/s and 3.1, respectively. As the density of Norman Wells crude is 0.83 g/cm³ and the interfacial tension around 21 dynes/cm, the calculated droplet diameter is 1.2 cm using the method of Hayworth and Treybal. (See Appendix A, Section 1, for the calculation.)

It was observed that the crude, while injected under the ice in water, formed a liquid jet of approximately 20 cm in length, broke up into drops of 0.1 cm to 2.0 cm in diameter, and then rose to the ice-water interface. Most of the drops, however, were found to be around 1.0 cm in diameter and were in fair agreement with the value calculated. The smaller drops are the so-called secondary drops, whereas the larger drops could be the result of coalescence during the rising period. An oil drop, 1.0 cm in diameter, resting at the ice-water interface is shown in Figure 4.

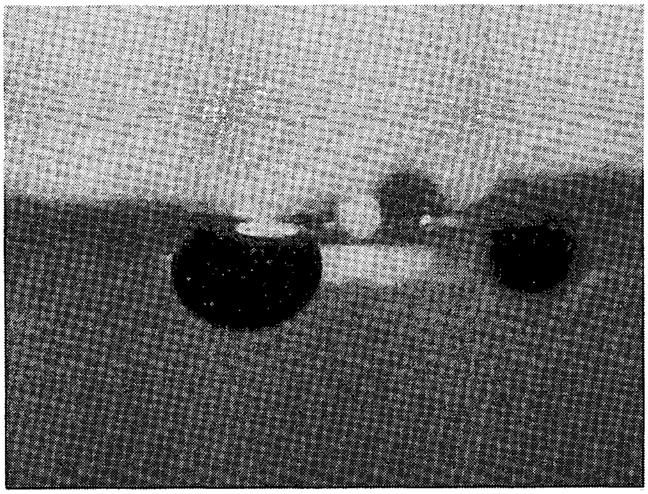

Figure 4. **Oil drop at the ice-water interface.**

Emulsification

If the water under ice is relatively calm, the oil drops formed will rise at their terminal velocities to the ice-water interface. The behaviour of drops in a liquid medium is much more complicated than that of rigid spheres, as the drops undergo deformation, oscillation and internal circulation during the rising period. The internal circulation is known to increase the drop rising velocity, while prolate-oblate type oscillation reduces the velocity; the deformation causes an increase in the total surface area producing a higher drag coefficient and thus a smaller rising velocity.

Several correlations are available for predicting the drop terminal velocity. For the present system, the equation by Klee and Treybal (9) is used, and the terminal velocities for oil drops with a diameter of 0.1 cm, 1.0 cm and 2.0 cm are calculated to be 4 cm/s, 21 cm/s and 35 cm/s, respectively. (See Appendix A, Section 2, for the calculation.)

If sufficient turbulence exists in the water, instead of rising quickly to the ice-water interface, the oil drops may be broken up further and dispersed in the water column; then an oil-in-water emulsion is formed. Once the emulsion is formed, it may be stabilized by the hydrophilic groups such as $-COO^-$, $-OH^-$, $-CHO$, OSO_3^{2-} and $-SO_3H$ which occur naturally in the crude (10). Chen reported (11) that crude oil-in-water emulsions are fairly stable; emulsion droplets less than 4 μm in size are stable in water for weeks, whereas emulsions containing 10 ppm to 100 ppm of oil are stable for months. If the emulsions are subjected to freezing-thawing cycles, they will partially break down owing to coalescence of the drops caused by the mechanical effect of ice formation (12).

In the experiment of oil under ice with current, it was observed that oil drops 0.1 cm to 0.5 cm in diameter became dispersed in the water column. Droplets of these sizes, however, are not classified as an emulsion; they are suspended in water due to the circular current which prevents them from freely rising to the ice-water interface. In an actual case, e.g., an oil spill under the Arctic ice, oil-in-water emulsions are expected to be formed because the motion of the rough bottom topography of the pack ice relative to the underlying ocean is bound to generate a turbulent flow in the water.

As oil drops rise to the ice-water interface and coalesce there to form a slick, water-in-oil emulsions may also be formed. The water-in-oil emulsion consists of droplets of water enclosed in sheaths of oil and is rendered stable by the presence of various resinous and asphaltic materials which also occur naturally in crudes. This type of emulsion is known to be extremely stable and may contain up to 85% water (13,14). The resultant water-in-oil emulsion differs in properties, especially in viscosity, from the original oil. The viscosity may increase in value up to a power of 3; it is a function of the water content and exhibits a maximum (15). For the crude oil used in this investigation, the water-in-oil emulsion has a maximum viscosity which is ten times the value of the original oil at a water content of around 55% (Appendix B).

In the experiment of oil under ice with a circular current, the change in colouring toward a chocolate-brown, which signals the formation of a water-in-oil emulsion, was observed. Samples of the oil taken one day after oil injection under the ice were found to contain 23% water. This confirms the existence of a water-in-oil emulsion. Yet samples taken one day after the spill under no current conditions were found to contain only 700 ppm water, indicating that water-in-oil emulsions will not be formed if the water is calm. The coalescence of oil drops at the ice-water interface alone does not create sufficient turbulence to produce the emulsion.

The water content in the crude was determined by the Karl Fischer method using a Metrohm automatic titrator.

Dissolution

When crude oil is in contact with water, its water-soluble components begin to dissolve and leach out. Lee and Craig (16) identified these water-soluble components to be the low-boiling aromatic hydrocarbons, namely, benzene; toluene; m-, p-, o-xylenes; ethylbenzene; m-, p-ethyltoluenes; 1,2, 4-trimethylbenzene; and 1,2, 3-trimenthylbenzene. The total solubility of these components in water was found to range from 0.5 ppm to 1.6 ppm depending on the crudes. Although the low-molecular weight hydrocarbons have a finite solubility in water, their solubilities must be negligible since they have not been identified in the water extract.

The transfer of these water-soluble components may take place during the drop formation period; the period in which the drops freely rise; coalescence at the interface; or when the oil remains as a slick under ice. It is believed that most of the mass transfer occurs during the drop rising period, since other periods either have a very short contact time or have a rather small contact area. To estimate the mass transfer rate, i.e., the dissolution rate, the mass transfer coefficient, k, from the drop surface to the aqueous phase must be determined first. Generally, k is correlated with the physical and flow properties of the system from the functional relationship

$$N_{Sh} = f\left(N_{Re}, N_{Sc}\right)$$

where N_{Sh}, N_{Re} and N_{Sc} are the Sherwood number, Reynolds number and Schmidt number, respectively. Considering oil drops of 0.1 cm in diameter (d = 0.1 cm) with a rising velocity of 4 cm/s and using Grassman's correlation (17), the Sherwood number (N_{Sh} = k d/D) was calculated to be 318; the diffusion coefficient (D) of the soluble hydrocarbons in water at 0°C was taken as 0.5 x 10^{-5} cm^2/s (18). Accordingly, the mass transfer coefficient was estimated to be

$$2.18 \times 10^{-3} \text{ g/(s)} - \left(cm^2\right) - \left(g/cm^3\right)$$

Assuming that the crude contains 1% of water-soluble compounds, then the dissolution rate is

$$1.8 \times 10^{-5} \text{ g/s-cm}^2$$

For oil drops of 0.1 cm in diameter and containing 1% of water-soluble compounds, the time required to leach out half of the soluble compounds is 7.6 s provided that the concentration does not change with time. (See Appendix A, Section 3, for details of all the calculations.) Smaller drops will give a higher dissolution rate. These values are based on certain assumptions and are in no way accurate. Nevertheless, they do give an idea of how fast the water-soluble components are being leached out during the drop rising period.

Besides dissolution, other ageing processes such as evaporation, oxidation and biodegradation are believed to be negligible as the crude is spilling under the ice and temperature of water is close to freezing.

Spreading

The spreading of oil under ice, by analogy to the spreading of oil on water or on ice, passes through three stages: gravity-inertia, gravity-viscous, and surface tension-viscous. In each stage, one spreading force is balanced by a retarding force. Here the gravity should be replaced by the buoyancy. Yet in continuous spreading of oil under ice, the buoyancy-viscous region should be of primary importance because surface tension spreading is not likely to happen and the buoyancy-inertia spreading, which occurs only in the first few seconds, will not be observed.

Using the argument of Chen, Overall and Phillips (19), the outward pressure force, F_p, caused by buoyancy per unit volume, is

$$F_p = F_b = c\,\rho_w\,ghA/V = c\,\rho_w g \qquad (1)$$

and the viscous force, F_v, per unit volume is

$$F_v = \tau A/V = \mu(du/dh)\ (A/V) = \mu R/(t\,h^2)$$
$$= \pi\mu\ R^5/(t\,V^2) \qquad (2)$$

where

F_b = buoyancy force per unit volume
c = constant
ρ_w = density of water
g = gravitational constant
A = area of oil slick = πR^2
R = radius of oil slick
V = oil volume = h A
h = thickness of oil slick
τ = shear stress
μ = oil viscosity
u = spreading velocity
t = elapsed time.

For buoyancy-viscous spreading at equilibrium, the two forces are equal, that is

$$c\,\rho_w g = \pi\mu\,R^5\,/\left(t\,V^2\right) \qquad (3)$$

As the oil volume, V, is equal to (Q t), where Q is the rate of spilling, equation (3) becomes

$$t\,(Q\,t)^2\,c\,\rho_w g = \pi\mu\,R^5 \qquad (4)$$

The radius of the oil slick may therefore be expressed as a function of the elapsed time, t, as follows:

$$R = \left(\frac{c\,\rho_w g\,Q^2}{\pi\mu}\right)^{0.2} t^{0.6} \qquad (5)$$

As oil drops rise through water and coalesce at the ice-water interface, a layer of water may exist between the oil and the ice. Equation (5) may not then be correct since the viscous force, i.e., equation (2), is based on an oil layer. If the viscous force is based on a water layer, then, as suggested by Fay (20), the thickness of the water film so set into motion by the viscous force has the magnitude

$$\delta = \left(\mu_w\,t/\rho_w\right)^{0.5} \qquad (6)$$

where μ_w is the viscosity of water.

The viscous force per unit volume therefore is

$$F_v = \mu_w\left(R/t\right)/h\left(\mu_w t/\rho_w\right)^{0.5}$$
$$= \left(\mu_w\rho_w\right)^{0.5} R/\left(t^{1.5}\,h\right)$$
$$= \pi\left(\mu_w\rho_w\right)^{0.5} R^3/\left(Q\,t^{2.5}\right) \qquad (7)$$

Equalizing equations (1) and (7) gives

$$c\,\rho_w g = \pi\left(\mu_w\rho_w\right)^{0.5} R^3/\left(Q\,t^{2.5}\right) \qquad (8)$$

The radius of oil slick is equal to

$$R = \left(\frac{c\,\rho_w^{\ 0.5}\,g\,Q}{\pi\,\mu_w^{\ 0.5}}\right)^{0.3} t^{0.8} \qquad (9)$$

Spreading experiments of oil under ice in calm water were made to determine whether equation (5) or equation (9) is applicable. A plastic grid and a clock were placed on top of the ice. Five litres of Norman Wells crude

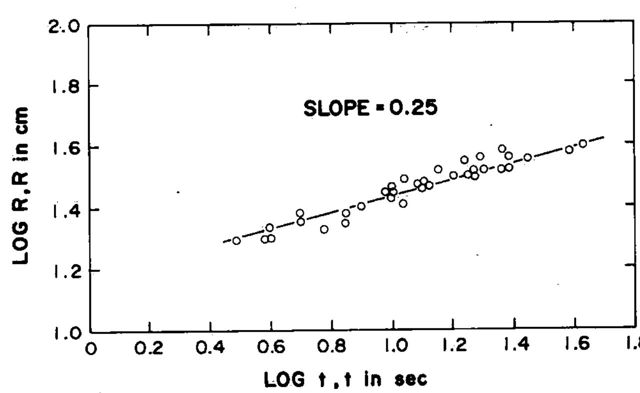

Figure 5. Log R vs log t – experimental results.

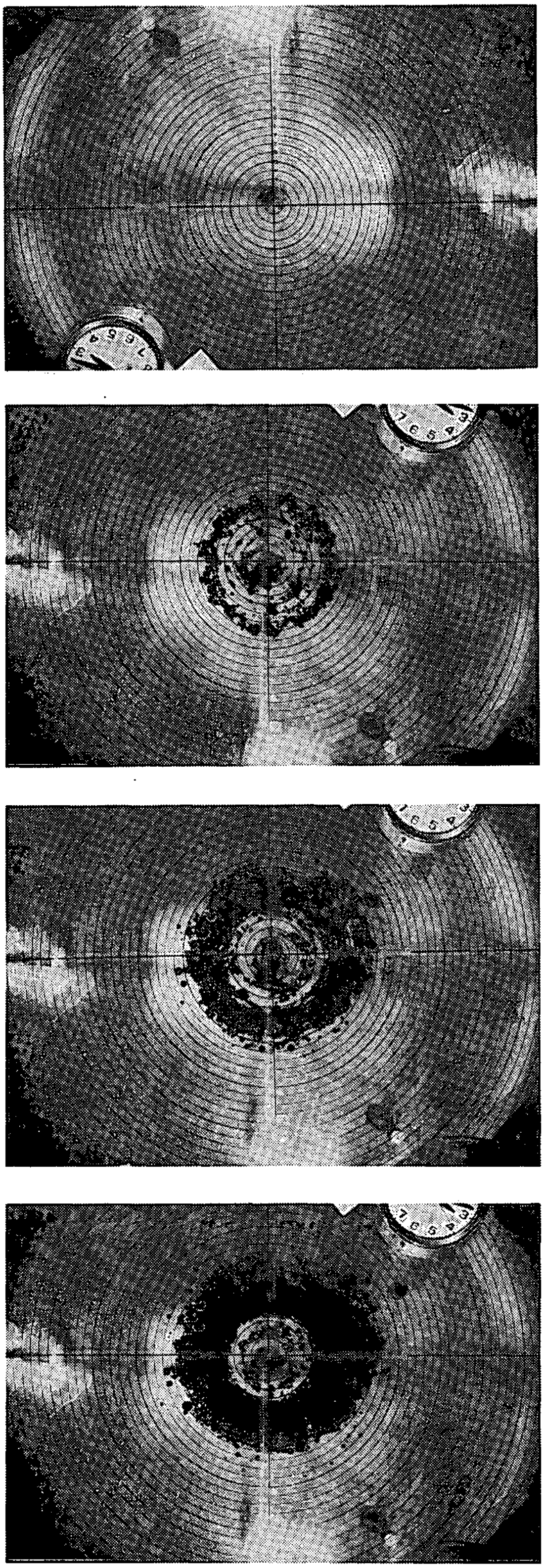

Figure 6. Time-lapsed photographs for oil spreading under ice: a) 0 seconds after release; b) 5 seconds after release; c) 10 seconds after release; d) 15 seconds after release.

oil was injected under a smooth ice surface at a rate of 70 ml/s, and the spreading motion was recorded by a camera. The rates of spreading were obtained by analyzing the time-lapsed photographs. The results were plotted as log R versus log t, as shown in Figure 5. (Spreading data are given in Table C-1.) The slope was found to be 0.25; it agrees neither with equation (5) nor equation (9). Yet this is not unexpected, as the spreading of oil under ice is complicated by the coalescence of oil drops at the ice-water interface. Besides, the physical process is different from that of oil on water or on ice; the oil comes to the ice-water interface as droplets; the oil drops coalesce to form larger drops which coalesce further and spread to form an oil lens with a few drops still remaining independent. Figure 6 shows four time-lapsed photographs taken at five-second intervals, and Figure 7 is an oil lens under ice three hours after the spill.

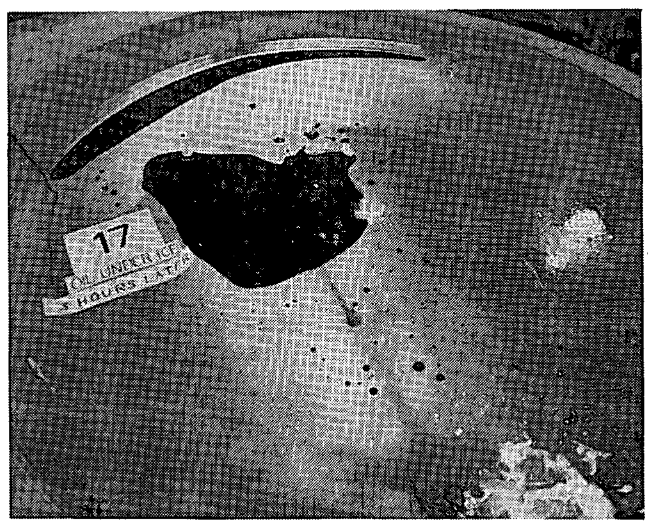

Figure 7. Oil lens under ice.

For the spreading of oil under a circular current, it was observed that the oil, when released, rose to the ice-water interface as droplets and circled around the basin (Fig. 8). The oil drops broke up and coalesced on account of the rotating motion and did not adhere to the smooth under-ice surface.

During another test under a circular current, freezing of slush ice produced a very rough and uneven ice-water interface. After injection most of the oils were found collected in holes and pockets, and one day later were sandwiched by the growing ice (2 cm/day).

In the tests with water flowing in one direction using the recirculating flume, it was observed that the oil, when injected, separated into droplets and rose to the interface following the direction of flow, as is shown in Figure 9. The oil formed an oil layer that varied from 0.3 cm to 1.0 cm in thickness.

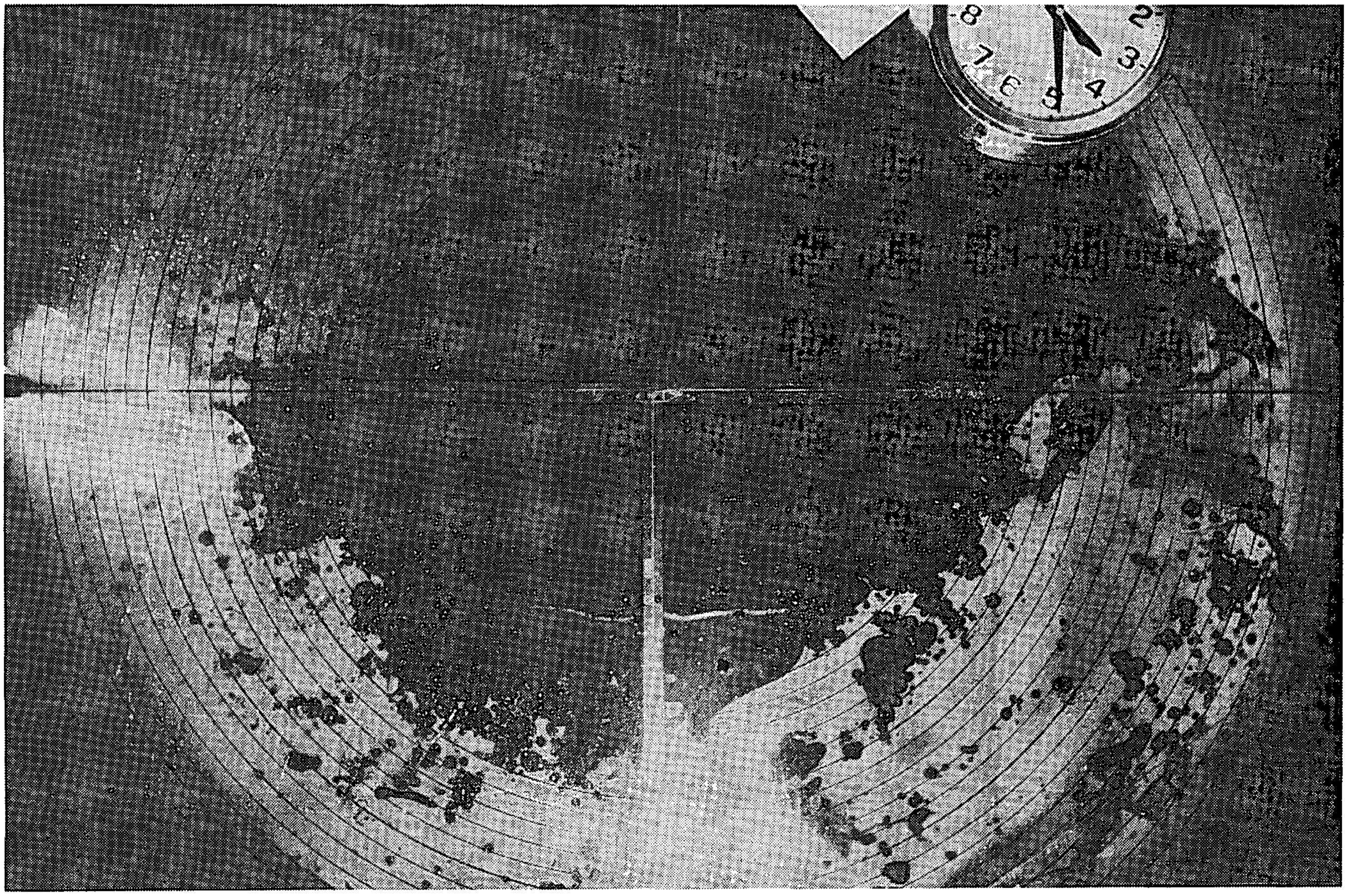

Figure 8. Oil under ice with a circular current.

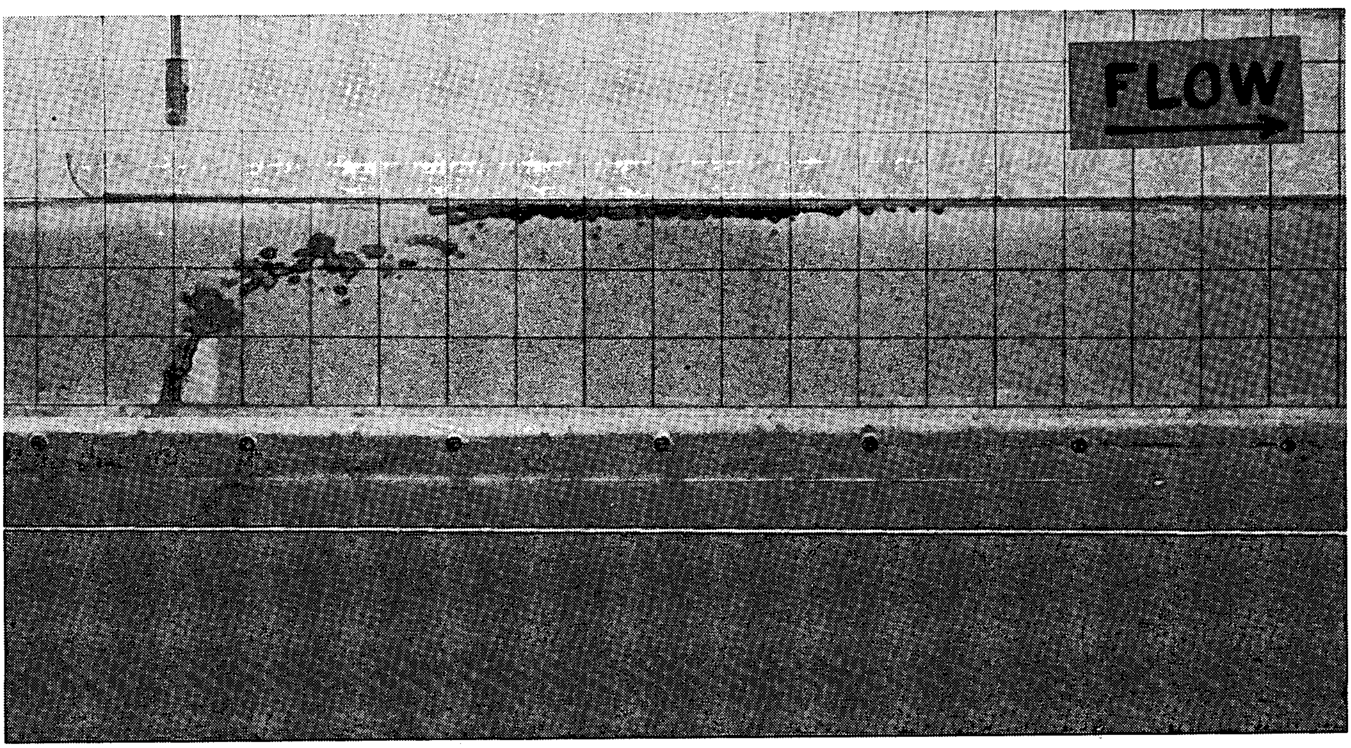

Figure 9. Oil under ice with water flowing in one direction.

Thermal Effect

It is known that an ice surface covered with black crude oil will absorb more solar radiation than will the clean ice, consequently leading to an increase in melting rate of the ice. But when oil is spilled under ice, the effect of oil on the absorption of solar radiation will likely be negligible, since the oil will be located far below the ice surface. Most of the solar radiation will not penetrate through a thick ice layer and reach the oil; it is known not to penetrate through 10 cm of snow (21). Moreover, the ice, as a nonconductor, will absorb practically all incident infrared radiation in very thin layers immediately below the surface (22), and only 8% of the total solar radiation will penetrate through 30 cm of river ice (23).

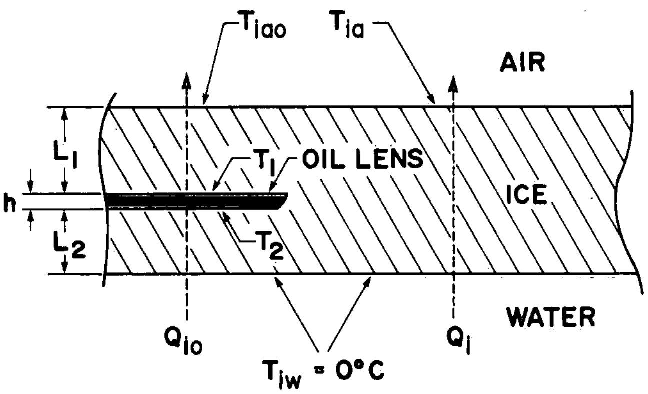

Figure 10. Schematic diagram of oil sandwiched between ice layers.

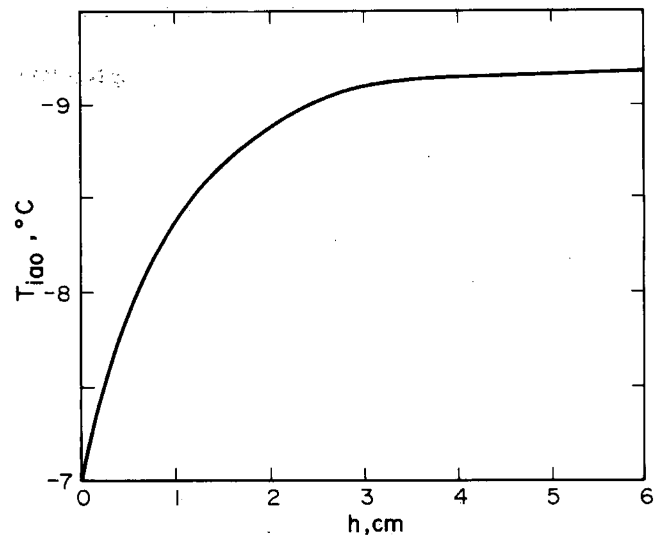

Figure 11. Temperature of ice surface, T_{iao}, as a function of oil lens thickness, h.

Although the oil may not have any significant effect on the absorption of solar radiation when it is under a thick layer of ice, it will certainly affect the transfer of heat through the ice because the thermal conductivity of crude oil (24) (0.0003 cal/s-cm-°C to 0.0004 cal/s-cm-°C at 0°C) is smaller than that of ice (25) (0.005 cal/s-cm-°C at 0°C). The effect may be seen from the following example.

If an oil lens is sandwiched between the ice, as shown in Figure 10, the amount of heat transfer per unit area

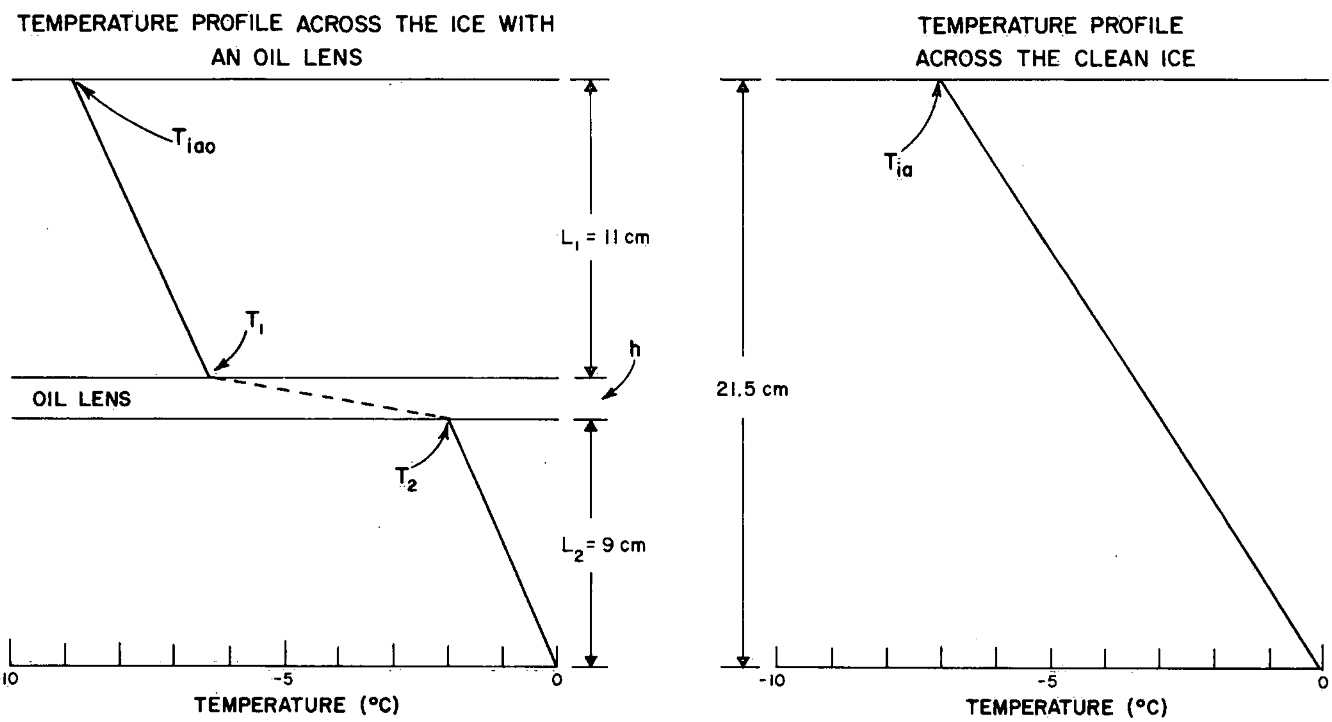

Figure 12. Temperature profiles —a sample of calculation.

through the clean ice, Q_i, and through the ice with an oil lens, Q_{io}, is, respectively,

$$Q_i = \frac{K_i\left(T_{ia} - T_{iw}\right)}{\left(L_1 + h + L_2\right)} \tag{10}$$

$$Q_{io} = \frac{K_i\left(T_2 - T_{iw}\right)}{L_2} = \frac{K_o\left(T_1 - T_2\right)}{h} = \frac{K_i\left(T_{iao} - T_1\right)}{L_1} \tag{11}$$

where K_i is the thermal conductivity of ice and K_o, the thermal conductivity of oil. The temperature at the ice-water interface, T_{iw}, must be 0°C, whereas the temperature at the ice-air interface depends on the air temperature and the age of the ice. Assuming that temperatures along the ice-air interface are all at -7°C ($T_{ia} = T_{iao} = -7$°C) and if $h \doteq 1.5$ cm, $L_1 = 11$ cm, and $L_2 = 9$ cm, then $Q_i = 5.86$ cal/cm²-hr and $Q_{io} = 3.04$ cal/cm²-hr. The ice growing rates under the clean ice and under the ice with an oil lens were calculated to be 1.90 cm/day and 0.99 cm/day, respectively. Temperatures at the top and bottom of the oil lens were -5.14°C and -1.52°C, respectively.

As crude oil is a better insulator than the ice and since the heat is transferring from the water to the air, the temperature at the ice-air interface for ice with an oil lens should be lower than that of the clean ice. The assumption made previously that both temperatures (T_{iao} and T_{ia}) are equal to -7°C is therefore incorrect. Based on this, however, T_{iao} may be estimated by trial and error; it is -8.7°C using the value of -5.14°C for T_1 and the slope of the temperature profile across the clean ice (Fig. 11 is a

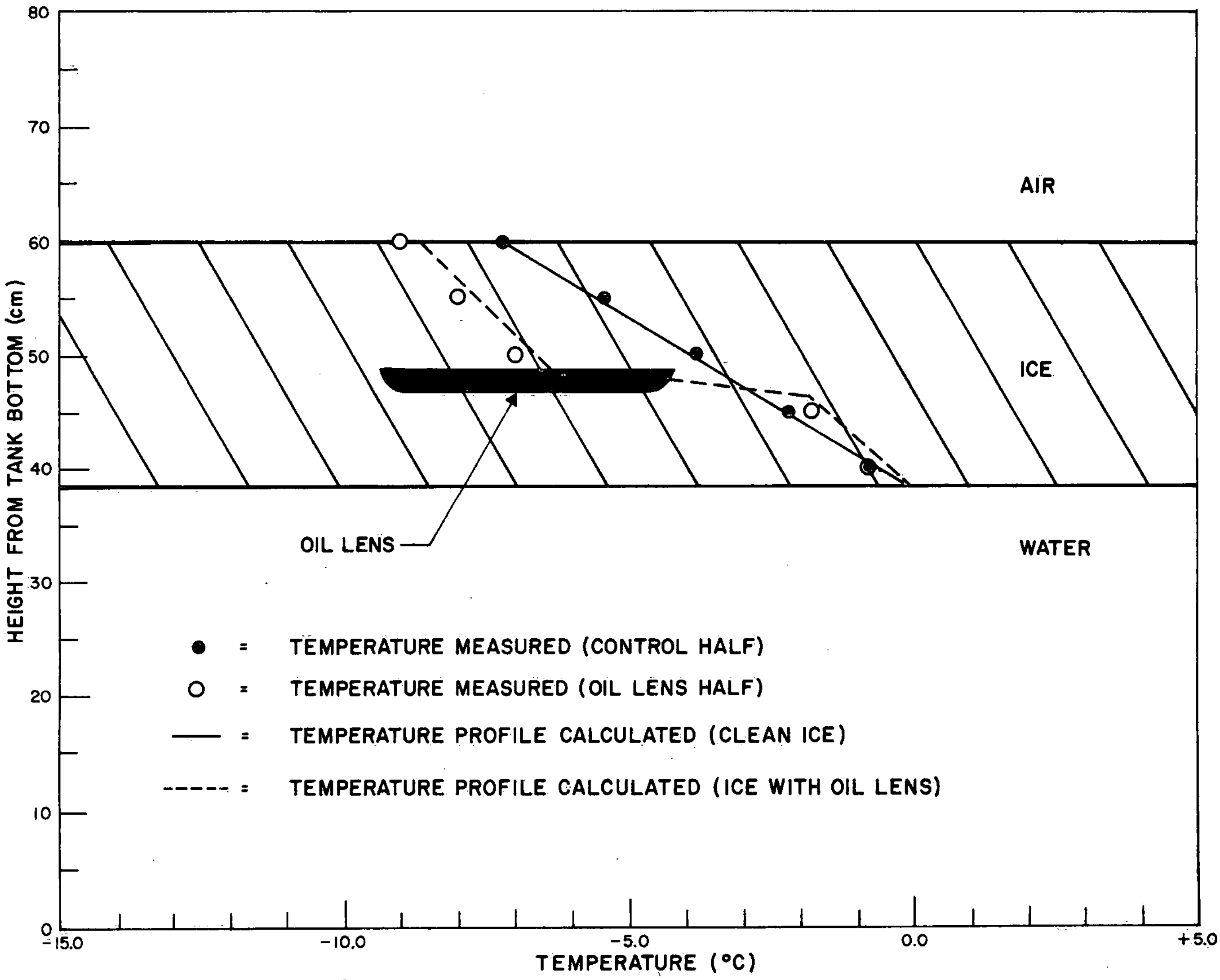

Figure 13. Measured vs calculated temperature profiles across the ice seven days after the oil spill.

plot of T_{iao} versus h). The recalculated value for Q_{io} was 3.91 cal/cm^2-hr and the ice growing rate, accordingly, 1.27 cm/day. The calculated temperature profile across the ice with an oil lens and the temperature profile across the clean ice are shown in Figure 12. (Details of all calculations are given in Appendix A, Section 4.)

To investigate the thermal effect of a sandwiched oil lens, experiments were carried out by dividing the circular basin in half with polystyrene. One half was a control; in the other, oil was injected under 11 cm of ice forming an oil lens about 1.5 cm thick. Ice was growing continuously, and the oil lens was sandwiched between the ice one day after the spill. Figure 13 shows the measured temperature profiles and the calculated temperature profiles across each half of the ice seven days after the oil spill (all experimental data are given in Appendix C). It is seen that the measured temperature profiles are in good agreement with those calculated. The ice growing rate was about 2 cm/day, which agrees with the theoretical value (1.90 cm/day) for the clean ice. The total ice thicknesses between the halves, i.e., between the clean ice and the ice with an oil lens, however, showed no significant difference; this is contrary to the prediction by calculations.

REPORTED OIL SPILLS IN CANADIAN RIVERS

To understand the behaviour of accidental oil spills in rivers, a survey of the recent oil spills in Canadian rivers was made. A summary is given in Appendix D. The information was gathered from the *Significant Event Reports* prepared by the National Environmental Emergency Centre of the Environmental Protection Service, Department of the Environment, Ottawa. As some of the events are reported by lay observers, figures on gallons spilled could be inaccurate; nevertheless, these reports are the only up-to-date sources of data on accidental oil spills in Canada.

From August 1972 to December 1974, 68 oil spills in or near Canadian rivers have been reported with a total spillage of about one million gallons (4,546,000 l). Only oil spills directly into rivers and streams or land spills with oil flowing into rivers via sewers and ditches were considered. Originally, it was hoped that some documentation on the downstream spread of a river oil spill or observations of what happened to the oil would be found. Most reports, however, only mention that spilled oil disperses rapidly in fast flowing waters.

The 68 reported oil spills are categorized according to the following causes: 1) marine spills that include tanker collisions, groundings and transfers; 2) road spills that include tank truck accidents and transfers; 3) railroad accidents; 4) pipeline failures that include transmission lines and also connecting lines between storage facilities; 5) stationary sources; and 6) unidentified slicks. The spills are summarized in Figure 14 and in Table 2. An analysis of frequency may be misleading if the volume of oil spilled is not simultaneously considered. For example, in Figure 14 pipelines account for 24% of the number of

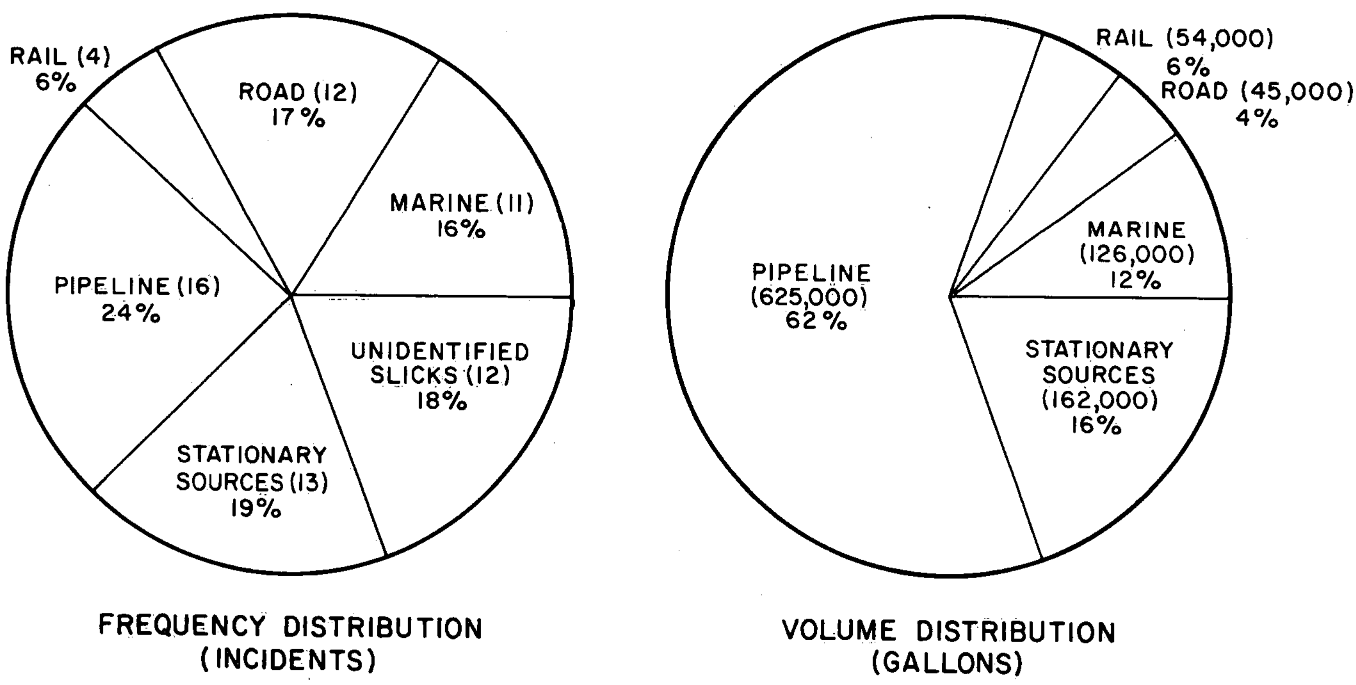

Figure 14. Accidental oil spills in Canadian rivers.

spills but 62% of the volume of spilled oil in rivers. This indicates that pipelines continue to be the most serious source of oil spilled in rivers.

Table 2. Accidental Oil Spills in Canadian Rivers, August 1972 to December 1974

Type	Number of incidents	Percent of total incidents	Gallons spilled	Percent of gallons spilled
Marine	11	16	126,000	12
Road	12	17	45,000	4
Rail	4	6	54,000	6
Pipeline	16	24	625,000	62
Stationary sources	13	19	162,000	16
Unidentified slicks	12	18	unknown	-
Totals	68	100	1,012,000	100

Only seven major spills greater than 20,000 gal (90,920 l) have been reported, and of these only two in ice-covered rivers. The first spill occurred in March 1974 from a storage tank line at a fish processing plant on rivière Saint-Paul, Duplessis County, Quebec. The storage tanks were located about 15 m above sea level, 30 m from the river edge. A single 10-cm line runs from the tanks to a discharge point near the river. About 10 m from the river the pipe sagged between two supports because of 4-m snow cover, stripped the threads at a union and opened a gap about 0.2 m wide (26). The oil, about 27,000 gal (122,742 l), flowed down the bank and under ice 1.2 m thick. The period over which the spill occurred was unknown; it probably took a number of days for the tank to drain. Some 35 days after the spill, 6,600 gal (30,003 l), or about 25% of the total oil spilled, was still entrained in the ice and in the tidal crack system. Ice cores recovered seaward of the outer tidal crack yielded no free oil when melted, suggesting that tidal cracks serve as a barrier against the flow of oil along the bottom of the ice sheet. Most of the remaining 20,000 gal was removed by tidal flushing downstream.

The second spill occurred in Alberta in December 1974, when a 16-in. (40.64-cm) pipeline crossing underneath the House River ruptured. About 200,000 gal (909,200 l) of synthetic crude oil seeped from a steep bank about 300 m from the river. Some oil flowed into the river ice and toward an open water area 3.5 mi (5.6 km) downstream. Light traces of oil were found 3.5 mi downstream, but none was found at open water 5 mi (8 km) and 15 mi (24 km) downstream. Two days after the spill, a pool of oil on open water was successfully burned. Chicken wire and hay booms were deployed 3.5 mi downstream. About 25,000 gal (113,650 l) was recovered from a pond above a dam.

The only other documented oil spill in an ice-covered river occurred in Sweden (27). In February 1972, an estimated 250,000 gal (1,136,500 l) of diesel oil was spilled under the frozen Ume River. The oil spread underneath the ice at the ice-water interface and collected in the hollow surfaces beneath the ice. The diesel oil was not usually sandwiched under the ice. When the oil was sandwiched, the thickness was estimated to be about 0.5 cm. In the initial stages of the spill, 100,000 gal (454,600 l) was contained in the ice and did not move more than 7 km downstream.

Two conclusions may be drawn from this survey of reported oil spills in Canadian rivers: 1) oil spilled in ice-free rivers is quickly dispersed downstream and 2) the behaviour of oil spilled in ice-covered rivers depends mainly on the ice conditions and the current at the time of the spill.

SUMMARY

The oil, when released in water under the ice, separates into droplets; the drops rise to the ice-water interface where they coalesce and form a slick.

In calm waters, the oil drops rise vertically and spread at the ice-water interface. The spreading process is complex. The radius of the oil slick is proportional to ~ 0.25 power of the elapsed time.

In turbulent waters, the oil drops also rise to the ice-water interface. They travel some distance following the flow direction of water, however, before reaching the interface. Some of the small drops are suspended and dispersed in the water column. The slick formed at the ice-water interface does not adhere to the ice and contains some water-in-oil emulsions.

The oil, when spilled under the ice, acts as an insulating layer and thus increases the temperature drop across the ice; the surface temperature of ice with an oil lens underneath is a few degrees lower than that of the clean ice.

If the oil is spilled as a lens under the ice and the ice continues to grow, the oil will be sandwiched between the ice layers.

The behaviour of oil spilled in ice-covered rivers is difficult to predict. Observations of accidental oil spills show that the oil, when spilled in a river, will quickly be dispersed downstream.

ACKNOWLEDGMENTS

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Significant Event Reports prepared by the National Environmental Emergency Centre, Environmental Protection Service, Ottawa, were used.

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Appendix A
Details of Calculations

DETAILS OF CALCULATIONS

1) Droplet Size

$D_n = 1.27$ cm
$Q = 70$ ml/s
$v_n = Q/(\pi D_n^2/4) = 13.8$ cm/s
$\rho_d = 0.83$ g/cm³
$\Delta\rho = 0.17$ g/cm³
$\sigma = 21$ dynes/cm
μ_w at 0°C $= 0.017$ poise
$\rho_d v_n^2/(\Delta\rho \times 30.48) = 1.0$

$$\frac{\sigma D_n}{\Delta\rho \times 62.4 \times 30.48} + \frac{396(D_n/30.48)^{1.12}(v_n/30.48)^{0.547}(\mu_w \times 100)^{0.279}}{(\Delta\rho \times 62.4)^{1.5}}$$

$= 0.29$

From the chart provided by Hayworth and Treybal (7), it was found that the droplet diameter

$d = 0.038$ ft $= 1.2$ cm

2) Terminal Velocity of the Drop

$\rho_w = 1.0$ g/cm³
$\mu_w = 0.017$ poise
$\Delta\rho = 0.17$ g/cm³

Using the equation by Klee and Treybal (9) for the region where the terminal velocity increases with drop diameter,

$$v_t = 38.3\,\rho_w^{-0.45}(\Delta\rho)^{0.58}\mu_w^{-0.11}\,d^{0.70}$$

For $d = 0.1$ cm, $v_t = 4$ cm/s
$d = 1.0$ cm, $v_t = 21$ cm/s
$d = 2.0$ cm, $v_t = 35$ cm/s.

3) Dissolution Rate during the Drop Rising Period

$d = 0.1$ cm
$v_t = 4$ cm/s
$\rho_d = 0.83$ g/cm³
$\rho_w = 1$ g/cm³
$\mu_w = 0.017$ poise
$D = 0.5 \times 10^{-5}$ cm²/s
$N_{Re} = d\,v_t\,\rho_w/\mu_w = 23.53$
$N_{Sc} = \mu_w/\rho_w D = 3.4 \times 10^3$

Using the equation given by Grassman (17)

$$N_{Sh} = k\,d/D = 2.0 + 0.6\,N_{Re}^{1/2}\,N_{Sc}^{1/3} = 45.65$$

$$k = N_{Sh}\,D/d = 2.18 \times 10^{-3}\ \text{g/s - cm}^2\text{ - (g/cm}^3)$$

If the crude contains 1% of water-soluble components, the concentration in g/cm³ is

$$\frac{1 \times \rho_d}{100} = 8.3 \times 10^{-3}$$

Therefore the mass transfer rate is

$$2.18 \times 10^{-3} \times 8.3 \times 10^{-3} = 1.81 \times 10^{-5}\ \text{g/s-cm}^2$$

The mass of an oil drop 0.1 cm in diameter is

$$\rho_d V = 0.83 \times 4.189\,(d/2)^3 = 4.3 \times 10^{-4}\ \text{g}$$

One percent of this is 4.3×10^{-6} g

and surface area of the drop is

$$\pi d^2 = 3.14 \times 10^{-2}\ \text{cm}^2$$

The time required to dissolve half of the soluble compounds in the drop, assuming that the concentration in the drop does not change with time, is

$$\frac{4.3 \times 10^{-6}}{1.81 \times 10^{-5} \times 3.14 \times 10^{-2}} = 7.6\ \text{s}$$

4) Heat Transfer and Temperature Profiles

$L_1 = 11$ cm
$L_2 = 9$ cm
$h = 1.5$ cm
$T_{iw} = 0$°C
$T_{ia} = -7$°C
$K_i = 0.005$ cal/s-cm-°C
$K_o = 0.00035$ cal/s-cm-°C

The amount of heat transferred through the clean ice

$$Q_I = \frac{K_i(T_{iw} - T_{ia}) \times 3600}{L_1 + h + L_2} = 5.86\ \text{cal/cm}^2\text{-hr}$$

The latent heat of fusion of ice is 79.7 cal/g.

If the water temperature is 1°C, it requires the removal of 80.7 cal of heat to produce 1 g of ice from water.

The ice growing rate under the clean ice is

$$\frac{Q_i}{80.7 \times \rho_i} \times 24 = 1.90 \text{ cm/day}$$

where ρ_i is the density of ice which is 0.917 g/cm³.

The temperature profile across the clean ice may be calculated from the following equation:

$$-T_L = \frac{Q_i \times L}{K_i \times 3600} = \frac{5.86\ L}{0.005 \times 3600}$$

where L is distance from the ice-water interface and T_L is the temperature there. Temperatures at 5 cm, 10 cm, 15 cm and 20 cm from the ice-water interface were calculated to be -1.63°C, -3.26°C, -4.88°C and -6.51°C, respectively. The temperature profile is with a slope of -0.326°C/cm.

Assuming that $T_{iao} = T_{ia} = -7°C$

$$Q_{io} = \frac{K_i(T_{iw} - T_2) \times 3600}{L_2}$$

$$= \frac{K_o(T_2 - T_1) \times 3600}{h}$$

$$= \frac{K_i(T_1 - T_{iao}) \times 3600}{L_1}$$

That is

$$-T_2 = 9\ Q_{io}/(0.005 \times 3600) \qquad \text{(a)}$$

$$T_2 - T_1 = 1.5\ Q_{io}/(0.00035 \times 3600) \qquad \text{(b)}$$

$$T_1 + 7 = 11\ Q_{io}/(0.005 \times 3600) \qquad \text{(c)}$$

Solving equations (a), (b) and (c) simultaneously,

Q_{io} = 3.04 cal/cm² - hr

T_1 = -5.14°C

T_2 = - 1.52°C

Because the oil is a better insulator than the ice and the heat is flowing upward, T_{iao} should be lower than T_{ia} and may be estimated by assuming that T_1 is -5.14°C and using the slope of the temperature profile across the clean ice, that is

$$(-5.14 - 11 \times 0.326) = -8.73°C$$

Equation (c) should be modified as

$$T_1 + 8.73 = 11\ Q_{io}/(0.005 \times 3600) \qquad \text{(d)}$$

Solving equations (a), (b) and (d), gives

Q_{io} = 3.91 cal/cm² - hr

T_1 = -6.33°C

T_2 = -1.96°C

The temperature profile across the ice with an oil lens may be calculated by the following two equations.

Above the oil lens

$$T_{L'} = T_1 - \frac{Q_{io} \times L'}{0.005 \times 3600}$$

$$= -6.33 - \frac{3.91 \times L'}{0.005 \times 3600}$$

where L′ is distance from the top of the oil lens and $T_{L'}$ is the temperature there.

Below the oil lens

$$T_L = \frac{3.91 \times (-L)}{0.005 \times 3600}$$

Appendix B

Viscosity of Water-in-Oil (Norman Wells Crude) Emulsions

VISCOSITY OF WATER-IN-OIL (NORMAN WELLS CRUDE) EMULSIONS

Water-in-oil emulsions containing various amounts of water were prepared by mixing Norman Wells crude oil with a desired amount of water using a Virtis 45 Homogenizer (at 10,000 rpm for 10 min). Viscosities of the emulsions were then determined by a Haake Rotovisko, which is a rotary viscometer. As the emulsions are non-Newtonian, their viscosities are no longer constant with respect to the shear rate, the "apparent" viscosity at a single rotation speed (at a velocity factor of 6) was used. Results are shown in Figure B-1.

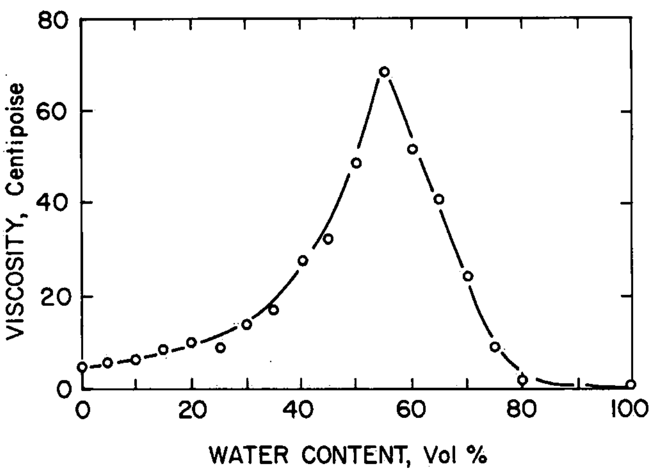

Figure B-1. Viscosity as a function of water content in the emulsion.

Appendix C
Experimental Data

Table C-1. Oil Spreading Data

	Elapsed time t (s)	Log t	Radius of oil slick R (cm)	Log R
Test 1	5	0.70	24	1.38
	10	1.00	28	1.45
	13	1.11	30	1.48
	18	1.26	32	1.51
	24	1.38	34	1.53
Test 2	1	0	10	1.00
	4	0.60	20	1.30
	6	0.78	22	1.34
	11	1.04	26	1.41
	16	1.20	32	1.51
	20	1.30	34	1.53
	24	1.38	36	1.56
Test 3	1	0	10	1.00
	7	0.85	24	1.38
	10	1.00	28	1.45
	13	1.11	30	1.48
	18	1.26	32	1.51
	23	1.36	34	1.53
	28	1.45	36	1.56
	38	1.58	38	1.58
	43	1.63	40	1.60
Test 4	1	0	10	1.00
	2	0.30	16	1.20
	3	0.48	20	1.30
	4	0.60	22	1.34
	5	0.70	24	1.38
	7	0.85	28	1.45
	10	1.00	30	1.48
	11	1.04	32	1.51
	14	1.15	34	1.53
	17	1.23	36	1.56
	19	1.28	38	1.58
	23	1.36	40	1.60
Test 5	1	0	4	0.60
	4	0.60	20	1.30
	8	0.90	26	1.41
	10	1.00	28	1.45
	13	1.11	30	1.48
	18	1.26	32	1.51

Table C-2. Temperature Profiles across the Ice (0-6 days)

Height from tank bottom (cm)	Day 0 control	Day 0 oil lens	Day 1 control	Day 1 oil lens	Day 2 control	Day 2 oil lens	Day 3 control	Day 3 oil lens	Day 4 control	Day 4 oil lens
70	-11.8	-12.2	-11.8	-13.2	-13.4	-14.8	-13.8	-14.8	-10.6	-11.6
65	-11.2	-11.6	-11.4	-12.8	-12.8	-14.4	-13.2	-14.4	-10.2	-11.4
60	-5.4	-5.8	-5.6	-9.2	-6.2	-9.6	-6.8	-11.2	-5.8	-7.8
55	-3.0	-3.2	-3.4	-7.8	-4.0	-8.2	-4.8	-8.6	-4.4	-6.8
50	-0.6	-0.6	-1.2	-6.4	-1.8	-6.8	-2.8	-6.0	-3.0	-5.8
45	0.0	0.0	+1.6	0.0	0.0	-0.4	-0.8	-0.8	-1.8	-1.4
40	0.0	0.0	+1.8	+1.2	+0.6	+0.4	0.0	0.0	-0.2	-0.4
30	+0.2	+0.2	+2.0	+1.8	+1.0	+1.0	+0.4	+0.4	+0.2	+0.2
20	+0.4	0.4	+2.0	+2.0	+1.4	+1.4	+0.4	+0.4	+0.4	+0.4
10	+0.8	+0.8	+2.2	+2.2	+1.8	+1.8	+0.8	+0.8	+0.8	+0.8
					Ice thickness (cm)					
	11.0	–	12.5	–	14.0	–	16.0	16.0	20.0	20.0

Table C-3. Temperature Profiles across the Ice (7-13 days)

Height from tank bottom (cm)	Day 7 control	Day 7 oil lens	Day 8 control	Day 8 oil lens	Day 9 control	Day 9 oil lens	Day 12 control	Day 12 oil lens	Day 13 control	Day 13 oil lens
70	-12.4	-12.4	-11.4	-12.2	-12.6	-12.4	-13.0	-13.8	-13.4	-13.2
65	-12.0	-12.4	-11.0	-12.0	-12.2	-12.4	-12.6	-13.4	-13.2	-13.0
60	-7.2	-9.0	-6.6	-8.6	-7.4	-9.8	-8.6	-10.6	-8.8	-13.0
55	-5.4	-8.0	-5.2	-7.6	-6.2	-8.8	-7.2	-9.6	-7.4	-9.8
50	-3.8	-7.0	-3.8	-6.6	-4.6	-7.6	-5.8	-8.6	-6.0	-8.6
45	-2.2	-1.8	-2.4	-1.8	-3.0	-2.6	-4.4	-3.8	-4.6	-4.0
40	-0.8	-0.8	-1.0	-1.0	-1.6	-1.4	-2.8	-2.6	-3.2	-2.8
30	+0.2	+0.2	+0.2	0.0	0.0	0.0	-0.2	0.0	-0.6	-0.4
20	+0.2	+0.2	+0.2	+0.2	0.0	0.0	0.0	0.0	0.0	0.0
10	+0.4	+0.4	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2
					Ice thickness (cm)					
	22.0	21.5	23.0	23.0	25.0	25.0	30.0	30.0	32.0	32.0

Appendix D

Summary of Reported Oil Spills in Canadian Rivers

Table D-1. Oil Spills Reported in Canadian Rivers

Oil spill location	Date	Cause	Volume spilled (gal)	Oil type	Oil behaviour
St. Lawrence River near Brockville, Ontario	August 3, 1972	unknown laker	minor	diesel	Two miles of shoreline was lightly covered; oil was concentrated in heavier pockets by winds and currents
Mackenzie River, Inuvik, N.W.T.	August 5, 1972	a barge transferring oil to a storage tank was left unattended and overflowed	38,000	diesel	Not reported
Rivière-du-Loup, Quebec	August 22, 1972	cracked pressure reservoir	20,000 to 30,000	diesel	The oil spilled from a cracked pressure reservoir, filled two wells, then flowed into Rivière-du-Loup about 3 mi upstream from the mouth of the St. Lawrence River. The oil passed over a waterfall, which mixed it with water, then through two log booms. The oil was also taken into a pulp company water supply
Black Creek, Toronto, Ontario	September 17, 1972	truck driver failed to shut off a pump	7,000	diesel	Oil boomed with sandbags and some recovered
Humber River, Toronto, Ontario	October 20, 1972	truck driver mistook a sewer breather pipe for a tank filling pipe	1,500	fuel	Contained and cleaned up
Humber River, Woodbridge, Ontario	November 13, 1972	tank truck traffic accident	1,000	fuel	Not reported
St. Lawrence River, Île Verte	November 22, 1972	experimental oil spill	270	Persian crude	Oil emulsified
La Tuque, Quebec	December 26, 1972	derailment of 26 railway cars	10,000	gasoline Bunker C	Five tank cars containing gasoline and 14 containing Bunker C toppled into the valley of Petite rivière Bostonnais. The gas cars ignited and eventually set the oil cars on fire. Some burning and unburned gas and oil flowed into rivière Saint-Maurice and spread downstream in a current of 22 mph. Isolated pools of oil collected in quiet bays and inlets downstream
Clarkson Harbour, Ontario	January 17, 1973	pipeline fracture	1,000	Bunker C	Oil spilled into a small creek which flows into Lake Ontario
Margaree River, Cape Breton, Nova Scotia	February 9, 1973	tank truck overflowed	1,000	stove and furnace	Oil was flushed down river
East Flamboro Township, Ontario	February 19, 1973	pipeline fracture	not reported		Oil flowed into creek and swamp; some areas of swamp had 3 in. pure oil on top of drainage water
Sainte-Anne-de-Bellevue, Montreal, Quebec	March 1973	unknown	unknown	black oil	A thick black oil covered a strip of shoreline about 0.75 mi long

Table D-1. Continued

Oil spill location	Date	Cause	Volume spilled (gal)	Oil type	Oil behaviour
Kaministikwia River, Thunder Bay, Ontario	March 1973	unknown	unknown	fuel	In December, small quantities of oil pools were observed on the river where the ice was open. It was suspected that the oil was seeping through the soil at a rate of 50 gal per week from a fueling facility. In March, mild weather increased surface runoff and additional oil was trapped behind a walled dock. When the ice broke up the oil came to the surface in pools and was contained by a vessel which had been tied up at the dock during the winter. About 25,000 gal of oil and water was recovered from behind the dock and 5,000 gal, from the river
Miramichi River, Newcastle, New Brunswick	March 1, 1973	fuel tank ruptured	300	furnace fuel	Furnace fuel tank ruptured in a variety store, the oil spilled into a sewage line and then into the Miramichi River. The river was covered with at least 16 in. of ice and nothing could be done to track, contain or clean up the spill
Mackenzie River, N.W.T.	April 1973	spilled from a tank being moved on a tracked vehicle	800	diesel	Ice-covered river, but behaviour not reported
Ottawa River, Papineauville, Quebec	June 11, 1973	semi-trailer truck with freight train	34,000	Bunker C	Oil spilled into a small brook and flowed into Ottawa River. A dam constructed 6 hours after the spill across the brook apparently contained most of the oil. Between 7,000 gal and 34,000 gal escaped to the Ottawa River
Athabasca River, Jasper National Park, Alberta	June 24, 1973	hairline fracture 4 in. long in 24-inch pipeline	20,000 to 30,000 (estimated)	sweet crude, specific gravity 0.85	Oil entered Athabasca River and was sighted 30 mi downstream; turbulent water emulsified and dispersed oil
Confluence of La Biche and Liard rivers, British Columbia	June 18, 1973	flood washed out tank farm	13,000	diesel	Not reported
Horners Creek, Brant Township, Ontario	July 24, 1973	pipeline ruptured by excavating machine	20,000 (estimated)	turbo fuel	Dams were constructed on main drainage system to intercept the fuel; about 9,000 gal of fuel and water mixture recovered
St. Clair River below Sarnia, Ontario	August 3, 1973	unknown	unknown	unknown	Thin film observed spreading 10 mi downstream
Ottawa River, East Aylmer, Ontario	August 26, 1973	unknown	unknown	unknown	Sludge coated 300 yd of waterfront
St. Lawrence River, Île des Soeurs, Quebec	September 6, 1973	unknown	minor	"heavy black oil"	Oil slick 600 ft by 50 ft; sheen clearly visible on top of algae
Deep Valley Creek, Alberta	September 11, 1973	storage tank overflowed and oil escaped through break in surrounding dike	8,400	crude	Oil eventually reached a tributary of Deep Valley Creek where it was contained about 2,000 ft from spill point

Table D-1. Continued

Oil spill location	Date	Cause	Volume spilled (gal)	Oil type	Oil behaviour
Mackenzie River, Fort Simpson, N.W.T.	October 11, 1973	children playing on dock opened valves on hoses	1,000 500	turbo fuel aviation gas	Fuels dispersed rapidly in fast-flowing river
East Prairie River, Alberta	October 18, 1973	8-inch pipeline pierced by .308 rifle bullet	52,000	Alberta medium crude	Oil flowed on land into East Prairie River then into South Heart River. Oil trapped by boom on East Prairie River and by log jam on South Heart River. About 35,000 gal recovered by skimmer pumps
St. Lawrence River, Saint-Lambert Lock, Quebec	November 6, 1973	puncture in ship tank	932	crude	Most of oil boomed and recovered in lock, 2 small slugs of oil escaped downstream and dispersed in fast waters
Montreal Harbour, Quebec	November 28, 1973	ship tank overflowed while refueling	400	No. 1500	Oil dispersed by current
Cooksville Creek, Ontario	January 15, 1974	tank truck traffic accident	2,700	Bunker	Oil flowed into creek via storm sewer
Matapedia River near Millstream, Quebec	January 21, 1974	train derailment	6,000	heating	Oil flowed into Matapedia River
Huron River, Sainte-Madeleine, Quebec	February 6, 1974	tank truck accident	3,500	heating	Oil flowed into Huron River via a ditch. Cleanup crew broke through ice to recover oil in river with pumps and Sorbent C
St. Lawrence River off Longue Pointe, Quebec	February 24, 1974	unknown	unknown	unknown	Unknown quantity trapped under ice
Caribou River, Yukon	February 24, 1974	Fuel truck overturned 60 ft from river	5,000	diesel	Entire contents of truck discharged onto bank of Caribou River. Some fuel burned off about 30 hours later. No fuel found in snow or ice of river
Rivière Saint-Paul, Duplessis County, Quebec	March 16, 1974	storage tank pipe broke	27,000	diesel	Oil flowed down hill and under about 4 ft of ice in Champlain Passage on the St. Lawrence River. About 6,000 gal trapped in ice around wharf, but most escaped downstream under ice. Holes cut through ice showed less than 1 % by volume of oil in ice
St. Lawrence River, La Tabatière, Quebec	March 20, 1974	suspect break in pipeline of storage tank	14,000	diesel	Estimated 2,500 gal flowed into St. Lawrence River under the ice
Black Creek, Toronto, Ontario	March 24, 1974	tank truck accident	5,000	No. 4	Oil flowed into Black Creek; about 2 mi affected
River John, Scotsburn, Pictou County, Nova Scotia	April 3, 1974	storage tank overflowed	2,000 to 3,000	furnace	Some of the oil flowed down a pipe and into a brook that eventually leads to River John
St. Lawrence River, Natashquan, Quebec	April 5, 1974	break in a line	4,000	diesel	About 100 gal went into the river with the ice

Table D-1. Continued

Oil spill location	Date	Cause	Volume spilled (gal)	Oil type	Oil behaviour
St. Lawrence River, Verchères, Quebec	April 5, 1974	unknown	unknown	unknown	Spilled oil was not cleaned up as current was too strong
St. Lawrence River 6 miles upstream from Brockville, Ontario	April 15, 1974	vessel ran aground	35,000	western crude	Oil spilled into river close to shoreline. Two slicks, 15 ft wide, were observed for about 4 mi downstream from the ship. The oil was observed rolling under the water before rising to the surface. Some oil was washed onto beaches
Sackville River, Sackville, Nova Scotia	April 15, 1974	crack in pipe	500	furnace	Oil escaped via a temporary drainage ditch to a swamp and then to Little Sackville River
Swan Hill Oil Field, Alberta	May 2, 1974	small landslide broke 3-inch flow line between well-head and battery station	17,500 to 21,000	Alberta crude	Oil spilled on land and entered nearby Edith Creek, and despite attempts to contain the oil, some escaped into Swan River. One day later oil sheen observed on river 20 mi down-stream. Oil emulsified rapidly in fast-flowing waters
Nelson River, Norway House, Manitoba	May 5, 1974	continuation of previous spill in November 1973	unknown	unknown	Oil slick observed on Nelson River under ice; oil in drinking water holes
St. Lawrence River, Montreal, Quebec	unknown	suspect line leak during first week of March	7,000 to 14,000 (estimated)	Bunker C	Oil was observed May 14, 1974, in St. Lawrence River extending from Sorel to Montreal. Oil spill source traced back to a drainage ditch in Montreal. The oil flowed from industrial land into a ditch, then into the sewers of Montreal and then into the river
Salmon River near Shelley, 3 mi upstream from Fraser River, British Columbia	May 14, 1974	ruptured 12-inch pipeline at river crossing	164,000	light crude	Pipeline was buried in gravel substrate of river bed. Oil was not contained on Salmon River and 3 mi of shoreline was heavily polluted. Some oil in pools burned off and recovered with absorbent. Oil proceeded down Fraser River at about 4 mph mixing in current and forming sheen on surface. Three days after spill oil front estimated at Hope, B.C.; air surveys, however, found only trace amount of oil
Mackenzie River, N.W.T.	June 1, 1974	storage tank overflowed	49,000	unknown	About 350 gal escaped from dyke into river and was contained with booms
Flat River, N.W.T.	June 5, 1974	leak in buried pipeline to boiler plant	10,000 maximum estimated	diesel	Oil reported leaking into Flat River at rate of about 1 gal per minute
Mackenzie River, Norman Wells, N.W.T.	June 10, 1974	pipeline break	49,000	diesel	Oil seeped through gravel and 1,750 gal escaped into Mackenzie River. A slick 15 mi long on the river resulted. Fuel moved fast in river midstream
St. Lawrence River, Montreal East	July 6, 1974	strainer broke	18,700	Jet Fuel B	Earth absorbed part of the oil, the rest went into sewers and then into the St. Lawrence River

Table D-1. Continued

Oil spill location	Date	Cause	Volume spilled (gal)	Oil type	Oil behaviour
Mackenzie River, Fort Simpson, N.W.T.	July 11, 1974	discharge hose burst in barge	100	Bunker C	About 40 gal went into Mackenzie River
Salmon River, Truro, Nova Scotia	July 16, 1974	suspect faulty valve in heating pipes	200	Bunker C	Oil leaked out of line into storm sewer, then into a small pond and eventually flowed into Salmon River. Grass along banks was oiled
St. Lawrence River, Port of Montreal	July 23, 1974	unknown, suspect defective separator	unknown	unknown	Oil slick 15 mi long observed coming from docks
Yukon River, Whitehorse, Yukon	August 8, 1974	tank overflowed	600	diesel	Small slicks observed on river downstream
Camsell River, N.W.T.	August 12, 1974	leaky joint in piping from dock to tank farm	400	diesel	Fuel lost slowly to Camsell River; sheen observed on river
St. Lawrence River, Montreal, Quebec	August 13, 1974	unknown	unknown	Bunker C	Oil observed continuously flowing in water under Champlain Bridge
Mackenzie Highway near Fort Simpson, N.W.T.	August 13, 1974	upset fuel tanker truck	5,900	diesel	Most of fuel soaked into ground and burned off. About 100 gal entered a small creek and flowed into Liard River
Hay River, N.W.T.	August 13, 1974	barge tank overflowed	200	JP 4 jet fuel	Slick observed on Hay River
St. Clair River	August 24, 1974	hose coupling broke	175	bunker	Not reported
St. Lawrence River, Montreal, Quebec	September 7, 1974	pipe break	70	unknown	At the time of a test in a 10-inch pipeline under the river, oil was observed rising to water surface
Elmsdale, Nova Scotia	September 9, 1974	train derailment	3,500	fuel and crankcase	Oil spilled into a stream and the Shubenacadie River
Northwest River, Labrador	September 11, 1974	broken fuel pipe	200	diesel	Oil reached river along a sewer line
St. Lawrence River between Leclercville and Lotbinière, Quebec	September 13, 1974	unknown	35	fuel	Oil slick 2 ft wide along south bank for 7-8 mi
Haines Junction, Yukon	October 3, 1974	open valve on fuel line	150	diesel	Fuel flowed into river
Saguenay River, Chicoutimi, Quebec	October 18, 1974	pipeline that runs under Saguenay River broke	76,000	Turbo B aviation fuel	Evaporation rate of this fuel is quite high, and 24 hours later volume remaining estimated to be only 7,600 gal
Beauport River, Quebec	November 1, 1974	truck overturned	2,700 1,300	diesel heating	Part of the oil went into Beauport River
Quebec City Airport, Quebec	November 7, 1974	truck overturned	6,600	jet fuel	The oil went into a stream, but was stopped before entering the river

Table D-1. Concluded

Oil spill location	Date	Cause	Volume spilled (gal)	Oil type	Oil behaviour
St. Lawrence River off Cherry Island, U.S. side	November 21, 1974	vessel struck bottom and sank in 194 ft water	50,000	diesel	Vent pipes in diesel fuel tank vented oil. When rising through water, oil was emulsified and dispersed by current (3-7 knots). Some oil was contained by booms
House River, Alberta	December 27, 1974	a 16-inch pipeline ruptured probably owing to bank slumping or pressure buildup by sedimentary overburden	210,000	synthetic crude	Pipeline crossed underneath House River. Oil seeped from steep bank about 300 yd from the river, and a considerable quantity flowed into the river ice and moved toward an open water area 3.5 mi downstream. Booms were deployed 3.5 mi downstream and at the junction of House and Athabasca rivers. A pool of oil on open water was successfully burned. About 25,000 gal of oil recovered from a pond above a dam. When oil layer is thin, however, it forms an oil-ice slush which clogs the pumps
Ottawa River, Montebello, Quebec	December 27, 1974	fuel tank truck overturned	1,800	furnace	Most of oil escaped into a small creek and then into the Ottawa River