RU 567
#4073
FE-AK8

RTD Report No. 258

INTERACTION OF OIL WITH ARCTIC SEA ICE

BY

D. R. Thomas

February 1983

Flow Industries, Inc.
Research and Technology Division
21414-68th Avenue South
Kent, Washington 98032
(206) 872-8500
TWX: 910-447-2762

REGISTERE

RTD Report No. 258

INTERACTION OF OIL WITH ARCTIC SEA ICE

BY

D. R. Thomas

February 1983

Flow Industries, Inc.
Research and Technology Division
2141 4-68th Avenue South
Kent, Washington 98032
(206) 872-8500
TWX: 910447-2762

RTD Report No. 258

INTERACTION OF OIL WITH ARCTIC SEA ICE

•

D. R. Thomas

February 1983

Flow Industries, Inc.
Research and Technology Division
21414 68th Avenue South
Kent, Washington 98032
(206) 872-8500
Twx: 910-447-2762

FOREWORD

This study was supported by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multiyear program responding to needs of petroleum development of the Alaskan Continental Shelf is managed by the Outer Continental Shelf Environmental Assessment (OCSEAP) Office. The report will also appear in The Alaskan Beaufort Sea (edited by P. Barnes, E. Reimnitz and D. Schell; published by Academic Press, New York), which will be published in 1983.

TABLE OF CONTENTS

Interaction of Oil with Arctic Sea Ice

D. R. Thomas

Research and Technology Division
Flow Industries, Inc.
Kent, Washington

I. INTRODUCTION

Worldwide, about 1 in 3000 offshore oil wells experiences some kind of blowout. Many of these are relatively harmless in terms of environmental damage. It has been estimated that the chance of a "serious" blowout incident is less than 1 in 100,000 wells drilled. Although this is a very low probability, it happens often enough (for example, the Santa Barbara and the IXTOC 1 blowouts) that the consequences must be considered.

During the next few years, many exploratory and possibly production oil wells will be drilled on the continental shelf in the Beaufort Sea off the north coast of Alaska. Drilling will initially be from natural or artificial islands in relatively shallow waters. While this procedure will reduce the probability of blowouts and provide a stable base for control efforts and spill containment, it is possible for a blowout to occur away from the drill hole. The 1969 blowout in the Santa Barbara Channel occurred through faults and cracks in the rock as far as 0.25 km from the drill site.

Previous regulations required that any offshore drilling in the Beaufort Sea be done during the period from November through March. Present regulations allow exploratory drilling year-round in some areas of the Beaufort, while drilling is prohibited during September and October in other areas. Due to logistic considerations and site-specific environmental concerns, much of the exploratory drilling will still be done during the ice season. The entire sea surface is covered by a floating ice sheet during that time, except for occasional leads of open water. Thus, sea ice will have an important bearing on the fate of oil spilled by a blowout.

There has been little practical experience with oil spills in ice-covered waters. Accidental surface spills that have occurred in ice-covered waters in subarctic regions, as in Buzzards Bay, Massachusetts, in 1977, have not been in arctic-type ice, which generally continues to build throughout the winter and is thicker and more continuous than subarctic ice.

Recently, several experimental oil spill studies involving arctic sea ice have been performed. The Canadian government sponsored an oil spill experiment at Balaena Bay, N.W.T., during the winter of 1974-75, as part of the Beaufort Sea Project. The initial spreading of the oil and incorporation into the ice sheet were studied. The effects of oil on the thermal regime of the ice was also studied, *as* were weathering of the oil and clean-up techniques. An experimental spill was performed in 1978 by Environment Canada in Griper Bay, N.W.T., to study the fate of oil spilled beneath multi-year ice. During the winter of 1979-80, Dome Petroleum carried out an experimental oil spill in McKinley Bay, in the Canadian Beaufort. Plume dynamics under the ice, the effects of gas on under-ice spreading, the formation of emulsions, and the surfacing of oil in the spring were some of the topics studied.

The purpose of this paper is to summarize relevant knowledge about the interactions between arctic sea ice and oil. Previous works by Lewis (1976), NORCOR (1977), and Stringer and Weller (1980) have also addressed this topic. The completion of further experimental oil spill studies, along with recent laboratory studies of the interaction of oil and sea ice and studies of environmental conditions, makes an updating of those works desirable. An attempt is made to identify the major factors in the interaction between oil and arctic sea ice and to present them in a way that defines the scope of the problem. Generally, this paper is restricted to factors that can be expected to play a major role in the sequence of events following a large under-ice blowout in the Beaufort Sea during winter. Blowouts that occur during the summer, in subarctic waters, or beyond the continental shelf are not considered here.

II. THE INTERACTION OF OIL AND SEA ICE

If an underwater blowout occurs, releasing large quantities of crude oil and gas into the water beneath the arctic ice cover, one can expect a different chain of events than from an open-water blowout. No such under-ice blowout has occurred yet, but from experimental work (NORCOR, 1975; Martin, 1977;

Topham, 1975; Topham & Bishnoi, 1980; Cox *et al.*, 1981; Buist *et al.*, 1981) and from observations made at accidental surface spill sites in icy waters (Ruby et *al.*, 1977; Deslauriers, 1979), one can predict the course of events for an under-ice blowout with reasonable confidence. In general, an under-ice blowout in the winter will follow the course outlined below:

(1) Initial Phase -- the underwater release of oil and gas and their subsequent rise to the surface.
(2) Spreading Phase -- the spreading of oil due to water currents and buoyancy.
(3) Incorporation Phase -- the incorporation of oil into the ice cover.
(4) Transportation Phase -- the motion of the oiled ice.
(5) Release Phase -- the release of the oil from the ice.

Three areas and types of ice cover must be accounted for when considering blowouts on the Beaufort Sea continental shelf of Alaska. These are the fast ice zone, the pack ice zone, and the area of interaction between the moving pack ice and the stationary fast ice.

The fast ice zone includes ice that forms nearshore each year, although occasional multiyear floes (ice that has survived one or more melt seasons) or remnants of grounded ridges may be incorporated. The ice begins to form in early October and for a month or two it is susceptible to movement and deformation by the winds. Eventually, this nearshore ice becomes immobilized, protected by the shore on one side and barrier islands or grounded ridges on the other. Since motions and deformations occur for only a short period of time, the fast ice tends to be relatively flat and undeformed. This ice begins to melt in place in late May or June and is mostly gone by the end of July.

Further offshore is the pack ice zone. The ice in this zone is a mixture of multiyear ice and seasonal ice. Winds and currents cause the ice to be in almost constant motion. Cracks open to form leads that quickly freeze, developing *a* layer of thin ice. Some leads are closed by moving ice, which breaks and piles up the thin ice to form ridges and rubble piles.

Where the moving pack ice interacts with the stationary fast ice, a great deal of ice deformation takes place. The winds tend to move the pack ice westward and toward shore causing much shearing deformation. Many large ridges form in this area. Water depths here are from 10 to 30 m. Since many ridge keels are deeper than that, a band of grounded ridges often forms. Following Reimnitz *et al.* (1977), this is called the Stamukhi zone (after the Russian word stamukhi, meaning grounded ice rubble piles).

In the rest of this section, the five sequential phases of interaction between crude oil and sea ice are discussed separately.

A. Initial Phase

The blowout is assumed to consist of the continuous release over a minimum of several days of large quantities of crude oil and many times that amount of gas. The blowout occurs under an ice cover in the period from November through March. The blowout is also assumed to occur on the Beaufort Sea continental shelf in relatively shallow waters (less than about 200 m deep).

1. Effects of Gas. Topham (1975) reports the results of experimental releases of oil and compressed air underwater. The experiments were simulations of small well blowouts in open-water conditions. As gas is released in shallow water, it breaks up into small bubbles and rises to the surface, carrying oil and part of the surrounding water along to form an underwater plume. This plume is initially conical in shape, but becomes nearly cylindrical as it rises above the release point. The centerline velocities of experimental plumes did not vary significantly with the depth or air flow rate for the range of experimental values (flow rates of 3.6 to 40 m^3 rein-l at depths of 33 to 60 m).

As the plume reaches the water surface, the vertical transport changes to a radial current flowing outward. During tests in open water (Topham, 1975), a concentric wave ring was produced at some distance from the plume, marking the location of a reversal in radial surface currents. A downward current is found here, extending to a depth of about 10 m. During Dome's simulated blowout beneath sea ice (Buist *et al.*, 1981), no wave ring was observed, but downward flow did occur about 15 to 20 m from the plume. Small droplets of oil or oil-and-water emulsions will likely be carried downward, but the majority of the oil from the blowout will rise to the surface in drops with a mean diameter of 1 mm. One or two percent will be in fine droplets of approximately 0.05 mm in diameter (Topham, 1975). Drops of this size have a natural rise rate of about 0.5 mm S-l. Subsurface currents could carry the very small droplets many kilometers downstream during their slow rise to the surface. However, Buist *et al.* (1981) observed that 90 percent of the oil that was released surfaced within a 50-m radius. Dissolution is generally not considered important in the Arctic (NORCOR, 1975). The formation of stable emulsions was not observed during Dome's simulated blowout.

The first interaction between the blowout and the ice cover is the collection of gas beneath the ice. Assuming that the ratio of gas to oil by volume is 150 to 1 at the surface, then gas will be released at rates near 33 m^3 min^{-1} in the case of a blowout releasing 2000 barrels per day (0.22 m^3 min^{-1}) of oil. Within minutes, large pockets of gas will have *accumu*-lated beneath the ice.

Topham (1977) studied the problem of a submerged gas bubble bending and breaking an ice sheet. For thin ice, there is little doubt that a gas bubble a few centimeters in thickness and a few meters in radius will crack the ice. During Dome's simulated blowout (Buist *et al.*, 1981), air released beneath ice 0.65 m thick caused the ice to dome upward until it cracked, releasing the gas. For thicker ice (up to 2 m), the situation is not so clear. In rough ice where large, thick pockets of gas can collect, the radius needed to crack the ice is a few tens of meters. In smoother ice where the gas will collect only to a few centimeters in thickness, the critical radius can extend from a few hundred meters to several kilometers.

It is likely, nevertheless, that the gas will break the ice cover in the fast ice areas. In fast ice, natural weaknesses exist in the form of thermal cracks that probably occur every few hundred meters (Evans and Untersteiner, 1971). Thus, the gas will only spread a few hundred meters under the ice before it either cracks the ice or comes to a natural crack. Once a crack exists near the blowout site, the ice over the blowout is likely to be further fractured and broken up by turbulence or by sinking into the low-density gas-in-water mixture near the center of the plume.

A moving ice canopy may also be broken up as it passes over the gas plume. If the ice is moving at the rate of 3 km day^{-1}, this amounts to an average of about 126 m hr^{-1}. A gas flow rate of 40 m^3 min^{-1} will deposit 2400 m^3 of gas under the ice in 1 hour. If this gas collects to an average depth of 0.1 m, the under-ice bubble will cover an area of 24,000 m^2 in 1 hour. For first-year ice, the motion experienced during that hour is probably of no significance; the ice will be broken up much as stationary ice would be. If the ice is moving at several kilometers per day over a small blowout, however, it is possible that breakage will not occur.

It has been the opinion of some investigators (Logan *et al.*, 1975; Milne and Herlinveaux, n.d.) that large multiyear floes will not be broken up as they move across an underwater gas plume. Topham's work (1977) seems to support this view. Breakage of multiyear floes might occur, though, if consolidated ridge keels trap deep bubbles of gas or if thermal cracks have weakened the ice. Thermal cracks themselves provide an alternate path for releasing the gas.

2. *Thermal Effects.* A possible contributory factor in the breaking of a stationary or slowly moving sheet of first-year ice is the heat content of the oil. If hot oil escapes from the blowout outlet, it breaks up into small droplets (0.5 to 1.0 mm in diameter). Most or all of the surplus heat of the oil is transferred to the water column, which in turn is carried to the underside of the ice by the gas-induced plume. Some of the heat from the warmed water will then go into melting the ice, with the greatest part of the melting occurring directly over the blowout plume.

In addition to the heat content of the oil, the water column (except in very shallow areas) will be above freezing and can contribute to the melting of ice. The temperature above freezing of the bottom water will generally be 2 to 4 orders of magnitude lower than the temperature of the oil, but the volume of water circulated in the plume will be about 4 orders of magnitude larger than the volume of oil. The total heat transported to the bottom of the ice will thus be roughly 2 to 20 times (depending on the temperature of the water) the amount from the hot oil alone.

The specific heat of sea ice is about 2010 J $(kg\ °K)^{-1}$ and that of a typical crude oil is 1717 J $(kg\ °K)^{-1}$. The heat of fusion of water (fresh) is about 334 kJ kg-l. If the ice sheet has an average temperature of -10°C, it will require 10″C x 2010 J $(kg\ °K)^{-1}$ + 334 kJ kg-l or 354 kJ kg-l to warm and melt the ice. Crude oil provides 1717 J kg-l of heat for each degree of temperature above freezing. To warm and melt each kilogram of sea ice at -10″C, about 206 kg ‘K of crude oil is required. Since the densities of ice and crude oil are about the same, each volume of oil will melt roughly one two-hundredth that volume of ice for each degree above freezing of the oil temperature.

Oil at a temperature of 100″C, corresponding to a reservoir depth of about 4000 m, would therefore melt about 0.S m^3 of ice for each 1.0 m^3 of oil released. At least an equivalent amount will be melted by water circulation. However, some of this heat will be spread over a large area by existing currents and by plume-induced circulation. The result will be a small area where significant ice melt takes place and a much larger area with only a slightly reduced ice thickness or a decrease in growth rates.

One would expect the ice directly over the blowout to receive a major proportion of the heat from the oil. In stationary ice or very slowly moving first-year ice, melting will tend to weaken the ice over the blowout, making it more probable that gas bubbles trapped beneath the ice will fracture it and escape. For very-large blowouts, a significant amount of ice may be melted, leaving a pool of open water directly over the blowout. Large amounts of oil could collect in this open-water pool, and some of the oil could spill over onto the surrounding ice surface.

The density of sea water is about 1020 kg m^{-3} and the density of sea ice is about 910 kg m^{-3}. Densities of fresh crude oils may range from about 800 to 900 kg m^{-3}. Thus, if one tries to fill a hole through the ice with crude oil, the oil will overflow the top of the hole before it is filled to the bottom. However, during much of the ice season, the air temperature is so low that crude oil exposed to the atmosphere behaves more like a solid than a liquid. The oil will therefore be limited to a small area on the surface until it pools deep enough to begin spreading beneath the ice. Even during the spring, when the air temperature is above the oil's pour point, the snow cover and natural roughness of the ice surface will limit the spread of oil on the surface, so that spilled oil will still tend to spread beneath the ice.

B. Spreading Phase

Once oil gets underneath an ice sheet, several factors, such as the bottom roughness of the ice, the presence of gas under the ice, the magnitude and direction of ocean currents, and movement of the ice cover, will control the concentration and areal extent of the oil spread. Of secondary importance are oil properties such as density, surface tension, equilibrium thickness, and viscosity. The effects of these latter properties are fairly well understood (NORCOR, 1975; Cox *et al.*, 1980; Rosenegger, 1975; Malcolm and Cammaert, 1981) and, while important to understanding the basic mechanisms of oil-water-ice interactions, they will not be as influential on the extent of oil coverage as the grosser, more variable factors.

1. Bottom Roughness and Oil Containment. The bottom roughness of the ice will vary significantly between the fast ice, the pack ice, and the Stamukhi zones. The fast ice zone will have roughness determined chiefly by spatial variations in snow cover causing differences in ice growth rates (Barnes et *al.*, 1979). The Stamukhi zone will be dominated by deep ridge keels. In the pack ice zone, both the above types of roughness are present along with frequent refrozen leads and a high percentage of multiyear floes that have exaggerated underside relief. In addition, all ice growing in sea water has a microscale relief due to the columnar nature of new ice growth.

If oil alone is released under sea ice, or if any accompanying gas is vented, the oil begins filling under-ice voids near the blowout. As a void fills downward with oil, the oil eventually reaches a depth where it can begin escaping over neighboring summits of ice or through "passes" to the next void. If the ice itself is moving over the site of the blowout, the voids may not be completely filled, and only that ice passing directly over the blowout plume will collect oil.

If new ice forms in calm conditions, the underside of the ice will have an essentially flat, smooth surface. Oil will spread underneath this ice to some equilibrium thickness, depending upon a balance between surface tension and buoyancy. Cox *et al.* (1980) report test results for oil of various densities. The equilibrium slick thickness ranged from 5.2 to 11.5 mm for oils with densities in the range of crude oils. For a constant surface tension, a good approximation of slick thickness can be made using the empirical relationship (Cox *et al.*, 1980)

$$\delta = -8.50\ (\rho_w - \rho_o) + 1.67,$$

where δ is the slick thickness in centimeters and $(\rho_w - \rho_o)$ is the density difference between oil and water. The minimum stable drop thickness for crude oil under ice has generally been reported to be about 8 mm (Lewis, 1976). Using this value, we see that 8000 m^3 (50,000 bbl) of oil will spread under each square kilometer of smooth ice. This is the minimum volume of oil that can spread under 1 km^2 of ice in the absence of currents or ice motion. Generally, sea ice, even smooth new ice, will not be perfectly smooth, so each square kilometer will actually hold more oil than that.

During October and November, a snow cover accumulates in drifts parallel to the prevailing wind direction. Barnes *et al.* (1979) found these snow drifts to be fairly stable throughout the ice season. The drifts insulate the ice from the low atmospheric temperatures, causing reduced ice growth beneath. The underside of the ice takes on an undulating appearance and, as ice continues to grow throughout the winter, these undulations become more pronounced, increasing the oil containment capacity.

NORCOR (1975), reporting on the Balaena Bay experiment, found ice thicker than about 0.5 m to have a thickness variation of about 20 percent the mean ice thickness. Not all of this variation will be available for oil containment. Because of natural variations in the snow cover and drift patterns, voids under the ice will tend to be interconnected by passes. These passes may be at any depth within the range of ice drafts, but presumably the most likely depth will be the mean ice draft.

Kovacs (1977, 1979) and Kovacs *et al.* (1981) have mapped the underside relief of the fast ice at various places near Prudhoe Bay in the early spring using an impulse radar system that "sees" the ice water interface. From the contour maps of the ice bottom, they calculated the volume of the voids that lie above the mean ice draft. This volume (the oil containment potential) varied from 10,000 to 35,000 $m^3 km^{-2}$ for areas of undeformed fast ice with no large slush-ice accumulations. The variation seemed to be related mostly to variations in the snow cover. For areas of slightly deformed ice, the containment potential was observed to be as high as 60,000 $m^3 km^{-2}$. While these numbers seem large, they are only a few times the containment potential of perfectly flat ice (8000 m^3 km-2).

If deformation occurs in the inner fast ice zone, it takes place in the fall when the ice is thin. Most of this deformation is minor in character: raised rims on edges of individual floes, rafting, and a few small ridges or rubble fields. The relief is generally only a few centimeters deep, which will tend to increase the oil containment capacity. As the ice grows thicker and stronger, deformation ceases, and the existing deformed features below the ice tend to be leveled out by differential ice growth between thicker and thinner ice.

Kovacs and Weeks (1979) have observed major deformations occurring inside the barrier islands. A *severe* storm in early November 1978, with winds at 55 to 65 km hr^{-1} (30 to 35 knots) gusting to 110 km hr^{-1} (60 knots), broke up the fast ice, produced ice motions greater than 1 km, and built ridges up to 4 m high. During the three previous years, such events had not been observed but, obviously, they must be considered. In terms of the spreading of oil under the ice, the increased roughness created by the deformations should limit the spread by creating more voids for the collection of oil. If frequent enough and intersecting, the ridges would limit the directions in which oil could spread or possibly trap deeper pools of oil.

Outside the inner fast ice zone, in the Stamukhi zone, reformational events continue to occur throughout the winter, creating a bottomside relief many meters deep. Tucker *et al.* (1979) observed a maximum of 12 ridges per kilometer in the 20 km just north of Cross Island. If the average sail height is 1.5 m (Tucker *et al.,* 1979) and keels are 4 times as deep as sails (Kovacs and Mellor, 1974), then the potential exists for pools of oil to collect that are several meters deep and from one to a few hundred meters across, assuming that ridges frequently intersect each other. Whether the oil can actually collect in pools that deep is another matter. The only direct evidence we have of the interaction of oil and ridges occurred in Buzzards Bay, Massachusetts, in 1977. Deslauriers (1979) observed that the spilled oil tended to be trapped between the ice blocks making up the ridges, with some oil appearing on the surface. These observations may not be applicable to large arctic pressure and shear ridges that can be several tens of meters in width with a lower probability of interconnecting voids extending through the ridges at shallow depths. This is even more unlikely as the ridges age and some of the interior voids freeze.

If oil collects in deep pools surrounded by ridge keels, buoyancy could force significant amounts of oil onto the surface through openings that exist. Large volumes of gas could remain trapped by the ridges in the Stamukhi zone; however, it is unlikely that enough large areas will be impermeable to cause a significant volume of gas to be contained.

Further out, in the pack ice zone, the variety of under-ice relief increases. Not only are there first-year ice floes and pressure ridges, but variable amounts of multiyear ice and refrozen leads.

Underneath multiyear ice, there is an order of magnitude increase in the quantity of oil or gas that may be contained. Kovacs (1977) profiled the bottom of a multiyear floe and estimated that 293,000 m^3 km^{-2} of space existed above the mean draft of 4.31 m. Other investigators (Ackley et *al.,* 1974) also report greater relief under multiyear ice than under first-year ice.

Refrozen leads also hold large amounts of oil or gas. The ice in a lead is relatively thin and smooth, while the ice of the original floe will have a draft up to 3 m deeper than the ice in the lead. A large lead may be several kilometers wide and many kilometers long, limiting the direction of spreading of the oil but not the area covered. A large flaw lead often forms along the Alaskan coast at the southern boundary of the moving pack. However, most leads will be quite narrow, less than 50 m wide (Wadhams and Home, 1978). Since leads do not form as perfectly straight lines but, rather, follow meandering floe boundaries or recent thermal cracks, there will generally be many points of contact along a lead. Thus, if oil *or* gas does come up beneath a refrozen lead, or flows into it from the surrounding ice, it will usually be collected in an elongated pool rather than spreading indefinitely along the lead. The oiled ice in a refrozen lead has a high probability of being built into a ridge.

There is also some probability of oil from a blowout coming up in open water in a newly opened lead. Throughout most of the ice season in the Beaufort Sea, this probability must be fairly low. New ice begins to form immediately and, within one day, a solid ice cover will exist in new leads. Oil beneath thin ice in leads will have a higher probability of appearing on the surface than oil beneath thicker ice. The ice motion that produces leads will also make leads wider or close leads by rafting or ridging the thin ice. Gas collecting under a lead can also break the ice.

2. *Currents.* A possible contribution to the spread of oil beneath sea ice is ocean currents. Until the oil is completely encapsulated by new ice growth, currents of sufficient magnitude can move the oil laterally beneath the ice until either an insurmountable obstruction is reached or the currents cease.

NORCOR (1975) performed some oil spill experiments near Cape Parry in March 1975 in the presence of currents about 0.1 m s^{-1} in magnitude. In one test, the ice appeared to be perfectly flat with roughness variations of 2 to 3 mm. Oil discharged under this ice spread predominately downstream to a thickness of about 6 mm. After all the oil had been discharged, movement of the oil lens appeared to stop.

A second test was performed nearby in the same current regime, but in ice with more underside relief. Troughs of up to 0.5 m in depth were present, as well as a small ridge keel downstream from the test site. This time, the oil spread downstream until one of the depressions was reached. At that point, the oil collected in a stationary pool averaging about 0.1 m in depth.

Evidently, currents of only 0.1 m s^{-1} may influence the direction of the spread of crude oil under ice, but will not greatly affect the amount of spreading.

More recently, the relationship between current speed, bottom roughness, and the movement of oil under ice has been quantified (Cox *et al.*, 1980). From flume experiments, it was determined that, for smooth ice or ice with roughness less than the equilibrium slick thickness, there is a threshold water velocity below which the oil does not move. For smooth ice, the threshold velocity was about 0.035 m s^{-1}; for ice with roughness scales of 1 mm, the threshold was 0.10 to 0.16 m s^{-1} (depending upon oil density); and for roughness scales of 10 mm, the threshold velocity was 0.20 to 0.24 m s^{-1}. For currents above the threshold velocity, the oil moved at some fraction of the current speed.

For bottom roughness elements with depths several times the slick equilibrium thickness, a boom-type containment/failure behavior was observed. The oil collected upstream of the obstruction to some equilibrium volume, after which additional oil flowed beneath the obstruction. The size and shape of the obstruction had little effect on oil containment. Thus, even mild slopes act as barriers to oil movement.

As the water velocity increases beneath the ice, a Kelvin-Helmholtz instability eventually occurs, in which case the entire slick is flushed from behind the obstruction. For the range of oil densities tested, the failure velocities ranged from about 0.14 to 0.22 m s^{-1}.

When roughness elements are spaced closer than the slick length for a given current speed and oil density, cavity trapping rather than boom containment occurs (Cox and Schultz, 1981). Cavities have the potential for containing more oil in the presence of currents than do simple barriers, and they retain oil at higher current speeds. Some oil was observed to remain in cavities at current speeds of 40 cm s^{-1}.

Measurements of nearshore under-ice currents reported in the literature (Kovacs and Morey, 1978; Weeks and Gow, 1980; Matthews, 1980; and Aagaard, 1981) indicate that the current speed is generally small, less than about 0.1 m s^{-1}, and will not cause significant oil spreading.

3. *Ice Motion.* The motion of the ice cover over a blowout is another mechanism by which oil can be spread beneath the ice. As ice motion increases, the containment potential of the ice decreases, leading to potentially larger contamination areas. High ice velocities also increase the possibility that gas concentrations under the ice will not be sufficient to crack thick ice and will increase oil spread.

Motions of the ice in the fast ice zone are largely confined to the fall just after freezeup or after breakup in the spring. Kovacs and Weeks (1979) have observed that motions several kilometers in magnitude can occur in the fast ice soon after freezeup while the ice is thin and weak. Motions of this magnitude are due to severe storms, which are not uncommon in the fall. During the majority of the ice season, motions of the fast ice amount to a few meters (Tucker *et al.*, 1980).

A blowout in the pack ice zone is most likely to occur under a moving ice cover. The area of ice under which oil spreads will depend upon many factors: the velocity of the ice; the discharge rate of oil and gas from the blowout; the amount of gas that can escape; the diameter of the blowout plume; the roughness of and amounts of different ice types and thicknesses; and the duration of the blowout. It is possible, however, to estimate the area of moving ice that would collect oil in a typical blowout situation.

Assume that a blowout releases 5000 bbl of oil during one day. If the ratio of gas to oil is 150 *to 1,* then *a* total of 120,000 m^3 of oil and gas is released during one day. If the containment potential of the ice passing over the blowout is 30,000 m^3 km^{-2}, then 4 km^2 would be contaminated if all the gas remains beneath the ice. The length and width of the swath of oiled ice will depend upon the speed at which the ice is moving. The minimum width will be roughly the diameter of the radial currents above the plume. If this diameter is 100 m then the ice would have to be moving faster than 40 km day^{-1} for more than 4 km^2 day^{-1} to be contaminated. Therefore, 4 $km^2 day^{-1}$ can be considered a maximum for this example. The *actual* area would probably be much smaller, since much of the gas would be released through thermal cracks or broken ice.

4. *Ice Growth.* During the fall and winter, the first-year ice over the inner continental shelf is increasing in thickness up to 10 mm day^{-1}. For a blowout lasting several days under a stationary ice cover and in the absence of large currents, this ice growth may be significant in limiting the spread of the oil. When an area of ice contains a layer or pools of gas and oil, the ice does not immediately begin growing beneath the oil. In the region near the blowout site, the heat from the warm oil or from bottom water circulated by the blowout plume will reduce ice growth or actually melt ice. Meanwhile, unoiled ice outside this region will continue growing, increasing its oil containment potential.

C. Incorporation Phase

Oil incorporated into the ice cover will vary with the ice morphology and the season. The oil may be incorporated into the new ice forming in leads, may appear on the ice surface through cracks or unconsolidated ridges to be soaked up by any snow cover, and may be frozen into existing ice by new ice growth. As a secondary form of incorporation, oiled ice may be built into ridges.

1. *Oil on the Ice Surface or in Open Water.* In the fall, *new ice* forms as a highly porous layer of ice crystals. Oil spilled underwater will rise to the surface through this porous ice and, within a few days, the ice will solidify beneath the oil, trapping it on the surface. Snow will cover most of the oil through the remainder of the ice season.

There are two differences between oil trapped above and below thin ice. The first is the presence of suspended sediments in the water during the fall freezeup period. Barnes et *al.* (1982) documented the presence of sediment-laden ice within the fast ice zone. Sediment concentrations ranged from 0.003 to 2 kg m^{-3} of ice with considerable variations in regional distribution and yearly amount. Oil in the water beneath the ice cover will have an opportunity to adhere to this suspended matter. Second, the oil on the ice surface, even when covered by snow, is subject to evaporation. The evaporation rate varies considerably, depending upon the constituent hydrocarbon fractions of the crude oil, the temperature, and exposure to the atmosphere. NORCOR (1975) measured evaporation rates as high as 25 percent within one month. This was for a Norman Wells crude on the surface during the winter with a few centimeters of snow cover. Rates decreased sharply after the first month, but a total of 30 percent or more of the oil could have evaporated by spring.

Oil that surfaces in newly opened leads or in the broken ice directly over a blowout will also have new ice growing beneath it and will be subject to weathering throughout the remainder of the winter. Oil, being less dense than sea ice, will tend to overflow the tops of cracks. Cold temperatures and an absorbent snow cover will limit the spread of the oil to a distance of approximately 1 m (NORCOR, 1975). Thereafter, the oil will spread beneath the ice.

2. *Oil Under Undeformed Ice.* Most of the oil from a winter blowout will end up beneath the ice. Gas trapped under the ice will probably escape within a day. Observations made by divers beneath first-year ice in late February and early March confirm this (Reimnitz and Dunton, 1979). In the spring, trapped air has been observed to escape through open brine channels within minutes (Barnes *et al.*, 1979).

The majority of the oil will end up as films, drops, or pools beneath the sea ice. In the absence of strong ocean currents, the oil becomes encapsulated by new ice growth. NORCOR (1975) found that the time needed to form an ice sheet below an oil lens is a function of the thermal gradient in the ice and the thickness of the oil. In the fall, a layer of new ice will completely form beneath the oil within 5 days. During the winter, that time increases to 7 days, and in the spring, 10 days.

Martin (1977) observed no traces of oil in the ice that forms beneath an oil lens. The skeletal layer in the ice above an oil lens does appear to become heavily oiled 0.04 to 0.06 m into the ice, but has been found to contain less than 4 percent (volume) of oil (Martin, 1977; NORCOR, 1975). This is equivalent to an oil film about 2 mm in depth, or about 25 percent of the equilibrium thickness of oil under thin, smooth ice.

A layer of oil beneath sea ice tends to raise the salinity of the ice above the oil and lower the salinity of the new ice directly below the oil (NORCOR, 1975). The oil layer may trap rejected brine in the ice above, or, by insulating the ice from the sea water, lower the ice temperature above the oil lens. This insulating effect also causes slow initial ice growth below the oil, which results in lower salinity ice. The high-salinity ice directly above the oil will likely accelerate the migration of oil into brine channels when the ice begins to warm, but the effect on ice growth appears to be minimal beyond the first few days (NORCOR, 1975).

The incorporation of oil into multiyear ice presumably will occur much as it does in first-year ice. Growth rates are lower under thick multiyear ice than under thinner first-year ice, but it has been postulated that a thick oil lens, as would collect under multiyear ice, will actually enhance ice growth due to convective heat transfer through the oil.

3. Oil Incorporated in Deformed Ice. Oil spilled in the fall under thin ice, or in newly refrozen leads, may be incorporated into pressure or shear ridges. Some of the oil may remain in these ridges in an unweathered state through several melt seasons. The oiled ridges can travel great distances releasing the oil along their paths, which may be advantageous since the oil would be released slowly over a greater area. This would remove the oil from the sensitive coastal regions and release it in lower concentrations elsewhere, which is desirable.

The building of large ridges does not generally occur in the fast ice zone because of the barrier islands along this part of the coast, which, along with grounded ridge systems, serve to protect the fast ice zone from effects of the pack ice. Exceptions certainly occur, especially in the Harrison Bay or Camden Bay regions during early freezeup before protective ridges become grounded.

The most common deformation in newly formed ice is rafting. Rafting will halve the area of oiled ice and double the average oil concentration under the ice. The effect of rafting will be hardly noticeable at breakup, and, due to ice growth through the winter, rafted and undeformed ice will be approximately the same thickness. Thus, in the fast ice zone, all the ice will break up and release oil at about the same time.

Outside the fast ice zone and the barrier islands lies the Stamukhi zone. This zone comprises the past, present, and future position of the active shear zone between the moving pack ice and the stationary fast ice. All observations indicate that this zone is the most heavily ridged area in the southern Beaufort Sea with ridge densities as high as 12 ridges per kilometer (Tucker *et al.*, 1979). If, during the fall, the ice in the Stamukhi zone becomes contaminated with oil, then there is a good chance of the oiled ice becoming incorporated into a ridge. Using some typical values (an average sail height of 1.5 m; an average keel depth of 4 times the sail height; average sail and keel slopes of 24° and 33°, respectively; and a 10-percent void volume in ridges), the area of ice in a typical ridge profile is computed to be about 54 m^2. If the ice blocks in a ridge are 0.5 m thick, then to get 12 ridges in 1 km, a 2.3-km lateral extent of ice must have been deformed to a 1 km width. As a first approximation, then, more than one-half the area of ice in the Stamukhi zone becomes ridged. Of course, the problem is much more complicated than this. Many of the ridges are built from new ice grown in leads that have opened. Many ridges are much larger than the typical ridge described and are built from thinner ice. Nevertheless, the possibility of oiled ice becoming incorporated into a ridge is significant in the Stamukhi zone.

Proceeding from the Stamukhi zone out to the pack ice zone, we can make a rough estimate of the probability of oiled ice being built into a ridge. First, if the oil comes up under a large multiyear floe, there is only a small chance of it later becoming part of a ridge. Most of the ice involved in ridging has been observed to be young ice, thinner than 0.5 m (R. M. Koerner, Personal communication, in Weeks *et al.*, 1971). It is possible that, when a lead opens across a multiyear floe, oil trapped in the ice nearby could drain into the open lead and later be incorporated into a ridge if the lead closes up. Kovacs and Mellor (1974) state that there is 1 to 5 percent open water in the seasonal pack ice zone. Wadhams and Home (1978) report from 0.1 to 3.5 percent thin (ridging-prone) ice (less than 0.5 m), with a mean value of 0.9 percent. These percentages certainly vary with the time of year, especially in the fall, and also *vary* with the distance from shore. If we use the value of 1 to 5 percent open water and thin ice as the measure of ice available for ridging, then this is the probability of oiled ice being built into a ridge at any one time. The cumulative probability over the entire ice season will be higher, but the increasing thickness of the oiled ice will eventually reduce the possibility of its being ridged.

In the fall, a much larger percentage of the seasonal pack ice zone is covered by thin ice. While not all of this thin ice will be involved in ridging, the probability will certainly be larger than later in the winter.

D. Transportation Phase

Estimating possible motions of oiled ice in the southern Beaufort Sea is difficult due to the lack of data. Only a few buoy observations made by AIDJEX during the winter and spring of 1976 (Thorndike and Cheung, 1977) and some radar ranging by Tucker et *al.* (1980) during 1976 and 1977 in and near the fast ice exist in the public domain. These data are insufficient for making reliable predictions of ice motions. Statistics might be formulated using *historic* winds and ice motion models, but ice motions are strongly dependent on the strength of the ice sheet, and data on ice strength are very limited. However, the *range* of possible motions can be computed.

The fast ice lies motionless throughout most of the ice season. Measurements of fast ice motions (Tucker *et al.*, 1980) confirm its wintertime rigidity within barrier islands *or* grounded ridge systems. In October and November, strong winds are able to move nearshore ice. Large motions are probably not common, but one case has been reported in the literature (Kovacs and Weeks, 1979) where motions of a few kilometers were observed near shore in early November as the result of high winds. By December, the fast ice is thick enough to resist typical storms and it will remain so until breakup in June or July.

Rivers begin flooding the nearshore fast ice in late May or early June. Shore polynyas form and spread from mid-June through early July. The ice sheet becomes thinner and rotten. Sometime during July, the ice becomes weak enough that winds will cause it to move. At first, the most likely direction of motion is towards the shore polynyas, as the ice is weakest in that direction. Soon, enough open water exists that the ice can move in any direction. The winds during the summer are predominantly from the east or northeast, so typically, the ice will be driven westward and alongshore. Maximum motions are probably comparable to pack ice motions.

Grounded ridges along the outer boundary of the fast ice, in the Stamukhi zone, will sometimes remain stranded throughout the summer. If not securely grounded, they will be driven by the winds and currents. Ridged ice driven out to sea into the pack may last for several years and travel great distances.

The pack ice motion has a long-term westward trend. During the winter, there are often periods of days or weeks when no significant pack ice motion occurs. This happens when the pack is very consolidated and light winds have blown from the north or west for long periods. When the pack is unconsolidated, the ice has little or no internal resistance t-o wind and water forces, and it moves about freely. This condition, known as free drift, represents the maximum extreme of possible ice *motion.* In between the extremes of *no* motion and free drift, the motion depends upon the atmospheric and oceanic driving forces, the sea surface tilt, the Coriolis effect, and internal stresses transmitted through the ice. This last term is difficult to model for long periods of time, since small errors in velocity affect the distribution of ice and, thus, the ice strength , which in turn affects future velocities.

Thomas (1983) computed typical pack ice motions and standard deviatons of daily motions using historical wind data, a range of ice conditions and ocean currents, and an ice model. The model was "tuned" so that average motions corresponded to the limited observations of ice motions.

The computed trajectories showed an average westward motion of about 3.7 km day^{-1} during the fall, 1.3 km day^{-1} during the winter, 2.1 km day^{-1} during the spring, and 3.6 km day^{-1} during the summer. The standard deviation of daily motions was more than 5 km. The motions near the shore tend to be smaller than those further offshore. Along the Alaskan coast, the ice has a shoreward component of motion, but west of Point Barrow the motion turns toward the north. While the westward trend persists from month to month over many years, daily motions exhibit a great deal of meandering and back-and-forth motion in all directions.

E. Release Phase

Oil spilled in the winter beneath the sea ice is not seen to be an immediate threat to the environment. This is due to the ice itself, which contains the spill in a relatively small area away from land and insulates the oil from interacting with the ocean and the atmosphere. Eventually, the oil is released from the ice and begins to interact with and become a danger to its environs.

For first-year *sea ice,* this release is well understood and has been documented by NORCOR (1975), Martin (1977), and Buist *et al.* (1981). The oil trapped in first-year ice may be released by two major routes: by rising to the ice surface through brine drainage channels or by having the ice melt completely. Some oil will be released from newly opened cracks or leads. The release of oil from beneath multiyear ice probably occurs more slowly. Comfort and Purves (1980) report that, of the oil placed beneath multiyear ice in Griper Bay (Melville Island, N.W.T.), over 90 percent had surfaced at the end of two melt seasons.

1. Brine Drainage Channels. In late February or early March, the mean temperature begins to rise in the southern Beaufort Sea. As the ice begins to warm up, brine trapped between the columnar ice crystals begins to drain. Oil trapped beneath the ice will probably accelerate this brine drainage by raising the ice salinity directly over the oil. Martin (1977) observed that oil released beneath the ice during the winter migrated 0.16 m upward through brine channels by 22 February. Once the air and ice temperature approach the freezing point, the brine channels will have extended through the ice. This occurs in late April or May. Once the channels are extended to the surface and are of sufficient diameter, oil will begin appearing on the ice surface. Oil released under ice with top-to-bottom brine channels also begins to appear on the surface within an hour (NORCOR, 1975).

Flow rates must be fairly low, since it has been observed that not all the oil is released until the ice has melted down to the initial level of the oil lens (NORCOR, 1975; Buist *et al.*, 1981). An upper bound can easily be set. Oil has been observed to take about 1 hour to migrate up through about 2 m of ice with open brine channels. The brine channels were about 4 mm in diameter, so each brine channel had a maximum volume flow of 8×10^{-6} m^3 hr^{-1}. The brine channels were spaced from 0.2 to 0.3 m apart, so each square meter of ice contained about 16 brine channels, and the flow rate per square meter was about 0.0004 m^3 hr^{-1}. This is equivalent to an oil film 0.4 mm thick being released each hour. The actual flow rate probably is smaller.

Oil that surfaces through brine channels will primarily be found floating on the surfaces of melt pools. If melt pools do not exist when the oil surfaces, they soon form due to the lowering of the surface albedo. Snow forms an effective barrier to the spread of the oil, but wind and waves will splash oil onto surrounding snow, causing pools to grow in size. Oil-in-water emulsions were observed to form in the melt pools when winds were over 25 km hr^{-1}. As much as 50 percent of the oil in a melt pool could be in the form of emulsions but, generally, emulsions break down within a day after winds subside (NORCOR, 1975; Buist *et al.*, 1981).

The rates at which the oil evaporates, emulsifies, or dissolves will be considerably lower in arctic regions than they would be in lower latitudes. Not only does the ice serve to protect the oil during the winter, but, as it melts in the spring, it releases the oil slowly over periods of weeks. The ice also acts to moderate wind effects, so smaller waves and less mixing occur in melt pools and open leads. The lower temperatures also increase the stability of the oil. In general, the process that has the most significant effect on oil quantity during spring release is evaporation.

NORCOR (1975) estimated that by early June, at some test sites of the Balaena Bay experiment, 20 percent of the oil had evaporated. By 16 June, it was reported that “the flow of oil from the ice had almost completely stopped,” since the ice had melted down to the trapped oil lens in most cases. More than 50 percent of the oil had evaporated by late June.

2. surface Melting. Most of the undeformed first-year ice near shore will melt down to the oil layer during the summer months. Any oil that does not reach the ice surface through open brine drainage channels will then be released. Typically, the nearshore area first begins to open and break up around the end of June and is mostly ice free by the end of July (Barry, 1979). Oil on the ice surface (via brine channels) will accelerate ice melting and breakup by lowering the albedo. NORCOR (1975) estimated that ice contaminated by oil would break up about two weeks earlier than unoiled ice.

III. FATE OF OIL

We have seen that the vast majority of oil spilled in the Beaufort Sea during the ice season would be held in abeyance by the ice until spring, when it would begin to appear on the ice surface. The surfaced oil begins to weather and to cause accelerated melting of the ice. Typically, all the ice in the contaminated area will have melted by mid-July, at which time about 50 percent of any remaining oil will have evaporated. Emulsification, dispersion, and dissolution of the oil on the open-water surface will also occur, and silt from flowing rivers may cause the oil to become sedimented.

Until all the ice has melted, the *rates* at which natural processes degrade and disperse the weathered oil will be low. *The* release of the oil *over a* period of time, the reduced surface area because of confinement by the ice, and small fetches for wind energy input all contribute to the low rates. The amounts of oil removed by natural processes will be insignificant, but may have *a* critical effect on the ecology of the area.

Once the area becomes free of ice, conditions parallel an open-water spill. The major difference is the evaporative losses of the oil by this time. Because of prevailing winds *in* the southern Beaufort Sea, an open-water slick will likely be driven onshore to the west or southwest. Since the oil is partially weathered, the slick will tend to be more concentrated than a recent spill from a blowout. Southerly or easterly winds will drive the slick offshore, breaking it up and spreading oil over larger areas. Eventually, the winds will reverse, and an even larger stretch of coast is in danger of contamination.

Oil deposited upon beaches will probably be the second largest sink for hydrocarbons (after evaporation). Sedimentation to the sea bottom will also be important. Over much longer time periods, oxidation and biodegradation will dispose of small percentages of the oil.

IV. THE EFFECTS OF ICE ON CLEANUP

It is not the purpose of this report to propose or evaluate methods of oil spill cleanup in Arctic waters. It is worthwhile, however, to review the characteristics of the ice cover and oil-ice interactions that will affect cleanup activities. Again, we are only considering a major blowout and release of large quantities of oil during the ice season.

A. Pack Ice Zone

Oil from a blowout under temporarily stationary pack ice might be partially collected from the blowout site if the blowout occurs near an island or other facility that could allow pumping and storage of the oil. Burning of oil and gas during the blowout could also be partially useful if recovery is impractical. If the pack ice is moving more than a few hundred meters per day, recovery would probably be impossible and even burning would be difficult. In this case, it would be most important to ensure gas release over or near the blowout to reduce oil spread under the ice. To help locate the oiled ice in the spring when the oil begins to surface, markers and beacons could be placed near the blowout site. Then, the oiled melt pools could be ignited, probably by air-dropped incendiary devices, to dispose of some of the oil. Most of the oil and the residue from burning would remain on the ice surface or in newly opened leads. Dispersants could be used as soon as oil appears in open-water leads and polynyas. As summer proceeds and the lighter, more-toxic components evaporate, seeding with petroleumlytic microbes and fertilization could enhance biodegradation. Since the long ice season halts or slows the natural processes acting to degrade and disperse the spill, summertime activities would be important for reducing the chances of harm in future years. The environmental contamination would probably persist for several years in any case, especially since oiled ridges may be capable of retaining some oil through the summer.

B. Fast Ice Zone

A blowout and oil spill in the fast ice zone could potentially be the most harmful because this is the area in which open water first appears in the spring, but effective cleanup may be possible. The ice will not move between November or December and the following June; currents are low, so the oil will not be moved about under the ice; and the ice provides a stable work platform. Nevertheless, a large spill could cover several square kilometers. The spill area could be reduced considerably by early ice season preventive measures. These measures would be as simple as cleaning the snow from narrow strips surrounding possible blowout sites to promote faster ice growth and more under-ice containment potential. Other methods of increasing oil containment under the ice can be postulated (skirts frozen into the ice, air-bubble systems to reduce ice growth), but none of these methods are feasible until after the ice has become thick and strong enough to resist movement by winds. Another requirement is that the ice be safe for surface travel.

The blowout will likely create an area of open water in the fast ice directly above it. Gases will escape through this opening, and a great deal of oil trapped on the water surface will be contained by the surrounding ice. This area of open water could be enlarged by blasting. If storage facilities are available, oil could be pumped directly from the pool during the blowout.

Oil from a large blowout that has been allowed to spread beneath the ice, especially early in the ice season when bottomside relief is small, will be more difficult to collect during the winter. The oil can cover a large area and will collect in many small pools beneath the ice. At the moment, no proven technology exists for locating these pools other than trial and error drilling. The negative correlation between depth of snow cover and ice thickness (Barnes *et al.*, 1979) would aid in the search. Other possibilities are being developed, but they will probably also be very labor intensive. Even when pools of oil are found, it would be virtually impossible to remove all of the oil from the ice. After new ice growth has completely encapsulated the oil lens, it will be even more difficult to remove oil from beneath the ice.

When oil begins to appear on the ice surface in the spring, concentrations will still be so low that removing the oil would be difficult. Burning the oil at this time would be much simpler and, for small spills or remnants of large spills, a significant proportion might be disposed of in this fashion. Since the oil is released from the ice over a period of weeks, burning of the oil on each melt pool will have to-be done several times. It is unlikely that all the oil will surface to be burned before breakup.

C. Stamukhi Zone

Oil spill cleanup in this region depends on many factors. A large amount of ridge building takes place, but a grounded ridge can extend the fast ice boundary seaward. The greater bottomside relief will tend to concentrate the oil in the region inside grounded ridge systems. Oil within ridges may be impossible to clean up, since ridges may be able to hold oil for several years. This could be advantageous, since the oil would be released slowly over several seasons and over a large area as the ridges drift with the pack, reducing contamination at any one place and time. Oil trapped in deep pools behind ridge keels should be recoverable, but would require considerable effort. In this case, the distance from shore and the difficulty of surface travel would be obstacles to cleanup.

The most successful cleanup would involve concentrating oil in a small area. Since it would be difficult to enhance the bottomside relief in the Stamukhi zone, one could only hope that ridges are located to provide this concentration. If the oil is not contained by natural features, or cannot be collected directly from the blowout site, springtime burning of surfaced oil must be considered. For small amounts of oil this can be effective, but for very large spills the majority of the oil will remain. Even after cleanup and evaporation, as much as 40 to 50 percent of a large spill will remain in ridges, on unmelted ice floes, or on the water surface. If the pack retreats northward, conventional open-water cleanup methods and dispersants might remove more of the oil. If the pack remains near shore through the summer, cleanup will have to concentrate on the beaches and open-water lagoons behind the barrier islands. Release of oil from the ice is likely to occur in subsequent summers making cleanup a long-term, wide-area project.

V. SUMMARY

The events following an under-ice blowout may be divided into five phases: (1) initial, (2) spreading, (3) incorporation, (4) transportation, and (5) release. Depending upon the season, location, and duration of the blowout, several of these phases may occur simultaneously or not at all.

The initial phase of an under-ice blowout consists of the release of oil and gas from the sea floor, the rise of the oil and gas to the surface, and the initial interaction of the oil and gas with the existing ice cover. The buoyant gas and oil entrain large amounts of water while rising to the surface.

This plume and the resulting surface currents are only marginally important to the eventual fate of the oil. The turbulence at the surface may play some part in breaking up the ice over the blowout, especially when the ice cover is moving. A much more important factor is the buoyancy of the gas from the blowout. Under a stationary ice cover, this gas is almost certain to rupture the ice, allowing gas to escape to the atmosphere. Under a moving ice cover, especially for thicker multiyear ice, it is not certain that gas trapped beneath the ice will cause the ice to break. Large amounts of gas trapped beneath the ice will have a significant effect on the spread of oil under the ice. Only a limited quantity of gas is likely to remain trapped, however, due to the presence of naturally occurring thermal cracks. From theoretical studies and casual observations, these thermal cracks appear to occur frequently enough that only a small percentage of the gas from a blowout will be trapped under the ice.

The heat from the oil and bottom water circulated by the blowout plume can also be instrumental in producing an ice-free area directly over the blowout. Oil will replace the melted ice, although this may be a fairly small percentage of the total oil released. This melt hole could, however, act as a reservoir from which oil could be pumped.

It is unlikely that much oil will be deposited on the ice surface during a winter under-ice blowout. The oil will tend to overflow onto the ice wherever an opening occurs, but low air temperatures and snow on top of the ice will act to restrict the horizontal spread.

A spreading phase follows the initial phase of the blowout. This phase depends on the relative motion and concentration of oil beneath the ice layer. Factors that are particularly important during the spreading phase are the bottom roughness of the ice, ice growth, ocean currents, existing ridge keels, and the motion of the ice cover. The roughness of the underside of the ice generally provides an upper limit to the size of the under-ice slick, except under very smooth, new ice where the size of the slick is determined by the equilibrium thickness of oil under ice.

For blowouts lasting more than a few days, the spread of oil beneath the ice may be significantly restricted by the increasing thickness of the ice outside the immediate blowout vicinity. For very large blowouts, and in the absence of ice motion or large under-ice currents, this mechanism would tend to collect much of the oil in a single, relatively small, deep pool.

In the nearshore area of the Beaufort Sea, currents are generally too small during the ice season to affect oil spread. Tidal channels-between barrier islands (and possibly grounded ridges) are an exception, but probably not significant in terms of area since the tidal currents are oscillatory.

Ridge keels can have a major effect on the direction and extent of oil spread. In the Stamukhi zone, ridges may be frequent enough to control the size of the under-ice slick.

Motions of the ice cover may also control the size of the slick by allowing some gas to be trapped. The amount will depend upon ice speed and thermal crack spacing.

An incorporation phase will follow the spreading phase. Oil spilled under sea ice during the winter will generally become encapsulated within the ice. This oil is protected from weathering until the ice begins to warm in the spring, releasing the oil. This is probably the most important aspect of under-ice oil spills in the Arctic. It means that spills that occur from October through May will, in effect, occur at the beginning of ice breakup. Oil is released into a limited amount of open water at a time critical to all levels of biological activity. This delay also allows time for cleanup activities between the actual and effective release of the oil.

Oil spilled outside the grounded ridges that delineate the protected fast ice zone has a relatively high chance of being incorporated into a ridge. Due to ice motion relative to a fixed boundary, a large amount of ridge building occurs in this area during periods of pack ice motion. The amount of oil and the length of time it can be held within a ridge are important questions when considering the possibility of a blowout in the Stamukhi zone.

During the transportation phase, oil trapped by bottom roughness or frozen into the ice moves with the ice cover. In the fast ice zone, transport occurs early in the ice season when the ice is thin and weak or late in the season as the ice breaks up and begins to move. Even during these times, the amount of ice motion is usually less than a few kilometers.

Significant transportation of oil by the ice takes place in the pack ice zone. The pack generally meanders to the west, and oil from a blowout will be spread over large areas in low concentrations. Differential motions of individual floes within the pack will tend to further separate oiled areas of ice.

The release phase occurs in the spring, when all the oil except possibly that trapped within ridges begins to be released from the ice. The oil is released by two means: through brine drainage channels and by the melting of the ice cover. By mid to late July, most of the oil-contaminated ice will have melted, leaving partially weathered oil on the water surface. Open-water areas and shorelines to the west, possibly as far as the Chukchi Sea, may be contaminated with oil during the summer. During the period when the oil is being released and the ice is melting and breaking up, the motion of the oil already on the water is unpredictable. The concentration of the ice cover and the motion of the ice would undoubtedly influence the motion of the oil.

Cleanup of large under-ice oil spills will be difficult in the spring, because oil will surface slowly in many separate melt pools. As soon as the oil surfaces, it begins to weather, making it difficult to burn. The continuous release and weathering of the oil makes it necessary to burn each melt pool containing surfaced oil several times. The surfaced oil also accelerates the deterioration of the ice cover, decreasing the time interval when the ice is safe for surface work. A spill covering several square kilometers will surface in thousands of separate pools. In the pack ice, these pools are likely to be spread over many kilometers.

Cleaning the oil from the water surface as the ice melts will also be difficult. Conventional open-water cleanup methods will be difficult to use until the ice concentration is low, which may be too late to prevent widespread dispersion of the oil. For small spills or remnants of large spills, a combination of burning and open-water cleanup methods might be practical.

A much safer cleanup strategy involves pumping the oil from beneath the ice during the winter or early spring. Logistically, this would be extremely difficult, unless the oil was pooled in large concentrations beneath the ice. It is unlikely that this would occur naturally, except perhaps in the fast ice zone, where ice growth can outpace oil accumulation, or in heavily ridged areas of the Stamukhi zone. However, in the fast ice zone, an effective preventive measure would be to create under-ice reservoirs by artificially redistributing snow in areas where blowouts might occur. In the pack ice, this procedure would be impractical due to ice motion.

915R

REFERENCES

Aagaard, K. (1981) "Current Measurements in Possible Dispersal Regions of the Beaufort Sea," *Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators, Vol.* 3, *Physical Science Studies,* NOAA/OSCEAP, Boulder, Colorado, pp. 1-74.

Ackley, S. F., Hibler W. D. III, Kugzruk, F. K., Kovacs, A., and Weeks, W. F., (1974) "Thickness and Roughness Variations of Arctic Multi-Year Sea ice," *AIDJEX Bulletin No.* 25, University of Washington, Seattle, pp. 75-96.

Barnes, P., Reimnitz, E., Toimil, L., and Hill, H. (1979) *Fast Ice Thickness and Snow Depth in Relation to Oil Entrapment Potential, Prudhoe Bay, Alaska,* U.S. Geol. Survey Open-File Report 79-539, Menlo Park, California.

Barnes, P. W., Reimnitz, E., and Fox, D. (1982) "Ice Rafting of Fine-Grained Sediment, a Sorting and Transport Mechanism, Beaufort Sea, Alaska," *J. Sedimentary Petrology* 52 (2), 493-502.

Barry, R. G. (1979) "Study of Climatic Effects on Fast Ice Extent and its Seasonal Decay Along the Beaufort-Chukchi Coasts," *Environmental Assessment of the Alaskan Continental Shelf,* Final *Reports,* NOAA/OCSEAP, Boulder, Colorado, Vol. 2. Physical Science Studies, pp. 272-375.

Buist, I. A., Pistruzak, W. M., and Dickins, D. F. (1981) "Dome Petroleum's Oil and Gas Undersea Ice Study$" *Proceedings of the Fourth Arctic* Marine *Oilspill Program Technical Seminar,* Edmonton, Alberta, June 16-18, 1981, pp. 647-686.

Comfort, G. and Purves, W. (1980) "An Investigation of the Behavior of Crude Oil Spilled under Multi-year Ice at Griper Bay, N.W.T.," *Proceedings of the Third Annual Marine Oilspill Program Technical Seminar,* Edmonton, Alberta, June 3-5, 1980, pp. 62-86.

Cox, J. C., and Schultz, L. A. (1981) "The Mechanics of Oil Containment Beneath Sea Ice," *Proceedings of the Fourth* Arctic *Marine Oilspill Program Technical Seminar,* Edmonton, Alberta, June 16-18, 1981, pp. 3-44.

Cox, J. C., Schultz, L. A., Johnson, R. P., and Shelsby, R. A. (1981) "The Transport and Behavior of Oil Spilled In and Under Sea Ice," *Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators,* NOAA/OCSEAP, Boulder, Colorado, Vol. 3, Physical Science Studies, pp. 427-597.

Deslauriers, P. C. (1979) "The *Bouchard* No. 65 Oil Spill in the Ice-Covered Waters of Buzzards Bay," *J. Petroleum Technology, 31,* 1092-1100.

Evans, R. J., and Untersteiner, N. (1971) "Thermal Cracks in Floating Ice Sheet s," *J. Geophys. Res.* 76 (3), 694-703.

Kovacs, A. (1977) "Sea Ice Thickness Profiling and Under-Ice Oil Entrapment," *Proceedings 1977 Offshore Technology Conference,* Houston, Texas, Vol. III, pp. 547-554"

Kovacs, A. (1979) "Oil Pooling Under Sea Ice," Environmental *Assessment of the Alaskan Continental Shelf, Annual Reports,* Vol. VIII. Transport, pp. 310-353.

Kovacs, A., and Mellor, M. (1974) "Sea Ice Morphology and Ice as a Geologic Agent in the Southern Beaufort Sea," *The Coast and Shelf of the Beaufort Sea,* (C. *Reed and* E. Slater, eds.), Arctic Institute of North America, Arlington, Virginia, pp. 113-162.

Kovacs, A., and Morey, R. M. (1978) "Radar Anisotropy of Sea Ice Due to Preferred Azimuthal Orientation of the Horizontal C Axes of Ice Crystals," *J. Geophys. Res.* 83 (C12), *6037-6046.*

Kovacs, A., Morey, R., Cundy, D. and Dicoff, G. (1981) "Pooling of Oil Under Sea Ice," *Proceedings Port and Ocean Engineering Under Arctic Conditions,* Quebec, Canada, Vol. II, pp. *912-922.*

Kovacs, A., and Weeks, W. F. *(1979)* "Dynamics of Near-Shore Ice," *Environmental Assessment of the Alaskan Continental Shelf, Annual Reports,* NOAA/OCSEAP, Boulder, Colorado, Vol. VII, Transport, pp. 181-207.

Lewis, E. L. (1976) *Oil* in *Sea Ice*, Pacific Marine Science Report 76 12, Institute of Ocean Sciences, Patricia Bay, Victoria, B.C.

Logan, W. J., Thornton, D. E., and Ross, S. L. (1975) *Oil Spill Counter Measures for the Beaufort Sea,* Appendix, Beaufort Sea Technical Report No. 31b, Beaufort Sea Project, Dept. of the Environment, Victoria, B.C.

Malcolm, J. D. , and Cammaert, A. B. (1981) "Movement of Oil and Gas Spills Under Sea Ice," *Proceedings Port and Ocean Engineering Under Arctic Conditions}* Quebec, Canada, Vol. II, pp. 923-936.

Martin, S. (1977) *The Seasonal Variation of Oil Entrainment in First Year Sea Ice: A Comparison of NORCOR/OCS Observations,* Dept. of Oceanography, Spec. Report #71, University of Washington, March.

Matthews, J. B. (1980) "Observations of Surface and Bottom Drifter Movements in the Beaufort Sea Near Prudhoe Bay, Alaska," Submitted to *J. Geophys. Res.*

Milne, A. R., and Herlinveaux, R. H. (n.d.) *Crude Oil in Cold* Water (R. J. Childerhose, cd.), Beaufort Sea Project, Institute of Ocean Sciences, Sidney, B.C.

NORCOR Engineering and Research, Ltd. (1975) *The Interaction of Crude Oil with Arctic Sea Ice,* Beaufort Sea Technical Report #27, Beaufort Sea Project, Dept. of the Environment, Victoria, B.C.

NORCOR Engineering and Research, Ltd. (1977) *Probable Behavior and Fate of a Winter Oil Spill in the Beaufort Sea,* Technology Development Report EPS-4-EC-77-5, Environmental Impact Control Directorate.

Reimnitz, E., and Dunton, K. (1979) "Diving Observations on the Soft Ice Layer Under the Fast Ice at DS11 in the Stefansson Sound Boulder Patch," *Environmental Assessment of the Alaskan Continental Shelf, Annual Reports,* NOAA/OCSEAP, Boulder, Colorado, Vol. IX. Hazards, pp. 210-230.

Reimnitz, E., Toimil, L. J., and Barnes, P. (1977) "Arctic Continental Shelf Processes and Morphology Related to Sea Ice Zonation, Beaufort Sea, Alaska," *AIDJEX Bulletin No. 36,* University of Washington, Seattle, pp. 15-64.

Rosenegger, L. W. (1975) *Movement of Oil Under Sea Ice,* Beaufort Sea Technical Report No. 28, Beaufort Sea Project, Dept. of the Environment, Victoria, B.C.

Ruby, C. H., Ward, L. G., Fischer, 1. A., and Brown, P. J. (1977) "Buzzards Bay Oil Spill - An Arctic Analogue," *Proceedings Fourth International Conference on Port and Ocean Engineering Under Arctic Conditions,* St. John's, Newfoundland, pp. 844-855.

Stringer, W., and Weller, G. (1980) "Studies of the Physical Behavior of Oil in Ice," *Proceedings of the Third Annual Marine Oilspill Program Technical Seminar,* Edmonton, Alberta, June 3-5, pp. 31-44.

Thomas, D. R. (1983) "Potential Oiled Ice Trajectories in the Beaufort Sea," Flow Research and Technology Report No. 252, Flow Industries, Kent, Washington.

Thorndike, A. S., and Cheung, J. Y. (1977) "AIDJEX Measurements of Sea Ice Motion, 11 Apr 1975 to 14 May 1976," *AIDJEX* Bulletin No. 35, January, University of Washington, Seattle.

Topham, D. R. (1975) *Hydrodynamics of an Oil Well Blowout,* Beaufort Sea Technical Report No. 33, Beaufort Sea Project, Dept. of the Environment, Victoria, B.C.

Topham, D. R. (1977) "The Deflection of an Ice Sheet by a Submerged Gas Source," *J. Appl. Mech.*, June, 279-284.

Topham, D. R., and Bishnoi, P. R. (1980) "Deep Water Blowouts," *Proceedings of the Third Annual Marine Oilspill Program Technical Seminar,* Edmonton, Alberta, June 3-5, 1980, pp. 87-95.

Tucker, W. B., Weeks, W. F., and Frank, M. (1979) *Sea Ice Ridging Over the Alaskan Continental Shelf,* CRREL Report 79-8, Hanover, New Hampshire.

Tucker, W. B., Weeks, W. F., Kovacs, A., and Gow, A. J. (1980) "Nearshore Ice Motion at Prudhoe Bay, Alaska," Sea *Ice Processes and Models,* (R. S. Pritchard, cd.), University of Washington Press, Seattle, pp. 261-272.
Wadhams, P., and Home, R. (1978) *An Analysis of Ice Profiles Obtained by Submarine Sonar in the AIDJEX Area of the Beaufort Sea,* Scott Polar Research Institute Technical Report 78 1, Cambridge.
Weeks, W. F., and Gow, A. J. (1980) "Crystal Alignment in the Fast Ice of Arctic Alaska," *J. Geophys. Res.* 85(C2), 1137-1146.
Weeks, W. F., Kovacs, A., and Hibler W. D. III, (1971) "Pressure Ridge Characteristics in the Arctic Coastal Environment ," *Proceedings 1st International Conference on Port and Ocean Engineering under Arctic Conditions,* Trondheim, Norway, Vol. I, pp. 152-183.

915R