EXPERIMENTAL SPILLS OF CRUDE OIL IN PACK ICE

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ABSTRACT: *A field research program was carried out to investigate the fate of crude oil spilled in dynamic pack, or broken, ice. The presence of ice dramatically reduced the spreading of 1 m^3 test spills compared with that expected on open water. Evaporation of the oil and subsequent property changes could be adequately predicted using conventional theories.*

The behavior of oil spilled in pack (or broken) ice has been the subject of research and study over the past decade.[2,3,4,6,7,8,11,12,13,14,17] Prior to this experiment, however, no field spill data existed which could validate the results of small scale test tank work or verify various spill behavior theories.

The objective of this study was to conduct a preliminary investigation of the physical and chemical fate of crude oil spilled among pack ice.

More specifically, the study was designed to:

1. Relate oil spreading behavior to ice conditions ranging in concentration from 5 to 9 tenths
2. Evaluate the fate of oil spilled in pack ice by monitoring the processes of evaporation, emulsification, dispersion, and incorporation into or on top of the ice
3. Identify possible countermeasures strategies
4. Provide data with which to plan larger, longer term field experiments on the behavior of oil in pack ice and cleanup techniques

Methods

On March 9 and 10, 1986 three spills of 1 cubic meter each of Alberta sweet mixed blend crude oil (Table 1) took place approximately 140 km east of Chedabucto Bay, Nova Scotia (Figure 1). Environmental conditions for each of the spills are summarized in Table 2.

For the first spill, in 3 to 5 tenths ice, one cubic meter of oil was transfered from drums on the deck of the *MV Brandal* (Figure 2) to a plastic bladder mounted on a raft (Figure 3). The raft was then slung over the side of the ship and placed in the center of the test area. The bag was slit open to release the oil after the ship had moved away from the raft and the ice had returned to normal conditions (Figure 4). For the second two spills, the drums were tipped from the edge of an ice floe (Figure 5). Two Zodiac inflatable boats powered by 10hp outboard motors were used to take oil samples and ice measurements. These proved to be surprisingly maneuverable in pack ice. An underwater video camera was used to document subsurface oil/ice interactions.

A Bell 206 helicopter was used as a remote sensing platform (Figure 6). Sensors mounted on the helicopter included: a Barr and Stroud IR-18 infrared video, a low light level television (L^3TV) camera, a true color half-inch video system, a true color 70 mm Vinten aerial camera, and a black-and-white 70 mm Vinten aerial camera filtered for ultraviolet (UV) photography. Colored nylon disks were placed around each site to aid in aerial video and photo interpretation; a 10 m × 1 m colored nylon swatch was placed on a centrally-located floe at each site for scale (see Figures 4 and 5). Positions were determined by Loran-C receivers on both the ship and the helicopter.

Surface oil samples were taken at predetermined times and locations from both thick and thin portions of the slick using the Belore sampler.[1] The sorbent pads were placed in 500 ml glass jars containing 100 ml of hexane, "killed" with mercuric chloride, and sealed with Teflon-lined lids. Grab samples (125 ml) were also taken whenever possible and similarly stored. Evaporative loss was determined by comparing gas chromatograph (GC) traces of the samples with those of a lab-weathered standard; oil concentrations were determined using UV spectroscopy.

Ice conditions

Spill No. 1, March 9, 1986. Ice concentrations were between 4/10 and 6/10 in the area of spill No. 1. The ice was composed of grey white to thin first year ice. Ice floes ranged from small pancakes to large floes with dimensions on the order of 10 m × 5 m. Ice thicknesses in

Table 1. Properties of Alberta sweet mixed blend crude oil

Density at 0° C	0.8566 g/cm^3
Density at 15° C	0.8448 g/cm^3
Viscosity at 0° C	43.7 cp
Interfacial tension	
air/oil	25.7 dynes/cm
oil/seawater	19.0 dynes/cm
oil/water	26.2 dynes/cm
Pour point	−8° C
Flash point (closed cup)	7° C

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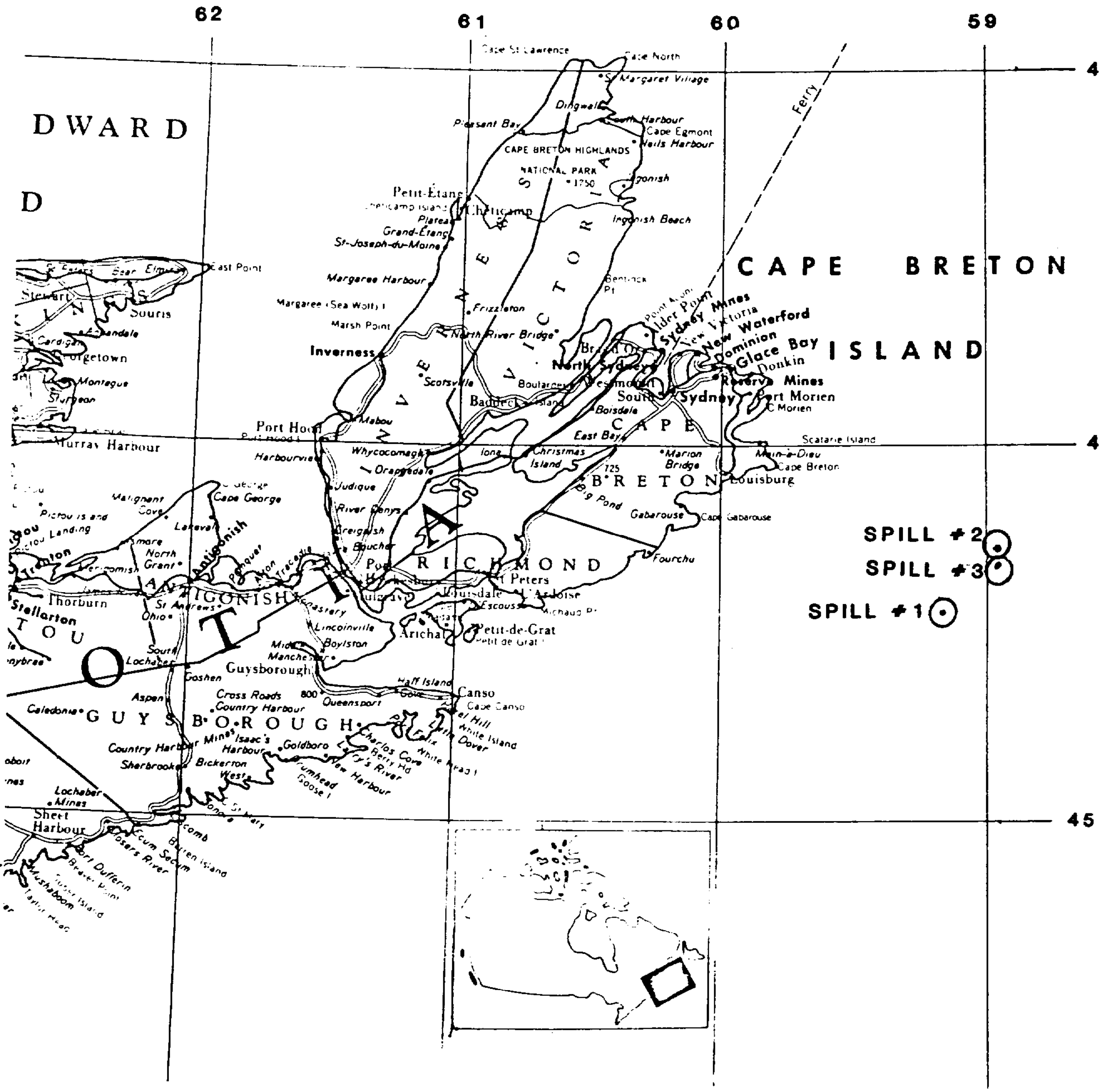

Figure 1. Spill locations

Table 2. Environmental data for oil in pack ice spills

Spill number	Ice conditions (tenths)	Oceanographic conditions		Meteorological conditions		
		Swell	Ice drift[1]	Air temp. (°C)	Wind speed (km/h)	Wind direction (°T)
1	4–6 small floes and pancakes	3–4m	1.1 km/hr to 140°T (1.9 km/hr to 158°T overnight)	−8	35–45	270–285
2	7–8 medium floes surrounded by freezing brash	—	0.8 km/hr to 195°T	−14	30–35	310–335
3	4–6 medium floes surrounded by freezing brash	0.3–0.6 m (occasional)	0.7 km/hr to 155°T	−11	18–22	290–335

1. From ship's loran

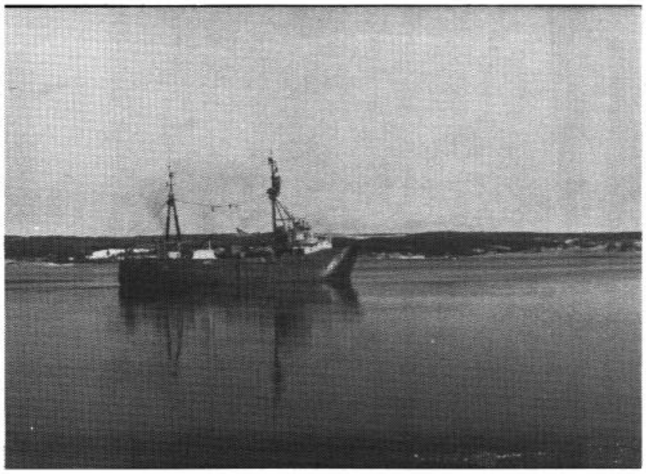

Figure 2. The *MV Brandal*

the center of the large floes were from 50 cm to 105 cm. Freeboard around the flow perimeters ranged from 5 cm to 44 cm. A thin crust of snow covered the floes. Slush ice filled the open water areas between floes at the start of the experiment.

Ice conditions during the experiment were very dynamic due to the proximity to the ice edge and the propagation of a 3–4 m swell through the ice field. As the experiment progressed conditions became more dynamic. By then the experiment site was within several hundred meters of the ice edge. At the ice edge, the pack was rapidly broken up by the swell and large open water areas were exposed.

Figure 3. The oil-filled raft for spill No. 1

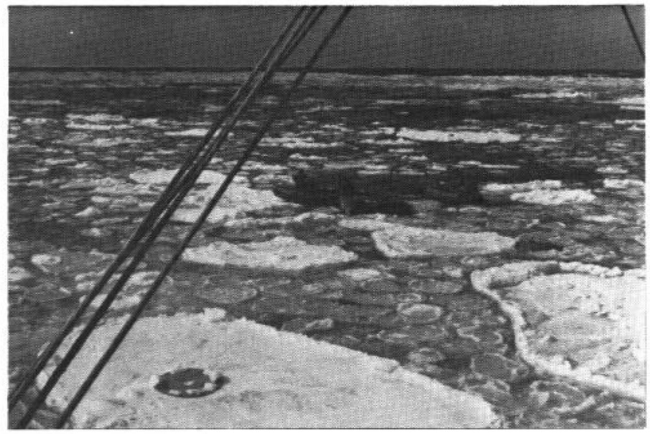

Figure 4. Oil release, spill No. 1—note the disk marker for aerial photography on floe in foreground

Water temperature	−1.4 to −1.6° C
Oil temperature	−1.0 to −1.5° C
Ice core temperature	−2.2° C top to −1.3° C bottom
Seawater salinity	24 ppt (approximately)
Ice core salinity	0.5 ppt top to 5.0 ppt bottom
Relative floe motion	minimum −7 cm/s
	mean +2.4 cm/s
	max 16 cm/s
	mean convergence −3.4 cm/s
	mean divergence 5.4 cm/s
Floe size	mean 7 m
	max 24 m

Spills No. 2 and No. 3, March 10, 1986. Ice conditions were 9+/10 in the areas of spills 2 and 3. The ice was composed of young to thin first year ice in a state of moderate compression. Ice floes ranged from small pancakes to large floes with dimensions in the order of 28 m × 16 m. Total ice thickness ranged from 120 cm to 160 cm with a layer of slush found at about 80 cm to 95 cm. Many floes were rafted and several underlying layers of ice were observed. Freeboard ranged from 5 cm to 52 cm. Snow cover on the floes was between 17 cm and 40 cm deep. Heavy slush ice up to 40 cm thick covered the leads between floes.

Ice motion during spills 2 and 3 was relatively static compared with the dynamic ice conditions observed during spill 1. The swell was almost completely damped. Leads opened by the passage of the ship closed rapidly at about 15 cm/s.

	Spill No. 2	Spill No. 3
Water/slush temperature	—	−1.7° C
Oil temperature	−3.4° C	−3° C
Ice core temperature	−2.8° C top to −1.6° C bottom	—
Relative floe motion	0.1 cm/s	not measured
Floe size	mean 13 m	mean 9 m
	max 30 m	max 22 m

Oil spreading

Figure 7 shows the results of an analysis of spill area (corrected to exclude ice) from the true color 70 mm aerial photography. The presence of high concentrations of brash ice in spills 2 and 3 dramatically reduced spreading. After 2 hours the oil in spill 2 had spread only to an area of 30 m^2 with an equivalent thickness of 3 cm. The slightly lower brash ice concentrations in spill 3 and the leads created by the ship next to the spill site allowed the oil to spread more rapidly than in spill 2, though the final spill areas were almost identical.

Figure 5. Oil release from drums on ice floe for spill No. 3—note the 10 m long orange nylon swatch at far side of the floe to provide scale for aerial photography

In the lower ice concentrations of spill 1, with only some brash ice present, and under the influence of very dynamic ice conditions (3–4 m swell), the oil spread to cover about 1×10^5 m^2 after 3 hours with the thick slick covering about 4,000 m^2. It was interesting to note that although the sheen had, after 3 hours, spread to cover a large area in the ice, the thick portion of the oil remained around the same floes where it had been discharged. It thus seems that oil and ice floes both drift at the same rate under the influence of winds and currents.

Also shown on Figure 7 is a plot of Fay's[5] spreading curves for the oil at 0° C corrected for oil viscosity[15] and ice concentration (by multiplying the calculated area by the fraction of the sea surface that is ice free). This simple approach fits the data surprisingly well. Further details may be found in the project report.

Figure 6. Remote sensing helicopter with sensors mounted on struts

Figure 8 shows the results of the thickness sampling of spill No. 1. Samples were taken in the north end, center and south end of the slick, aligned with the northerly winds. Also shown for comparison is the theoretical prediction including the oil viscosity and ice concentration corrections for the oil at 0° C. This independent data set confirms the spreading data and model shown on Figure 7. The thicker areas of the slick at the center and downwind south end of spill 1 were spread primarily by the gravity-viscous regime of Fay[5] while the north, upwind portion of the slick was quickly spread by the surface tension-viscous regime. Again, the simple, corrected Fay model predicts the data reasonably well.

Evaporation

Figure 9 shows the evaporative loss for all three spills as a function of evaporative exposure.[16] Evaporative exposure is a dimensionless number that contains time, slick volume divided by area (i.e., thickness) and an air-side mass transfer coefficient. Also shown on Figure 9 are the results of artificial weathering of the crude oil by bubbling air through it at 20° C and the theoretical curves to predict evaporative loss derived from a modified ASTM distillation procedure.[16] The fit of the theory to the data is quite good considering the range of conditions over which the samples were collected (slicks ranging from 30 μm to 5 cm in thickness at −8 to −13° C offshore and a small scale laboratory test at room temperature).

Weathering effects on oil properties

Figures 10 and 11 show the effects of evaporation on the density and viscosity of the spilled oil at 0° C. Also shown are the predictions from spill property models proposed by Mackay et al.[10] The properties of the oils in spills 2 and 3 changed little since the oil remained thick and concentrated.

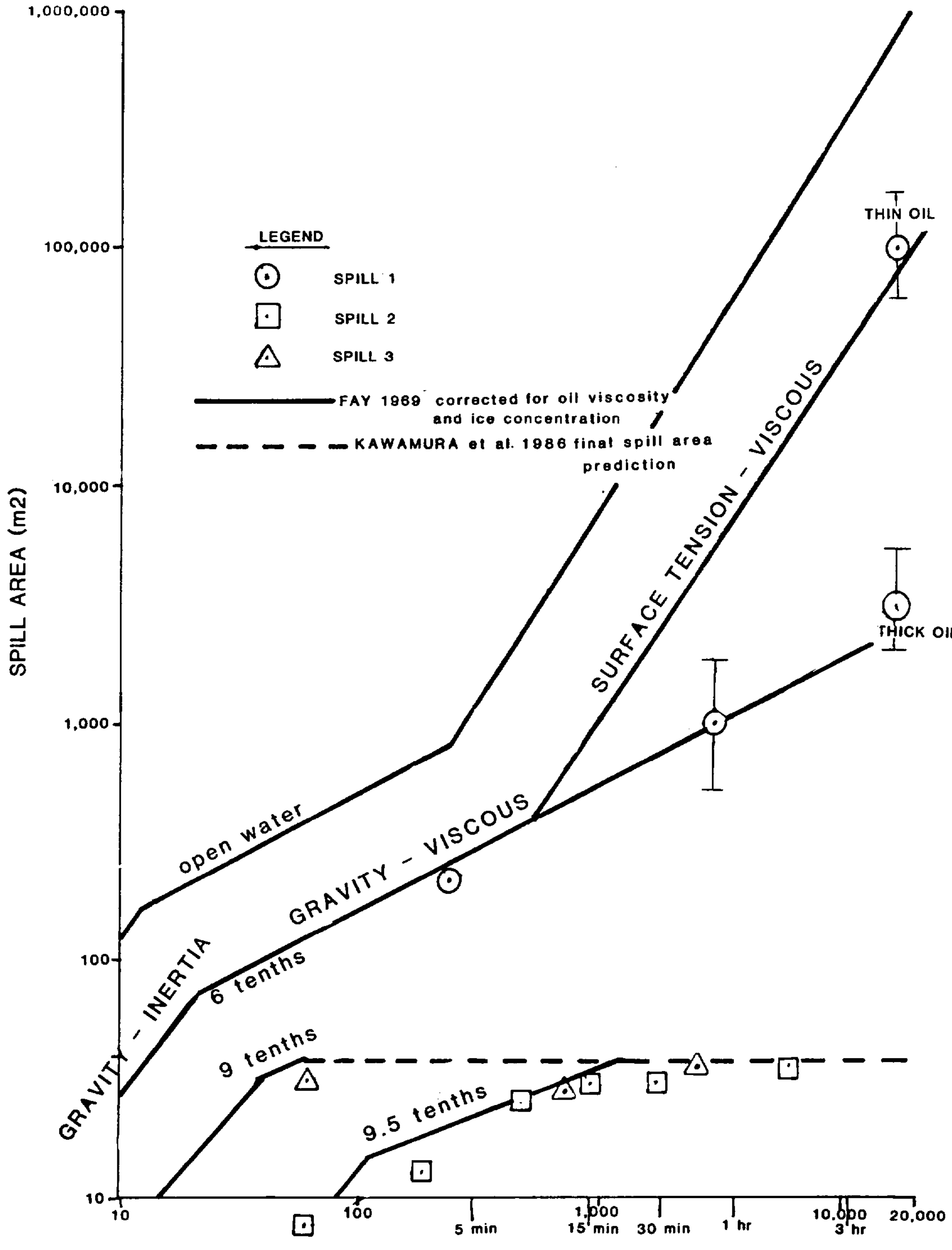

Figure 7. Oil spreading in pack ice

Emulsification and dispersion

No emulsification of the oil was observed to occur despite the dynamic conditions in spill No. 1 and the fact that the oil is known to be prone to emuslification.

Underwater video recording at ice floe edges showed that droplets of oil were being swept beneath the ice by currents, although this did not seem to be occurring at a significant rate. In 3–4 m seas in open water a slick such as spill 1 would disperse rapidly; this was not the case in the pack ice.

Interaction with ice

The oil interacted with the ice in three ways: it saturated the brash ice surrounding floes, it splashed onto small pancakes of ice, and droplets were swept beneath the floes by the currents.

The brash ice proved to be an effective barrier to limit the spread of oil. However, in dynamic conditions the oil eventually mixed with the ice to produce a brown slush which, with the rocking action of the floes, coated the outer rim of small floes and pancakes (Figure 12). In the less energetic conditions of spills 2 and 3, very little mixing of oil

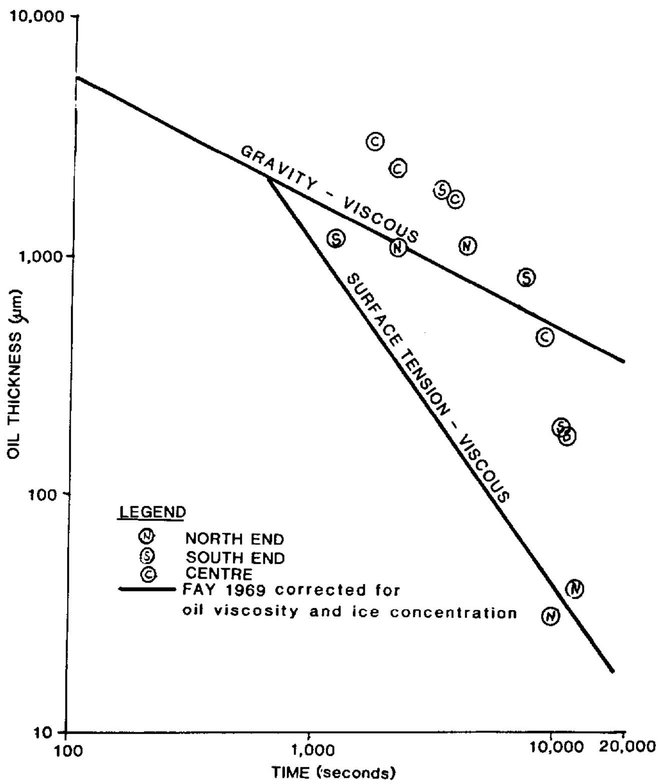

Figure 8. Thickness of spill No. 1 vs time

into brash ice occurred; rather, the oil saturated an area of brash ice, then ceased spreading. The final area of the oiled brash ice corresponds well to that predicted by Kawamura et al.[9] (see the project report for details).

In spill No. 1 oil droplets, about 1 mm to 3 mm in diameter were observed being swept by currents beneath floes. A core sample from the edge of a floe showed that these droplets were trapped by the underside of the floe and had migrated upward some 25 cm into the brine channels. Analysis of the melted cores showed oil concentrations equivalent to an under-ice oil thickness of approximately 0.15 mm.

Some oil was also found on top of the occasional pancake (Figure 13), though this was rare. Analysis of one such sample scraped from the snow showed that the oil had an effective thickness of 0.25 mm and was extremely weathered.

Countermeasures

Remote sensing. Of the sensors used, true color video and photography, and the infrared video were the most useful tools for documenting oil in pack ice. It proved impossible to detect the sheen with

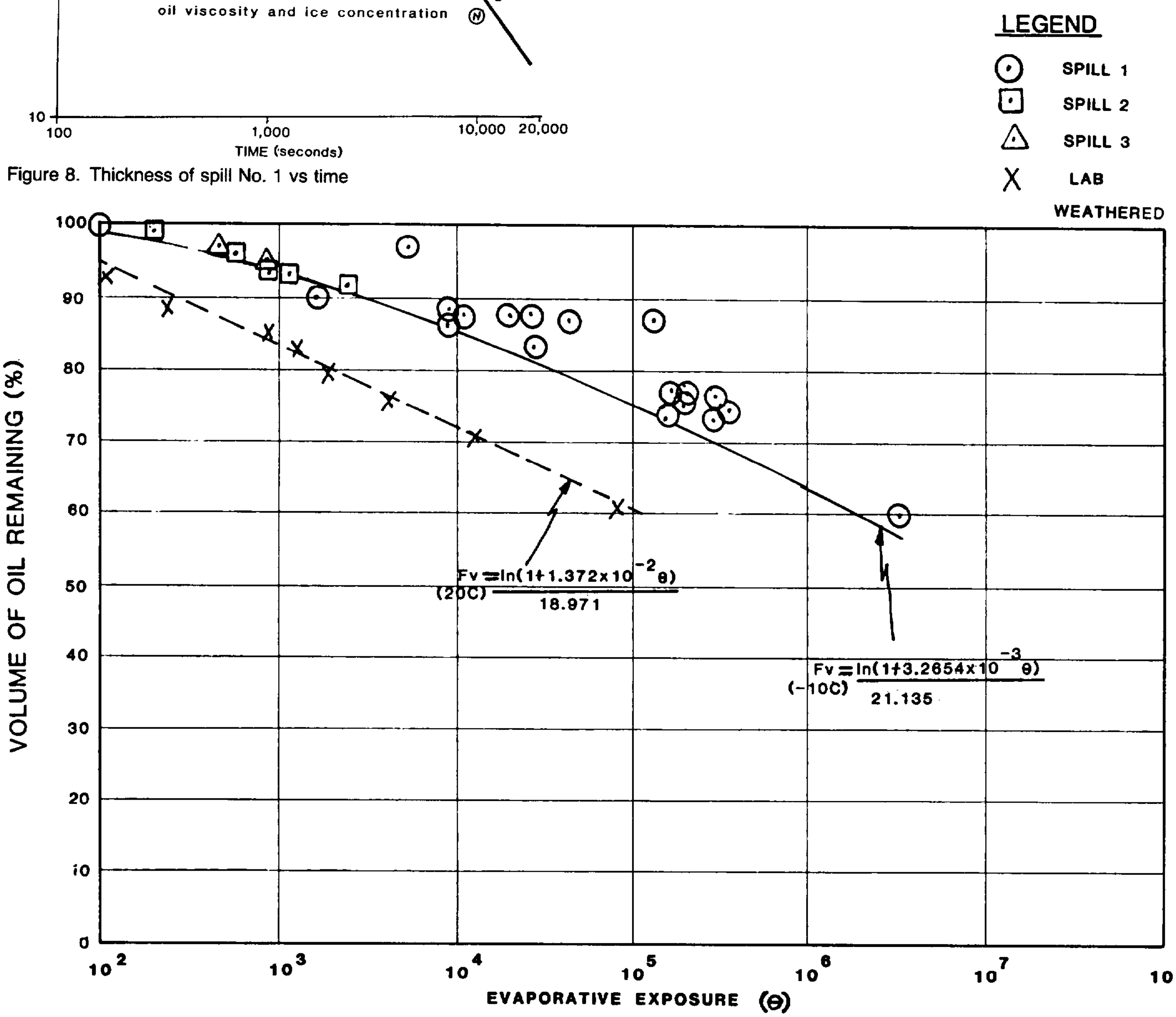

Figure 9. Evaporative loss

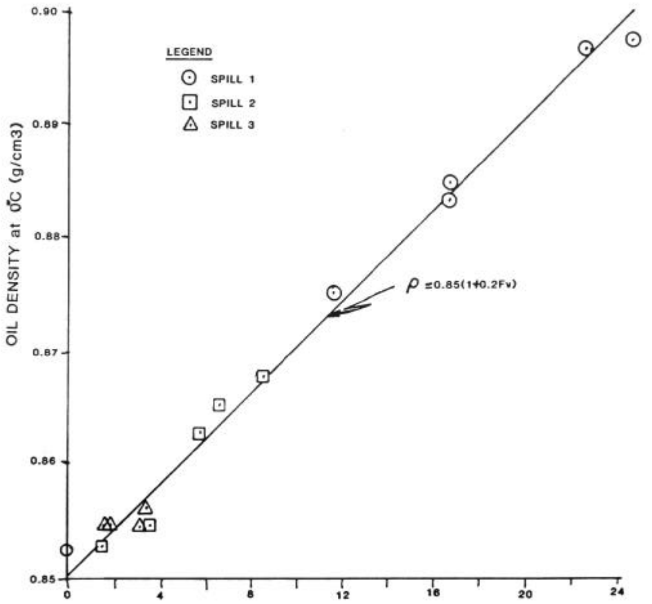

Figure 10. Density vs evaporation

the UV filtered black and white photographs; the L^3TV imagery did not have sufficient sensitivity to distinguish oil from water.

Physical recovery. Although skimmers and pumps were aboard the ship they were never deployed. In the case of spill No. 1 the oil was

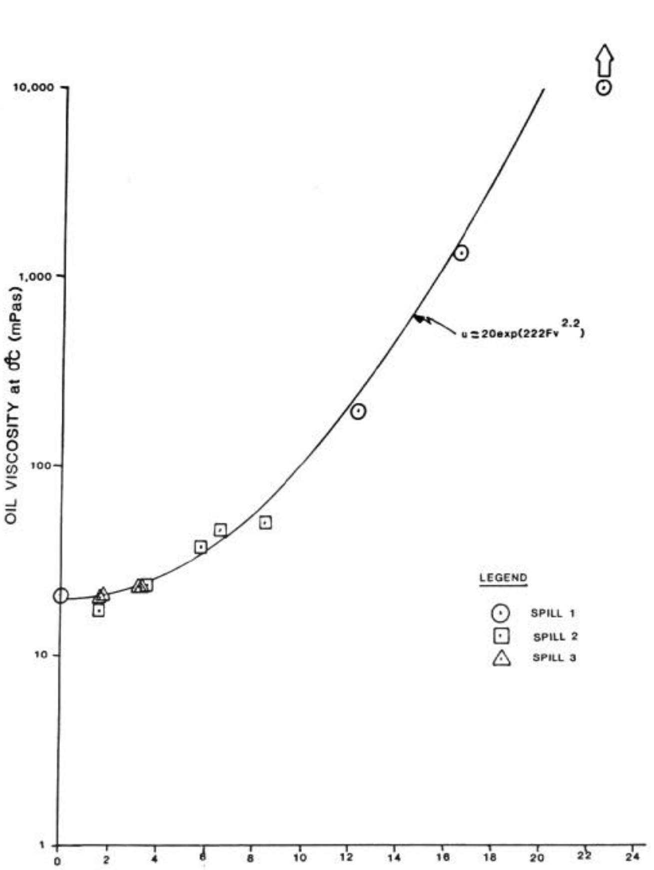

Figure 11. Viscosity vs evaporation

Figure 12. Oil from spill No. 1 after three hours

too thin and widespread for skimming and attempts to concentrate it with booms would have been pointless because of the ice.

It would have been possible to skim or directly pump the oil contained by the ice in spills No. 2 and No. 3 but it proved simpler to just burn the oil. The residue from the spill 2 burn was picked up with shovels and placed in plastic garbage bags for disposal.

In-situ burning. Since the oil was thick and concentrated at the end of spills 2 and 3 it was ignited with a burning, oil-soaked sorbent pad (Figure 14). The burns lasted about 20 minutes each and consumed about 80% of the oil. Table 3 shows the mass balance for each spill.

Samples of the oil, soot, and burn residue were subjected to extensive analyses by Environment Canada's EPS Analytical Services Division to determine levels of the 25 polyaromatic hydrocarbons (PAH) on the U.S. EPA priority list. The fresh crude oil contained 440 μg/g total PAH, the two burn residue samples contained 190 and 510 μg/g total PAH, and the soot contained 420 μg/g total PAH. No significant difference between samples was evident.

Conclusions

Although this work was only a first step in the process of understanding the behavior of oil spills in pack ice conditions the following conclusions can be drawn:

1. Spreading of oil in pack ice is dramatically reduced, over that in open water, by the presence of ice forms. Simple correction factors to Fay's equations[3] to account for oil viscosity and ice concentration seem to be adequate to predict oil spreading in pack ice. The final area of oil spreading in brash ice is predicted well by the equation proposed by Kawamura et al.[9]

Figure 13. Oil on top of small ice pancake (near center of photo) amidst sheen

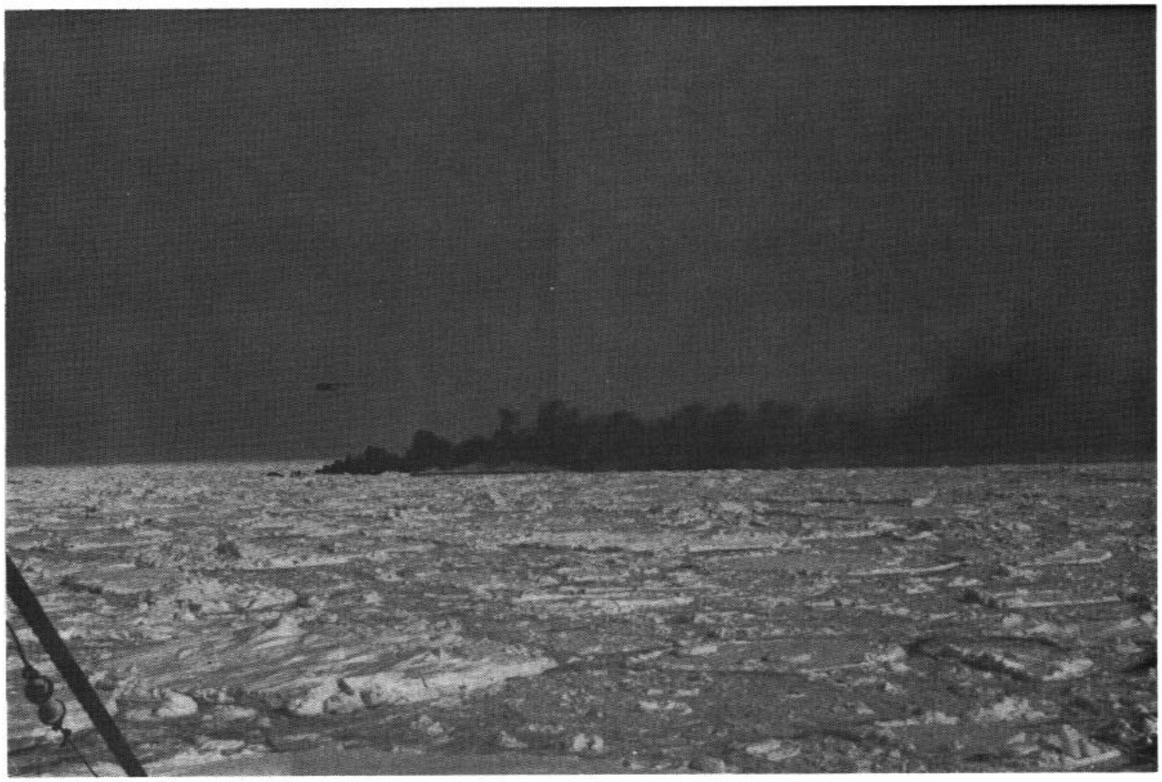

Figure 14. Burning oil from spill No. 2

Table 3. Oil mass balance

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

2. Evaporation and subsequent oil property changes can be adequately predicted using the evaporative exposure approach of Stiver and Mackay[16] and the predictive equations of Mackay et al.[10]
3. Emulsification and natural dispersion do not seem to play as important a role in determining the fate of an oil spill in pack ice as they do for spills on open water.
4. In-situ burning is an effective countermeasure for oil spills in brash ice, in high ice concentrations.

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