Available online at www.sciencedirect.com
SCIENCE DIRECT®

PERGAMON

Marine Pollution Bulletin 47 (2003) 333–340

MARINE POLLUTION BULLETIN

www.elsevier.com/locate/marpolbul

Research

Review of behaviour of oil in freezing environments

M.F. Fingas *, B.P. Hollebone

Emergencies Science and Technology Division, Environment Canada, Environmental Technology Centre, 3439 River Road, Ottawa, Ont., Canada K1A 0H3

Abstract

The current knowledge of the physical fate and behaviour of crude oil and petroleum products spilled in Arctic situations is reviewed. The fate and final deposition of oil in marine conditions is presented as based on the extant literature.

Spreading models were evaluated for oil on ice, under ice, in snow, in brash ice, and between blocks of ice. Models of oil transport under sheet and broken ice were considered, both for sea and river conditions. The ability of ice sheets to trap oil is discussed in relation to oil storage capacity. The effects of oil on a growing ice sheet were examined, both in terms of ice formation and the thermal effects of oil inclusions in ice. The migration of oil through ice was reviewed, focussing primarily on the movement through brine channels. The effects of oil on the surface of ice were considered, with emphasis on the effects of surface pools on ice melt. Similar consideration was given to the effects of oil on snow on the surface of ice.

The few quantitative studies of oil in open and dynamic ice conditions are reviewed. Observations of intentional small-scale spills in leads and ice fields are reviewed and compared with observations from real spills. The conditions under which "oil pumping" from leads occurs were quantified. The most common ultimate fate of oil in an ice field is to be released onto the water surface.

Keywords: Arctic; Polar; Ice; Spill behaviour; Spreading; Ice-infested; Snow; Oil in ice; Gas under ice

1. Introduction

Significant research (including field tests and observations, laboratory tests, and numerical studies) has been done to understand the interactions that occur when oil, and oil and gas mixtures are discharged in waters where ice is present. Research has often been conducted using laboratory or test tanks. There have been several significant field experiments, however, and much has been learned from accidental spills in ice-infested environments.

A previous paper summarized the accidental spills and the experiments conducted to gain the present knowledge (Fingas, 1993). This paper will focus on summarizing the knowledge gained from these events and also on the specific mathematical relationships that might be used to predict the behaviour of oil in ice environments. A specialized study was conducted to combine existing knowledge into one report (Hollebone et al., 2000). This study summarized key papers related to oil behaviour in ice-infested environments.

This paper summarizes the studies of oil behaviour in ice environments under the topics of the specific ice situation or behavioural mechanism. The behavioural mechanisms will then be summarized.

2. Oil spreading on ice

All the 'theoretical models' of oil spreading on ice were based on Fay and Hoult's (1971) semi-empirical model of oil spreading on open water. The dynamics of spreading were divided into three successive regimes or phases characterized by opposing forces that dominated each phase. The phases are: gravity–inertia, gravity–viscosity, and interfacial tension–viscosity.

Glaeser and Vance (1971) studied the spreading of hot oil on ice using releases onto ice from two sizes of openings. The ice was a crystalline mass about 5 cm thick. The ice surface absorbed the oil to a saturation level of about 25%. Glaeser and Vance calculated spreading as:

* Corresponding author. Tel.: +1-613-998-9622; fax: +1-613-991-9485.

E-mail addresses: fingas.merv@etc.ec.gc.ca (M.F. Fingas), hollebone.bruce@etc.ec.gc.ca (B.P. Hollebone).

0025-326X/$ - see front matter © 2003 Published by Elsevier Ltd.
doi:10.1016/S0025-326X(03)00210-8

$$L = 2.75V^{1/4}t^{3/4} \quad (1)$$

where L is the length parameter (or D), V is the volume spilled, t is the spreading time.

Chen (1972) conducted studies in the field using small spills. He found that there was no spreading below −19 °C. He also found that warm oil spread rapidly.

McMinn (1972) developed spreading equations based on Fay and some empirical work. The final radius was given by:

$$\text{radius} = \sqrt{[Qt/\pi z_0]} \quad (2)$$

where Q is the average leak rate, t is time of flow (and therefore Qt would be the amount spilled), z_0 is average ice surface roughness (∼3 cm fit the data best).

McMinn also concluded that gravity is the only important spreading force and thus radius could be given as a function of time:

$$\text{radius} = [g * Q/\pi]^{1/4}t^{3/4} \quad (3)$$

where Q is the average flow rate, g is acceleration due to gravity, t is time of flow.

But experimental evidence yielded the following equation:

$$\text{radius} = 1.3(Q^3g)^{0.1}t^{1/2} \quad (4)$$

where Q is the average flow rate, g is the acceleration due to gravity, t is time of flow.

McMinn and Golden (1973) later revised this equation to read:

$$\text{radius} = 0.756(Qg)^{1/4}t^{3/4} \quad (5)$$

where Q is the average flow rate, g is the acceleration due to gravity, t is time of flow.

While these were based on further theoretical considerations, the second round of field work results were consistent with Eq. (4).

Chen et al. (1974) conducted laboratory experiments on spreading and developed a quasi-empirical equation based partially on Fay:

$$r/V^{1/3} = 0.24[t\rho gV^{1/3}/\mu]^{1/5} + 0.35 \quad (6)$$

where r is the slick radius as a function of time, V is the volume spilled, t is the time after spillage, ρ is the oil density, g is the acceleration due to gravity, μ is the oil viscosity.

Equation (6) was found to reproduce laboratory-scale spreading on smooth ice surfaces. From this result, Chen concluded that oil-on-ice spreading in the absence of surface roughness effects is dominated by gravity and oil viscosity. Furthermore, over a temperature range of −3 to −14 °C, the effect of temperature was accounted for by the change in viscosity with temperature.

Kawamura et al. (1986) conducted extensive laboratory experiments and some small-scale field experiments on the spreading of oil on ice. Considering all the forces on a slick, Kawamura et al. concluded that the final size of the slick must have the form:

$$A = V/h_f[1 - e^{-(t/\gamma)x}] \quad (7)$$

where A is the final area, V is the volume spilled, h_f is the final spill thickness, t is the spreading time, γ is an empirical spreading constant, x is a slope term from experimental data.

Fitting experimental data for h_f, the final extent of spreading was determined to be:

$$\frac{A_f}{V^{2/3}} = 6.0\frac{V^{0.18}\rho_c^{0.33}g^{0.21}}{\mu^{0.24}\sigma^{0.09}} \quad (8)$$

where A is the final area, V is the volume spilled, ρ is the oil density, g is gravity, μ is viscosity, σ is the interfacial tension with water.

Noting that σ and ρ do not vary significantly between oils, Kawamura et al. (1986) simplified Eq. (8) to directly yield the slick thickness:

$$h_f = 0.008V^{0.15}\mu^{0.24} \quad (9)$$

Comparison of these forms of spreading has never been done on a rigorous basis. It is obvious that these equations will not show identical results because even simple quantities, such as spill amount, have quite different relationships in the different equations. In particular, while Chen et al. (1974) concluded that gravity and viscosity were the dominant forces, the work by Kamamura et al. showed that oil–ice interfacial tension was also important. Tests showed that the Kawamura work as given in Eq. (8) did predict field results to some degree.

3. Oil spreading on snow

Kawamura et al. (1986) extended the oil-on-ice equations to predict the spreading of oil on snow:

$$\frac{A_f}{V^{2/3}} = 4.5\frac{V^{0.2}d^{0.2}\rho_o^{0.8675}g^{0.4125}\mu^{0.05}}{(\varsigma\rho_s)^{0.48}\sigma^{0.4375}} \quad (10)$$

where A_f is the final area, V is the volume spilled, d is the depth of the snow cover, ρ is the oil density, g is gravity, μ is viscosity, ς is the snow type, 1 for fresh, 0.5 for crusty, and 0.1 for hard, ρ_s is the density of the snow, σ is the interfacial tension with snow.

Similar to the ice equation, an expression for spill depth was also given:

$$h_f = 5.3 \times 10^{-4}V^{0.13}d^{-0.2}\mu^{-0.05}(\varsigma\rho_s)^{0.48} \quad (11)$$

where symbol definitions are as above.

4. Oil spreading under ice

Glaeser and Vance (1971) studied the spreading of oil under ice using several small releases. They found that the oil remained near the site with little spreading, but filled nearby undulations under the ice.

Keevil and Ramseier (1975) studied the sub-ice behaviour of oil by releasing hot crude oil under the ice. They found that the oil separated into droplets 0.1–0.2 cm in diameter. Upon contact with the ice sheet above, these droplets spread concentrically at about 1 cm/s and formed an oil lens about 1 cm thick which then became trapped into the growing ice sheet.

NORCOR Engineering (1975) studied the behaviour of oil released under a first-year ice sheet in the Beaufort Sea. Upon release, the oil formed small droplets less than 1 cm in diameter and spread to form a thickness of no less than 0.8 cm and up to 20 cm in deep depressions under the ice. A lip of ice formed around the oil lenses within hours and within days the oil was completely encapsulated.

Chen et al. (1976) observed the spreading of oil under a freshwater ice sheet in a small test tank. In the absence of currents, the spreading rate was proportional to the 1/4 power of the elapsed time. In the presence of a strong current, the droplets travelled a distance before rising and many droplets did not adhere to the ice surface.

Greene et al. (1977) studied the spreading and behaviour of oil using an experimental spill of warm crude oil under the ice of a freshwater pond. The oil spread to thicknesses of about 0.5–2 cm. Spreading lasted only a few hours.

Dome Petroleum Ltd. (1981) studied the behaviour of oil and gas releases (the gas was simulated by compressed air) under first-year ice in the Beaufort Sea. The release rate was equivalent to 400 m^3/day of oil (2500 barrels per day) at a gas-to-oil ratio of 200:1. The particle size of droplets under the ice varied with distance from the centre of the rise point. This factor can be given by:

$$D = \sqrt{\frac{18\mu V_c Z}{gx(\rho_w - \rho_p)}} \tag{12}$$

where D is the droplet size, μ is the oil viscosity, V_c is the drift current under the ice (here it was 0.04 m/s), g is the acceleration due to gravity, Z is the vertical distance from the discharge to the ice sheet (here it was 5 m), x is the lateral drift distance, ρ_w is the density of the water, ρ_p is the density of the oil.

Goodman et al. (1987) developed a technique using molding to copy under-ice surface contours and then measure the volume of under-surface ice. This was carried out at several locations. Literature values of storage volume fractions (m^3/m^2) are reported to range from 0.01 to 0.06.

Uzuner et al. (1979) studied the movement of oil under a smooth ice sheet in a test flume. They found that the velocity of crude oil can be approximated as:

$$U_s = 8.6 \times 10^{-6} U_w \tag{13}$$

where U_s is the velocity of the oil, U_w is the water velocity.

The above equation was applicable for water velocities up to 28 cm/s. For velocities of 28–36 cm/s, the following equation was developed:

$$U_s = 10U_w - 16.6 \tag{14}$$

where U_w is in cm/s.

A separate equation was also developed for diesel fuel which showed significantly different behaviour.

Puskas and McBean (1986) studied the movement of oil under ice and developed a theoretical model which was calibrated using a small-scale laboratory flume. The following equation resulted:

$$U_s = 0.0185 \frac{h\rho_w}{\mu_o} R_t^{-1/5} (u_w - 2u_s)^2 \tag{15}$$

where U_s is the velocity of the oil, h is the thickness of the oil, ρ is the density of the water, R_t is the Reynolds number, μ_o is the viscosity of the oil, u_w is the water velocity, u_s is the mean slip velocity.

Puskas et al. (1987) further developed the above equation and came up with equations for slick thickness based on static fluid equations.

Yapa and Chowdhury (1989) tested an empirical equation of the form:

$$R = K \left[\frac{\Delta\rho g Q^3}{\mu_o} \right]^{1/8} t^{1/2} \tag{16}$$

where R is the radius of the oil slick, K is a constant, $\Delta\rho$ is the density difference between water and the oil, g is acceleration due to gravity, Q is the discharge rate, μ_o is the viscosity of the oil, t is the time after the spill started.

Yapa and Chowdhury (1989) also developed the following expression for the final radius of oil spreading under ice:

$$R_F = \left(\frac{1}{2\pi^2} \right)^{1/4} \left(\frac{\Delta\rho g}{\sigma_n} \right)^{1/4} V^{1/2} \tag{17}$$

where R_F is the final radius of the oil slick, $\Delta\rho$ is the density difference between water and the oil, g is acceleration due to gravity, σ_n is interfacial tension of oil and water, V is the total volume discharged.

Izumiyama and Konno (2002) studied the spreading of oil under ice surfaces in a test tank and correlated the data with the values in Eq. (17).

In summary, under quiescent conditions (low currents), the oil will spread upon reaching the under-ice surface under the combined actions of buoyancy, viscous, and surface tension forces. A number of force-balance models have been developed to predict spreading under a smooth ice bottom. However, in practice, sea-ice is characterized by significant under-ice roughness and field observations have shown that the final under-ice configuration is dominated by the under-ice topography. The oil has been observed to spread systematically, filling the nearest under-ice depressions first before "overflowing" into the next depression.

Local ice conditions are much more important to the final oil disposition than microscale spreading behaviour. A volumetric analysis is considered to be the most effective approach for predicting the spread of large oil and gas discharges under an ice sheet, and several general spreading models have utilized this method. The key parameters are oil and gas volumes, under-ice storage capacity, and potential for gas venting through the ice. Some field studies have been carried out to measure typical under-ice storage capacities. All of the volumetric models developed to date have used an empirical approach to predict the under-ice storage capacity. While this is a reliable approach, a relatively small base of field data is available.

The presence of currents will affect the spread of the oil under ice. At relatively high currents (i.e., greater than 20 cm/s as observed in laboratory tests), oil and gas may be stripped from the under-ice depressions. At lower currents, field tests have shown that the oil rising through the water column will be carried downstream until it reaches the under-ice surface, after which it will remain adhered to the rough skeletal layer of growing ice.

Comparison of the numerical under-ice spreading models has shown that the results are not comparable. The reason for this is that such factors as under-ice roughness were probably not considered in formulation.

5. Spreading on water with ice present

Sayed and Løset (1993) studied the spreading of oil on water and among brash ice. They found that the following equation could describe their data:

$$\frac{2.5 \times 10^6 \mu R^3 \dot{R}}{\gamma V} + \frac{2.5 \times 10^4 \sigma R}{\gamma \sqrt{V}} = 1 \tag{18}$$

where μ is the oil viscosity, R is the final radius, $\dot{R}$ is the time derivative of the radius, σ is the oil surface tension, γ is the oil density, V is the volume released.

Laboratory testing of oil spreading in brash ice (5–8 tenths concentration) has shown that the ice effectively confines the oil, but as the conditions are not comparable to actual ice environments, the equations developed are likely inadequate to describe the situation in the field. A modified Fay equation for spreading based on the results of small field spills represents the most suitable analysis to date, but requires more verification to be used with confidence.

6. The effect of gas on oil-under-ice spreading

Purves (1978) studied the spread and behaviour of oil released under saline ice in a test tank along with a 60:1 ratio of gas to oil. The oil spread to thicknesses of about 0.2 cm and spread more rapidly and thinner in the presence of gas. While the oil appeared to coat the gas bubbles, at the 60:1 ratio used in this experiment, there was insufficient oil to coat all the gas. Furthermore, it was found that the presence of the gas did not change the release rate of the oil when the ice melted. Gas was released quickly upon melting.

Dome Petroleum Ltd. (1981) used compressed air to simulate a gas and oil well blowout under ice. Release of gas only resulted in ice fractures and ice heaving. Discharges under ice in April and May resulted in less fractures and heaving because gas was able to penetrate the ice more readily. When oil was released with the air, it coated the air bubbles under the ice. Most of the bubbles were a few millimetres in diameter. The gas-to-oil ratio was 200:1.

As gas is likely to be released in much greater quantities than oil during a blowout, the area of contamination will be affected significantly if the gas is vented (which can occur if the ice sheet is cracked by the buoyant force of the trapped gas bubble). One of the available spreading models analyzes venting by determining, at each time step, if the ice has failed, while the others utilize an empirical treatment. The former approach is preferable as it treats ice failure and gas venting as separate events impacting the spread of the oil and gas.

7. Movement through ice

NORCOR Engineering (1975) studied the behaviour of oil released under a first-year ice sheet in the Beaufort Sea. The oil rapidly became encapsulated and remained in place until February and March when it began to migrate through former brine channels to the surface. About 20 cm of vertical movement had taken place by March. This rate increased until in April, a lens of oil under 150 cm of ice appeared on the surface in less than an hour.

Martin (1979) studied the formation of brine channels in the field. When sea ice forms, the surface ice has a saline layer. When the ice warms in spring, the layer of surface salt liquefies and drains through the ice, preferentially through columnar interstitial spaces, leading to the formation of top-to-bottom brine channels.

Dome Petroleum Ltd. (1981) studied the release of oil and air (to simulate gas) under first-year ice in the Beaufort Sea. Several releases were made from December to May. The December spill started appearing on the surface in early June. The April and May spills started appearing in mid-June. Oil was released to the surface by both migration through brine channels and simple ice ablation (melting of the ice). The oil surfaced slowly in all cases.

Buist et al. (1983) conducted experiments in which oil and water-in-oil emulsion were placed under first-year ice in the Southern Beaufort Sea. Both the oil and emulsion were encapsulated within 48 h. The oil migrated to the surface through the brine channels and the emulsion remained as emulsion and appeared on the surface only by ice ablation.

When the oil and gas are discharged under a growing ice sheet, the oil and gas will be encapsulated in the ice by subsequent growth beneath it. Two aspects of this process need to be considered: (1) the time required for encapsulation to occur, and (2) the effect of the encapsulated oil and gas on subsequent ice growth.

The time required for encapsulation to occur depends on many factors, including the air–ice–water temperature gradient, the under-ice topography, and the volume and properties of the spilled oil and gas. During all the field tests to date, the oil and gas have been encapsulated relatively quickly (i.e., within about 24 h, sometimes partially within 4 h). The encapsulation time has not been analyzed numerically to date. An empirical approach is recommended at present as it is simple and a relatively large database of field experience is available to document the effect of the encapsulated oil and gas on subsequent ice growth. Numerical models based on heat flow across the oil and gas lens generally predict that the ice growth beneath the lens will be reduced (as the thermal conductivity of the oil is less than that of the ice for most field situations). However, no measurable difference in thickness has been observed between oiled and unoiled ice at field spills. This can be attributed to the presence of a snow cover (and its natural variations in thickness), which produces natural variations in ice thickness that are greater than those induced by the oil and gas. Unless very thick pools are involved, the effect of encapsulated oil on subsequent ice growth will probably be minimal.

The available field and laboratory test data show that the encapsulated oil will be released in the spring as the ice sheet deteriorates. Oil escapes from the ice sheet by a combination of two general processes: (1) vertical rise of the oil through the brine channels in the ice, and (2) ablation of the ice surface down to the oil lens in the ice. For a combined oil and gas spill, the gas will be released before the oil.

Both release processes are important and have been observed to occur in the field. The relative quantities of oil released depend on several factors including the depth of the oil lens in the ice, the rate of brine channel opening, and the configuration of the oil in the ice, e.g., discrete droplets versus pools of oil. No theoretical models are available to describe the release of oil by surface ablation.

Two simple models have been developed to predict release by vertical migration and these models have been compared to laboratory test results. However, the combination of vertical migration and surface ablation has not been analyzed. As proven models are not available at present, an empirical approach is considered to be the most reliable method for modelling oil release from the ice sheet.

During all the field spills conducted to date under first-year sea-ice, the encapsulated oil was released in the next melt season. The only information relating to the release from under multi-year ice comes from one series of small-scale field spills. These data indicate that the oil will rise quickly to the surface through cracks, but persists for at least two melt seasons and possibly as long as five melt seasons on the surface of the ice.

8. Oil in leads

Cammaert (1980) conducted preliminary tank tests on the movement of oil out of leads. It was found that a current of 44 cm/s was required to force oil out of an undulation 1.5 cm deep and a current of 25 cm/s was required to force oil out of an undulation 0.5 cm deep.

Buist et al. (1987) studied the behaviour of oil in leads using a test tank. Experiments showed that only a fraction of oil was incorporated into newly formed ice. A formula for wind-herding was developed:

$$T_h = 1.01h_0 + 0.72U \quad (19)$$

where T_h is the thickness of the wind-herded slick, h_0 is the original thickness (mm), U is the wind speed (m/s).

MacNeill and Goodman (1987) studied the effect of lead closure rates on the movement of oil up or down under the ice surface. Tests were conducted in an outdoor basin. It was found that at low lead closure rates most of the oil was forced under the ice when the lead closed. At lead closure rates at or above 12 cm/s, most of the oil was forced up to the top of the ice.

The phenomenon known as "lead pumping" has been postulated as a mechanism to redistribute oil from the water to the ice surface under dynamic conditions. "Lead pumping" is the movement of oil to the surface of the ice as a result of the pumping action of rapid lead closure. An analysis of lead closure rates in the Beaufort Sea and Lancaster Sound revealed that typical rates were much lower than those required for "lead pumping". Except for the case of ice closing behind ships' tracks, lead closure is unlikely to serve as a mechanism for distributing oil onto ice surfaces.

9. Absorption to snow

McMinn (1972) found that snow absorbed 20% oil by volume to yield a mulch that was fairly stable. Buist et al. (1987) report a value of 25%.

10. Containment on ice

Deslauriers et al. (1977) studied the fate and behaviour of an oil spill incident in Buzzards Bay. Rafted ice led to the formation and containment of oil pools of up to 0.15 m in depth. These pools held approximately 30% of the spilled oil. The ice prevented oil from reaching nearshore areas. After ice breakup, oiled floes distributed oil over a wide area. Oil was not contained by the ice edge and oil moved under ice with the strong tidal currents of about 0.5 m/s.

11. Heating effect of oil on the surface of ice

Glaeser and Vance (1971) studied the heating of oil on ice using releases onto ice. They found that there were large variances, but overall, oil absorbed 30% more heat from the sun than did normal ice. Chen (1972) measured the temperature of oil under snow and found that the oil temperature was 3–6 °C higher than the air temperature. NORCOR (1975) measured the effect of albedo on the surface and found that the presence of oil may have accelerated the melting of the ice by as much as 1–3 weeks. The albedo of the oil test area was as low as half of the surrounding unoiled area. The albedo of the oil is similar to that of melt water pools on the surface. Subsequent field studies (Dome Petroleum Ltd., 1981) did not detect any increase in breakup caused by oiling.

12. Oil under multi-year ice

Comfort and Purves (1982) report on a study of an experimental crude oil spill under multi-year ice in the Canadian high Arctic. Oil was placed under the ice and when the site was revisited for the first time, most of the oil had migrated to the surface. A revisit to the site five years later showed no oil left, even on the surface. The oil had presumably been absorbed by the snow and carried away by winds.

13. Oil in pack ice

S.L. Ross and D.F. Dickins (1987) report on three experimental spills in pack ice off the eastern coast of Canada. Conditions for each spill varied and ranged from relatively open to closed conditions. The spreading of oil was measured and then compared to an adjusted Fay model and the adjusted empirical model of Kawamura. The adjusted Fay model was able to predict the spreading to a large degree and the Kawamura model was less successful. The adjusted Fay model is:

$$\text{gravity–inertia} \quad A = 4.1(\Delta g V t^2)^{1/2} \tag{20}$$

$$\text{gravity–viscous} \quad A = 6.6\frac{[\Delta g V^2 t^{3/2} \rho^{1/2}]^{1/3}}{\mu^{1/2}} \tag{21}$$

$$\text{surface tension–viscous} \quad A = 16.6\left(\frac{\sigma^2 t^3}{\rho\mu}\right)^{1/2} \tag{22}$$

For spreading in pack ice, the authors recommend using:

$$A_{\mu I} = \left[\frac{\mu_o}{\mu}\right]^{-0.15}(1 - f_I)^A \tag{23}$$

where A is the area, $A_{\mu I}$ is the corrected area for spreading in pack ice, Δ is the fractional buoyancy of the oil, g is the acceleration due to gravity, V is the slick volume, t is the time, ρ is oil density, μ is the viscosity of the water, μ_o is the viscosity of the oil, σ is the spreading coefficient, f_I is the fraction of ice cover.

14. Effect of oil on ice properties

NORCOR (1975) measured the effect of five large, oiled under-ice surfaces on the growth rate of ice compared to surrounding areas. They found no measurable effect on ice growth.

Chen et al. (1976) studied oil under freshwater ice in a small basin and found that the ice above an oil lens was 2–6 °C cooler. This was attributed to the insulating effect of the oil.

Greene et al. (1977) studied the behaviour of a warm oil release under ice in a freshwater pond. The heat transfer to the water and ice occurred rapidly and did not affect ice growth after a few hours.

Martin et al. (1977) studied the growth of grease and pancake ice in a test tank. It was found that oil released to the water surface quickly surfaced to the top of the grease ice. The presence of the oil did not affect the ice growth. Oil spilled under pancake ice rose to the surface around the edges of the individual pancake formations. Once oil was on the surface of the pancake ice, the rims of the pancake formation served to contain it.

Wilson and Mackay (1987) studied the incorporation of oil into grease ice during formation using a small laboratory test tank. It was shown that large amounts of oil are incorporated into the ice as grease ice is formed. Increasing turbulence increased the amount of oil incorporated.

Oil in developing and brash ice has been observed to behave in many ways during various spills of opportunity, including the following (Fingas, 1993):

- trapped in the ice slurries at the ice edges and incorporated into the ice crystalline structure (*Arrow* spill of Bunker C);
- held in the crystalline structure of grease ice (Matane, Quebec, spill of No. 6 oil);

- transported under ice for large distances, dispersed under the ice as leads opened, and incorporated into deformed ice as the leads closed (Buzzards Bay, Mass., spill of No. 2 oil); and
- carried beneath water and ice, mixing in brash ice, and trapped on floe surfaces (*Kurdistan* spill of Bunker C).

Field and laboratory tests of oil behaviour in developing ice (grease, slush, and pancake ice) are inconclusive. Oil has been observed to surface easily through slush if some agitation is present, but too much agitation can result in incorporation of oil into the ice. Horizontal spreading of oil seems to be hindered by slush, resulting in equilibrium thicknesses greater than that of open-water spreading. Wave action has been observed to distribute oil onto the surfaces of pancake ice during two laboratory tests and during the *Kurdistan* spill. However, a small field spill in pack ice failed to produce significant oiling of ice surfaces.

15. Recommendations

Many of the algorithms proposed in the literature are based on limited laboratory experiments. There is a need to verify these experiments on a large scale. Some of the algorithms are based only on one series of experiments or even one experiment. Further, many of the experiments are old and in some cases, there are much better analytical methods available to perform the work.

Spreading on ice and oil spreading on snow requires larger-scale verification. Oil spreading on snow was determined using one set of experiments. Oil spreading under ice requires further tank testing and then subsequent larger-scale testing. Oil spreading under ice resulted in different algorithms from each worker who conducted tests and sometimes the results from these are contradictory. Furthermore, some of the oil spreading under ice did not consider the effect of under-ice roughness. Spreading on water with ice present requires work at all scales as there is only one set of experiments. The effects of gas on oil-under-ice spreading also require work at all scales since current knowledge is based on observations of one series of experiments.

There are no mathematical algorithms to predict the movement of oil through ice. This aspect then requires extensive studies. The movement of oil in leads is based on a set of small experiments and work on all scales is recommended. Absorption to snow estimates are based on two observations. Extensive studies with different snow types would be useful in prediction. The containment of oil by ice is based on one set of observations and again could benefit from extensive work. The solar heating of oil is likewise based on few observations and could benefit from extensive research. The observations reported in this paper for the behaviour of oil under multi-year ice was based on one set of experiments. The movement occurred so rapidly that by the time the observers returned, the process was complete. Further studies on multi-year ice and oil interaction are suggested. Oil in pack ice behaviour was based on one set of experiments in a rotting ice pack. Other work in different ice packs should be conducted. The effect of oil on ice properties is documented with a series of casual observations in several situations. These effects require further quantitative research.

It is recommended that real spills be studied as much as possible. The complex environments of cold water and ice sometimes cannot be replicated in the laboratory or in a test tank with sufficient accuracy to ensure compliance to the field. Further the field situations vary with time and location so that a good overview may be obtained only through replication under different situations. Specific effects, such as the effects of under-ice roughness on oil spreading, will require careful laboratory studies.

16. Summary

Oil spills in ice-infested waters undergo complex behaviour and fate processes. The understanding of these certainly displays some significant gaps. Much more research, especially quantitative, is needed before there is a capability to predict oil behaviour and fate in ice-infested environments. In addition, much of the work is now 20 years old and some measurement methods have improved to the extent that older results may not be valid.

References

Buist, I.A., Potter, S.G., Dickins, D.F., 1983. Fate and behaviour of water-in-oil-emulsions in ice. In: Proceedings of the Sixth Arctic Marine Oilspill Program Technical Seminar. Environment Canada, Ottawa, ON, pp. 263–279.

Buist, I., Joyce S., Dickins, D.F., 1987. Oil spills in leads: tank tests and modelling. Manuscript Report EE-95, Environment Canada, Ottawa, ON, 126 p.

Cammaert, A.B., 1980. Oil and gas under ice laboratory study. Beaufort Environmental Impact Statement RWC17, Environment Canada, Ottawa, ON, 38 p.

Chen, E.C., 1972. Arctic winter oil spill test. Technical Bulletin No. 68, Environment Canada, Ottawa, ON, 20 p.

Chen, E.C., Overall, C.K., Phillips, C.R., 1974. Spreading of crude oil on an ice surface. Canadian Journal of Chemical Engineering 52, 71–74.

Chen, E.C., Keevil, B.E., Ramseier, R.O., 1976. Behaviour of Oil Spilled in Ice-covered Rivers. In: Scientific Series No. 61. Environment Canada, Ottawa, ON.

Comfort, G., Purves, W., 1982. The behaviour of crude oil spilled under multi-year ice. EPS 4EC824, Environment Canada, Ottawa, On, 76 p.

Deslauriers, P.C., Martin, S., Morson, B., Baxter, B., 1977. The physical and chemical behaviour of the Bouchard No. 65 oil spill in the ice-covered waters of Buzzards Bay. National Oceanic and Atmospheric Administration (NOAA), Environmental Research Laboratory, Boulder, CO, 185 p.

Dome Petroleum Ltd., 1981. Oil and gas under sea ice. Report CV1, Canadian Offshore Oil Spill Research Association (COOSRA), Calgary, AB. vol. I and II, 286 p.

Fay, J.A., Hoult, D.P., 1971. Physical processes in the spread of oil on a water surface. AD-726 281, United States Coast Guard, Washington, DC, 16 p.

Fingas, M.F., 1993. The Behaviour of Oil in Ice. In: Combatting Marine Oil Spills in Ice and Cold Conditions. National Board of Waters and the Environment, Helsinki, Finland, pp. 5–22.

Glaeser, J.L., Vance, G., 1971. A study of the behaviour of oil spills in the arctic. Report Number 714/08/A/001,002, United States Coast Guard, Washington, DC, 53 p.

Goodman, R.H., Holoboff, A.G., Daley, T.W., Waddell, P., Murdock, L.D., Fingas, M., 1987. A technique for the measurement of under-ice roughness to determine oil storage volumes. In: Proceedings of the 1987 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 395–398.

Greene, G.D., Leinonen, P.J., Mackay, D., 1977. An exploratory study of the behaviour of crude oil spills under ice. Canadian Journal of Chemical Engineering 55, 696–700.

Hollebone, B.P., Fingas, M.F., Permann, D., 2000. The fate and behaviour of oil in freezing environments. Environment Canada, Unpublished Report.

Izumiyama, K., Konno, A., 2002. Experimental study on the spreading of oil under ice covers. In: Proceedings of the 2001 Ice Conference.

Kawamura, P., Mackay, D., Goral, M., 1986. Spreading of chemicals on ice and snow. Manuscript Report EE79, Environment Canada, Ottawa, ON, 106 p.

Keevil, B.E., Ramseier, R., 1975. Behaviour of oil spilled under floating ice. In: Proceedings of the 1975 Conference on Prevention and Control of Oil Pollution. American Petroleum Institute, Washington, DC, pp. 497–501.

MacNeill, M.R., Goodman, R.H., 1987. Oil monitoring during lead closure. Environmental Studies Research Fund, Report No. 053, National Energy Board, Calgary, AB, 13 p.

Martin, S., 1979. A field study of brine drainage and oil entrainment in first-year sea ice. Journal of Glaciology 22, 473–502.

Martin, S., Kauffman, P., Welander, P.E., 1977. A laboratory study of the dispersion of crude oil within sea ice grown in a wave field. In: Proceedings of the Twenty-Seventh Alaska Science Conference, vol. II. American Association for the Advancement of Science, Fairbanks, AK, pp. 261–287.

McMinn, T.J., 1972. Crude oil behaviour on arctic winter ice. Project 734108, United States Coast Guard, Washington, DC, 75 p.

McMinn, T.J., Golden, P.C., 1973. Behavioral characteristics and cleanup techniques of north slope crude oil in an arctic environment. In: Proceedings of the 1973 Joint Conference on Prevention and Control of Oil Spills. American Petroleum Institute, Washington, DC, pp. 263–276.

NORCOR Engineering and Research Ltd., 1975. The interaction of crude oil with arctic sea ice. Beaufort Sea Technical Report, No. 27, Beaufort Sea Project, Department of the Environment, Victoria, BC, 201 p.

Purves, F., 1978. The interaction of crude oil and natural gas with laboratory-grown saline ice. EPS4EC789, Environment Canada, Ottawa, ON, 18 p.

Puskas, J.K., McBean, E.A., 1986. The transport of crude oil under saline ice. In: Proceedings of the Fourth International Conference on Cold Region Engineering. American Society of Civil Engineers, New York, NY, pp. 670–684.

Puskas, J.K., McBean, E.A., Kouwen, N., 1987. Behaviour and transport of oil under smooth ice. Canadian Journal of Civil Engineering 14, 510–518.

Sayed, M., Løset, S., 1993. Laboratory experiments of oil spreading in brash ice. In: Proceedings of the Third International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers, Golden, CO, pp. 224–231.

S.L. Ross Environmental Research Ltd., D.F. Dickins Associates Ltd., 1987. Field research spills to investigate the physical and chemical fate of oil in pack ice. Environmental Studies Research Fund, Report No. 062, National Energy Board, Calgary, AB, 116 p.

Uzuner, M.S., Weiskopf, F.B., Cox, J.C., Schultz, L.A., 1979. Transport of oil under smooth ice. EPA-600/3-79-041, Environmental Protection Agency, Corvallis, OR, 62 p.

Wilson, D.G., Mackay, D., 1987. The behaviour of oil in freezing situations. Manuscript Report EE92, Environment Canada, Ottawa, ON, 65 p.

Yapa, P.D., Chowdhury, T., 1989. Spreading of oil spilled under ice. Report No. 8910, Clarkson University, Potsdam, NY, 98 p.