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Experimental Oil Releases in Ice: Past Projects Informing Response to Present-Day Spill Risks in Arctic and Subarctic Areas

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ABSTRACT. Much of our present-day understanding of oil behavior in ice derives from a relatively small number of deliberate, difficult to execute, and, arguably, impossible to replicate large-scale field releases permitted in Canada, Norway, and the United States. This paper identifies 14 projects involving experimental oil releases in ice over the period 1970–2015, with brief synopses provided for five of these. Three previously unpublished projects in Canada (1974–86) are reviewed and discussed in greater detail with the findings interpreted in light of changing oil spill risks in Arctic and subarctic areas.

Despite the sharp decline in Arctic oil exploration since 2015, numerous potential sources of accidental spills in ice remain, for example, the high density of winter vessel traffic in the Baltic Sea, and extensive oil infrastructure in the Bohai Bay and Sea in China. Changes to the Arctic and subarctic oil-in-ice risk profile are tied to increasing use of the Russian Northern Sea Route, and to a lesser extent the Northwest Passage, by large vessels, and the adoption of low sulfur fuel oils with variable behavior in cold water, potentially impacting the effectiveness of current response strategies.

The small number of oil-in-ice field experiments reviewed here still forms the basis for much of our understanding of how oil behaves in a range of sea ice types. The emphasis on in situ burning as a primary countermeasure for spills in or on ice, pursued successfully in many of the significant historical experimental releases, is increasingly valid in the context of many current scenarios where the remoteness and sparse logistics support continue to favor countermeasures requiring minimal resources. Key findings from these historical projects can guide today's responders in developing strategies to address present and future spill risks in Arctic and subarctic areas.

Keywords: shipping in ice; oil spills in sea ice; Arctic and subarctic oil production; oil-in-ice field experiments; spill scenarios

RÉSUMÉ. Une grande partie de notre compréhension actuelle du comportement du pétrole dans la glace découle d'un nombre relativement restreint de déversements volontaires sur le terrain à grande échelle, difficiles à exécuter et, sans doute, impossibles à reproduire, autorisés au Canada, en Norvège et aux États-Unis. Ce document recense 14 projets impliquant des rejets expérimentaux de pétrole dans la glace sur la période de 1970 à 2015, dont cinq font l'objet de résumés. Trois projets inédits au Canada (réalisés de 1974 à 1986) sont passés en revue et discutés plus en détail, leurs résultats étant interprétés à la lumière de l'évolution des risques de déversement d'hydrocarbures dans les zones arctiques et subarctiques.

Malgré la forte diminution de l'exploration pétrolière dans l'Arctique, de nombreuses sources potentielles de déversements accidentels dans la glace subsistent. Notons par exemple la forte densité du trafic maritime hivernal dans la mer Baltique et l'importante infrastructure pétrolière dans la baie et la mer de Bohai en Chine. L'évolution du profil de risque pétrolier dans la glace dans les zones arctiques et subarctiques est liée à l'utilisation croissante de la route maritime du Nord en Russie et, dans une moindre mesure, du passage du Nord-Ouest par de grands navires, ainsi que l'adoption de fiouls à faible teneur en soufre dont le comportement est variable en eau froide, ce qui pourrait avoir une incidence sur l'efficacité des stratégies d'intervention actuelles.

Le faible nombre d'expériences de terrain sur le pétrole dans la glace examinées ici constitue toujours la base d'une grande partie de notre compréhension du comportement du pétrole dans divers types de glace de mer. L'importance accordée au brûlage in situ comme principal outil de lutte contre les déversements dans ou sur la glace, employé avec succès pour de nombreux déversements expérimentaux historiques significatifs, reste pertinente dans le contexte de nombreux scénarios actuels où l'éloignement et le manque de soutien logistique continuent de favoriser les contre-mesures nécessitant un minimum de ressources. Les principales conclusions de ces projets historiques peuvent guider les intervenants actuels dans l'élaboration de stratégies pour faire face aux risques de déversement présents et futurs dans les zones arctiques et subarctiques.

Mots-clés : navigation dans la glace; déversements de pétrole dans la glace de mer; production pétrolière en zones arctiques et subarctiques; expériences de terrain sur le pétrole dans la glace; scénarios de déversement

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INTRODUCTION

This paper discusses the findings of historical oil-in-ice field experiments in the context of today's spill scenarios involving the risk of accidental spills in ice in Arctic and subarctic marine waters. Many of these findings are also applicable to spills in Antarctic sea ice and freshwater ice, but any discussion of differences in behavior and related spill risks in those regions falls outside the scope of the present analysis. The overall focus here is on assessing the relevance of key experimental findings from a small number of unique projects to the changing risk landscape associated with current and evolving Arctic and subarctic marine activities.

The paper outlines the basic parameters of known projects involving experimental spills in sea ice over the period 1970–2015 (updated from Dickins, 2011). Five projects are summarized, and three large-scale Canadian projects from 1974 to 1986 are selected for more detailed review and discussion. In these three cases the original reports are not easily accessible, and the findings were never published in peer-reviewed papers. An additional factor motivating the review of older work is the very remote likelihood that experiments like these will ever be permitted in the future.

Specific objectives of this paper are to identify and summarize:

- the range of current oil-in-ice spill scenarios;
- areas with the greatest qualitative risk for future spills in ice, based on the relative traffic volumes, length of marine pipelines, and number of offshore oil fields and terminals;
- selected historical oil-in-ice field experiments and key findings; and
- the relevance of past projects to current oil-in-ice risks.

Previous reviews of past oil spill research projects under Arctic conditions include Fingas and Hollebone (2003), Dickins (2011), Velez (2015), and Heshka et al. (2024). Several comprehensive guides and field manuals also address spill response strategies, issues, and countermeasures for spills in snow and ice, including Owens and Dickins (2015), Owens et al. (2017), Bi et al. (2025), and National Oceanic and Atmospheric Administration (NOAA, 2025).

A CHANGING RISK ENVIRONMENT

The first large-scale oil-in-ice field projects were conceived and executed in the 1970s and 1980s. A primary motivating factor at that time was the need to understand what would happen in the event of a worst-case subsea blowout leading to crude oil rising to collect on the underside of solid ice or between floes during Arctic offshore oil exploration.

The last offshore oil exploration campaign in Arctic waters took place in the Canadian Beaufort Sea in 1989, off the west coast of Greenland in 2011, and in the Chukchi Sea in 2015. Since then, the United States (2021–25), Canada (2016), and Greenland (2021) all imposed moratoria on Arctic offshore oil drilling. As of 2026, Norway and Russia remain the only Arctic nations still conducting active offshore oil exploration, although future exploration is possible in the U.S. Arctic.

The prospect of having to deal with worst-case spill volumes from drilling blowouts has shifted from exploration scenarios to production ones. But while production results in a lower relative risk on a per well basis (Whylie and Visram, 1990), it still entails a significant likelihood of a spill, given the number of producing platforms.

Oil types of most concern have shifted from predominantly crude oil, associated with oil exploration, to a mix of produced crude oil and marine fuel oils, including the rapidly expanding use of low and ultra-low sulfur fuel oils (LSFOs) in the Arctic (IPIECA, 2024).

In contrast to the decline in Arctic offshore oil exploration, shipping in Arctic and subarctic regions continues to increase. In terms of numbers of transits through ice and the associated risk of accidental spills, the frequency of regular winter shipping in the Baltic Sea dwarfs traffic volumes in any other part of the world. Oil transportation by tankers in this region quadrupled in the 10 years from 2000 to 2010 (Brunila and Storgård, 2012). Finnish and Swedish icebreakers assist commercial shipping an average of 2515 times per winter season (2018–24), and up to 11,000 times in a severe winter (Finnish Ministry of Transport and Communications, 2024). Notably, the most significant vessel spills in ice have occurred in subarctic areas with regular winter commercial ship traffic (Table 1).

Although still relatively small, the number of ships (including container ships, oil tankers, and liquified natural

TABLE 1. Significant accidental vessel spills in ice (Dickins, 2011). Incident references in order of occurrence: Baxter et al. (1978), Bonsdorff (1981), Vandermuelen and Buckley (1985), Hirvi (1990), Wang et al. (2008), and Bergstrom (2012).

	Location	Vessel	Oil type	Spill amount
1977	Buzzards Bay, USA	*Bouchard #65*, barge	Fuel Oil #2	270 tonnes (t)
1979	Nova Scotia, Canada	*Kurdistan*, tanker	Bunker	7000 t (no recovery)
1979	Baltic, USSR	*Antonio Gramsc*i, tanker	Crude	4540– 5440 t (~500 t recovered)
1987	Baltic, Finland	*Antonio Gramsci*, tanker	Crude	650 t (~ 40 t recovered)
1998	St. Lawrence River, Canada	*Saraband*, general cargo	Bunker	18 t (~ 50% recovered) 1400 t ice to get 10 t oil
2006	Tallin, Estonia	*Runner 4*, general cargo	Fuel oil	100 t heavy, 35 t light (some oil recovered from thin slicks on open water)
2011	Norway	*Godafoss*, container vessel	IFO380 fuel oil	125 t (> 50% recovered)

gas, or LNG carriers) entering the Arctic Polar Code area (International Maritime Organization [IMO], 2017) annually, increased from ~1300 to almost 1800 from 2013 to 2023 (PAME, 2024). Marty et al. (2016) demonstrated that increased Arctic vessel traffic will lead to higher oil spill risk. Despite these trends, Arctic shipping remains unpredictable and relatively high risk (Brigham, 2022; 2025a, b), as highlighted by the recent grounding and challenging salvage of the bulk carrier *Thamesborg* in the Northwest Passage (NWP) (Marine Insight, 2025).

Compared to the NWP, the Russian Northern Sea Route (NSR) has experienced the most significant increase in the number of large vessels. Several Chinese shipping companies recently announced plans to initiate regular container service linking China with Europe along the NSR (Yang, 2025). Two recent examples demonstrate the risks posed by non–ice class, or minimally ice-strengthened, vessels operating along the NSR. The *Arctic Metagaz*, serving Russia's sanctioned Arctic LNG 2 project, had to reverse course due to heavy ice on 29 August 2025 while being escorted by a nuclear icebreaker, highlighting the challenges non–ice class vessels can face in a worse-than-average summer season. Another tanker with no ice strengthening, *La Perouse*, entered a holding pattern in the same year because of impassable ice conditions (Humpert, 2025).

The Bering Strait provides the only access to and from the North Pacific and Bering Sea for vessels using the NSR along the Russian coast, or the NWP along the Alaskan North Slope and through the Canadian Arctic. Russian vessels transiting the Strait sail within a few miles of U.S. waters. Recent transits by low ice-class vessels, such as heavy-lift ships and tankers moving sanctioned Russian crude oil (sometimes without activating their automatic identification system), add a new element of spill risk (pers. comm., Alaska Marine Exchange). The Transportation Research Board (2014) highlighted a scenario where a damaged Russian tanker spills oil in the Bering Strait with potentially serious impacts in both Russian and U.S. waters.

Over the period of 2010 to 2024, the Marine Exchange of Alaska (2025) logged 6350 transits north and southbound through the U.S. and Russian sides of the Strait. Beginning in 2019, in the space of just five years, traffic numbers increased from, typically, 250 to 350 vessels per season, to over 600.

While most transits occur during the summer period (July–September), an increasing number of vessels pass through the Strait late in the season, when an accident could lead to a spill in ice should the salvage operation fail or be delayed past freeze-up. Most of this traffic occurs on the Russian side of the Strait. For example, over 15 years (2010–24), 235 transits were classed as "late season" on the Russian side vs. only 34 on the U.S. side. The peak numbers of late-season voyages doubled over the past four years (2021–24) compared to the previous 10 years.

In contrast to the NSR, the Canadian Arctic sees far fewer commercial voyages during an average summer navigation season from July to late September. Although still very small, the frequency of transits through the NWP has also increased substantially in the last decade, with 115 large vessels over nine years (2015–24) compared to just 112 large vessels in the previous 62 years (from data compiled by Headland, 2025).

Scenarios: Spills in Ice

A wide range of situations around the world present diverse risk scenarios for crude and fuel oil spills in ice, from a variety of sources. These include:

- Buried marine pipelines connecting producing platforms to shore or connecting on-land fields to a tanker loading terminal in areas with seasonal ice cover: Northern Caspian Sea; Cook Inlet and Beaufort Sea, Alaska; Bohai Sea, China; Baltic Sea; and Sea of Okhotsk, Pechora and Kara Seas, Russia. Scenario: batch release under moving or stable ice.
- Offshore producing oil fields and associated tanker loading terminals, for example, off Sakhalin Island and the Pechora Sea, Russia. Scenario 1: Production surface well blowout resulting in a thick buildup of oil on the ice surface. Scenario 2: Transfer spill during loading resulting in a spill onto the ice surface and between ice floes or both. Scenario 3: Tanker spill in transit due to ice damage and/or grounding or allision.
- Tankers, oil barges, ore carriers, bulk carriers, container ships, and other vessels in areas with a history of regular winter navigation, for example, the Bohai Gulf or Sea, China; the Baltic Sea; the Gulf of St. Lawrence; Labrador and Northern Quebec, Canada; Cook Inlet, Alaska; the Kara Sea, Russia; the U.S. Eastern Seaboard; and the Northern Caspian Sea. Scenario 1: Oil in ice cakes and slush within the broken ship track and on, or underneath, the surrounding ice cover if the damage is below the waterline. Scenario 2: Oil chronically leaking and collecting under ice from a sunken vessel.
- A vessel damaged late in the summer shipping season that results in a spill extending into freeze-up, for example, the Bering Strait, NSR or the Northwest Passage. Scenario: Oil trapped in new and young ice.

Shift to Low Sulfur Fuels

The 2024 International Maritime Organization (IMO) amendment to the International Convention for the Prevention of Pollution from Ships (MARPOL) (Annex 1) banned the use and carriage of heavy fuel oils in the Arctic (with exemptions through 2029 for vessels with protected fuel tanks). The aim was to reduce the risks of heavy fuel oil spills, as well as black carbon and sulfur emissions. The mandated replacement, LSFOs, can be distillate marine fuels. That is, they have properties like regular marine diesel or residual marine fuels, and the American Petroleum Institute (API) gravities like conventional intermediate and heavy fuel oils (Daling and Sørheim, 2020). Thrift-Viveros et al. (2023) noted that the viscosity of residual LSFOs can vary significantly, making their behavior in cold water unpredictable.

The Arctic Council, through their working groups Emergency Prevention, Preparedness and Response and Protection of the Arctic Marine Environment, sponsored a five-year research program to look at the fate and behavior of LSFOs in cold water (PAME, 2025). Findings indicated that residual LSFOs can have a wide range of pour points. For example, one residual LSFO solidified immediately when released into water close to freezing, while another remained fluid. Some residual LSFOs are designed with lighter paraffins to reduce their viscosity to meet new fuel regulations, but this can exacerbate the issue of clumping in cold water. Conversely, distillate LSFOs have pour points lower than ambient sea temperature, meaning they will remain fluid and spread easily. This can also make containment and recovery more challenging, as the oil can spread over a larger area.

Equipment and techniques used in responding to traditional fuel oils may not be effective for all types of LSFOs (IMAROS, 2022). The International Petroleum Industry Environmental Conservation Associate (IPIECA, 2024) provides a fact sheet for responders summarizing the state of knowledge regarding LSFO properties, behavior, and response.

EXPERIMENTAL OIL RELEASES IN ICE, 1970–2015

Much of our present-day understanding of oil behavior in sea ice derives from a small number of deliberate and difficult to execute field releases (Table 2). These field projects allowed testing in natural environment conditions that cannot be fully replicated in smaller-scale laboratory or meso-scale experiments (e.g., Brandvik and Faksness, 2009; Buist et al., 2009).

Velez (2015) discusses the significant challenges to planning, permitting, and executing an experimental oil release in the marine environment. Changing environmental and political sensitivities now make it highly unlikely that regulators will allow future large-scale field experiments with oil in ice-covered waters. The last approved experimental oil releases in ice in the U.S. occurred in 1981 (Nelson and Allen, 1982), Canada in 2008 (Lee et al., 2011), and in Norway in 2015 (Camus and Smit, 2019).

Figure 1 shows the locations of experimental crude oil releases conducted in sea ice. Table 2 provides key particulars of 14 projects spanning the period 1970–2015. Brief synopses of five selected projects are provided below, along with detailed discussions of three large-scale, unpublished studies carried out in the Canadian Beaufort Sea and on the East Coast of Canada in 1974–75, 1979–80, and 1986. Projects are presented in chronological order. Due to space limitations, it was not possible to summarize every project listed in Table 2. Relevant references for numbered projects (spills) not expanded on in the text are: 3: Comfort

TABLE 2. Summary of known experimental oil releases in ice, 1970–2015 (after Dickins, 2011).

Project #[1]	Project title/topic	Year	Location	Environment	Volume/spills	Recovery
1	Behavior of oil spills in the Arctic	1970	North Chukchi Sea	on and under fast ice	1–2 bbl/5 spills	Burning
2	Interaction of crude oil with Arctic sea ice	1974–75	Canada Beaufort Sea	under fast ice	340 bbl/9 spills	Burning and manual
3	Oil behavior under multiyear ice	1978–82	Canada High Arctic	under old ice	11 bbl/single spill	None
4	Oil and gas under sea ice	1979–80	Canada Beaufort	under fast ice	116 bbl/3 spills	Burning
5	Oil migration in solid sea ice	1979–80	North Slope, Alaska	under fast ice	18 spills of 1.5 to 18 gal each	Manual
6	Interaction of crude oil with solid FY ice[2]	1980–81	North Slope, Alaska	on fast ice	3 spills sprayed onto snow: 6 bbl each	Manual and burning
7	Emulsions in ice	1982	Canada Beaufort	under fast ice	2.4 bbl/2 spills	Burning
8	Spills of crude oil in pack ice	1986	Canada east coast	between floe; in leads in pack ice	18 bbl/3 spills	Burning
9	Marginal ice zone experiment	1993	Barents Sea	between floes; in leads in pack ice	164 bbl	None
10	Svalbard experimental spill	2006	Norway Svalbard	under fast ice	21 bbl	Burning
11	Field test of OMA in pack ice	2008	Canada Gulf of St. Lawrence	between ice pieces	~4 bbl/3 spills	Dispersing with OMA[3]
12	Oil in ice field experiment 08	2008	Barents Sea	in openings within pack ice	5 bbl/2 spills	Burning with herders, Mechanical
13	Oil in ice field experiment 09	2009	Barents Sea	between floes in close pack ice	110 bbl/5 main spills	Burning, Mechanical, Dispersants
14	Environmental effects of Arctic oil spills	2015	Svalbard	on freezing water in mesocosms	120 l (6 mesocosms)	Manual

[1] Projects under solid ice: 2–5, 7, 10;
Projects between floes: 8–9, 11–13;
Projects on water, ice, and snow: 1, 6, 14

[2] FY ice: First-year ice

[3] OMA: Oil-mineral aggregates

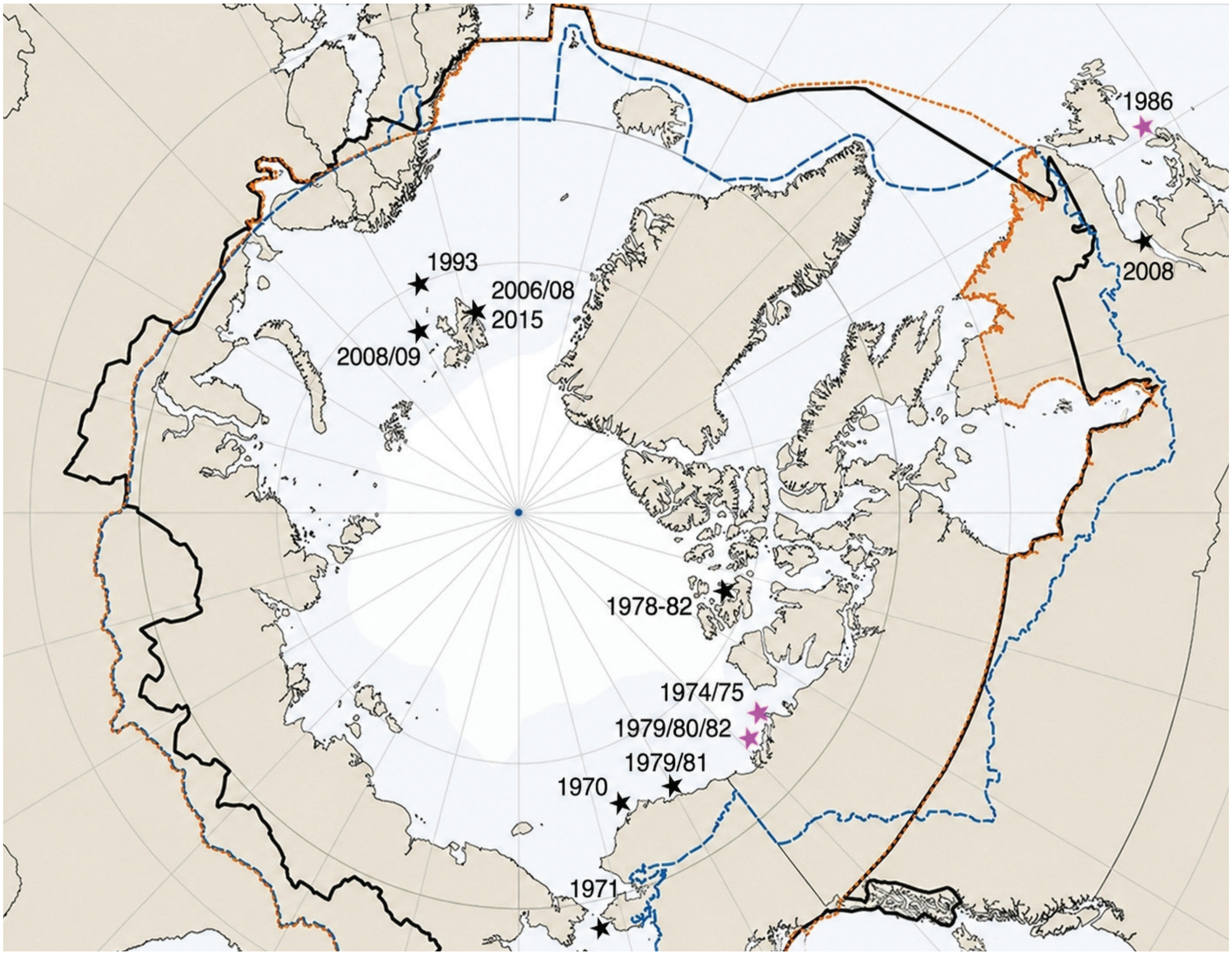

FIG. 1. Locations of experimental oil releases in ice, 1970–2015. Purple stars denote the three historical projects featured for in-depth discussion.

and Purves (1982); 5,6: Nelson and Allen (1982); 11: Lee et al. (2011), and 14: Camus and Smit (2019). The focus here is on findings concerning the physical, rather than biological, interaction and fate of oil with different types of ice, including the effect of oil on ice growth and break-up. Not included in this review are experiments involving oil releases in open water, on Arctic shorelines or tundra, or in smaller scale basins or tanks using artificially grown ice sheets.

Project 1

This project was called Behavior of Oil Spills in the Arctic (Glaeser and Vance, 1971). In it, the U.S. Coast Guard conducted a series of small-scale releases (one to two barrels) on fast ice in the Chukchi Sea in July 1970. The diesel and Alaska North Slope crude quickly drained through a permeable, recrystallized upper snow layer and collected on melt pools on the ice. Crude oil pumped under the ice at two sites rose and collected in under-ice depressions. The researchers concluded that the presence of ridges and underhanging blocks under the ice could contain large oil volumes, a finding confirmed in later modeling (Wilkinson et al., 2007). In 1971 the U.S. Coast Guard conducted three further spills on snow-covered ice and tundra in the Bering Strait area of Alaska (McMinn, 1972).

Project 2

Called Interaction of Crude Oil with Arctic Sea Ice (NORCOR, 1975), this first large-scale investigation into all aspects of oil-in-ice behavior involved the largest known cumulative oil volume deliberately released (340 bbl) and remains the only project where the oil behavior was monitored throughout an entire ice season. A total of 55.4 m^3 of two different crudes, Norman Wells (NW) and Swan Hills (SH), with pour points, ~ −45˚C and −4˚C, respectively, were released through the winter of 1974–75 (Table 3). Most of the oil was discharged beneath the ice within seven vertical containment skirts 30 m in diameter cut into fast ice within a confined bay (Balaena Bay) near Cape Parry on the Canadian Beaufort Sea coast (Fig. 2). Water depths ranged from 6 m to 10 m; water salinity

TABLE 3. Oil discharges at Balaena Bay, 1974–75 (all spills under ice except NW#1 onto freezing water).

Date	Oil type and test #	Quantity (m^3)	Average ice thickness (cm)
24 October	NW #2	7.3	38
1 November	NW #1	0.4	Opening cut in 43 cm ice
14 November	NW #3	8.3	53
7 December	SH #1	7.3	64
9 December	NW #4	8.2	64
16 February	NW #6	7.7	118
8 April	NW, offshore	1.6[1]	122
12 April	SH #2	6.4	154
15 April	NW #7	8.2	154
16 May	NW #8, no skirt	0.4	195

[1] = 2 releases.

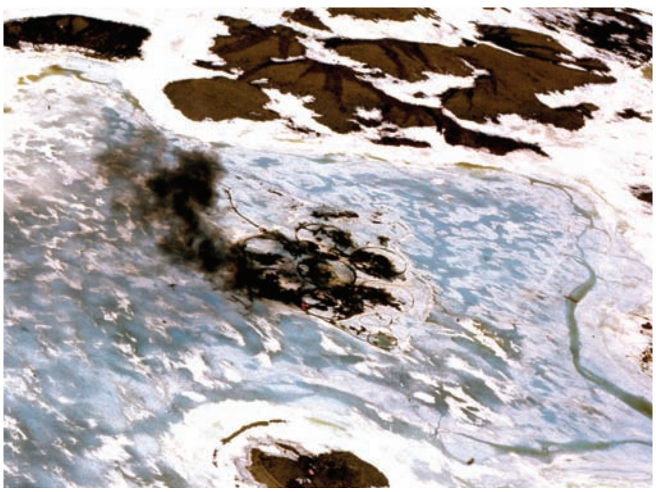

FIG. 2. Aerial view of the seven containment skirts with oil on the surface and initial burning under way, 7 June 1975, Balaena Bay, Canadian Beaufort Sea. Note the snow berm constructed around the site to prevent further spreading (Photo: Bill Adams).

averaged 29 ppt. Four releases were uncontained, two occurred 33 km offshore, and two took place in Balaena Bay (NW#1 and #8).

SH is a heavy crude, while NW is much lighter, about the same consistency as No. 2 heating oil. The oils were selected to span the range of properties expected in future exploration discoveries. Prior to discharge, the oil was heated to between –4˚C and +1˚C, close to the ambient water temperature of –1.3˚C. Principal findings are reviewed here.

Encapsulation: In the seven releases contained by skirts, the oil filled the natural under-ice depressions, averaging 15–20% of the average ice thickness. Over 95% of the oil collected in pools larger than one metre, with an oil depth of 2–5 cm. The minimum equilibrium thickness spreading under smooth ice was ~0.8 cm.

Due to the added thermal resistance of oil, a lip of new ice encircled each oil lens or pool within hours of the oil contacting the ice, effectively preventing further spreading. The time required for new ice to form beneath the oil varied with the oil thickness and the associated thermal gradient across the oil layer. In late fall, with a steep thermal gradient and thin ice, new ice was detected beneath the oil in about five days, stretching to seven days, with thicker ice in mid-winter, and to over 10 days near the end of the growth cycle in April.

Effect on Ice Growth: Although the thermal conductivity of most crude oils is about 15 times less than that of natural sea ice, the insulating effect of the oil was partially offset by free convection within the oil lens once oil was encapsulated as a distinct layer. The overall effect of the oil on eventual ice thickness was insignificant, falling within the natural variability caused by varying snow cover.

Migration: Initially, the vertical migration of oil through the ice was limited to the porous, soft skeletal layer at the base of the ice (5–7 cm). By February and March, ice cores showed the oil rising 15 cm to 20 cm into the ice. As solar radiation increased in the spring and internal ice temperatures approached the freezing point, the migration rate increased dramatically, as dense brine rapidly drained out of the sheet, leaving clear channels for the oil to rise through. No significant difference in migration rate was noted between the two oils. In contrast, following the Kurdistan tanker spill in ice off Nova Scotia in 1979, highly viscous Bunker C oil surfaced more slowly or not at all (Vandermeulen and Buckley, 1985).

In a separate test adjacent to the contained releases, 0.4 m^3 of NW crude were released freely under 195 cm of ice in mid-May, with an average ice temperature of –4.0˚ C and air temperature between –1.5˚ C and –3.0˚ C. Traces of oil were detected on the surface within one hour. Cores showed that the brine channels in the ice were saturated with oil, identical to observations of other cores taken within the skirted areas in the spring.

Most of the oil in the main test area was exposed on the surface by 7 June, while the ice was still over 120 cm thick. A small percentage of the oil (~5%) remained trapped in the ice at the originally released depth until exposed by surface melt (Fig. 2).

Effect on Ice Depletion: On reaching the ice surface, the oil saturated the snow cover and substantially reduced the albedo. This increased the absorbed solar radiation, which accelerated the snow melt, encouraged the development of oiled melt pools, and heated the oil as much as 10˚ C above ambient. Oil splashed onto the surrounding snow at the pool edges through wind and wave action, and the melt pools gradually enlarged until interconnected.

New oil was continually released until the surface melt reached the initial level of the oil lens at time of discharge. Once melt holes developed and drained surface water, the ice in the test areas rapidly deteriorated, becoming unsafe to work on by 25 June, and clear of ice by 30 June. The surrounding unoiled ice sheet broke up seven days later.

Weathering: While the oil remained in the ice, very little evaporation or weathering occurred. Samples of oil trapped in the ice showed less than 5% evaporation from October to late May, while samples left on the ice surface as a control evaporated up to 28% by February.

Burning, Cleanup, and Impacts: The study demonstrated that effective surface removal of oil spilled under ice could be achieved through in situ burning in the spring after the oil surfaced in a relatively fresh state and before the ice broke up. Even after exposure on the surface for up to six weeks, oil was easily ignited at a minimum thickness of approximately 5 mm. Wind herding thickened the oil on melt pools, allowing thin, otherwise unignitable films to be burned efficiently.

Between 7 June and 17 July 1975, four burns were conducted, with an overall average removal of available oil of ~80%. On the first burn, approximately 20 m^3 or 90% of the oil on the surface was removed. The effectiveness of successive burns decreased to ~50% as the oil film thickness reduced.

Of the 54 m^3 of oil discharged, approximately 28% evaporated naturally, and 61% was removed by burning. Less than 3% of the oil reached the shore, of which one third was recovered. The removal of the remaining burn residue, although mechanically straightforward, was labour intensive. On average, 0.07 m^3 of residue was recovered per person day, with an overall recovery of 5 m^3.

Caution is advised in extending these findings directly to offshore areas with more dynamic ice. Balaena Bay was selected as an enclosed area with a stable, landlocked ice sheet that melted in place, allowing crews to work safely on the ice close to shore within days of break-up, maximizing the time available for cleanup. Removal was estimated at 70% as an achievable upper bound for burning oil under these conditions. Lower values in the 30–40% range were considered more realistic in dealing with a spill offshore in pack ice.

In July 1981, a combined chemical and biological study was conducted with the aim of assessing the degree of environmental impact from the 1974–75 oil releases. The study concluded that detectable impacts of the 1974–75 under-ice spills on sediment hydrocarbon content, histopathological condition of Pectinaria hyperborea and Macoma calcarea, and benthic community structure were small (Dickins et al., 1981).

Offshore Uncontained Releases: Two additional releases of 0.8 m^3 each took place 33 km offshore, where the oil was allowed to spread freely to collect in natural depressions under predominantly smooth ice. These remain the only known deliberate releases of oil under ice without artificial confinement.

Oil movement and spreading behavior were monitored on the surface by means of an underwater video system and still photography using a diver with a closed-circuit breathing system to avoid the possibility of gas bubbles affecting the oil distribution. Prior to the first discharge, the diver reported the ice underside to be perfectly flat, with variations less than 2–3 mm.

During Release No. 1, on 8 April 1975, although some oil initially spread several metres upstream, most of the oil moved in the general direction of the current. The oil did not flow as large drops, but rather, as complex shapes, ranging from patches several square metres in area to drops less than 1 cm across. Several oil "fingers" extended outwards from the initial oil pool, finally joined, then grew in width to create the final oiled patch of ice (Fig. 3).

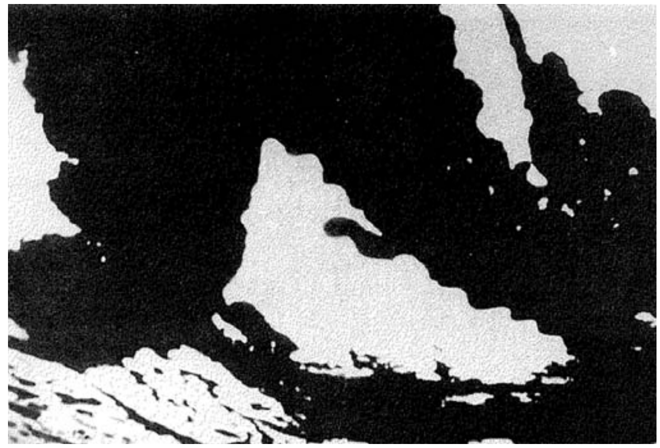

FIG. 3. Under-ice photograph of oil distribution following offshore discharge No. 1, after completion of pumping on 8 April 1975, Canadian Beaufort Sea. Approximate left-to-right dimension of the image: 7 m (NORCOR, 1975).

The oil eventually assumed an irregular, finger-like shape, measuring about 14 m long in the direction of the current, and 7 m wide. Clear patches of ice up to 0.5 m long and oriented in the direction of the current were scattered through the oiled area. Several large patches of oil separated from the main pool. The path taken by the oil to reach the equilibrium configuration was marked by small beads of oil remaining along the otherwise clear ice bottom. After completion of pumping, very small droplets, less than 0.1 cm in diameter, were suspended in the water column. The average thickness of the oil lens in heavily oiled areas was 0.60 ± 0.10 cm.

The second release occurred in rougher ice approximately 10 m up-current from a small first-year pressure ridge with a keel depth up to 2 m. A series of depressions or troughs, up to 0.5 m deep and 8 m wide, ran parallel to the pressure ridge and controlled both the movement and final disposition of the oil. As the oil was released, it flowed in the direction of the current and towards the pressure ridge (Fig. 4). Within several metres of the discharge point, long fingers, or rivulets, broke from the main body of oil. The rivulets were about 2–5 cm in width and varied in length. The velocity of the rivulets was between 5 cm/sec and 7 cm/sec, or about one half that of the current. They tended to continuously follow the same course, suggesting that minor depressions in the ice undersurface were influencing the direction of flow. Ice crystals broken from the skeletal layer and floated near the rivulets, which might indicate that the oil was cutting a path through the soft structure of the growing ice interface. Apart from small flecks and streaks, the ice remained relatively clean after the oil passed. Upon reaching the trough, the oil flowed parallel to the ridge and gathered in a pool measuring about 6 × 3 m with oil thickness ranging from 2.5 cm to 11.4 cm (Fig. 5).

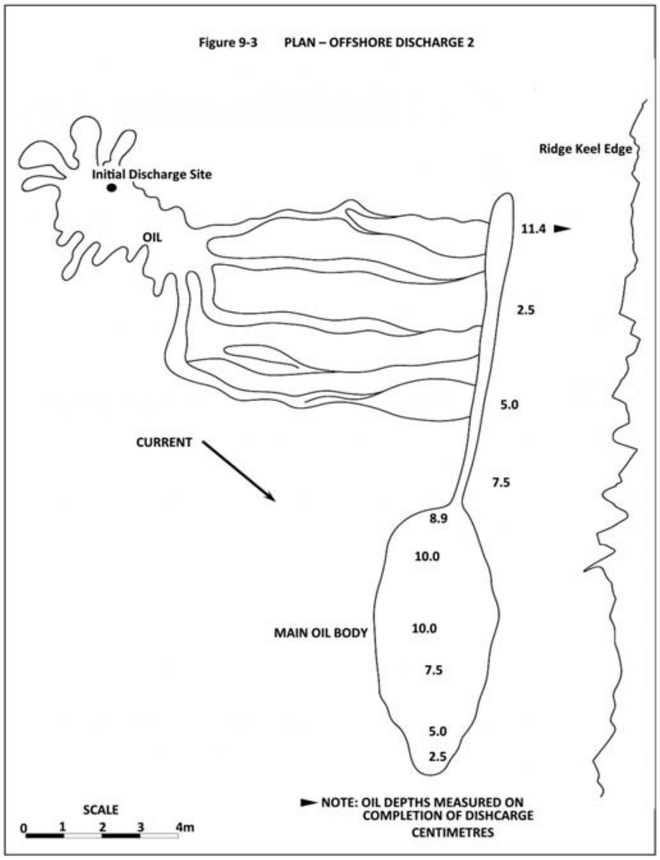

FIG. 4. Distribution of oil released in the second discharge offshore Cape Parry, Canadian Beaufort Sea, on 8 April 1975, mapped from diver observations. Depths within the main oil body ranged from 2.5 to 11.4 cm (NORCOR, 1975).

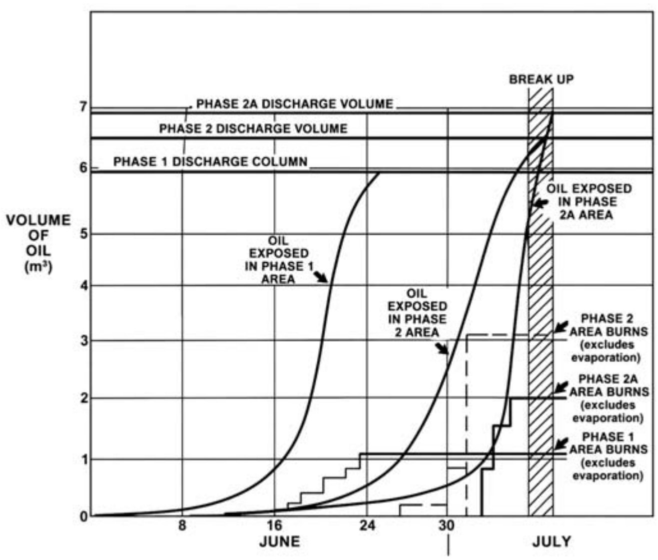

FIG. 5. Timing of oil surfacing, and volume removed by burning, McKinley Bay, Canadian Beaufort Sea (Dickins and Buist, 1981).

An overflight on 8 May showed no trace of oil. On 28 May, a patch of oiled snow, approximately 8 × 5 m, was visible near Discharge No. 1. Oil was also located under the snow above the under-ice pool from the second discharge. New ice had grown to a depth approximately 12 cm below the lens, fully incorporating the oil into the ice.

On 8 June, a burn was conducted at the offshore site. All the oil appeared to have surfaced at that time, and conditions before and after burning resembled the Balaena Bay nearshore test site in June (Fig. 2). This was the last observation of the offshore site. The ice in the area broke up and drifted away in late June.

TABLE 4. Oil Discharges at McKinley Bay, 1979–80.

	Phase I	Phase II	Phase II-A
Date	18 December 1979	10 April 1980	02 May 1980
Ice thickness (cm)	61	164	182
Oil volume (m^3)	5.9	6.6	6.8
Air volume (m^3)	1520	200	1240
Discharge time (min)	32	28	26
Calculated gas-to-oil ratio	210	25	180

Project 4

This project, called the Oil and Gas Under Sea Ice Study (Dickins and Buist, 1981; Dickins et al., 1981), investigated the fate and behavior of crude oil released with compressed air at a gas-to-oil ratio of ~200:1, simulating a shallow water blowout in ~25 m of water under stable fast ice at McKinley Bay on the Canadian Beaufort Sea coast. To date, this is the only known project of its kind. A key objective was to determine the efficiency of burning as a countermeasure and to optimize burning techniques.

Three releases of Prudhoe Bay crude, 6–7 m^3 each, were discharged over the winter of 1979–80 in December, April, and May (Table 4). A dry run, air-only discharge preceded the Phase I test with oil. During this discharge, the gas pushed the 58–64 cm–thick ice up into a dome 50 m across and ~1 m high. The ice then cracked and rapidly vented the gas. During the Phase II discharge in April, ice blockage in the supply line reduced the air flow, requiring a repeat test in May. The accident was fortuitous in allowing a comparison of oil behavior with and without substantial volumes of gas.

During the discharges, current meters were used to measure induced and residual currents, while echo sounder profiles and low-light video were used to map the discharge plume. Divers mapped the ice underside and recorded the distribution of oil and gas. Ice cores delineated the oil distribution fanning radially out from the discharge point. During the melt phase, aerial photography, slick thickness tools, and time-lapse cameras documented changes to the oil on the surface. Hundreds of oil, ice, and snow samples were taken for chemical analyses to determine oil weathering, soot fallout, polyaromatic hydrocarbon content, oil fractionation in ice, and burn efficiencies. Motion pictures and still photographs documented atmospheric dispersion in the smoke plumes.

Plume dynamics: Mean plume-induced currents were measured 1 m below the ice surface for the Phase II-A discharge in May, when the ice was too thick to vent the gas. The currents decreased rapidly with increasing radial distance from the plume centerline, from 30 cm/s at 15 m distance to background (~ 4 cm/s) at 35 m.

Violent turbulence as the gas – oil mixture left the discharge pipe broke the oil into spherical droplets ranging in diameter from 2 mm to tens of microns. At the same time, the vertical gas flow created an inward current that drew in some silty sediments from the sea floor. The rising gas carried the oil droplets and entrained sediment as it rose in a cylindrical jet towards the surface.

Approximately 6 m above the discharge pipe, the gas jet generated an upwards and outwards plume, spreading some of the oil particles and sediment laterally. The sediment settled out of the plume, while the gas quickly rose to fill the high points under the ice. Oil particles impinged on the ice directly or formed a film beneath gas pockets. Droplets sufficiently small to have very low rise velocities and a correspondingly high suspended residence time were carried by the residual currents to create a layer of very fine oil droplets, trapped in the ice up to 350 m from the plume centerline.

The distribution of oil droplets from the Phase 1 discharge in December was mapped in detail by taking 94 cores on lines radiating out from the discharge point. Slices of the core sections measuring 3 – 4 cm and containing the oil droplets were photographed against a backlit, 1 mm grid to analyze the oil particle size distribution. Most of the oil volume (present as relatively large droplets) was concentrated within a 50 m radius of the plume centerline. The droplet size rapidly decreased from ~1000 µm over the discharge point to less than 250 µm at a radial distance of 100 m. Model predictions, based on computed rise times and distance traveled with the residual current, compared favorably with the distribution of droplet diameters measured from the ice cores. The blocked air flow during the Phase II discharge reduced the area of heavy oil contamination by a factor of three.

The oil migration process during the melt period was greatly affected by the ability of very small oil particles to find an available pathway through the brine channels. Oil and gas under the ice assumed three distinct configurations: oil droplets, gas droplets with a coating of oil, and large pools of oil lying underneath gas pockets trapped in high points under naturally thinner ice. The oil and gas droplet configuration predominated for the December discharge under new flat ice, while the oil pool configuration predominated for the April and May discharges under thicker ice with more variability.

Regardless of the gas volume, the oil behaved differently in the April and May discharges in comparison with the Phase I discharge. In December, the under-ice surface was very smooth, with variations of only a few cm and much of the gas vented through cracks. Consequently, most of the oil was observed as discrete particles, and few deep pockets of combined oil and gas were found. In April and May, the under-ice surface was more undulating (tens of cm) because of the variable insulating effects of snow drifts. Much of the oil in the two later discharges collected in larger, deeper pockets under the ice, with the oil underlying the trapped gas.

Oil and gas pockets lying on the underside of the ice were encapsulated by the growing ice sheet within 20 – 48 hours, regardless of whether there was gas present. The oil distribution under the ice quickly became difficult to see once the oil was obscured by the new ice layer, pointing to the need for very rapid response to map the contaminated area in an actual spill with visible or sonar underwater sensors.

Even with over 165 cm of ice in April, the oil started to become encapsulated by new ice crystals the day after release. In one observation, a thin layer of new ice formed within 48 hours under oil lying beneath a 20 – 25 cm air layer. In contrast, a survey dive after the May discharge showed that only the smallest oil particles were encapsulated by new ice after 24 hours. Larger pools with thicker oil were still fully exposed. Later coring in June and July showed that over 10 cm of new ice had grown below the oil, proving that even in May, close to the end of the ice growth season, an oil spill can still become encapsulated. Thicker oil films without the presence of gas may remain unencapsulated for up to five days (NORCOR, 1975).

Surfacing of Oil in Spring: Oil appeared on the ice surface during the spring melt through two competing mechanisms. The first involved the ice sheet melting down from the surface to the level where the oil was originally encapsulated in the ice sheet. This process exposed most of the oil that spread as small droplets in the Phase I test. These isolated droplets could not effectively connect with brine channels and migrate to the surface.

The second mechanism relied on oil migration through brine channels. As in the 1974 – 75 experiment at Balaena Bay, this oil-surfacing mechanism was primarily responsible for oil surfacing in the heavily contaminated areas resulting from the April and May discharges. The most migration took place in the Phase II area, where the oil was highly concentrated in thicker films related to the reduced air flow. This confirmed that oil coverage or concentration under the ice was the dominant factor affecting oil migration. As with NORCOR (1975), oil viscosity played a secondary role for oils with pour points below 0˚C.

Figure 5 illustrates the timing of the appearance of oil on the ice surface from all three discharges, along with the volumes of oil removed through burning. The shape of the exposure curves was similar, starting slowly and rapidly increasing in an exponential manner. The timing of the onset of surface exposure depended on when the oil was released. With thinner smooth ice, the ice surface melted down to expose the trapped oil before the finely distributed oil droplets had a chance to migrate. With thicker, more variable ice, the concentrated oil had an opportunity to rise through brine channels well before being exposed by surface melt. Oil pools on the surface melt water ranged in size up to 135 m^2, with the average oil pool being 1 – 5 m^2 at the December site, and 10 – 20 m^2 at the spring discharge sites.

Prior to break-up in early July, ~81% of the original volume of oil reached the ice surface from all the sites. While none of the oil rising through the ice sheet appeared initially in an emulsified form, the oil began to assume a weathered, emulsified appearance after several weeks on the surface.

Oil left on the ice surface during winter as a control lost most of its light ends through evaporation. In contrast, the oil that migrated through the ice in the spring appeared in a nearly fresh state, but lost 25 – 30% by volume through evaporation after being exposed on the surface for a few weeks.

Cleanup involved multiple burns using aerial ignitors and mechanical removal of oil on the ice surface in June and early July (Fig. 5). In total, ~51% of the oil on the ice surface was removed by burning, with individual burn efficiencies ranging up to 90%. Not surprisingly, the lowest burn efficiency was associated with the December discharge, where the oil spread thinly over a very large area. Burning at the April and May sites achieved efficiencies of 77% and 63%, respectively. Measurable fallout from the burning was restricted to an area less than 50 m downwind.

An ignition success rate of 75% was achieved by sequentially deploying ignitors from a helicopter flying between melt pools at an altitude of ~5 m while being directed by spotters on the ice. Some of the aerial ignitors bounced on hitting the ice and missed their target. Hand deployment by crews on the surface was more accurate. As in the earlier Balaena Bay experiment, wind herding of oil on melt pools into thicker films aided ignition and provided more efficient burns. The study concluded that the most efficient use of burning as a countermeasure tool for an offshore spill would be to use helicopter-supported ground crews in the early stages of the melt process, then switching to a completely airborne operation once the ice could no longer safely support ground teams.

Manual cleanup on the ice continued to within a few days prior to the ice break-up using a crew of six working 10-hour shifts. Figure 6 shows site conditions six days prior to ice break-up. The final oil budget summary showed 33% burned on the ice surface, 30% evaporated, and 17% manually recovered. The remaining 21% was considered naturally dispersed through the gas plume. Following breakup on 8 July, overflights of the area revealed no trace of the oil on the water, and a shoreline search in the area found no beached oil. Notably, the oiled ice did not break up ahead of the surrounding unoiled sheet.

Project 7

This project, called the Emulsions in Ice (Buist et al., 1983), released crude oil under 1.65 m thick solid fast ice at McKinley Bay, Northwest Territories, Canada, in March 1982; 192 liters of 60% oil-in-water emulsion were discharged at two adjacent sites, and the same volume of fresh oil was released into a third skirted area as a control. The highly viscous emulsion formed an irregular lumpy surface under the ice, with no lateral spreading. In contrast, the fresh oil formed a more uniform coating within the skirted area similar in appearance to previous field experiments. New ice crystals started forming on the surface of the emulsion within 24 hours, and all the oil was encapsulated 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, again confirming previous observations in the same general location in the winter of 1979 – 80 (preceding project).

FIG. 6. Aerial view of the test sites, 2 July 1980, six days prior to break-up, McKinley Bay, Canadian Beaufort Sea. Responders on the ice provide scale. Response support barge in the background was on site all winter (Photo: D. Dickins).

The fresh crude started to appear on the ice surface by natural migration through the sheet in mid-June, while the surfacing of the emulsions was delayed for another three weeks. Buist et al. (1983) attributed this difference to the high viscosity affecting the ability of emulsions to flow up the open brine channels in the melting ice, mirroring the observations by Nelson and Allen (1982). The emulsified oil only appeared when the ice surface melted down to expose the trapped oil layer. Eventually, an estimated 90% of all the oil was released from the ice by the time break-up occurred on 8 July.

Project 8

This project was named Field Research Spills to Investigate the Physical and Chemical Fate of Oil in Pack Ice (Buist and Dickins, 1987; Ross and Dickins, 1987). It was the first known project focused on the behavior of crude oil in pack ice. Objectives were to evaluate spreading in variable pack ice conditions, document the fate of oil in pack ice (evaporation, emulsification, dispersion), and employ possible countermeasures (in practice limited to in-situ burning).

Three releases of 1 m^3 each of Alberta sweet mixed blend crude (density 0.856 g/cm^3 and pour point −8˚C) were conducted ~140 km off Cape Breton Island, Nova

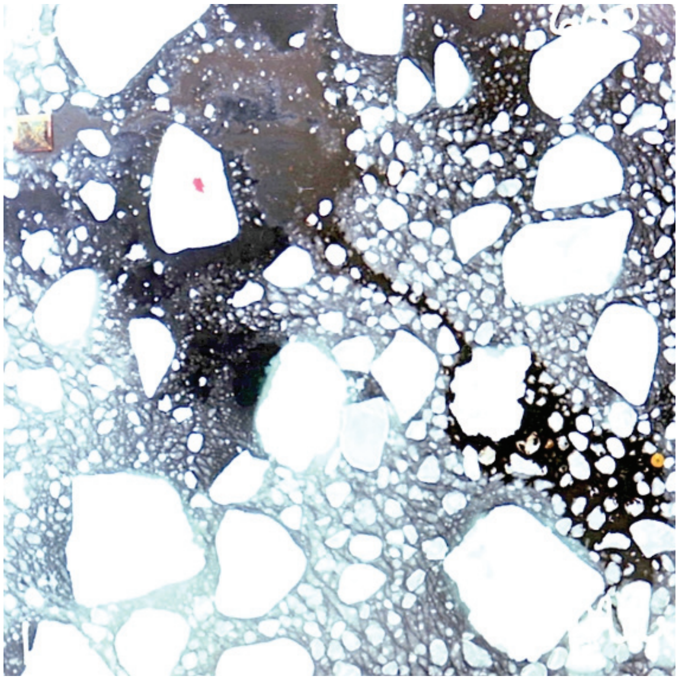

FIG. 7. Aerial photograph from 100 m, showing the ice conditions and oil spreading from the release raft (upper left) six minutes after the first release in open pack ice off Nova Scotia, 1986. For scale, the floe with an orange marker is ~ 4 × 7 m (Photo: R. Belore).

Scotia, Canada, in March 1986. Ice conditions ranged from a dynamic mix of floes and slush within an open-ocean swell, to a more static case of almost complete ice cover with slush-filled leads. Air temperatures were – 8 to – 14˚C, and wind speeds were 10 – 24 knots. Not surprisingly, the highest ice drift rates of 1.9 km/h occurred with the highest wind speeds.

Release No. 1, 9 March 1986: Ice concentrations were highly variable in an expanding and diverging pack ice environment, ranging between an average of 4/10 to 6/10, with concentrations varying greatly over distances of tens of metres (Fig. 7). Ice floes ranged from small pancakes (1 – 2 m) to larger floes with dimensions on the order of 10 × 5 m, and thickness ranging from 50 cm to 77 cm. Slush ice filled the open water areas between floes at the start of the experiment. Ice floes interacted continuously as a 3 – 4 m ocean swell propagated through the ice field. As the experiment progressed, conditions became even more dynamic, with the site within several hundred metres of the ice edge. Once at the ice edge, the oil spread into thin films as the pack ice rapidly broke up and floes separated.

Oil in the first release interacted with the ice in three ways: it saturated the brash and slush ice surrounding the floes and pancakes; it splashed into small pancakes of ice; and a very small proportion was swept as droplets beneath the floes by the relative motion of the ice and water. The oil mixed with the slush ice, which in turn coated the outer rims of small floes and pancakes with an oil stain (Fig. 8). Oil was rarely transported to the ice surface, although some oil was found on top of the occasional pancake.

FIG. 8. Oil in slush between pancakes in a dynamic ice environment after the first release off Nova Scotia, 1986. The support vessel Brandal in the background (Photo: Environment Canada).

Some oil droplets ~1 – 3 mm in diameter were swept by currents beneath floes. A core sample from the edge of a floe showed these droplets trapped on the underside of the floe and having migrated some 25 cm into the brine channels. Analysis of the melted cores showed oil concentrations equivalent to an under-ice oil thickness of ~ 0.15 mm.

Releases No. 2 and No. 3, 10 March 1986: The pack ice in these releases was compressed and much more tightly packed than in the first release. Release #2 was in area with 7 – 8/10 medium floes surrounded by freezing brash ice, while Release #3 experienced lower concentrations of medium floes and more extensive areas of brash and slush filling the spaces between the floes to a depth up to 40 cm. Conditions ranged from small pancakes to larger floes with dimensions up to 28 × 16 m. Total ice thickness was 120 – 160 cm, with a layer of slush at about 80 – 95 cm, indicating rafting of loosely bonded ice layers. The pack was static, with relative motions between floes in the order of 2 cm/s or less. The swell was almost completely damped, ranging from zero in Release #2, to occasional vertical motions of 0.3 – 0.6 m in Release #3. Leads opened by the passage of the support vessel closed rapidly at about 15 cm/s, indicating a pack under compression.

The large amounts of slush filling the leads in Releases #2 and #3 effectively stopped oil from spreading. Once the oil saturated the slush, it ceased spreading or spread very slowly. Most of the oil remained at, or close to, the surface, with no evidence of oil being suspended at depth in the slush.

Results: No emulsification was observed in any of the releases, despite a water temperature of – 1.5˚C and the known propensity for the oil to emulsify. Samples from Release #1 showed evaporative losses of 12 – 25% within a few hours, reflecting the very thin films (0.05 mm) in the open drift ice conditions. In contrast, most of the samples from the thick oil films following Releases #2 and #3 showed < 4% evaporation (peaking at ~9%).

The experiments demonstrated that if slush and brash ice are not major factors, spreading of oil in pack ice can be predicted by simple modifications to standard open water

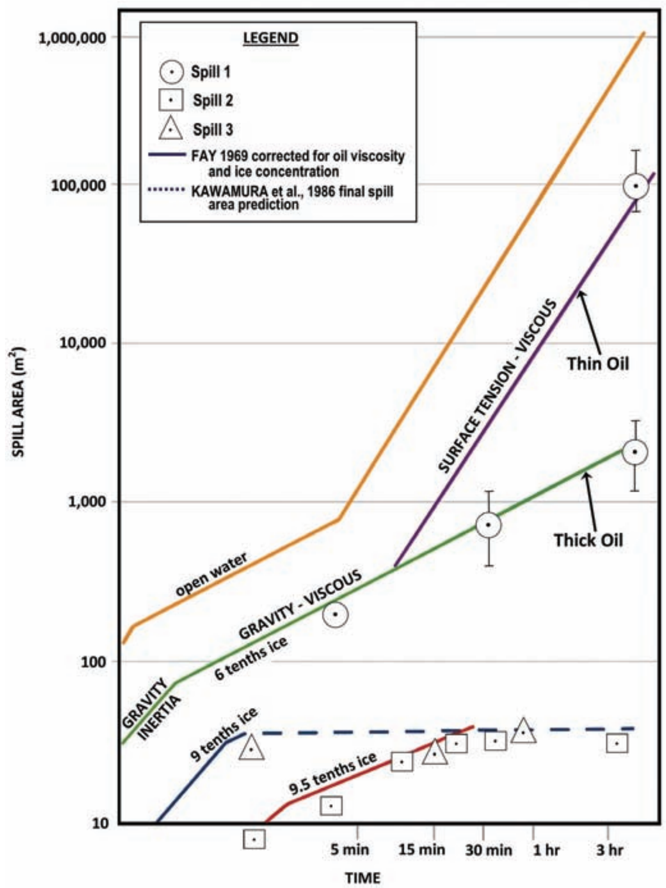

FIG. 9. Oil spreading in pack ice comparing model predictions to observed results for the Nova Scotia field releases in 1986 (Fay, 1969; Kawamura et al., 1986; Ross and Dickins, 1987).

equations, accounting for ice concentration. Figure 9 shows a plot of spreading curves for the oil at 0°C corrected for oil viscosity and ice concentration. This simple approach fitted the experimental data well, indicating that the slick area in broken ice can be estimated by multiplying the spill area in open water by the reciprocal of the ice concentration.

Although skimmers and pumps were available, they were not deployed. In the case of Release #1, the oil was too thin and widespread for skimming, and the oil was too thin to sustain combustion. In Releases #2 and #3, several burns lasting about 20 minutes effectively removed 77–80% of the oil (Fig. 10, Table 5). Residue was recovered with shovels and bagged for disposal.

Project 9

This project, Marginal Ice Zone Experiment (Sørstrøm et al., 1994; Singsaas et al., 1994; Vefsnmo and Johannessen, 1994), was an experimental release of 26 m^3 of North Sea crude. It took place 185 km northeast of Bear Island, off the north coast of Norway, in the Barents Sea marginal ice zone, about 40–45 km from the ice edge in April 1993. Oil type was Oseberg crude, with a specific gravity 0.853 and pour point −24˚C. During a six-day period, the slick drifted to within 6 km of the ice edge, while the ice concentration

FIG. 10. Burning thick oil contained in a slush-filled lead off Nova Scotia in 1986 (Photo: D. Dickins).

ranged from 7–9/10. No significant ocean swell penetrated the pack ice.

This spill is the largest known, single deliberate release of oil in ice for research purposes. The high ice concentrations and cold temperatures kept the thick oil relatively immobile, and slowed the water uptake and evaporation compared to open water (Fig. 11). Approximately 2–5% of the total volume was smeared around the perimeter of floes, and an insignificant proportion of the oil was transported as small particles under the ice, similar to findings by Buist and Dickins (1987).

Buoys deployed in the oil closely followed the drifting ice, agreeing with earlier observations (Buist and Dickins, 1987) and more recent spills in very close pack ice (Sørstrøm et al., 2010). Localized spreading of oil within the ice field proved very sensitive to small changes in ice concentration. During the first few days, an ice concentration of ~9/10 limited the spreading and maintained the oil in thick films averaging 6–8 mm. On Day 6, the ice field diverged to ~7.5/10, and the oil started to spread and thin rapidly to a thickness of ~0.7 mm. On Day 7, the ice field compressed slightly to 8.5/10, and the oil thickness increased to ~1.1 mm. The experiment showed

TABLE 5. Estimated mass balance from the three releases offshore Nova Scotia in 1986.

		Volume of oil (m^3)			
Spill release #	Released (m^3)	Evaporated	Burned	Recovered manually	Totals
1	1	25% thick; 30 + % thin	0	0	25%
2	1	5%	77%	5%	87%
3	1	4%	80%	0	84%

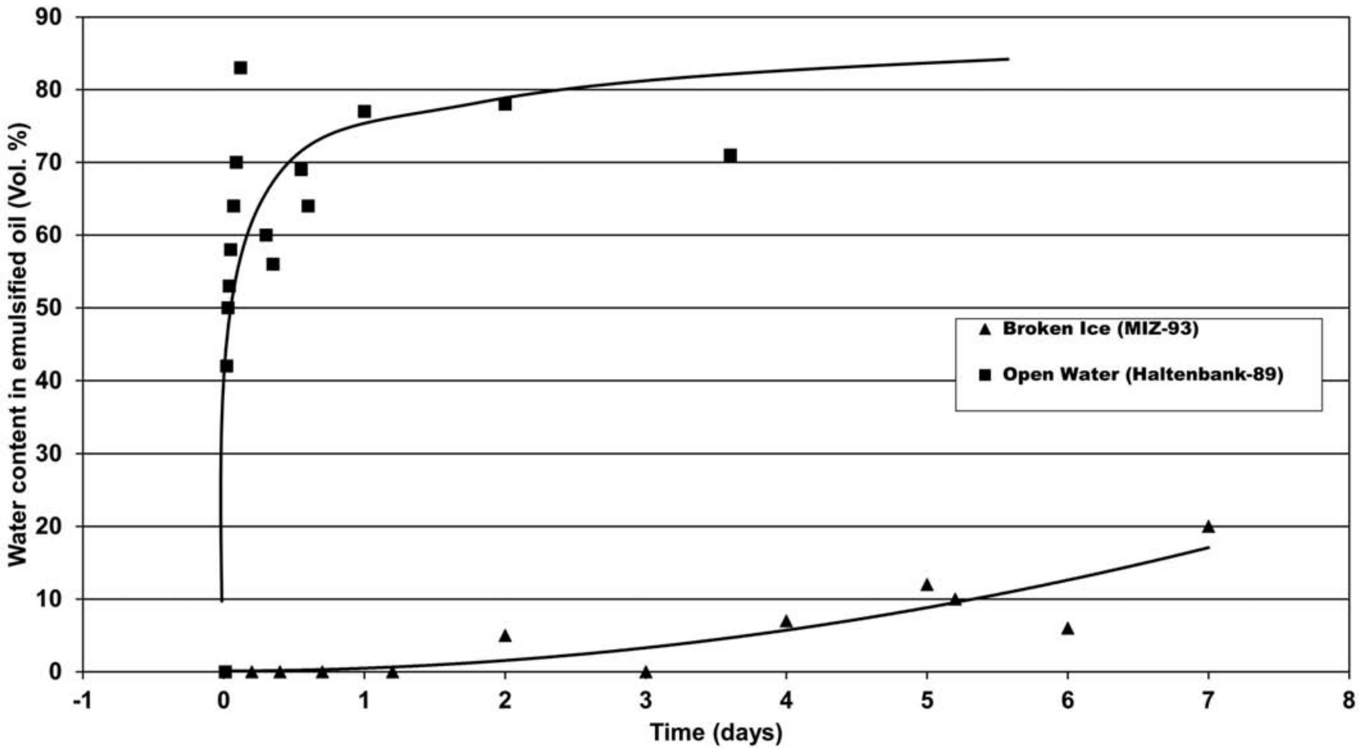

FIG. 11. Comparison of water content in oil vs. time using data from an earlier Norwegian open water release (Haltenbank, 1989) and the Marginal Ice Zone 93 Program (Sørstrøm et al., 2010).

how oil spreading is closely connected to the dynamics of expansion and contraction within the ice field.

Attempts to use an oleophilic rope mop skimmer for recovery were hampered when the support vessel inadvertently opened the ice cover, allowing the oil to spread rapidly, an effect also noted in the 1986 Canadian experiment. No other effort was made to recover the oil.

Project 10

This experiment, called Svalbard Experimental Oil Spill Under Ice 2006 (Dickins et al., 2008), involved a discharge of 3.4 m^3 of fresh Statfjord crude oil under 65 cm solid fast ice in a fjord on Svalbard in March 2006. The objectives of the experiment were to create an under-ice spill to test detection using ground penetrating radar, to document the weathering processes of the oil, and to assess the effectiveness of burning after the oil was exposed. The oil was contained within a containment skirt cut into the ice to encompass an area of 100 m^2. Average oil film thickness was 3.5 cm, but natural under-ice depressions led to pockets of oil over 10 cm deep. Oil started to migrate naturally to the surface 24 days after the release. Most of the oil had surfaced by May 30, just over 60 days following release. The oil surfacing curve closely resembled results from Dickins and Buist (1981) shown in Figure 6.

After lying exposed on the surface for over one month, the oil was 27% evaporated. The oil was then burned on 30 May with an estimated efficiency of 96%.

Project 12

This project was called Joint Industry Program (JIP) on Oil Spill Contingency for Arctic and Ice-covered Waters: Oil in Ice Field Experiments 2008 and 2009 (Sørstrøm et al., 2010). The first experiments took place in 2008, when two small, uncontained releases totaling 0.8 m^3 of Heidrun crude oil were conducted in the Norwegian Barents Sea between 78˚N and 79˚N, east of Svalbard, in 2008. The primary purpose was to test the application of herders to thicken an oil slick in open drift ice enough to support in situ burning. The trial was a success, with better than 90% removal effectiveness. This spill was the first trial combining herders and burning in an Arctic field setting

(Buist, 2010). Additionally, several brush and brush drum skimmers were tested with crude oil spilled into booms filled with ice pieces alongside the support vessel. A second series of skimmer tests took place in 2009 with and without oil (Singsaas et al., 2010).

The 2009 project consisted of three uncontained releases (0.5, 2, and 7 m^3) of fresh Troll B crude oil into close pack ice (>8/10) with the combined goals of assessing dispersant effectiveness while documenting oil weathering and fate. This remains the only known field test of chemical dispersants in ice (a small-scale test of oil – mineral aggregates as a natural dispersing agent took place in the St. Lawrence River in 2008 [Lee et al., 2011]). In the main dispersant trial in the Barents Sea, 2 m^3 oil were released in 7 – 8/10 ice with no wave action and treated after six hours' weathering with 300 l Corexit 9500 applied for 30 min from a spray arm articulated off the side of the vessel. Concentrations of dispersed and dissolved oil in the water column were monitored by in situ UV fluorescence, laser in situ scattering and transmissometry (LIST) droplet size measurements, and water sampling. Priority was given to areas along the edges of ice where the oil thickness was 2 – 3 cm. Dispersant dosage was estimated as 200 – 300 ml/m^2. After using the vessel's thrustors to add mixing energy, the dispersion efficiency was estimated as >90% (Daling et al., 2010).

In two additional tests, 4 m^3 of oil were released into towed booms filled with small ice pieces and then burned with an estimated efficiency >90% based on residue remaining (Potter and Buist, 2010).

The largest release was tracked for 10 days as the oil moved with the drifting pack. In one 24-hour period, the ice and oil moved 35 km in response to sustained winds exceeding 15 m/sec, closely matching the rule of thumb often used to predict ice drift rates, of ~3% of the wind speed with a turning moment to the right from the Coriolis effect.

The countermeasures assessment showed that:

> • burning thick oil films trapped between floes in close to very close (7 – 9/10) pack ice is highly effective (confirming earlier work in Canada);
> • dispersants are potentially useful to deal with a spill in pack ice if sufficient mixing energy is available;
> • fire-resistant booms can be used in very open drift ice to collect small pieces of oiled ice and subsequently burn oil within the boom at high efficiencies; and
> • skimmers can be effective in very open drift ice (up to 3/10 concentration), but their performance is significantly hindered in higher concentrations due to ice clogging and reduced oil flow.

Prior to the 2009 field experiments, tank tests examined the evaporative loss of a light oil under different ice concentration levels, current, wave height, and air temperature (Brandvik and Faksness, 2009). There was good agreement between the water uptake measured in the tank tests and the 2009 field trial (Sørstrøm et al., 2010). The JIP concluded that the reduced rate of water uptake in ice significantly increases the operational window for in situ burning and the use of dispersants.

HISTORICAL FINDINGS IN THE PRESENT-DAY CONTEXT

Principal findings from historical field experiments are highlighted here according to different aspects of oil and ice interaction.

Oil Weathering

- Slower evaporation and emulsification rates in ice as a function of thicker oil films.
- Reduced rates of natural dispersion compared to open water.
- Negligible weathering of oil trapped within the ice through the winter.
- Evaporation rates of crude oil on the ice or snow surface reaching 20 – 25%.

Movement

- Oil moves with the ice cover in over 6/10 concentration at close to the rule of thumb (3% of wind speed).

Spreading

- Oil under ice is effectively contained in localized areas by natural ice roughness.
- Cold water increases the equilibrium thickness (some crudes can gel, and newer low sulfur marine fuels may clump).
- Surface spills are effectively contained in slush ice and between floes in high ice concentrations ≥ 7/10.
- Oil film thickness is highly sensitive to small changes in ice concentration.
- In lower ice concentrations, application of very small volumes of herding agent can rapidly thicken the oil to enable effective in situ burning.

Encapsulation, Migration and Exposure

- New ice growing beneath oil trapped under ice can encapsulate the oil within a relatively short period of time depending on ice thickness and air temperature (e.g., 24 – 72 hours in early or mid-winter, 4 – 5 days in late winter).
- Oil will rapidly penetrate and saturate the soft, fragile skeletal layer at growing sea ice interface during winter, then gradually rise through the brine channels to the surface as the ice warms into late winter and spring.
- Once the ice internal temperature approaches the freezing point of sea water ~ –1.8˚C, oil can quickly rise to the surface in tens of minutes to hours.

- Oil spilled in a gas plume (subsea blowout) behaves very differently than a batch release (pipeline rupture), spreading widely as fine droplets that are unable to migrate naturally to the surface through brine channels.
- The presence of an encapsulated oil layer has no significant effect on the final ice thickness.
- The presence of oil on the ice surface resulted in earlier clearing by seven days in one experiment while another project saw no measurable effect.

Countermeasures

In situ burning was the primary and most effective response strategy applied in all projects where cleanup was attempted. Herding agents in open areas and dispersants in ice proved effective in the 2008 and 2009 Norwegian experiments. Mechanical recovery in most projects was limited to manual burn residue removal, while the ice remained safe for working. Skimmer tests with oil and small ice pieces confined within booms pointed to low effectiveness limited to open drift ice conditions (≤ 3/10).

Table 6 summarizes the key experimental oil releases discussed above in terms of their applicability to present-day oil-in-ice spill risks.

Only one of the original large-scale field experiments focused on the interaction of crude oil and ice in the presence of gas, as in a subsea exploration blowout. As spill risks in ice have shifted away from exploration in many parts of the world, historical observations of how oil spreads and weathers on a solid ice surface, or becomes trapped among mobile pack ice without the influence of gas, are still entirely relevant to any scenario involving surface blowouts during production drilling. Similarly, observations of how oil spreads beneath the ice and becomes encapsulated through the winter are still directly applicable to spill scenarios involving marine pipelines or sunken vessels. So too, the experience with burning oil in different ice conditions during the historical field experiments applies to a range of current spill scenarios from various sources: pipelines, offshore oil production platforms and artificial islands, and damaged vessels.

Many of the lessons learned from historical crude oil releases will likely apply to other oils to varying degrees, but there may be differences in the details of how the oil interacts with the ice, depending on the properties of the oil, principally pour point and propensity for gelling in cold water. Lighter oil products, such as gasoline, kerosene, and marine diesel, will likely migrate to the surface of sea ice much like the light-to-medium crude oils tested in the field experiments. Once on the ice surface, many of these oils will largely dissipate through evaporation within a few hours to days (depending on slick thickness), negating the need for countermeasures in some cases.

Some winter-grade residual fuel oils may have pour points low enough to remain fluid under the ice and, theoretically, to migrate to the surface. Characterizing future fuel oil spills in ice from vessel accidents will largely

TABLE 6. Selected experimental oil releases highlighted for their relevance to present-day oil-in-ice spill risks and scenarios (see Table 2 for a full list of studies).

Project title	Year	Focus	Directly applicable	Likely applicable in part
Interaction of crude oil with Arctic sea ice	1974–75	Oil behavior in solid ice. Countermeasures: burning	Pipeline or tanker spills of crude oil in 9–10/10 ice	Vessel fuel oil spills in high ice concentrations; validation needed of LSFO behavior
Oil and gas under sea ice	1979–80	Oil and gas behavior in solid ice. Countermeasures: burning	Subsea blowouts of crude oil under ice	Surface blowouts of crude oil onto the ice surface
Experimental releases of crude oil in pack ice	1986	Oil behavior in pack ice. Countermeasures: burning	Tanker and pipeline spills with variable pack ice 4–9+/10	
Marginal ice zone experiment	1993	Oil behavior in pack ice. No countermeasures	Blowouts in open water where oil drifts north into the marginal ice zone	Vessel fuel oil spills in drifting pack ice; validation needed to account for variable LSFO behavior in freezing water
Oil in ice JIP	2008–09	Oil behavior in pack ice. Countermeasures: mechanical, dispersants, burning with and without herders		

depend on the how the new residual LSFOs behave in cold water. More research is needed to understand the properties and variability of different residual LSFO blends and adapt response strategies to account for the known variability in properties of the new fuels. Confirmation is also needed to determine how effective in situ burning will prove to be with this new mix of fuels in cold water and on the surface of ice.

CONCLUSIONS

The emphasis on in situ burning as a primary countermeasure for spills in or on ice, employed successfully in many of the significant historical experimental spills, is still valid in the context of many current scenarios, where the remoteness and lack of logistics support continue to favor countermeasures requiring minimal resources. Research is needed to confirm the likely effectiveness of in situ burning for the new residual low and ultra-low sulfur fuel oils being introduced throughout the Arctic and many subarctic areas.

Despite the lack of current or planned offshore oil exploration in most Arctic areas, there are still numerous risk scenarios involving production drilling, marine pipelines, tankers, and general cargo vessels that could lead to spills in ice covered waters.

The relatively small number of historical oil-in-ice field experiments reviewed here still form the basis for much of our understanding of how oil behaves in a range of ice types. This understanding remains largely applicable to today's changing spill risk landscape, now dominated by oil production and transportation. While oil exploration activities in Arctic and subarctic waters have decreased, the level of vessel traffic continues to increase. The mix of expected oil-in-ice spill scenarios may have changed, but the fundamentals of how ice spreads within an ice field, becomes incorporated in growing ice, and becomes exposed during the melt season have not.

Key findings from these historical projects can still guide today's responders in developing effective strategies to address present and future spill risks in Arctic and subarctic areas. Notably, given the challenges involved in obtaining permits and cost of executing, it is very unlikely that projects on the scale of those carried out between 1970 and 2009 will ever be permitted again.

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