TESTS TO DETERMINE THE LIMITS TO *IN SITU* BURNING OF THIN OIL SLICKS IN BRASH AND FRAZIL ICE

Ian Buist
SL Ross Environmental Research
Ottawa, ON Ian@slross.com

Lee Majors and Ken Linderman
Alaska Clean Seas
Prudhoe Bay, AK

David Dickins
DF Dickins Associates
Escondido, CA

Joe Mullin
Minerals Management Service
Herndon, VA

Charlene Owens
ExxonMobil Upstream Research
Houston, TX

Abstract

The purpose of this study was to investigate the minimum ignitable thickness, combustion rate, residue amount and the effects of waves on thin oil slicks burned *in situ* on frazil or slush ice typical of freeze-up and brash ice typical of break-up. The study consisted of a literature review, small-scale burns in a chilled wave tank in Ottawa and mid-scale burns in an outdoor wave tank at Prudhoe Bay. A total of 114, 40-cm burns and 42, 170-cm burns were completed.

The experimental variables were:

- Oil type (Alaska North Slope, Endicott, Northstar and Pt. McIntyre crudes);
- Ice type (brash and frazil);
- Initial oil thickness on ice (3mm slicks and thinner);
- Mixing energy (calm and low waves to simulate natural mixing of an ice field); and,
- Degree of oil evaporation.

The small-scale tests involved:

- Minimum ignitable thickness tests for three degrees of weathering for each crude on open water, ice cubes (representing brash) and crushed ice (pulverized ice cubes representing frazil); and,
- Burn rate and removal efficiency tests in calm and low wave conditions with 3-mm thick slicks spread out on top of the ice for three degrees of weathering for each crude on open water, ice cubes and crushed ice.

The mid–scale tests mimicked the small-scale matrix and involved burn rate and removal efficiency tests in calm water and low waves conditions with 3-mm thick slicks spread out on top of open water, brash ice (grown in a nearby pit from brackish Prudhoe Bay water) and frazil, or slush, ice (simulated by using snow in water) for selected degrees of weathering of the various crudes.

This paper focuses on the methods and results of the mid-scale tests and the rules-of-thumb proposed.

1 Introduction

Recent field deployments of skimmers in broken ice conditions in the Alaskan Beaufort Sea (Bronson et al., 2002) have highlighted the severe limitations of containment and recovery systems in pack ice conditions. *In situ* burning may be the only option to quickly remove oil spilled in pack ice. The use of *in situ* burning as a response tool for oil spills in pack ice has been researched since the early 1980's using both tank tests and medium and large-sized experimental spills. Despite this level of effort, there were still questions about the limits to ignition and effective burning of spilled oil in pack ice conditions, particularly in fields of pack ice containing significant amounts of brash and slush ice and subjected to wave action. The purpose of this study was to investigate the minimum ignitable thickness, combustion rate, residue amount and the effects of waves on thin oil slicks burned *in situ* on frazil or slush ice typical of freeze-up and brash ice typical of break-up. The focus was on thin oil slicks, such as those that could be generated by blowouts or sub-sea oil pipeline leaks, because previous laboratory and field research studies have adequately addressed *in situ* burning of thick oil slicks in pack ice. Pack ice consists of a wide mix of ice types depending on the time of year. In the early stages of ice formation in the fall, pack ice may contain a mix of older ice left over from the previous winter, vast floes (kilometers in size) of thin new ice known as "nilas", and patches of newly forming ice. In the spring, pack ice generally consists of rotting first year floes with a wide range of sizes.

The consensus of the prior research on spill response in pack ice conditions is that *in situ* burning is a suitable response technique, and in many instances may be the only cleanup technique applicable (Shell et al., 1983; SL Ross, 1983; SL Ross and DF Dickins, 1987; Singsaas et al., 1994). A considerable amount of research was done on the potential for *in situ* burning in pack ice, including several smaller-scale field and tank tests (Shell et al., 1983; Brown and Goodman, 1986; Buist and Dickins, 1987; Smith and Diaz, 1987; Bech et al., 1993; Guénette and Wighus, 1996) and one large field test (Singsaas et al., 1994). Most of these tests involved large volumes of oil placed in a static test field of pack ice resulting in substantial slick thicknesses for ignition. The few tests in unrestricted ice fields or in dynamic ice have indicated that the efficacy of *in situ* burning is very sensitive to ice concentration and dynamics (and thus the tendency for the ice floes to naturally contain the oil), the thickness (or coverage) of oil in leads between floes, and the presence or absence of brash or frazil ice (which can sorb the oil). Brash ice is the debris created when larger ice features interact and degrade. Frazil ice is the “soupy” mixture of very small ice particles that forms as seawater freezes. Slush ice is formed when snow settles on open water. "Grease" is the official term given by the WMO to a thin layer of slush that results from small crystals of frazil ice forming in the water column and floating to the surface. When used to as a discrete ice type, the term "slush ice" refers to a condition where snow falling to the water appears as a viscous floating mass, similar in surface appearance to grease ice.

The key to the success of an individual burn in a pack ice field is, in part, controlled by how well the oil is contained by the ice it is in contact with. Other factors include oil weathering processes (i.e., evaporation and emulsification) and mixing energy from waves. Field experience has shown that it is the small ice pieces (i.e., the brash and frazil, or slush, ice) that will accumulate with the oil against the edges of larger ice features (floes) and control the concentration (i.e., thickness) of oil in a given area, and the rate at which the oil subsequently thins and spreads. Considering that the size of individual slicks available for burning, even only a few hours after a spill, will be on the order of metres (10's of feet), it was appropriate to focus the testing on the ignitability and burnability of oil/brash/slush mixtures in various combinations and situations.

2 Mid-scale Burns at Prudhoe Bay

This paper describes the mid-scale test burns conducted in October 2002 at the BP Fire Training Ground in Prudhoe Bay, AK. A full description of the small-scale tests may be found in the report (SL Ross and DF Dickins, 2003), which will be available on the MMS TA&R web site (www.mms.gov/tarprojects/). The same four Alaskan North Slope crude oils were used for both phases of the study: Alaska North Slope (ANS) crude from Pump Station 1 (PS-1) on the Trans-Alaska Pipeline System, Northstar crude, Endicott crude and Pt. McIntyre crude.

2.1 Methods

2.1.1 Oil Weathering

Some of the oils for the mid-scale tests were artificially evaporated. The oil samples were obtained in 55-gallon drums, and weathered by bubbling compressed air from the bottom of the drum until the desired weight of oil had been evaporated (determined by periodically weighing the drums on a 500-lb. electronic scale). The targets for the percentage loss for the oils were the same as for the small-scale tests. Table 1 shows the degrees of evaporation achieved. Note that only two of the oils (Northstar and Endicott) were artificially evaporated. Due to the limited time available to test in Prudhoe Bay only a certain number of tests could be undertaken and a reduced test matrix was designed to fit the available time window.

Table 1: Test oils for mid-scale burns.

Crude Oil | API Gravity	*Amount of Evaporation (% mass)*		
ANS | 32°	0	-	-
Endicott | 24°	0	9.4	13.9
Northstar | 42°	0	33.8	43.8
Pt. McIntyre | 28°	0	-	-

The most weathered sample of Endicott was intended to be 17.4% evaporated; however, some of the oil was ejected from the drum near the end of the weathering process, and it was decided to cease the weathering at 13.9%.

2.1.2 Test Ice

The mid-scale tests were designed around two forms of ice that could be readily simulated under natural field conditions. The rationale behind selecting the general forms of test ice is described in the report (SL Ross and DF Dickins, 2003). The procedure to produce the test ice is described below in more detail.

The aim was to create two basic pack ice conditions on demand with rapid cycling between tests (tens of minutes): homogeneous grease and/or frazil ice with very small particle sizes (equivalent to a slurry in consistency), and a non-homogeneous mix of brash ice with piece sizes up to 30 cm on a side and 10 to 12 cm thick (representing the upper limit to be categorized as *new ice* under recognized nomenclature for sea ice – WMO, 1970). Full details on the growth, harvesting and loading of the ice may be found in the report (SL Ross and DF Dickins, 2003).

2.1.3 The Wave Tank

The burn tests were conducted in a transportable wave tank (Figure 1) maintained by Alaska Clean Seas on the North Slope. The tank was placed at the Fire Training Grounds in Prudhoe Bay, AK for these tests. The inside dimensions of the large wave tank are: 12 m long x 2.4 m wide x 2.25 m high (40' x 8' x 7.4'). The tank is fitted with a hydraulically-driven wave paddle at one end and passive wave absorbers at the other. The wave absorber design virtually eliminates any reflected waves from the ends of the tank. The waves used for these tests were very low and long (to simulate the type of wave that could propagate into pack ice fields), with a height of 15 cm (6 in.) and a period of 3.5 seconds. The length of the wave exceeded the distance from the wave board to the beach (10 m = 30 feet) and could not be reliably estimated. The tank has been used to conduct experimental *in situ* burns on the North Slope in the past (e.g., SL Ross, 1998) and is fitted with a water deluge system to protect the sidewalls from heat for this type of testing. Originally it had been intended to fill the tank with seawater (61 m^3 = 16,160 gallons) from the processing plant at West Dock; however this water proved to come from a large, indoor storage tank and was 21°C. This would have caused the test ice to melt very rapidly. As an alternative, fresh water from a nearby frozen lake was used.

In order to maintain the water at just above freezing, the tank was covered each night by a large 12 m x 30 m tarpaulin and hot air was blown under the cover using portable diesel-fired, forced-air heaters (Figure 2). This system proved very effective, especially considering the unseasonably warm weather (temperatures in the –10 to 0°C range) and calm conditions (only on the last two days of a 10-day period was there any measurable wind).

2.1.4 Site Layout and Ancillary Equipment

Full details of the layout of the major pieces of equipment at the Fire Training Ground may be found in the report (SL Ross and DF Dickins, 2003).

2.1.5 Gelled Fuel Preparation

The detailed procedures for mixing the gelled gasoline are given in the report. Plastic baggies containing 100 g (4 ounces) of gelled gas were used as igniters.

2.1.6 Burn Ring

The burn ring was created using a 20-foot section of old Shell fire boom formed into a 1.7 m (5.6-foot) diameter circle. The burn ring was held loosely in the center of the wave tank by wires attached to the side of the tank. Sufficient play was required in the attachment wires to allow the ring to move up and down with the waves. As well, in order to facilitate filling the ring with oil, applying igniters and recovering residue, the rigging was such that the ring could easily be moved to the side of the tank.

Figure 1: Transportable wave tank at the Fire Training Ground.

Figure 2: Wave tank covered with tarp for night.

2.1.7 Burn Test Procedures

The procedures for each test were as follows:

1. Place desired amount of ice type in burn ring (nominally a 10 cm thickness in the 1.7 m diameter ring was 225 L [60 gallons], or 200 kg [450 lbs] of sea ice).
2. Measure oil volume for desired thickness and weigh (nominally, each mm of oil was 2.25 L [0.6 gallons], or 1.9 kg [4.2 lbs]) and add to burn ring using a spill plate.

3. After the oil had been added to the ring, and the ring positioned in the center of the wave tank, the wind speed was recorded from the weather station. The temperature of the air and water were also recorded.
4. First, ignition was attempted with a propane torch taped to a pole. If this failed, a baggie containing 4 fluid ounces of gelled gasoline was used to ignite the slick. The gelled fuel bag was placed on the oil then ignited with the propane torch. If this failed to ignite the slick, then the following sequence was used:
    a) Two pre-weighed gelled-gasoline igniters,
    b) Four pre-weighed gelled-gasoline igniters.

    For most of the tests involving waves four gelled gas igniters were used.
5. If desired, once the flame has spread to cover at least 50% of the surface of the slick, the waves will be turned on at specified settings (Amplitude potentiometer at 0.8, Frequency potentiometer at 6).
6. For each burn test the following was recorded:
    - Preheat time - the time from lighting the igniters until flames begin to spread away from the burning gelled fuel (measured in increments of the percent of the total ring area covered);
    - Ignition time - the time from firing the igniters until the flames cover the entire ring surface;
    - Vigorous, or intense, burn time - the time for the water beneath the slick to boil causing higher flames, greater flame radiation, oil droplets to be sprayed up from the slick and/or a hissing sound;
    - Extinction time - the time from firing the igniters until the flames completely extinguish (measured in increments of the percent of the total ring area covered).
7. Each burn was videotaped and photographed from an elevated platform and observed visually from the top of the stairs up to the deck of the tank.
8. After each burn, the residue was allowed to cool. Once cooled, the residue was collected with a steel-mesh covered pitchfork and pre-weighed sorbent sheets and placed in pre-weighed plastic bag(s). If the residue could not be completely recovered without some ice, the bag containing the ice and residue was warmed for several hours to melt the ice. The water was then decanted and the residue reweighed.
9. Once the residue (and ice) was recovered, the ice and oil for the next burn was added to the ring and the process repeated.

The burn efficiency and burn rate were calculated for each test using equations (1) and (2), respectively. Burn efficiency is the ratio of the mass of oil burned to the initial oil mass. Oil burn rate is a measure of the decrease in the oil thickness over the period of the burn, from the time when 50% of the final burn area is aflame (ignition half-time) to the time when the flame area has decreased by 50% (extinction half-time).

$$\text{Burn Efficiency (mass \%)} = \frac{\text{(Initial Oil Mass - Residue Mass)}}{\text{Initial Oil Mass}} \times 100 \qquad \textbf{(1)}$$

$$\text{Oil Burn Rate (mm/min)} = \frac{\text{((Initial Oil Mass/Oil Density)–(Residue Mass/Residue Density))}}{\text{(Burn Area)(Extinction Half-Time - Ignition Half-Time)}} \qquad \textbf{(2)}$$

The residue was assumed to be water free (which was generally the case if the slick was successfully burned) and was assumed to have a density of 1 g/cm^3. If the slick barely ignited, or burned poorly, or the residue contained some water (as ice) these assumptions would be invalid. Negative values of burn efficiency and oil burn rate were obtained for some of the inefficient burns if the residue mass was greater than the initial oil mass. Any negative burn efficiency or oil burn rate was assumed to be zero. This situation was indicative of a poor burn.

The major sources of error in the mid-scale burns were:

- The accuracy of the scale used to weigh the oil added to the test ring (200 grams in about 6800, or about 2.9%);
- The residue recovery procedure: the recovery using hand tools and sorbent was not likely 100%, but it was not possible to estimate the error involved. Some residues that were not melted and decanted may have contained some ice. The same scale was used to weigh the residue, with an accuracy of 200 g in as little as 2000g, or up to 10%.
- Calculating burn rates using the time for the flame to expand and contract to cover half of the fully involved burn area.

All things considered, the burn rates and removal efficiencies determined should be accurate to within 15%.

2.2 Mid-scale Burn Test Results

Complete test results from the mid-scale burns at Prudhoe Bay may be found in the report (SL Ross and DF Dickins, 2003). The first experiment was intended to be a Minimum Ignitable Thickness test; however, it proved to be impossible to evenly spread a very thin (0.5 mm) layer of oil over the ice surface in the cold, and further attempts at these tests were abandoned. The test plan was altered to incorporate open water tests for all the candidate oils. In total, 42 burns were conducted, including the one Minimum Ignitable Thickness attempt. Figure 3 shows the burn ring filled with a typical batch of fresh brash ice, Figure 4 shows the subsequent burn and Figure 5 shows the ice after the residue has been recovered. Figures 6 through 8 show the same sequence for frazil, or slush, ice. Figure 9 shows a typical open water burn.

2.2.1 Thin Oil Removal Rate

Alaska North Slope. Figure 10 shows the burn rate data obtained for the fresh ANS crude (recall that no evaporated samples of ANS were tested). The fresh

Figure 3: Brash ice in ring prior to oil addition.

Figure 4: View of test burn on the brash ice.

Figure 5: Brash ice after burn and residue recovery.

Figure 6: Fresh frazil, or slush, ice in ring prior to adding oil.

Figure 7: Test burn on frazil, or slush, ice.

Figure 8: Recovering residue from burn ring after burn on frazil, or slush, ice.

oil in calm conditions on open water had a burn rate of 1.6 mm/min, as expected. The burn rate on frazil, or slush, ice was only slightly less, at 1.2 mm/min. The burn rate in calm conditions on brash ice was considerable lower, at 0.3 mm/min. The open water burn rate in waves, at 1.5 mm/min, was slightly lower than the removal rate in calm conditions. The burn rate on frazil ice in waves was about 0.8 mm/min and the rate on brash ice in waves was 0.2 mm/min.

Endicott. Figure 11 shows the oil removal rates measured for the Endicott crude. The rates for the open water burns are in the range of what would be expected for 3-mm, 1.7-m diameter crude burns, about 1.7 mm/min (Buist et al., 1994). The tests on frazil ice were conducted in windy conditions. The fresh oil was burned in 15 to 19 knot winds, the 13.9% evaporated burn took place in 16 to 22 knot winds and the 9.4% evaporated burn took place in 17 to 23 knot winds, a wind speed close to the limits of combustion (Buist et al., 1994). Under these high winds, the flames only spread directly downwind from the igniters. Ignoring the 9.4% evaporated burn, since it took place in marginal wind conditions, the burns on frazil, or slush, ice resulted in removal rates about ½ those measured for the open water burns, the same as for the lab-scale burns with this oil. The burns on brash ice were very slow, at about ¼ of the open water rate, even though they took place in much lower winds. These results are consistent with those reported by Brown and Goodman (1986 and 1987) who reported burn rates in brash ice (represented by ice cubes) at about 20% the open water burn rate. In the lab-scale burns the tests on brash ice resulted in burn rates about ½ of the open water rate. The proportionately lower mid-scale results are quite likely related to the proportionally much rougher interface presented by the mid-scale brash ice than in the lab tests. This increased roughness would both inhibit flame spreading and further increase heat transfer to the substrate. The burn rate (0.2 mm/min) measured for the 9.4% evaporated Endicott in waves was unusually low. Even though previous experiments (SL Ross, 1998 - in this tank) have shown that waves can cause reductions in burn rates for thinner slicks, the wave steepness (height/wavelength) required to cause this degree of burn rate reduction is about 0.06, considerably higher than the maximum steepness that the waves in this experiment could achieve (0.016). Perhaps the combination of cold water, weathered oil, a very thin slick, and possible emulsification combined to result in this low burn rate.

The burn rates in brash ice in waves were also very low, though not unexpectedly. The burn test with fresh oil on brash ice in waves yielded a burn rate about ½ that of the same burn in calm conditions. This was the same trend as in the lab tests. The burn test with the 13.9% evaporated Endicott on brash ice in waves was faulty in that the wave generator was inadvertently not started until well after the flames had reached 50% coverage after ignition. This would have raised the calculated burn rate.

Northstar. Figure 12 shows the removal rates obtained for the Northstar test burns in the wave tank. The open water burn in calm conditions with fresh oil resulted in an high burn rate (2.3 mm/min), but fresh Northstar is a very light crude with a large volatiles content, and would be expected to have a higher burn rate than the other, heavier crudes. The burn rates obtained for the evaporated Northstar were more in line with the other crudes. The lab-scale tests with Northstar did not show

Figure 9: Typical open water burn test.

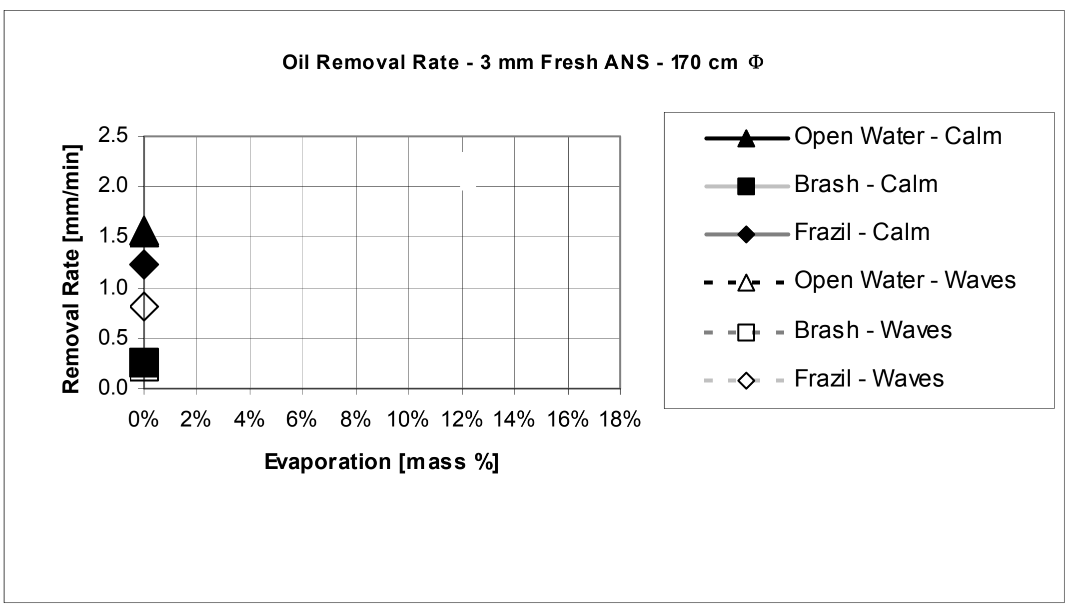

Figure 10: Oil removal rate results for fresh ANS test burns.

this trend of declining burn rate with increased evaporation. The quiescent burns on frazil, or slush, ice had burn rates of about 50% of the open water rates, and burn rates on brash ice were about 25% of the open water rates.

The waves also reduced burn rates. Comparison of the burns on open water with and without waves showed that the waves reduced removal rates to about 66% of the calm rate, presumably due to enhanced heat transfer through the slick induced by the wave action. The burns on frazil ice in waves had about the same removal rates as in calm conditions, because the frazil ice moved on the waves as one mass, and did not agitate the oil. Burn rates on brash ice in waves were even lower than those on brash ice in calm conditions because the brash ice pieces could move independently and increase heat transfer through the slick.

Pt. McIntyre. The results for the fresh Pt. McIntyre crude are shown on Figure 13. Rates on open water were almost the same in waves and calm conditions at 1.5 and 1.3 mm/min respectively. The burn rate in calm conditions on frazil ice was 0.4 mm/min and on brash ice was 0.3 mm/min. In waves on brash ice the burn rate was 0.2 mm/min.

2.2.2 Thin Oil Removal Efficiency

Alaska North Slope. Figure 14 gives the removal efficiency results for the fresh ANS crude. The fresh ANS on open water in both calm and wave conditions had a removal efficiency of about 75% (a residue of 0.75 mm). The burns on ice in calm conditions resulted in removal efficiencies of 60% (residue = 1.2 mm), and the burns on ice in waves had efficiencies of about 45% (residue thickness of 1.8 mm).

Endicott. Figure 15 shows the oil removal efficiencies measured for the Endicott burns in the wave tank at Prudhoe Bay. The results for the open water burns in calm conditions are as expected. Theoretically, using the 1-mm of reside remaining "rule-of-thumb", these burns should have removal efficiencies of 67%. The absence of any significant winds (i.e., no wind herding effect) means that the slightly higher removal efficiencies obtained (77 and 79%) were as a result of the slick burning down to 0.67 mm. These slightly higher removal efficiencies were also obtained in the lab-scale tests with Endicott crude on calm, open water. Evaporation of the oil did not appear to have an effect on the burn efficiency, unlike during the lab-scale tests where it decreased the burn efficiency; however the highest degree of evaporation used in the mid-scale tests (13.9%) was not as high as that used in the lab-scale (17.4%).

The burns on frazil, or slush, ice resulted in slightly reduced burn efficiencies (recall that the burn with the 9.4% evaporated Endicott on frazil ice in calm conditions was carried out in very windy conditions, near the limits). The burn efficiencies obtained were in the 60% range, indicating about 1.2 mm of residue remaining, about 1.8 times that from the equivalent open water burns. The burns on brash ice in calm conditions resulted in burn efficiencies of about 50%, equivalent to a residue of about 1.5 mm. The one open water burn in waves, with the 9.4% evaporated Endicott resulted in an inexplicably low burn efficiency. The two burns with Endicott crude on brash ice resulted in low removal efficiencies, on the order of 20%, equivalent to residues of about 2.5 mm.

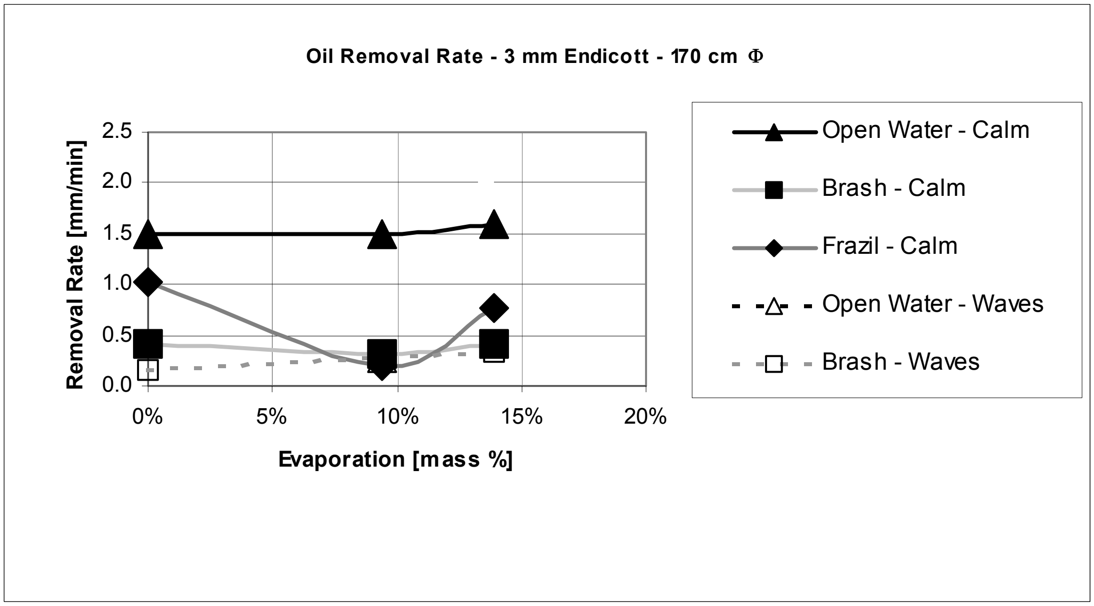

Figure 11: Oil removal rate results for Endicott test burns.

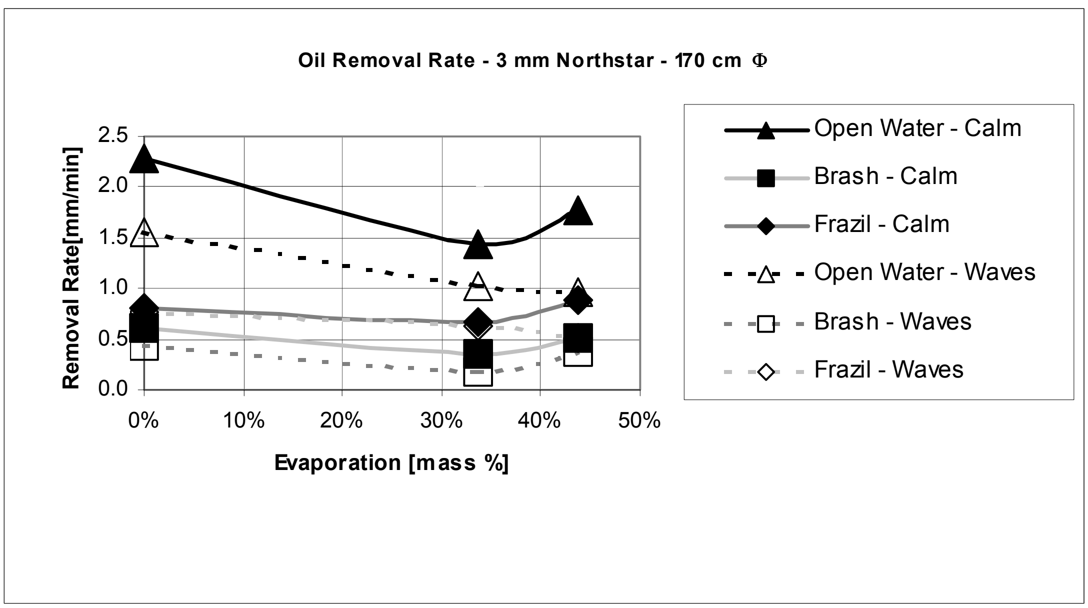

Figure 12: Oil removal rate results for Northstar test burns.

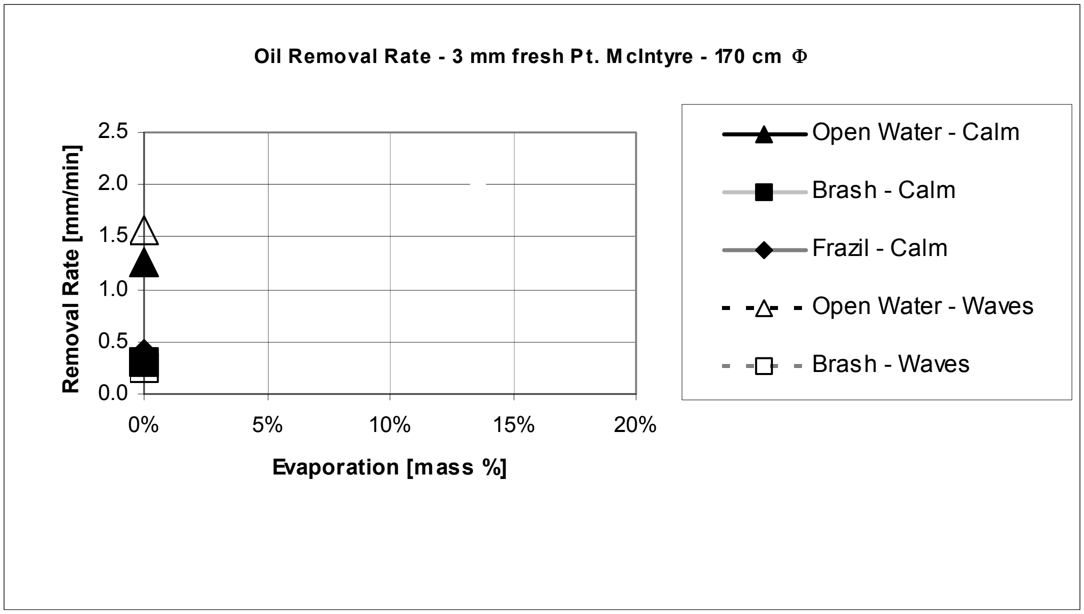

Figure 13: Oil removal rate results for fresh Pt. McIntyre test burns.

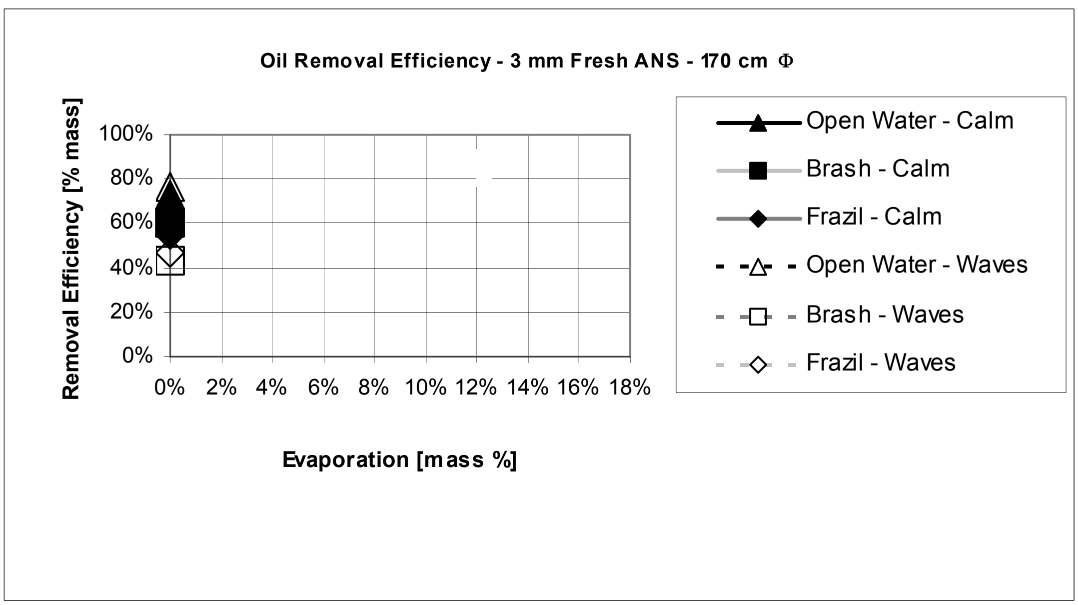

Figure 14: Mid-scale burn efficiency results for fresh ANS crude.

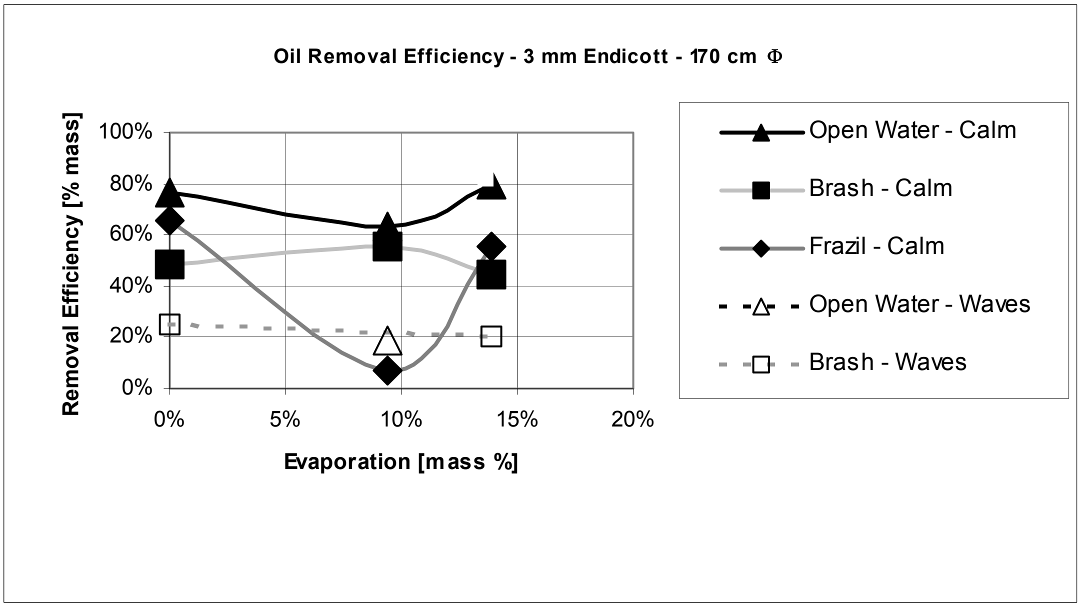

Figure 15: Mid-scale burn efficiency results for Endicott crude.

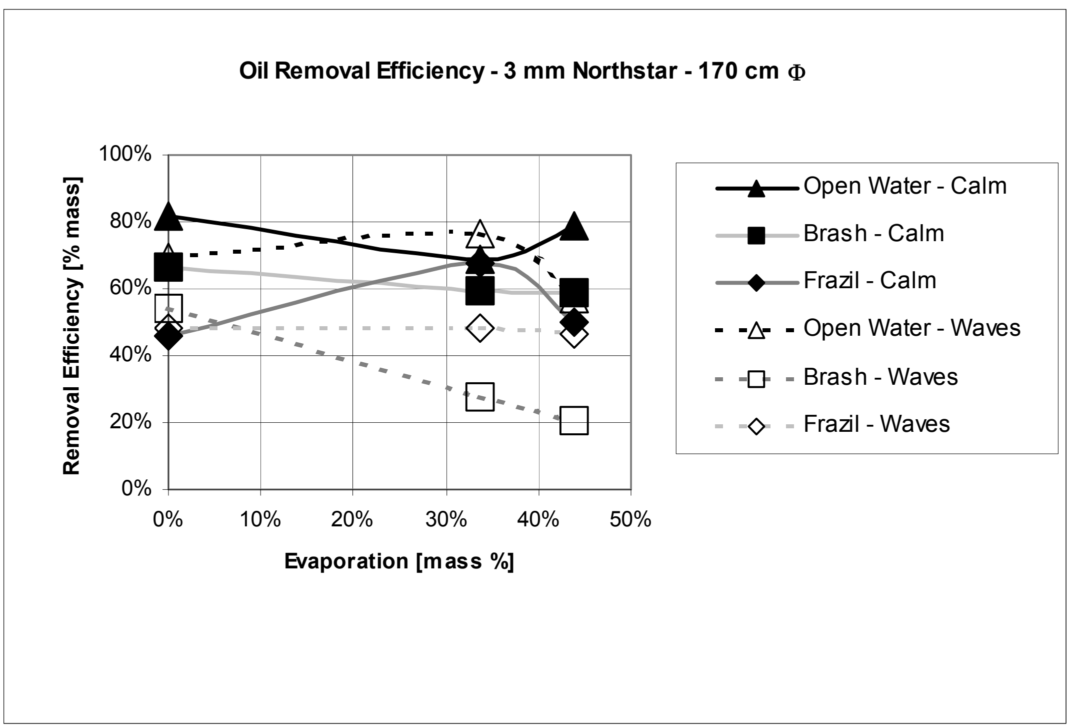

Figure 16: Mid-scale burn efficiency results for Northstar crude.

Northstar. Figure 16 shows the burn efficiencies achieved with the Northstar crude. The burn efficiencies on calm open water were again slightly higher than expected (70 to 82%), indicating that the residue remaining was on the order of 0.67 mm. This was similar to the results obtained in the lab-scale burns. The burns in calm conditions on frazil ice resulted in lower burn efficiencies. The fresh Northstar on frazil ice resulted in an unexpectedly low 46% removal, but this was the first burn test conducted and the residue was not melted to remove recovered slush. In subsequent burns, this was done. The residue from the Northstar burns was essentially gelled, and could easily have incorporated large amounts of slush. In the burn test on frazil ice in calm conditions with the 43.8% evaporated Northstar, the flames only spread to cover 75% of the slick area, explaining the lower than expected efficiency obtained for this test. The results for the burn tests in calm conditions on brash ice had removal efficiencies in the range of 60%, equivalent to a residue thickness of 1.2 mm.

Removal efficiencies for the Northstar tests on open water in waves were slightly reduced over those in calm conditions, being equivalent to approximately a 1 mm residue, as would be expected. The burn efficiencies for Northstar on frazil ice in waves were further reduced to around 50%, equivalent to a residue of 1.5 mm and similar to the trend observed in the lab-scale tests. The burn of fresh Northstar on brash ice in waves yielded an unusually high removal efficiency (54%), and a review of the experimental data does not provide an explanation. The burn efficiencies for the weathered Northstar on brash ice in waves resulted in removal efficiencies in the 20 to 25% range, equivalent to a residue of 2 to 2.5 mm, again similar to the lab-scale results.

Pt. McIntyre. Figure 17 shows the results for the fresh Pt. McIntyre crude. As with the ANS tests, the burns on open water in calm and wave conditions had nearly identical results at 75% removal, or a residue of 0.75 mm. The burns on brash ice (in both calm and wave conditions) resulted in removal efficiencies of about 45%, or a residue of 1.6 mm. The low burn efficiency obtained for the test on frazil, or slush, ice is not explicable. The videotape of the burn was reviewed and it appears to be a reasonably efficient burn, with relatively high flames over the entire ring area for several minutes, and looks like the burn on brash ice in calm conditions. Either the residue recovery, or the residue weighing must have been in error. This data point should probably be discounted as erroneous.

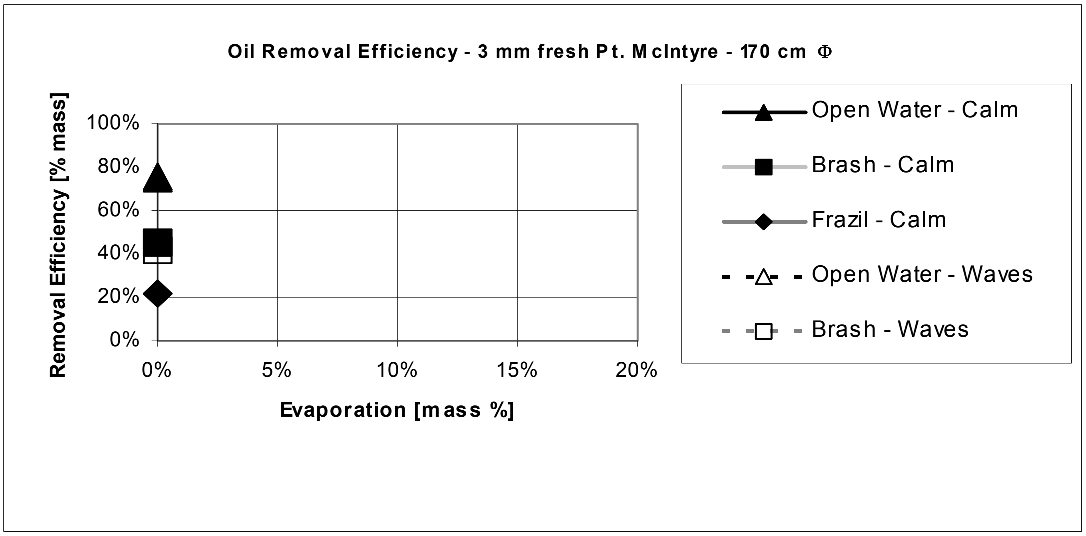

Figure 17: Mid-scale burn efficiency results for Pt. McIntyre crude.

3 Rules-of-thumb

The following section distills the lab-scale and mid-scale results down to simplified "rules-of-thumb" for the burning of thin oil slicks *in situ* on brash or frazil ice.

3.1 Minimum Ignitable Thickness

Based on the results of the lab-scale tests, (not given in this paper- see SL Ross and DF Dickins, 2003), the "rules-of-thumb" for minimum ignitable thickness for oil slicks on brash or frazil ice appear to be:

- The minimum ignitable thickness for fresh crude on frazil ice or small brash ice pieces is up to double that on open water, or about 1 to 2 mm.
- The minimum ignitable thickness for evaporated crude oil on frazil ice or small brash ice pieces can be higher than on open water, but is still within the range quoted for weathered crude on water, about 3 mm, if ignited with gelled-gasoline igniters.

3.2 Oil Removal Rate

Table 2 shows the combined results of all the lab-scale and mid-scale rate and efficiency tests. Also shown are the "rules-of-thumb" for open water, and the averages of all the data points in a given test series. From this, it is proposed that the "rule-of-thumb" for oil removal rate for burning thin slicks on brash or frazil ice be:

- For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil ice and halved again on rougher, brash ice (at least for the larger, mid-scale burns where the brash ice was more realistic). Wave action slightly reduces the burn rate on open water, but the halving rule seems to apply in waves as well.

Table 2: Summary of all 3-mm burn test results.

Oil	Evaporation (mass %)	Oil Removal Rate											
		Calm Conditions						Waves					
		Open Water		Frazil/Slush Ice		Brash Ice		Open Water		Frazil/Slush Ice		Brash Ice	
		lab-scale	mid-scale	lab-scale	mid-scale	lab-scale	mid-scale	lab-scale	mid-scale	lab-scale	mid-scale	lab-scale	mid-scale
ANS	0	1.3	1.6	0.6	1.3	0.5	0.3	0.9	1.5	0.4	0.8	0.7	0.3
	10.3	1.2		0.7		0.6		0.9		0.5		0.3	
	16.8	1.5		0.6		0.5		1.1		0.5		0.5	
Endicott	0	1.3	1.5	0.7	1	0.7	0.4	0.7		0.3		0.5	0.2
	9.1	1.1	1.5	0.7		0.5	0.4	0.8	0.3	0.4		0.7	
	13.9		1.6		0.8		0.4						
	17.4	0.9		0.3		0.3		0.4				0.3	0.3
Northstar	0	1.2	2.2	0.4	0.8	0.5	0.6	0.8	1.5	0.8	0.8	0.4	0.4
	33.8	1.2	1.5	0.7	0.7	0.4	0.4	0.7	1	0.2	0.6	0.7	0.2
	43.8	1.2	1.7	0.4	0.9	0.5	0.5	0.5	1	0.6	0.4	0.5	0.3
Pt. McIntyre	0	1.1	1.2	0.5		0.5	0.3	1.1	1.6	0.6		0.5	0.3
	9.1	0.8		0.6		0.5		0.9		0.4		0.7	
	18.2	1.1		0.8		0.2		1.1		0.5		0.1	
Rule of Thumb		1.1	1.8										
Average		1.2	1.6	0.6	0.9	0.5	0.4	0.8	1.2	0.5	0.7	0.5	0.3
		Oil Removal Efficiency											
ANS	0	0.66	0.75	0.3	0.6	0.35	0.6	0.55	0.75	0.35	0.45	0.2	0.4
	10.3	0.75		0.6		0.5		0.5		0.35		0.05	
	16.8	0.75		0.6		0.5		0.6		0.45		0.2	
Endicott	0	0.85	0.75	0.7	0.65	0.75	0.5	0.5		0.2		0.35	0.25
	9.1	0.75	0.65			0.6	0.55	0.55		0.2		0.45	
	13.9		0.8		0.55		0.45						0.2
	17.4	0.65		0.1		0.25		0.2		0.2		0.05	
Northstar	0	0.75	0.8	0.55	0.45	0.5	0.65	0.6	0.7	0.55	0.5	0.4	0.55
	33.8	0.75	0.7	0.45	0.65	0.3	0.6	0.4	0.75	0.3	0.5	0.3	0.3
	43.8	0.8	0.8	0.45	0.45	0.45	0.6	0.5	0.55	0.4	0.45	0.1	0.2
Pt. McIntyre	0	0.6	0.75			0.2	0.45	0.6	0.75	0.35		0.3	0.4
	9.1	0.55		0.55				0.55		0.3		0.2	
	18.2	0.55		0.45		0.15		0.55		0.2		0	
Rule of Thumb		0.67	0.67										
Average		0.70	0.75	0.48	0.56	0.41	0.55	0.51	0.70	0.32	0.48	0.22	0.33
		Oil Residue Remaining											
ANS	0	1.0	0.8	2.1	1.2	2.0	1.2	1.4	0.8	2.0	1.7	2.4	1.8
	10.3	0.8		1.2		1.5		1.5		2.0		2.9	
	16.8	0.8		1.2		1.5		1.2		1.7		2.4	
Endicott	0	0.5	0.8	0.9	1.1	0.8	1.5	1.5		2.4		2.0	2.3
	9.1	0.8	1.1			1.2	1.4	1.4		2.4		1.7	
	13.9		0.6		1.4		1.7						2.4
	17.4	1.1		2.7		2.3		2.4		2.4		2.9	
Northstar	0	0.8	0.6	1.4	1.7	1.5	1.1	1.2	0.9	1.4	1.5	1.8	1.4
	33.8	0.8	0.9	1.7	1.1	2.1	1.2	1.8	0.8	2.1	1.5	2.1	2.1
	43.8	0.6	0.6	1.7	1.7	1.7	1.2	1.5	1.4	1.8	1.7	2.7	2.4
Pt. McIntyre	0	1.2	0.8			2.4	1.7	1.2	0.8	2.0		2.1	1.8
	9.1	1.4		1.4				1.4		2.1		2.4	
	18.2	1.4		1.7		2.6		1.4		2.4		3.0	
Rule of Thumb		1	1										
Average		0.9	0.8	1.6	1.3	1.8	1.4	1.5	0.9	2.0	1.6	2.4	2.0

3.3 Residue Thickness Remaining

The normal “rule-of-thumb” for burns initially less than 20 to 40 mm thick on open water is that 1 mm of residue remains after the burn extinguishes naturally. The following is proposed for thin slicks burned on brash or frazil ice:

- The residue remaining on pack ice in calm conditions is about 1.5 mm. The residue remaining on brash or frazil ice in waves is slightly greater than in calm conditions, at about 2 mm.

The combination of the minimum ignitable thickness rule of 3 mm for weathered oil, and the residue thickness rules infers that 3-mm slicks on brash or frazil ice can be burned *in situ* with removal efficiencies on the order of 50% in calm conditions and 33% in wave conditions. The actual thickness of an oil slick in ice conditions from a hypothetical blowout or sub-sea leak will, of course, depend on the flow rate of oil from the well or pipeline, the initial spreading of the oil droplets before they impact the ice and the rate at which the ice is drifting past the site. Whether the removal efficiencies predicted by the rules-of-thumb offer a net environmental benefit for a specific scenario is something that must be decided on a case-by-case basis.

4 Acknowledgements

The project described in this report was funded by the U.S. Minerals Management Service (MMS) through Contract 1435-01-02-CT-85184. ExxonMobil also provided funding for the work. The authors would like to acknowledge the contributions of the staff of Alaska Clean Seas.

5 References

Bech, C., P. Sveum, and I. Buist, “The Effect of Wind, Ice and Waves on the *In Situ* Burning of Emulsions and Aged Oils”, *Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar*, June 7-9, Calgary, Alberta, Environment Canada, Ottawa, Ontario, pp 735-748, 1993.

Brown, H.M. and R.H. Goodman, “*In Situ* Burning of Oil in Ice Leads”, *Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar*, June 10-12, Edmonton, Alberta, Environment Canada, Ottawa, Ontario, pp 245-256, 1986.

Brown, H.M. and R.H. Goodman, *In Situ Burning of Oil in Experimental Ice Leads*, Environmental Studies Revolving Funds Report 064, National Energy Board, Calgary, 1986.

Bronson, M., E. Thompson, FD. McAdams and J. McHale, “Ice Effects on a Barge-Based Oil Spill Response Systems in The Alaskan Beaufort Sea*” Proceedings of the Twenty-fifth Arctic and Marine Oilspill Program Technical Seminar*, pp1253-1268, 2002.

Buist, I.A. and D.F. Dickins, “Experimental Spills of Crude Oil in Pack Ice”, *Proceedings of the 1987 Oil Spill Conference*, April 6-9, Baltimore, Maryland, American Petroleum Institute, Washington, D.C., pp 373-382, 1987.

Buist, I., D., Dickins, D., Devitis, A. Guarino, and K. Nolan, "Technical Aspects of SkimmerTesting in Brash Ice at Ohmsett", *Proceedings 25th Arctic and Marine Oilspill Program Technical Seminar*, pp. 1225-1252,Calgary, 2002.

Buist, I., S. Ross, K. Trudel, E. Taylor, T. Campbell, P. Westphal, M. Myers, G. Ronzio, A. Allen and A. Nordvik, *The Science, Technology and Effects of Controlled Burning of Oil Spills at Sea*, Marine Spill Response Corp, Washington, DC, MSRC Technical Report Series 94-013, 382 p, 1994.

Guénette, C.C. and R. Wighus, "*In Situ* Burning of Crude Oil and Emulsions in Broken Ice", *Proceedings of the 19th AMOP Technical Seminar,* Calgary, AB, June 12 -14, 1996, Environment Canada, pp 895 - 906, 1996.

Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company, U.S.A., Amoco Production Company, *Oil Spill Response in the Arctic - Part 2: Field Demonstrations in Broken Ice,* Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company, U.S.A., Amoco Production Company, Anchorage, Alaska, August 1983.

Singaas, I., P. Brandvik, P. Daling, M. Reed and A. Lewis, "Fate and Behaviour of Oils Spilled in the Presence of Ice-A Comparison of The Results from Recent Laboratory, Meso-Scale Flume and Field Tests", *Proc 17th AMOP Technical Seminar*, Environment Canada, Ottawa, pp 355-370, 1994.

S.L. Ross Environmental Research Ltd, *Evaluation of Industry's Oil Spill Countermeasures Capability in Broken Ice Conditions in the Alaskan Beaufort Sea,* report by S.L. Ross Environmental Research Limited for Alaska Department of Environmental Conservation, September 1983.

S.L. Ross Environmental Research Ltd, *The Efficacy of In Situ Burning for Alaskan Risk Oils.* Report to Alaska Dept. of Environmental Conservation and Alaska Clean Seas, June 1998, 114 p, 1998.

S.L. Ross Environmental Research Ltd. and DF Dickins Associates Ltd, *Field Research Spills to Investigate the Physical and Chemical Fate of Oil in Pack Ice,* Environmental Studies Revolving Funds Report No. 062, 95 p, 1987.

S.L. Ross Environmental Research Ltd. and DF Dickins Associates Ltd, *Tests to Determine the Limits to In Situ Burning of Thin Oil Slicks in Broken Ice*, Report to MMS and ExxonMobil Upstream Research, In press 2003.

Smith, N.K. and A. Diaz, "In-Place Burning of Crude Oils in Broken Ice", *Proceedings of the 1987 Oil Spill Conference*, April 6-9, Baltimore, Maryland, American Petroleum Institute, Washington, D.C., pp 383-387, 1987.

World Meteorological Organization, *WMO Sea Ice Nomenclature*, Geneva, 147 p, 1970.