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Behavior of Oil Spills in Ice and Implications for Arctic Spill Response

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Abstract

The paper reviews the history of research into the behavior spills in ice covered waters and documents our current state of knowledge, drawing on the findings from a number of milestone field experiments conducted over the past 40 years. In particular the paper focuses on the unique aspects of spill behavior in different ice regimes that can both hinder and benefit spill response, depending on the timing and type of release. With increasing interest in exploiting Arctic oil resources, the knowledge base summarized in this paper can be used to identify priority topics for future research and development.

There is an extensive background of research into all aspects of Arctic spill response and our level of understanding is extremely good in many areas, such as understanding how close pack ice contains the oil from spreading, how oil trapped in the ice through the winter is maintained in a fresh state, and how trapped oil is exposed on the ice surface in the spring. Key observations from large-scale field experiments are that the natural containment, reduced wave action and slower weathering in the presence of significant ice cover, can greatly extend the windows of opportunity and effectiveness for response operations such as burning and dispersant application. These benefits are not experienced with traditional response options relying on boom and skimmer systems where ice interference severely reduces the recovery effectiveness.

Future advances in our ability to respond to spills in ice will require a new approach to permitting experimental spills. The record shows that it is entirely possible to plan and execute experiments safely with no harm to the environment. Continued regulatory intransigence could jeopardize industry's ability to develop credible and effective contingency plans to permit future Arctic exploration and development activities.

Introduction and Background

The issue of oil spill clean-up in ice continues to grow in importance as exploration drilling outside of the traditional summer open water period becomes more and more technically feasible with advanced marine technology supported by active ice management and capable vessels. Exploiting this capability requires the operator to prepare a credible oil discharge contingency plan that covers the possibility (regardless of how remote) that a late-season blowout could lead to large volumes of oil trapped under moving ice and potentially drifting unrecovered through the winter. This is a fundamental issue that is now being considered through governmental hearings and commissions in the US and Canada prompted by the 2010 *Deepwater Horizon* incident. In order to understand the challenges of dealing with this scenario, it is important understand the different processes governing the likely behavior of oil in a variety of ice conditions and to assess our current state of knowledge in this area.

Over the past 40 years a small number of landmark field experiments and spills of opportunity, together with numerous laboratory, tank tests abd analytical studies have led to a good understanding of the basic processes controlling the behavior of fresh and emulsified crude oil, with and without gas, in a variety of ice conditions, including static fast ice and drifting pack ice. Most of this work has been performed in the US, Canada and Norway. A number of reviews and assessments summarize known studies and references on the subject, e.g. SL Ross et al. (2010), Brandvik (2007), Fingas and Hollebone (2002) and Dickins and Fleet (1992). In addition papers and reports by Dickins and Buist (1999), and Dickins et al. (2000) describe the key processes associated with oil and ice interaction.

It is impossible to cover all facets of the vast amount of research carried out specific to the problem of oil spills in ice within the confines of a single paper. This document focuses on what we have learned about the behavior of oil in ice from actual field experiments involving deliberate crude oil spills for research purposes. Motivated originally in the early 1970's by pending plans for offshore oil exploration in the Canadian Beaufort Sea, a number of experimental oil releases were conducted with fresh and emulsified crude under solid ice. Examples include: NORCOR (1975), Dickins and Buist (1981), Buist et al. (1983), and Comfort *et al.* (1983). The first experimental spill in pack ice was carried out in 1986 off Cape Breton Island on the Canadian East Coast (SL Ross and DF Dickins 1987). This was followed in April 1993 by the first large-scale experimental oil spill in Arctic pack ice in the Barents Sea marginal ice zone (Vefsnmo and Johannessen 1994, Singsaas et al. 2004). In 2006, oil was spilled under solid ice in a fjord on Svalbard to study oil migration and weathering and test detection and burning countermeasures (Brandvik et al. 2006). Most recently, the SINTEF Oil in Ice JIP carried out a series of small to moderate size spills in dynamic pack ice in the Norwegian Barents Sea in 2008 and 2009 to evaluate a variety of response techniques and to document the fate and behavior of oil over time (Sorstrom et al. 2010).

The ability to use experimental spills as a means of validating the more extensive meso-scale and lab-scale testing has proved invaluable to understanding the weathering processes of oil in a variety of spill scenarios and environmental conditions. The SINTEF Oil in Ice JIP, 2006-2010, included an extensive project directed at improving the understanding of the fate and behavior of oil under Arctic conditions (Brandvik and Faksness 2009). In addition, a comprehensive MMS-sponsored study (2006-08) included a series of laboratory and meso-scale experiments covering many aspects of oil weathering aimed at developed improved empirical algorithms to describe oil spreading under ice and in snow, oil migration, emulsification in broken ice etc. (Buist et al. 2009).

Sea Ice Conditions Governing Oil Behavior

Sea ice in its multitude of forms **(Fig. 1)** affects every aspect of spill behavior as well as the choice and implementation of countermeasures for over nine months of the year in much of the Arctic, and for up to six months out of the year in many sub-Arctic areas with extensive winter ice covers: e.g. Labrador, Baltic, North Caspian, Gulf of St. Lawrence, Sakhalin. This section introduces some general terms and common processes that define the ice cycle from freeze-up to melt.

Land-fast ice, or simply fast ice, is sea ice that has frozen along coasts ("fastened" to them) and/or in part to the sea floor. Unlike drift ice, fast ice does not move with currents and wind and tends to be most stable and extensive along shorelines with a broad shallow shelf extending offshore e.g. Alaskan North Coast, Canadian Beaufort Sea, Yamal Peninsula in the Kara Sea, and the Pechora Sea. Out to approximately 2 m of water, the ice is grounded for much of the winter and remains stable and relatively smooth in many areas out to the 10 to 12 m water depth – the so-called bottom fast zone. This zone can be used in cases to safely construct winter ice roads that can support the logistics of mechanical spill response, e.g., off Prudhoe Bay. Further offshore, the fast ice zone often extends out as far as 30 m water depth by mid-winter and remains relatively stable at these depths in mid-winter, albeit often highly deformed. In general, routine surface operations are not feasible in these water depths owing to the obstacles of ridging and rubble and the increasingly unpredictable nature of the ice cover with distance from shore.

Drift or pack ice makes up most of the ice cover in the Northern Hemisphere and consists of ice that floats freely on the surface of the water, as distinguished from fast ice attached to or contiguous with the shore. The aerial extent of pack ice present relative to visible open water is referred to as the ice concentration and expressed as tenths. When packed together in large masses over 6/10 concentration, drift ice is called pack ice as close (7-8/10) or very close (9-9+/10). While pack ice can remain static and close to unmoving for weeks at a time, these periods are not predictable and the pack can open or close on short notice in response to wind and current driving forces. This unpredictability generally precludes working on the ice within the seasonal pack for any extended period with response crews. Short term operations require continuous vessel and/or helicopter support together with established evacuation plans.

Ice coverage will largely govern whether an oil spill will tend to spread rapidly to an extent approximating an open water condition (ice concentrations up to ~3/10) or be largely contained when the majority of floes start to contact at some point on their perimeter in concentrations over 6/10. The intermediate ice condition of very open to open drift ice (1-5/10) is often raised as a “response gap” because it represents too much ice for traditional boom and skimmer systems to operate effectively, but too little ice to benefit from the natural containment realized in higher concentrations. Fortunately, ice concentrations in this intermediate range tend to be short lived and represent a transient condition, as the pack is either opening or closing in response to wind forces. For example, based on data collected by the National Ice Center, over a 20 year period from 1986 to 2006, the condition of 1-5/10 drift ice, representing perhaps the greatest challenge in terms of spill containment and recovery, existed on average for only 25 days a year along the shipping route between Point Barrow and Prudhoe Bay. New developments in the application of herding agents show great potential in being able to overcome the lack of artificial or natural containment under these conditions by creating and sustaining thick slicks without the need for booms or ice barriers (Buist et al. 2010)

In concentrations of 6/10 and greater the majority of the oil will tend to move with the ice at similar rates. Oiled ice drift rates impact oil spill response in a number of ways:

1. They play an important role in affecting the film thickness of oil trapped on or under the ice from a continuous surface or subsurface release – the faster the ice moves, the thinner the oil coating,
2. They dictate how rapidly oiled ice may drift across international borders or impact other another country’s marine resources e.g. Russia/Norway; Russia/Japan; Canada/Denmark; Canada/US, and
3. They affect the magnitude of any offshore logistics plan needed to access oil in the ice through the winter and into the following spring. Oiled ice can travel hundreds of kilometers from the source in a matter of a few months.

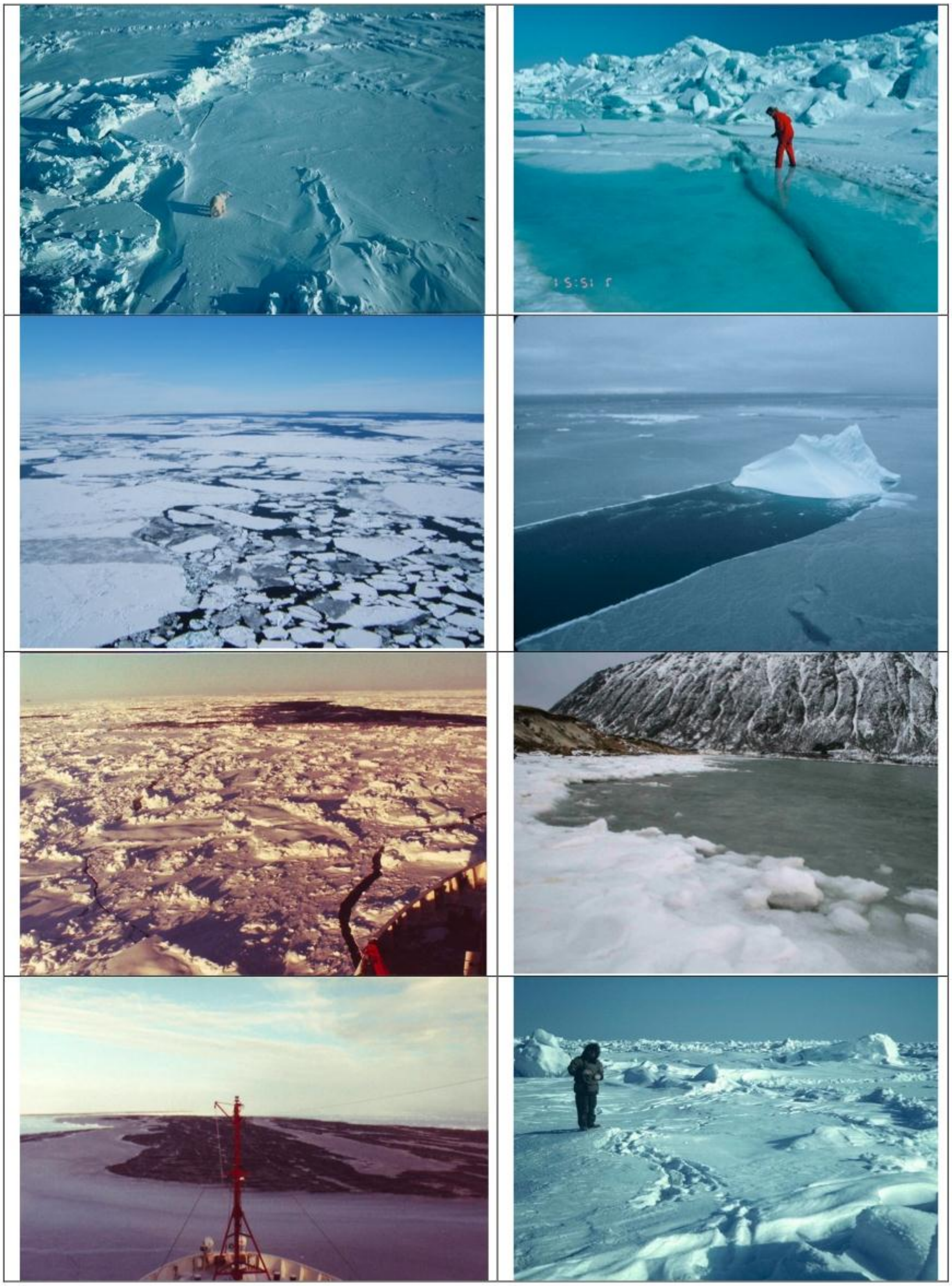


Fig. 1: Some examples of the wide variety of sea ice condition that will determine the spill behavior and fate and choice of response strategies. Top to bottom L-R: first-year winter ice in the Beaufort Sea transition zone, nearshore grounded ice pile-up, open drift ice in the Barents Sea, iceberg moving through new sea ice, rough pack ice with multi-year fragments, new ice forming along a shoreline in N Norway (E. Owens), grease ice (first ice form) in the Northwest Passage in October, surface of a multi-year floe over 4 m thick. Photos: D. Dickins except as noted.

Experimental Oil Spills in Ice

The following summaries highlight the principal particulars of most of the significant medium (a few to tens of barrels) to large-scale (hundreds of barrels) experimental crude oil spills conducted in sea ice, regardless of Latitude **(Table 1)**. This review does not include spills in open water, or terrestrial spills focused on oil spreading and absorption in snow, or oil on Arctic shorelines.

Project	Year	Organization and/or Author(s)	Location	Environment	Total Size/#spills	Clean-up
Behavior of Oil Spills in the Arctic	1970	USCG - Glaeser	Chukchi	on and under fast ice	1-2 bbl/5 spills	Burning
Crude Oil Behavior on Arctic Winter Ice	1971	USCG - McMinn	US Arctic	on fast ice	3 spills on snow	not known
Interaction of Crude Oil with Arctic Sea Ice	**1974/75**	Norcor - Dickins	Can Beaufort	under fast ice	340 bbl/9 spills	Burning & Mechanical
Oil Behavior Under MY Ice	1978-82	ESRF - Comfort	Can High Arctic	under old ice	11 bbl/single spil	None
Oil and Gas Under Sea Ice	**1979/80**	Dome - Dickins, Buist	Can Beaufort	under fast ice	116 bbl/3 spills	Burning
Oil Migration in Solid Sea Ice	1979/80	ABSORB - Allen	US Beaufort	under fast ice	18 spills of 1.5 to 18 gal each	Mechanical
Interaction of Crude Oil with Solid First-year Ice	1980/81	ABSORB - Allen	US Beaufort	on fast ice	three spills sprayed onto snow 6 bbl each	Mechanical & burning
Emulsions in Ice	1982	COOSRA - Potter, Buist, Dickins	Can Beaufort	under fast ice	100 gal/2 spills	Burning
Exp Spills of Crude Oil in Pack Ice	**1986**	ESRF - Buist & Dickins	Can East Coast - NS	between floes and in leads in pack ice	18 bbl/3 spills	Burning
Marginal Ice Zone Experiment	**1993**	SINTEF - Singsaas, Brandvik, Daling	Barents Sea - 75°N	between floes and in leads in pack ice	164 bbl	None
Svalbard Experimental Spill	**2006**	SINTEF/UNIS - Brandvik, Dickins, Faksness	Svalbard	under fast ice	21 bbl	Burning
Oil in Ice Field Experiment 08	**2008**	SINTEF JIP - Sørstrøm ++	Barents Sea 78°N	in openings within pack ice	5 bbl/2 spills	Burning & herders
Oil in Ice Field Experiment 09	**2009**	SINTEF JIP - Sørstrøm ++	Barents Sea 78°N	between floes in close pack ice	110 bbl/5 main spills	Burning, Dispersants

LEGEND

(white)	**Solid ice**
(light blue)	**Pack ice**

Table 1 – Known experimental spills in ice.

Selected projects are summarized briefly below in chronological order, 1971 to 2009.

Behavior of Oil Spills in the Arctic (Glaeser and Vance, 1971)

The USCG conducted a series of small-scale spills (one to two barrels each) on fast ice in the Chukchi Sea in July 1970. The surface spills (diesel and North Slope crude) quickly drained through a permeable, recrystalized upper layer and collected on the melt pools. The crude oil pumped under the ice at two sites rose and collected in the under-ice depressions. The researchers concluded that the presence of ridges and under hanging blocks under the ice would be able to contain fairly large oil volumes as long as currents and turbulence in the water column were low.

Crude Oil Behavior on Arctic Winter Ice (McMinn, 1972)

This project is considered one of the "classic" early experiments aimed at understanding the spreading of oil on snow and ice. Much of the work involved developing spreading theories from first principles. Three spills were made with warm North Slope Crude, on sea ice. The spreading rates measured in the field generally matched the theoretical predictions and confirmed that only gravity and inertia forces need to be considered. A key observation was that there was no significant penetration into the ice surface by the warm oil. Fresh snow blowing across the oil tended to stick and migrate downward, creating a dry mixture of 80% snow by volume. A heavy snowfall directly on top of the oil compacted the upper snow/oil interface and prevented the new snow from infiltrating the already spilled oil.

Interaction of Crude Oil With Arctic Sea Ice (Norcor, 1975)

This was the first large-scale investigation into all aspects of oil in ice behavior, including spreading under ice, encapsulation, progressive vertical migration as the ice warmed, spreading on surface melt pools in the spring and weathering (**Fig. 2**). A total of 54 m^3 (11,900 gallons) of two different crudes were released in stages throughout the winter of 1974/75 into seven containment skirts cut into fast ice within a confined Bay near Cape Parry on the Canadian Beaufort Sea coast. The oil became quickly encapsulated by new ice growth beneath the oil within 12 to 48 hours. In addition to the contained spills, two additional spills were carried out 30 km offshore, where the oil was allowed to spread freely in the presence of a 10 cm/sec current and movements documented by divers and underwater camera footage. This study demonstrated conclusively that effective removal of oil spilled under ice could be achieved through in situ burning in the spring (**Fig. 3**). Mechanical removal of the residue completed the successful clean up. The presence of the trapped oil had no significant effect on the eventual ice thickness, comparing control and oiled sites. As well the presence of oil pooled on the ice surface in the spring had only a minor local effect on the rate of ice deterioration and break-up, advancing the process by a few days to one week.

Fig. 2: Aerial view of oil surfacing through the ice at Balaena Bay, NWT in June 1975.

Fig. 3: First large-scale experimental burn of oil on ice in the Arctic, June 1975 at Balaena Bay. At the time of this photo, over 200 barrels of crude oil were burning with over 90% being consumed in 20 minutes.

Oil Behavior Under Multi-year Ice (Comfort et al., 1983)

Three small-scale spills of ~3.8 bbl each (0.6 m^3) Norman Wells crude were completed at Griper Bay in the Canadian High Arctic in June 1978. An over flight later that summer showed a considerable amount of oil on the surface at two of the spills. A field visit in Sept of the following year found oil in the ice at two of the sites (up to 10% of the original volume) and very little at the third side, which was bisected by a crack. No oil was found at any of the sites in the fall of 1982, four years after the spill. This is the only known field test involving oil and multi-year ice. The results were somewhat surprising in that it was generally believed that in the absence of well-defined brine channels leading to the surface, oil could remain trapped beneath old ice for much longer periods of time. Further experiments are needed to confirm whether these early findings under relatively thin old ice (2-3 m thick) would apply in the case of much thicker floes in the 4 to 5 m range.

Oil and Gas Under Sea Ice (Dickins and Buist, 1981)

The focus of this unique project was to investigate the fate and behavior of oil released with compressed air (GOR up to 300) to simulate a shallow water blowout in 20 m of water under stable fast ice. This is the only known project of its kind that comes close to approximating the conditions that would be faced with a subsea release in the presence of gas under ice. Three spills of Prudhoe Bay crude, ~ 6 m^3 each, were discharged over the winter of 1979/80 in December, April and May at a nearshore site in the Canadian Beaufort Sea. Individual spill volumes ranged from 5.9 to 6.8 m^3. Oil behavior and fate depended largely on the ratio of gas to oil and timing. Early in the season the thin ice sheet was uplifted by the gas, which vented through cracks. Finer droplets were carried further out from the discharge point as gas volumes increased. In all of the spills, the oil was encapsulated by new ice growth within a time frame of 24-48 hours regardless of whether there was gas present. The spills later in the winter led to larger pools of oil underneath gas pockets that filled the natural under-ice depressions. An estimated 85% of the spill volume appeared on the ice surface in the spring through, ablation of the surface down to meet trapped oil droplets and vertical migration of oil from larger trapped oil pools (**Fig. 4**). Approximately two thirds of the spill was removed through a series of effective in situ burns in numerous melt pools that removed an estimated 2/3 of the spill (**Fig. 5**). Teams on the ice recovered any remaining burn residue prior to break-up of the sheet in early July.

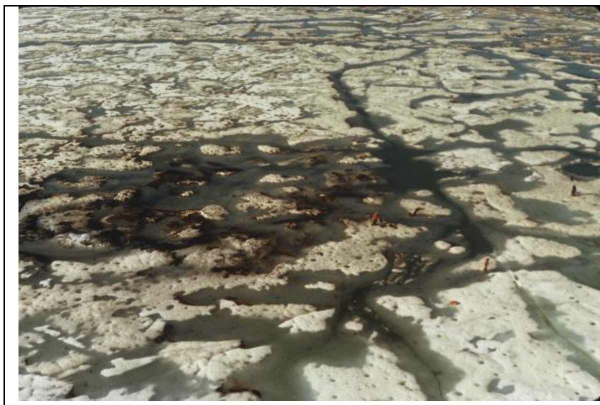


Fig. 4: Low-level aerial view in June 1980 showing oil on surface melt pools after migrating from trapped oil layers within the ice after a series of under-ice simulated blowouts during the winter of 1979-80 at McKinley Bay in the Canadian Beaufort Sea (note people on the ice for scale). Photo: D. Dickins

Fig. 5: Burning oil present on surface melt pools at McKinley Bay, NWT. July 4 1980, immediately prior to break-up. Photo: D. Dickins

Oil Migration and Modification Processes in Solid Sea Ice (Nelson and Allen, 1982)

This paper reports on a series of 18 small-scale spills (1.5 to 18 gal each) of fresh and emulsified Prudhoe Bay crude and diesel under first-year fast ice during the early part of the winter of 1979/80. Significant vertical migration quickly occurred when hot crude oil or diesel was injected without any opportunity for new ice to form beneath the oil. The authors noted that abnormally deep snowdrifts at times could have led to internal ice temperatures more representative of spring than winter conditions. Emulsions injected in the Prudhoe tests did not migrate vertically to any extent. The tests were terminated in March 1980 when the oiled ice was cut out of the parent ice and removed to shore (**Fig. 6**).

Fig. 6: Oil encapsulated in ice during an experimental spill in Alaska. Photo: A. Allen

Physical Interaction and Clean-up of Crude Oil with Slush and Solid First-year Ice
(Nelson and Allen, 1982)

During the winter of 1980/81, three experimental spills involved spraying 1 cubic meter (6 bbl) of hot Prudhoe Bay crude onto snow to simulate a surface oil well blowout in mid-winter and spring. Under cold temperatures with 30 cm of hard snow, the oil covered an area of close to 500 m^2 and penetrated less than 5 cm into the snow surface. In the first spring test in mid-April the oil immediately saturated the snow-slush mixture to a much greater extent. When left for two weeks, the low albedo oil surface gradually subsided relative to the surrounding clean snow. Oiled snow samples produced water contents in the range 75-90%.

Emulsions in Ice (Buist et al., 1983)

This project involved two spills of crude oil under 1.65 m thick solid fast ice at McKinley Bay, NWT Canada in March 1982: 192 liters of 60% oil in water emulsion at two adjacent sites, and the same volume of fresh oil in a third skirted area as control. The highly viscous emulsion formed a static irregular "lumpy" surface under the ice with no lateral spreading (**Fig. 7**). In contrast the fresh oil formed a more uniform coating within the skirted area. New ice crystals started forming within the emulsion within 24 hours and all spills were encased by a thin skim of new ice beneath the oil within 48 hours. The presence of the oil had no measurable effect on ice growth. The fresh crude started to appear in quantity on the ice surface through natural migration through the sheet by mid-June while the equivalent surfacing of the emulsions did not occur for another three weeks. This difference was attributed to viscosity affecting the ability of emulsions to flow up the open brine channels in the melting ice. In contrast to the fresh crude, the emulsified oil was brought to the ice surface by melting of the ice until the trapped oil layer was exposed. Eventually, an estimated 90% of all the oil was released from the ice by the time break-up occurred on July 8. The emulsions were stable through the entire project duration and did not "break".

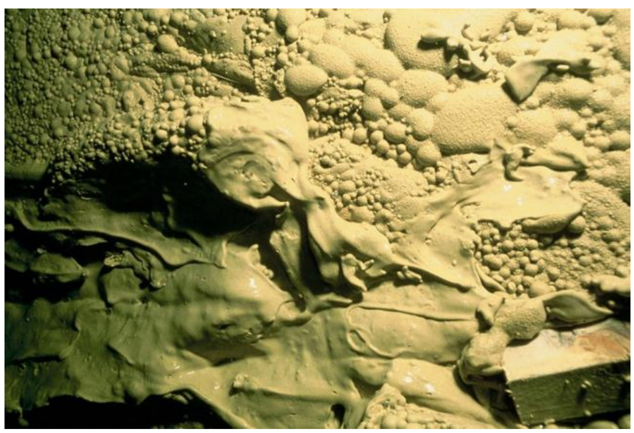


Fig. 7: Close-up view from a diver looking up at the ice underside. The emulsion is trapped under the ice as highly viscous clumps. The first evidence of new ice crystals is visible on the surface of the oil. Wood 2"x2" for scale.

Experimental Spills of Crude Oil in Pack Ice (Buist and Dickins, 1987)

This was the first project to involve experimental spills of crude oil in dynamic pack ice. Three discharges of 1 m^3 each of Alberta sweet mixed blend crude were completed offshore of Nova Scotia, Canada in March 1986. Ice conditions ranged from open drift ice (40-60% coverage) to close pack (70-80%). The main finding was that high concentrations of slush or brash ice between floes greatly reduced and in many cases stopped the oil spreading (**Figs. 8 and 9**). The oil in this case interacted with the ice by saturating the brash ice in the water between the floes and splashing onto the edges of small pancakes as the ice pieces ground together. Small volumes of oil were swept under the floes by relative water motion. Oil was rarely transported to the surface of ice. The experimental results demonstrated that as long as slush and brash are not major factors, spreading of oil in pack ice can by predicted by simple modifications to standard open water equations, to account for the effect of ice concentration. Existing models developed to predict the final area of a spill in snow, can be adopted for spreading of oil among slush and brash ice at sea. There was no evidence of emulsification in spite of a water temperature of -1.5°C. There was some evidence of natural dispersion but the oil droplets being created were relatively large and rapidly rose to collect under the ice. Two of the three discharges in the 1986 Canadian experiment were contained in very close pack and were successfully burned with efficiencies ranging from 80 to 93% (**Fig. 10**). There were no problems with ignition or sustaining the burn and the residue was easily picked up. The first spill in 4-6/10 ice cover was not contained in a thickness that could sustain combustion and no attempt was made to recover the oil. It was concluded at the time that burning appeared to be the only feasible countermeasure for spills in dynamic pack ice (assuming that ice concentrations were sufficient to maintain relatively thick oil films, over a few millimeters).

Fig. 8: Oil stopped from spreading by slush in a lead (Photo: D. Dickins)

Fig. 9: Oil in slush between floes in 4-6/10 pack ice

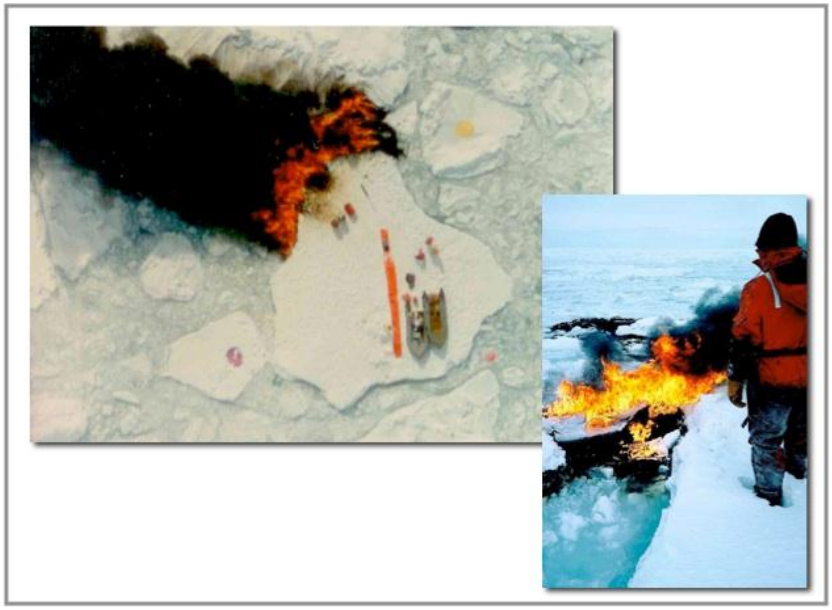
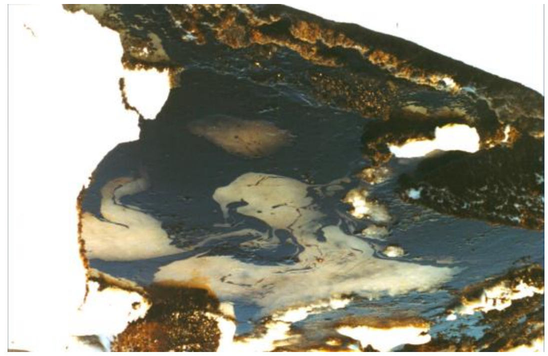


Fig. 10: Burning crude oil bounded by high concentrations of thick ice and slush filled leads during the 1986 oil spill in pack ice. Photos: R. Belore and D. Dickins

Marginal Ice Zone Experiment (Singsaas et al. 1994; Vefsnmo and Johannessen, 1994)

Following a series of test tank experiments, an experimental spill involving (163 bbl) 26 m^3 of North Sea crude took place in the Barents Sea marginal ice zone off the coast of Norway in 1993 (**Figs. 11 and 12**). The high concentrations of pack ice kept the oil thick and immobile. Combined with cold temperatures and limited wave action, these factors significantly slowed oil-weathering processes. Oil spreading and film thickness were sensitive to relatively small changes in ice concentration: the spill thickness rapidly dropped from 1 cm to 1 mm as the ice cover opened slightly from 80 to 70% coverage. Most of the oil remained in the slush and openings between floes. Approximately 2-5% of the total volume was smeared around the perimeter of floes and an insignificant proportion of the spill was transported as small particles under the ice. An attempt to use an oleophilic rope mop skimmer for recovery was hampered by the influence of the vessel opening up the ice cover and allowing the oil to spread – the same effect was noted during the Canadian experiment in 1986. No other effort was made to clean up or recover the oil.

Fig. 11: View of research vessel moored alongside the floe prior to discharging the oil in the MIZ93 Norwegian experiment in the Barents Sea.



Photos: SINTEF

Fig. 12: View of oil on melt pools during the Norwegian MIZ93 experiment.

Svalbard Experimental Spill 2006 (Brandvik et al, 2006; Dickins et al., 2008a)

This experiment involved a discharge of 3,400 liters of fresh Stratfjord crude oil under 65 cm solid fast ice in a fjord on Svalbard on March 27, 2006. The spill was contained within a skirted area of 100 $m^{2.}$ Average film thickness was 3.5 cm but under ice depressions led to pockets of oil over 10 cm deep. The primary objectives of the experiment were to create an under-ice spill as a target for ground penetrating radar, to document the weathering processes of the oil and to assess the effectiveness of burning after the oil was exposed for some time. Oil started to migrate naturally to the surface 24 days after the spill. Most of the oil had surfaced by May 30, just over 60 days following release**. Fig. 13** shows the progression of oil appearance on the surface. The oil was burned with an efficiency estimated at 96% after lying exposed on the ice surface for over one month and being 27% evaporated.

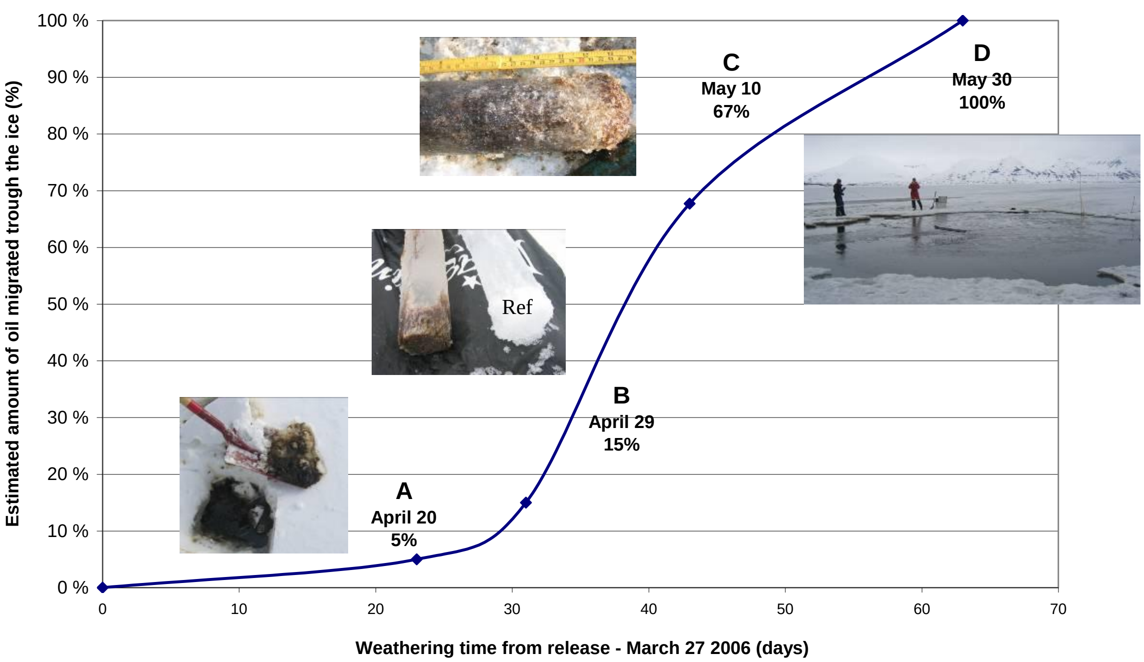


Figure 13: Estimated amount of oil penetrated through the brine channels in the ice and available on the ice surface. Inserted pictures show oil on top of snow (A), cores drilled through the ice to quantify oil captured in the ice (B + C) and the final melt pool (D). Source: Brandvik et al. (2006)

Japanese Oil Under Ice Spills (Ohtsuka et al. 1999, Ohtsuka et al. 2001)

A series of experiments on oil spilled under ice floes typical of the Sea of Okhotsk were undertaken in the late 90s and early 00s. The results showed that: oil will progressively fill under-ice cavities on the bottom of the ice floes, compressed gas (air) released under the floe will displace the oil and only a small amount (less than 1%) of the oil will permeate up to the surface of a 7 to 10-cm thick floe.

Russian Oil on Ice Spills (Serova 1992, Ivanov et al. 2005)

A series of experimental spills of diesel and petrol on ice floes in the Russian Arctic showed that light distilled fuels evaporate to completion rapidly on the surface of ice floes in spring and summer and that photo-oxidation is a more significant process in the 24-hour daylight than in more temperate climates. These experiments are mentioned here as examples only and do not represent the extent of possible research in this area during earlier Soviet times.

Joint Industry Program on Oil Spill Contingency for Arctic and ice-covered Waters: Oil in Ice Field Experiments 2008 and 2009 (Sorstrom et al., 2010).

As part of a large international, multi-disciplinary Joint Industry program carried out over four years (2006-09) two field projects were conducted in the Norwegian Barents Sea between 78 and 79°N, east of Svalbard, within the pack ice. Two small uncontained spills totaling only 0.8 m^3 (5 bbl) were completed in 2008 with the purpose of testing the application of herders to thicken an oil slick in open pack ice enough to support in situ burning – the result was a complete success with better than 90% removal effectiveness. This was the first time such a countermeasure combining herders and burning had been tried in an Arctic field setting. The 2009 project included three uncontained releases (0.5, 2 and 7 m^3) into close pack ice (over 80%) to document oil weathering and fate and assess dispersant effectiveness and two spills into towed booms. Findings showed that burning of thick oil films trapped between floes in pack ice is highly effective (confirming earlier work in Canada and elsewhere), showed that dispersants are potentially useful to deal with a spill in pack ice as long as sufficient mixing energy is available (**Fig. 14**), and showed that fire resistant booms can be used in light ice cover to both recover and burn oil at high efficiencies in very low ice concentrations that would otherwise not be ignitable (**Fig. 15**).

Fig. 14: RV Lance research vessel testing dispersant effectiveness in pack ice by directing mixing energy to the oil (lower right) with the MOB boat.

Fig. 15: Burning oil mixed with ice cakes and pieces collected within a fire resistant boom. Photos: SINTEF Oil in Ice JIP

Overview of Oil Behavior in Ice

The following overview provides highlights of experience gained from experimental spills and other research over the past four decades.

Scenarios

The behavior of oil in ice depends greatly on the oil properties and discharge conditions. Light crudes and condensates will quickly surface through slush and brash ice while heavy fuel oil can remain in suspension within the thick accumulations of slush common during freeze-up conditions and in leads through much of the winter in converging pack ice. Oil density and turbulence in the upper water column are the main factors governing the degree of oil incorporation in porous developing ice forms (slush, grease and frazil). The oil viscosity also controls the tendency for oil to break down into suspended particles. Heavier fuel oils can remain suspended at depth as larger denser oil particles in slush and brash ice. This behavior was observed during the well-documented *Kurdistan* tanker incident off the Canadian East Coast (Vandermeulen and Buckley, 1985).

Discharges can span the range from subsea batch releases (marine pipeline rupture), subsea continuous releases (e.g., subsea blowout, chronic sunken vessel or pipeline leak), surface blowouts and tanker accidents.

Fig. 16 used in many past presentations, shows the possible configurations of oil under, within, among and on the ice, depending on the time of year and type of release.

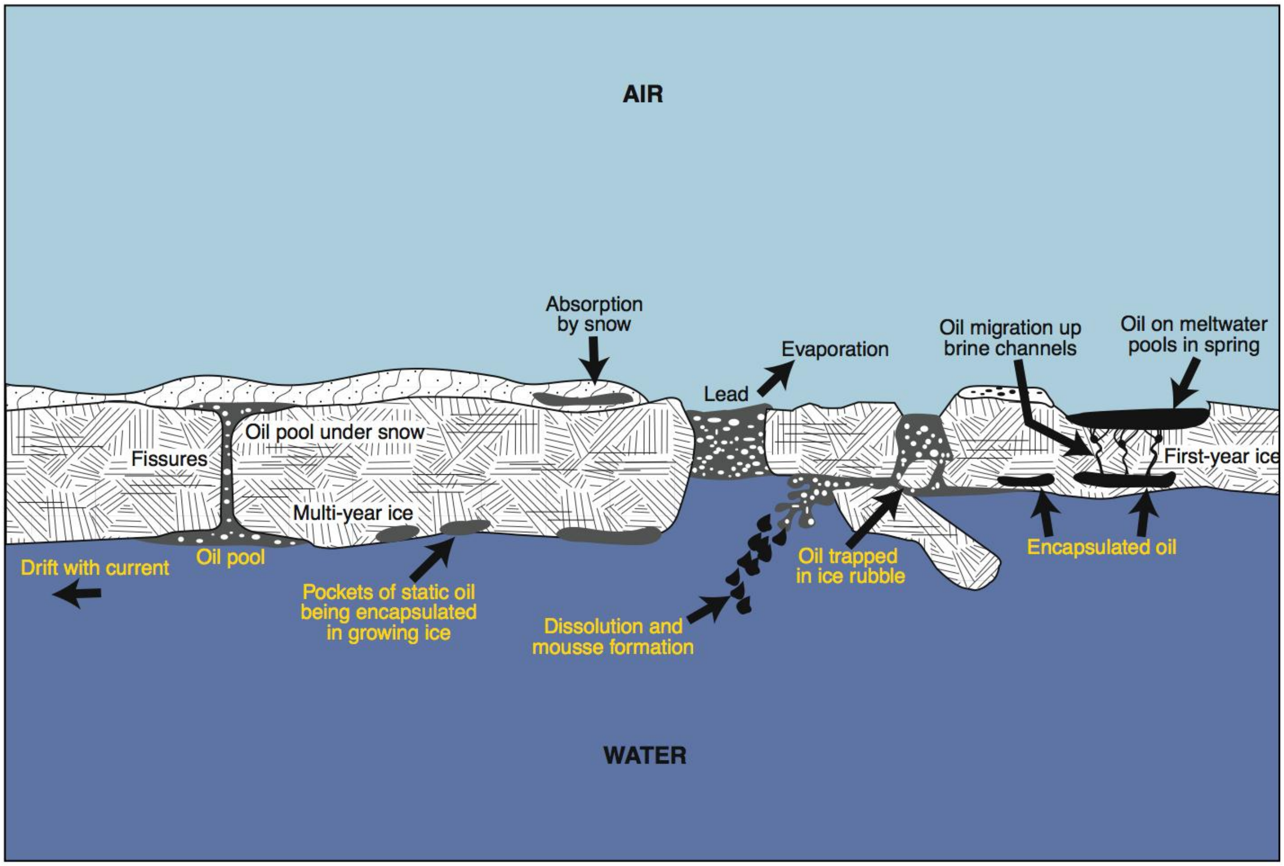


Fig. 16: Schematic showing the complex range of ice and oil configurations that can result from spills in ice. Derived from original sketch by A. Allen.

Weathering

The presence of ice implies low air and water temperatures and a relative lack of waves, all factors that combine to significantly reduce the rates of evaporation, natural dispersion and emulsification. Oil weathering processes during freezing conditions are summarized here from material prepared by I. Buist in Dickins et al., (2000).

Oil spilled during freeze-up conditions will be subjected (to some degree) to the weathering processes of evaporation, dissolution, emulsification and natural dispersion. Photo-oxidation and biodegradation of spilled oil will not be significant during this time. Most crude oils and light products (i.e., diesel) spilled during freeze-up will remain on, or quickly migrate to, the surface of growing ice forms and undergo significant evaporation. Exceptions would be situations where a crude oil had the opportunity to emulsify prior to being incorporated in a developing ice field.

The rate of evaporation of oil is partly controlled by slick thickness. As such, the thicker oil slicks under freezing conditions will undergo evaporation at a comparatively much slower rate (vs. open water). The cold temperatures during freeze-up also reduce evaporation rates. Snow adsorbing into surface oil and eventually covering the oil will add an additional resistance to evaporation. Ultimately however, oil exposed on the ice surface, even after being covered with snow during freeze-up, will lose about the same amount to evaporation as it would on water in more temperate waters.

The formation of water-in-oil emulsions (also known as “mousse”) and the natural dispersion of oil slicks are both processes driven by wave action mixing the oil slick. These weathering processes are not likely to be prevalent in ice, except at an ice field’s open-water edge. Wind waves (as opposed to swell) are very effectively damped by a broken ice field.

Natural dispersion of oil slicks (the process of breaking waves forcing oil droplets into the water column, the smallest of which do not resurface and remain in the water) is similarly unlikely in when the presence of ice restricts any significant wave action.

Weathering of oil during the winter depends primarily on whether or not the oil is exposed to the atmosphere. Oil spilled and trapped under ice floes will not evaporate; oil spilled on top of ice or into leads will evaporate. In the absence of any relative mixing energy under thick ice, oil trapped beneath the ice will not disperse or emulsify.

Gelling is an important oil-property change that may take place with oil spilled on ice in winter. Gelled oil will be a semi-solid material that will subsequently evaporate slower than fresh oil, and may develop a non-sticky, waxy surface coating. Oils that may be fluid in warmer temperatures can gel when the ambient temperature falls below their pour point (defined as the temperature at which sufficient waxes have precipitated from solution in the oil to prevent it from flowing under gravity).

Movement and Drift Rates

Oil trapped within pack ice over 6/10 concentration tends to move with the ice at ~3-5% of the wind speed with a turning moment ~20 to 30 degrees to the right in the N. Hemisphere due to the coriolis effect (reversed in Antarctica). Oil in more open drift ice can move at different rates from the ice – for example, thick rough floes with large sails and keels experience different driving forces from currents and winds than an oil slick on the surface or smooth thin ice sheet. It is not unusual to see an iceberg or old floe moving upwind in response to currents at depth (**Fig. 1**).

Winter under-ice currents in most Arctic near shore areas are not sufficient to spread spilled oil much beyond the initial point of contact with the ice under surface. Exceptions may be in fjord-like areas with strong tidal currents or in narrow Arctic straits such as Kara Gate. Several studies have determined that, with roughness values typical of undeformed first-year sea ice in mid-winter, the threshold current speed needed to initiate and sustain movement of an oil lens or pool along the ice under surface is approximately 20 cm/sec or ~0.5 kt.

Spreading

The most dramatic difference between spills in ice and open water is found by comparing the spreading behavior. In many situations, oil spilled in the presence of an ice cover will be naturally contained within a relatively small area. This fact has far-reaching implications (mostly positive) in terms of response times and options for recovery. **Table 1** shows a comparison of the predicted final areas and thicknesses covered by a 1600 m^3 (10,000 bbl) batch crude oil spill on open water, under solid sea ice and on smooth sea ice with and without snow. It is clear that the spreading of oil is greatly reduced by ice and snow, and the resulting slicks are much thicker than those on water.

	Open Water	Under Solid Mid-Winter Ice	On Smooth Ice	
			Ice	Snow
Final avg. oil thickness (mm)	0.016	40 to 90+	3	40
Final area (ha)	10,000	7 to 70*	50	4

Source: SL Ross et al. 2010

+ The maximum pool depth under ice depends on the depth of the under-ice depressions, which grow deeper as the ice grows over winter

* The range of areas reflects the variable processes of oil spreading under ice. The final contaminated area depends on both the available volume of under-ice depressions and how they fill with oil: a point source subsea release of oil beneath undeformed fast (static) first-year ice may flow outward under the ice by only filling interconnected under-ice depressions (after Wilkinson et al. 2007), but a point source subsea release beneath a moving undeformed ice sheet may result in all the available under-ice depressions filling, depending on the flow rate, ice velocity and gas volumes.

Table 1. Spreading comparison for a 1600 m^3 (10,000 bbl) crude oil spill

In pack ice, the degree of natural containment depends greatly on the ice concentration and other variables. As a general rule of thumb, the presence of 6-tenths ice will lead to a final slick area less than half as large as the same volume in open water. This simple "rule of thumb" applies mainly to close pack ice with over 6/10 coverage – a condition where most of the ice floes are touching at some point around their perimeter. The relationship between spill area and ice concentration is not linear at low concentrations. At some point in open to very open drift ice with concentrations less 6/10, the ice no longer contains the oil, and the spreading rates begin to approach those in open water.

Encapsulation, Migration and Release

Oil spilled under young ice will likely become encapsulated by new ice quickly growing beneath the oil within 12 to 24 hours. Under very thin new ice less than ~10 cm oil may migrate quickly to the surface but as the sheet cools and becomes less porous in November, the oil will remain trapped as a discrete layer, remaining relatively static until the onset of warming temperatures in late March and April. Even in mid-winter a solid layer of new ice will form beneath the oil within 48 hours. Oil spilled under ice late in the winter (May in the Beaufort Sea) is unlikely to become encapsulated as the ice growth rate approaches zero. As the brine starts to drain from the ice sheet in the spring, the oil utilizes the now vacant brine channels as a pathway to migrate vertically within the sheet.

The migration process accelerates rapidly in May as the ice sheet becomes isothermal and by early June (in a Beaufort Sea environment) over 80% of the oil can be found on the surface floating on melt pools. The oil appears at the ice surface as close to fresh crude with all of the light components attached. Once the oil is exposed in this manner, it is subject to normal evaporative loss - up to 30-35% by volume in many cases. These high rates reflect the effects of solar heating of black oil.

Twenty-four hours of sunlight can warm the surface oil up to +10ºC even in close to freezing air temperatures. The oil floats on the melt pools on top of the ice as the sheet deteriorates. Winds tend to concentrate the oil in thicker patches at the edges of these pools where it can be readily ignited and burned with high overall efficiencies – generally over 70% (individual burning efficiencies in a single pool often exceed 90%).

There are situations where the oil will migrate very slowly if at all, such as when the spill is distributed as fine droplets under the ice during a subsea blowout with large volumes of gas. In that case, it may be necessary to wait for the ice surface to melt down sufficiently to expose the trapped oil to gain access at the surface. **Fig. 17** shows a representative case where relatively thick oil films are trapped under the ice from spills occurring at different stages in the ice growth cycle.

As the remaining relatively thin ice quickly melts and disintegrates over a 3-4 week period (June for example in the Beaufort Sea, earlier in lower Latitudes), residual oil still trapped in the porous ice and any oil left on the ice surface will be released to the water as sheens, broken thin oil films or patches.

Gelled oil may be discharged into the cold water as thicker, non-spreading mats or droplets. Once exposed to significant wave action, most of the residual oil will begin to emulsify and naturally disperse at sea.

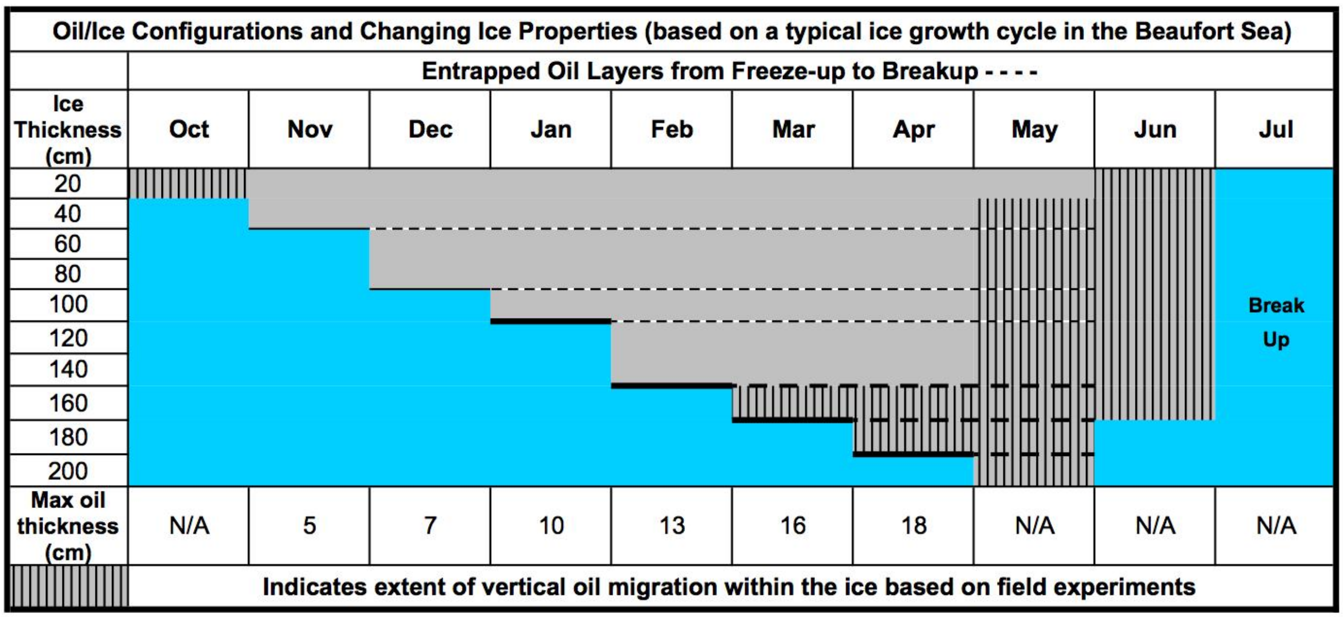


Fig. 17: Ice cross section by month showing the progressive entrapment of oil films spilled at different times in the growth cycle and the increase in the maximum possible oil film thickness in response to the increasing under-ice reliefn over time. Example shown is representative of the Canadian or US Beaufort Sea. Dickins et al. (2008b)

Conclusions and Recommendations

A key overall observation from field experiments in ice is that the natural containment, reduced wave action and slower weathering in the presence of significant ice cover, can greatly extend the windows of opportunity and effectiveness for response operations such as burning and dispersant application. However, at the same time, the presence of ice generally prevents the effective use of traditional mechanical clean-up methods in responding to large spills.

Experience has shown that the unique behavior of oil spills at low temperatures and in ice can enhance spill response and act to mitigate environmental impacts in many situations. For example:

- Low air and water temperatures coupled with the presence of ice generally lead to much greater oil equilibrium thicknesses, related to reduced spreading rates and smaller contaminated areas.
- Evaporation rates are reduced in cold temperatures and ice. As a result the lighter and more volatile components remain for a longer time, thereby enhancing the ease with which the oil can be ignited.
- The wind and sea conditions in many Arctic areas are considerably less severe than most open ocean environments, facilitating marine operations. The regional presence of ice dampens wave action and often limits the fetch over which winds might otherwise create larger fully developed waves.
- When ice concentrations preclude the effective use of traditional containment booms, the ice itself often serves as a natural barrier to the spread of oil. The natural containment of wind-herded oil against ice edges leads to thicker oil films that enhance the effectiveness of burning.
- With high ice concentrations (7/10 or more) most of the spilled oil (especially from a subsea blowout) will rapidly become immobilized and encapsulated within the ice.

- Oil encapsulated within the ice is isolated from any weathering processes (evaporation, dispersion, emulsification). The fresh condition of the oil when exposed at a later date (e.g., through ice management or natural melt processes) enhances the chances for effective combustion.
- The fringe of fast ice common to most Arctic shorelines acts as an impermeable barrier and prevents oil spilled offshore at freeze-up from entering and contaminating sensitive coastal areas.

Some notable response challenges related to the unique aspects of oil behavior in ice include:

- Difficulty in accessing oil trapped on or under ice especially offshore in moving pack where crews cannot maintain sustained operations on the ice without continuous, reliable and immediate means of evacuation.
- Lack of oil spreading or flow within often slush and brash- filled leads and openings in the pack ice, making skimming operations extremely difficult and ineffective.
- Sensitivity of oil spreading in ice to subtle changes in floe geometry and ice coverage. The implications of this are that the very action of maneuvering a vessel close enough to access the oil with for example over the side skimmers may create rapid spreading of the slick into much thinner, less recoverable films.
- Gelling of crude oils with pour points at or below 0°C.

Our understanding of the important aspects of oil in ice behavior is already at a very high level, based on 40 years of active research in the US, Canada and Norway. One remaining area where our knowledge base is deficient involves the behavior of oil spilled under multi-year or “old” ice. As exploration moves into deeper water in the Beaufort Sea and off Greenland, spill scenarios involving this much thicker, less porous ice will become increasingly important.

Much of what we have learned to date about how to deal with the possibility of Arctic oil spills can be directly attributed to the ability of researchers to conduct experimental spills. Over the past 15 years this ability has steadily eroded as the barriers to obtaining the necessary permits become more and more onerous. Industry needs to find a way to work with regulators, local residents, and special interest groups to encourage future experimental spills in different regions. The history of research in this area proves conclusively that such experiments can be conducted with no harm to the environment. Only if we can provide new opportunities for responders and scientists to conduct experimental spills in the field, can we maintain and expand the cumulative knowledge base needed to develop credible and effective response options for future Arctic operations.

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