IN-PLACE BURNING OF PRUDHOE BAY OIL IN BROKEN ICE[1]

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ABSTRACT: *Small-scale and large-scale experiments were performed at the U.S. Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility to explore the range of conditions in which oil slicks of Prudhoe Bay crude can be burned in broken ice and to determine the efficiencies of such burns.*

In laboratory experiments, the minimum slick thickness supporting combustion was found to be 2.5 mm on brackish water at temperatures from 2° to 6.5° C. Minimum slick thickness to support combustion on brackish water at temperatures from 18° to 22° C was found to be 2 mm. The wicking agent was found to vary in effectiveness as a burn-enhancing agent. Decreases in burn efficiencies and burn rates were observed with decreasing water temperatures.

Four burn tests were performed in the OHMSETT tank with varying ice cover, volume of oil, and wave conditions. The brackish tank water ranged from 3.8° to 7.7° C during testing. One test was performed using lightly weathered (topped) Prudhoe Bay crude oil. Burn effectiveness ranged from 85 to 95 percent by mass. Flame spread rates ranged from 1.3 to 2.4 m/min based on discrete measurements. The slicks were ignited along the downwind edge, and in all tests the flame was not significantly inhibited by the ice from spreading throughout the test area.

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In-place burning of Prudhoe Bay crude oil slicks was evaluated at the U.S. Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) in Leonardo, New Jersey, during February 1984. These tests were catalyzed by demonstrations performed in an onshore pit near Prudhoe Bay, Alaska, in 1983.[7] Fifty-five to 85 percent of the Prudhoe Bay crude oil distributed among scattered ice was burned off in two burn demonstrations. To provide additional data on burn efficiencies and explore the conditions in which in-place burning of oil slicks can be achieved, a series of laboratory and tank tests were performed at OHMSETT. Ice cover, wave conditions, slick thickness, and degree of oil weathering were varied in the tests. Preliminary laboratory experiments were performed to anticipate larger scale burn behavior and to establish the minimum conditions supporting combustion. Burning effectiveness was quantified as percentage burned.

Minimum slick thickness supporting combustion was determined from the labaratory tests and certain trends in burn behavior. Burning efficiencies were determined for each of the tank tests, and these data were compared to values reported from previous burn tests.[3,5,6,7,9]

Laboratory testing

Summary plan. Burn behavior was investigated and the test oil was characterized in the OHMSETT laboratory prior to the tank tests. The burn behavior tests determined minimum slick thickness needed to support combustion, burn rates, and the increase in burn efficiency from adding a fumed silica wicking agent. A small aluminum ring (approximately 60 mm in diameter) enclosed the oil slick, which ranged from 2 to 10.5 mm thick for these tests. The tests were performed on cold (< 6.5° C) and room temperature (20° to 24° C) saline tank water. The Prudhoe Bay crude oil was characterized by a series of ASTM tests.

Minimum slick thickness supporting combustion. The minimum slick thickness supporting combustion was determined in a rectangular aluminum pan approximately 26 cm × 10 cm deep filled with approximately 4 L of brackish tank water (salt content 20 parts per thousand) and ice (freshwater) if called for. The small aluminum ring previously described was supported on three aluminum legs in the center of the rectangular pan, and oil was distributed from a syringe into the small ring until a continuous slick formed. Slick thickness was measured using a steel wire about 2 mm in diameter in a "U" shape. The wire was inserted into the water and raised slowly so that one leg of the "U" penetrated the center of the slick. The length of the residual oil film adhering to the wire was then measured. Minimum slick thickness needed to support combustion on cold water was found to be 2.5 mm. Minimum slick thickness needed to support combustion on room temperature water was determined to be 2 mm.

Burn rates. Burn rates in the laboratory tests were quantified by the decrease in slick thickness and the total burn time. Total burn time was recorded as the time from ignition until natural extinction. Burning oil on saline water from 18° to 22° C yielded burn rates from 0.5 to 0.6 mm/min. On water at 2° to 6.5° C, burn rates ranged from 0.2 to 0.4 mm/min, with the exception of the minimum slick thickness test. Room temperature during those tests ranged from 20° to 24° C. Water temperatures are given in Table 1 along with other laboratory test data and results. Water temperature was measured using a mercury thermometer with the bulb placed 3 to 5 cm beneath the center of the test ring. Water temperature increased less than 2° C during each test unless noted in Table 1.

Wicking agent. Laboratory tests were performed to determine the added burn effectiveness from adding a fumed silica wicking agent to a crude oil slick. Oil was distributed on the water surface with a syringe. CAB-O-SIL™ wicking agent was spooned onto the oil surface and allowed to absorb the oil for approximately 10 min. The wicking agent was added in a mass ratio of 1 : 10 wicking agent to oil. Residue formed balls of oil residue and wicking agent in the cold water tests, so slick thickness measurements were not possible. How-

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ever, the volume of residue was visually estimated as greater in this test than in the previous test with the same initial slick thickness but no wicking agent. In the warm water tests, the wicking agent burn residue amounted to 15 percent of the original oil volume, representing an overall burning efficiency of 85 percent by volume. The results of these tests are also given in Table 1.

Percentage of oil consumed by burning. In addition to the minimum slick thickness and burn rates originally sought, percentage burned was easily quantified. Percentage burned by volume was determined for several of the test runs by measuring initial slick thickness and final slick thickness and using this data in the following equation:

$$\frac{d_i - d_f}{d_i} \times 100 \text{ percent} = \text{percentage burned by volume}$$

Where:

d_i = initial slick thickness
d_f = final slick thickness

Percentage burned *by volume* ranged from 60 to 70 percent on 18° to 22° C brackish water and from 40 to 55 percent on 2° to 6.5° C water, (Table 1) with the exception of the minimum slick thickness and wicking agent tests. Note that several of the final slick thicknesses and thus burn efficiencies and burn rates are not given. This is because the method of slick thickness measurement was developed after several tests were performed.

ASTM standard tests. The Prudhoe Bay crude oil used in the tests was characterized by specific gravity, viscosity, flash point, surface tension, interfacial tension, water content, and gas chromatography.

Table 1. Laboratory burn test data, Prudhoe Bay oil

Oil volume (ml)	Initial slick thickness (mm)	Burn time (min:s)	Percentage burned by volume	Burn rate (mm/min)	Comments
At water temperatures from 18° to 22° C					
4.59	2.0	1:07	ND[1]	ND	Minimum slick thickness
13.77	5.0	4:29	ND	ND	
13.77	5.0	5:35	60	0.6	
25.21	9.0	9:41	60	0.6	
25.21	8.0	11:00	70	0.5	Small quantity of oil leaked from ring
25.74	10.0	11:08	ND	ND	Wicking agent test
At water temperatures from 2° to 6.5° C					
12.50	3.0	4:34	55	0.4	Weathered oil test
8.58	2.5	1:07	ND	ND	Minimum slick thickness
7.37	2.5	0:12	15	2	Minimum slick thickness repeat
13.74	5.0	3:40	ND	ND	
13.74	5.0	4:50	ND	ND	
9.15	2.5	2:55	40	0.4	
9.70	2.5	3:00	40	0.3	
13.74	4.0	5:14	30	0.2	
25.74	10.5	11:29	50	0.2	
25.70	10.5	23:47	ND	ND	Wicking agent test

1. Not determined

Specific gravity was determined with hydrometers as specified by ASTM D1298-67. Viscosity was measured using a Brookfield Model LVT viscometer at room temperature and an elevated temperature. Viscometer measurements were converted to centistokes using the relationship expressed in ASTM D2161-74, Section 6, and plotted on ASTM D341 viscosity temperature charts for extrapolation to ambient conditions. Flash point was determined using a Fisher/Tag closed cup-tester as described by ASTM D56-70. Surface tension and interfacial tension with tank water were measured at room temperature (22.5° C) using a Fisher Scientific Model 21 Surface Tensiomat. Percent water and bottom solids were determined as specified in ASTM D1796-75. The results of these analyses are given in Table 2. Gas chromatograms were performed on both Prudhoe Bay fresh oil and weathered (topped) oil samples. The differences between the fresh and weathered oil chromatograms were a complete loss of the C_3 peak and a 30 percent drop in the C_7 peak height for the weathered oil.

Oil weathering. For the weathered oil tank tests and precursor laboratory work, 0.3 m^3 of Prudhoe Bay crude oil was topped in a 1-m^3 capacity rectangular tank 0.6 m × 1.5 m × 1.1 m deep. With an oil depth of 0.34 m, an air sparger 5.6 cm in diameter and 58 cm long was placed in the tank below the oil surface and operated for 28 h at an air flow rate of approximately 11 ft^3/min (cfm). Ambient temperatures averaged 4° C, peaking at 10° C. This resulted in an expected change in physical properties. The flash point increased from < 1° to 27° C, and specific gravity increased from 0.891 to 0.901 at room temperature.

Tank testing

Summary of the test plan. Four tests were performed in the OHMSETT tank to explore the conditions under which a crude oil slick can be burned in a broken ice field and to determine the effectiveness of such burns. Burn tests were performed in the OHMSETT tank within a 46.5-m^2 boomed area. Average ice cover in the center of the test area was varied from 45 to 60 percent, and average oil slick thicknesses were varied from 2 to 4 mm. Fresh and lightly weathered Prudhoe Bay crude oils were burned. One of the four tests demonstrated the effects of a regular (evenly propagating or breaking) wave on burn behavior. Burn efficiency was quantified by percentage mass loss. Burn times and flame spreading rates were also determined. (Refer to the section "Calculations" below for details on measuring flame spreading rate, ice coverage, and oil slick thickness.)

Testing arrangements. A timber boom was fabricated on site to delineate the test area as a rectangle 6.1 m × 7.6 m. Ice blocks, approximately 0.53 m × 1.0 m × 0.25 m, were positioned in a predetermined grid pattern within the boom for each test. The ice blocks were held stationary by a cable system attached to the boom. Oil was distributed from the main bridge through a 2.5-cm-diameter hose. A color video camera provided an overhead view of the test area from the end of a crane boom approximately 15 m above the test area (Figure 1).

Data gathering. Percentage ice cover, average slick thickness, and average channel width were determined using the overhead video recording displayed on a 12-in. color TV monitor screen in conjunction with other measurements. Air temperature, water temperature,

Table 2. Results of lab analysis of test oil

Sample	Specific gravity	Viscosity (cs)	Temperature (° C)	H_2O (Percent)	Tension (dynes/cm)	Interfacial tension (dynes/cm)	Flash point (° C)
Fresh Oil	0.890	30.3	21.6	0.02	25.8	29.7	<1
Sample #1	0.897[1]	62.0[1]	6.2				
Fresh Oil	0.892	31.4	21.6	0.02	26.1	29.7	<1
Sample #2	0.900[1]	62.0[1]	6.2				
Weathered	0.901	52.2	21.6	0.02	24.3	31.6	27
Oil	0.908[1]	160.0[1]	6.2				

1. Data extrapolated

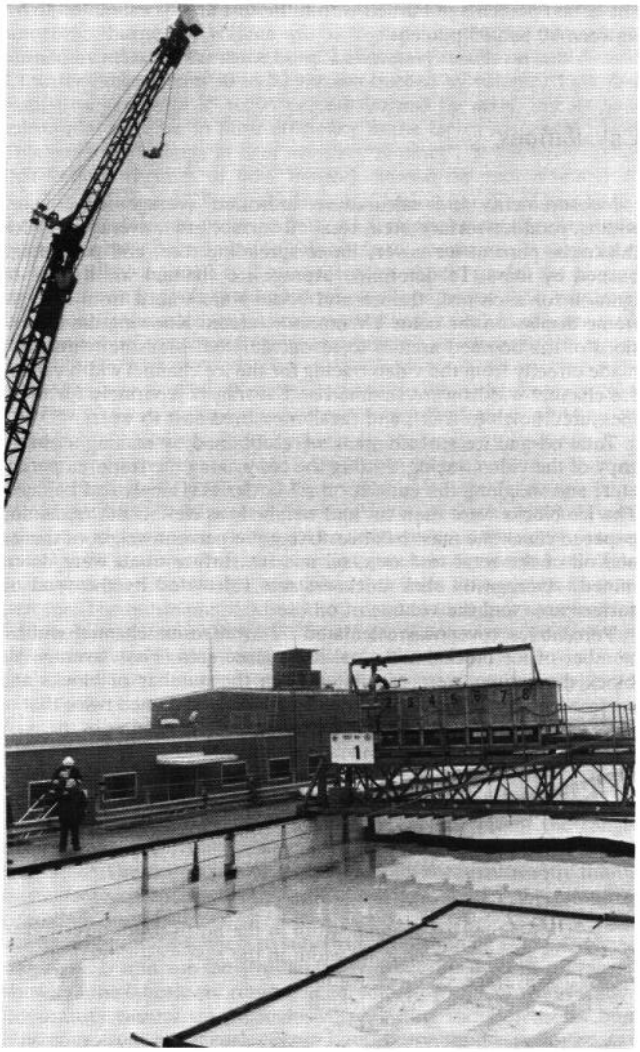

Figure 1. A Sony DXC-1000 color video camera was positioned approximately 15 m above the boomed area during the tests. Information obtained through the overhead video coverage was used to determine percent ice cover, average oil slick thickness, and average ice channel width.

and wind speed and direction were obtained with a Climatronics Weather Station. To determine percentage burned by mass, 3M brand oil sorbent pads 45 cm × 90 cm were weighed on a spring scale, then deployed to absorb the burn residue from the water and ice surfaces, and reweighed. (It was found that the sorbent pads absorbed no appreciable quantities of water.)

Safety. A fire control system was provided to prevent burning oil escaping the boom or flames otherwise creating a hazardous situation. OHMSETT crew members manned fire hoses, and the Naval Weapons Station Earle Fire Department was on standby during each test.

Calm water/fresh oil/45-percent ice cover test 1. Target conditions for this test were a 55-percent ice cover in the center of the pack and an average slick thickness of 3 mm. Thirty ice blocks were deployed in a pattern 6 blocks × 5 blocks. Seventy-six L of oil were distributed by sweeping east and west across the test area with the oil distribution hose while moving north to south on the main bridge over the ice and free water surface in the test area.

The slick was ignited at the downwind corner in all tests. To ignite the slick a "firelog" was ignited from an elevated bridge (the OHMSETT photo/video bridge) and allowed to slide along a wire cable across the test area to the desired ignition location. The firelog was an Ethafoam™ log approximately 13 cm in diameter and 32 cm

Table 3. Summary of test conditions and burn data

Wave conditions	Average slick thickness (mm)	Ice cover$_1$ (percent)	Water temperature (°C)	Burn time (min:s)	Flame spread rate$_2$	Percentage burned
Calm	1.7	45–35	3.8	7:53	1.3	85
Calm	4.0	45–30	5.4	8:15	2.4	95
Calm	4.0 (weathered oil)	60–45	7.7	11:00	1.5	90
Waves	ND$_3$	45–ND	7.7	9:40	ND	>85

1. In the center of the ice pack
2. Based on 1 discrete measurement in each test
3. Not determined due to the lack of a video recording after ice deployment and before oil distribution

long, wrapped in sorbent. This construction was soaked in crude oil and sprayed with ether-based starting fluid immediately prior to ignition. The stopwatch was triggered when black smoke first appeared. The burn was considered complete when the free-floating oil extinguished.

With winds from the east at 12 knots, the oil slick was ignited at an ambient air temperature of 4.9° C and tank water temperature of 3.8° C. (Winds above 15 knots from the 90° arc northwest to northeast and heavy precipitation were defined as "no go" conditions.) Ice cover in the center of the pack was 45 percent rather than the 55-percent target value due to melting. The total ice surface area was 13 m^2 and the oil on water surface area was 31 m^2. The oil covered 13 m^2 of the ice block surface area. Average channel width in this ice cover was 0.3 m. Average oil slick thickness was calculated to be 1.77 mm (calculations assumed uniform slick thickness on water and ice). The slick burned for 7 min 53 s and the weight of the oil residue recovered indicated that 85 percent by mass of the oil had burned. Flame spreading rate was determined along a channel 0.5 m wide to be 1.3 m/min. After the burn ice cover was reduced to 35 percent. The conditions and data from the tests are summarized in Table 3.

During this test with winds at 12 knots from the east, the heat was intense. A great deal of black smoke was generated in this and every test indicating incomplete combustion. At 1 min 45 s into the burn,

Figure 2. In the first test (calm water/fresh oil 45-percent ice cover) the slick was ignited in the northwest corner of the boomed area. Flames spread south and east through the ice channels. In this test, oil was distributed over the entire test area rather than from the center of the test area as in subsequent tests.

the water appeared to be boiling at the surface along the east side of the test area. Figure 2 is a photograph taken during this test.

Calm water/fresh oil/45-percent ice cover test 2. Twenty-five ice blocks were laid out in a grid pattern 5 blocks × 5 blocks. Four additional blocks were added to fill in the perimeter space between the ice grid and the boom. Target ice cover in the center of the pack was 60 percent. Eighty-three L of oil were distributed, primarily on the water surface at the center of the ice grid. Other test criteria and procedures were the same as in the previous test.

At ignition, winds were from the southeast at 14 knots; air temperature was 8.2° C; and water temperature was 5.4° C. The ice had again melted significantly after delivery, bringing ice cover down to 45 percent. Total ice surface area was 10 m^2, and the oil on water surface area was 21 m^2. The oil on ice surface area was 0.3 m^2. Average channel width in this ice grid was 0.3 m. Average oil slick thickness was calculated at 4.0 mm. The slick burned for 8 min 15 s and the oil residue recovered indicated that 95 percent of the oil had burned or evaporated. Flame spreading rate was determined along a channel 0.5 m wide to be 2.4 m/min. Ice cover was reduced to 30 percent after the burn. Burn behavior during this test was very similar to that during the first test. A great deal of black smoke was generated, and the burn appeared to be most intense in the area between the ice grid and the boom.

Calm water/weathered oil/60-percent ice cover test. After the first two tests ice cover was increased. Forty ice blocks were deployed 8 blocks × 5 blocks for a target ice cover in the center of the pack of 75 percent. Sixty-two L of lightly weathered Prudhoe Bay crude oil were distributed on the water surface around the center block.

With winds at 8 knots from the northeast, air temperature of 4.3° C, and water temperature of 7.7° C, the slick was ignited. Ice cover in the center of the pack was 60 percent, with a total surface area of 16 m^2. The oil on the water surface covered 15 m^2. The oil on ice surface was 1 m^2. Average channel width for this test was 0.3 m measured from north to south and 0.2 m measured from east to west. Average oil slick thickness was calculated at 4.0 mm. The slick burned for 11 min, and the weight of the oil residue indicated a percentage burned of 90 percent. Ice cover was reduced to 45 percent after the burn. The flame spreading rate determined during the test was 1.5 m/min in a channel 0.2 m wide.

Flames for this test were approximately two-thirds the height of flames in the previous tests. The black smoke emitted during the burn remained in a coherent cloud for several hundred meters, moving at an elevation of almost 50 m above the ground surface. Not all of the oil residue was recovered. An estimated 2 kg of oil, representing 3 percent of the original oil mass distributed, remained afloat on the water surface after the oil retrieval process was complete.

Regular wave/fresh oil/45-percent ice cover test. We also evaluated the impact of waves on burn behavior. This test was attempted twice. For the first wave test, the south side of the boom was removed and replaced with a cable to allow full impact of the waves. In spite of attempts to maintain control of the oil with fire hose spray, several liters of oil escaped to an area beneath the main bridge. In this situation, the slick was not ignited, but the wave proposed for the test was generated and evaluated. The wave was changed from 5.5 m long and 0.2 m high to 2.9 m long and 0.3 m high for the repeat test [(based on L and H (1/3)].[8] The dampening effects of the boom were observed to be negligible, so this test was repeated with the south side of the boom in position. For a target ice cover of 75 percent, 40 blocks were deployed in an 8 block × 5 block pattern. Sixty-two L of fresh Prudhoe Bay crude oil were distributed onto the water surface at the center of the test area.

With winds at 13 knots from the east, air temperature of 4.8° C, water temperature of 7.7° C, the slick was ignited. Ice cover in the center of the test area was approximately 45 percent, with surface area near 12 m^2. Average slick thickness, channel widths, and flame spreading rate were not determined for this test.

Waves reached the test area approximately 2 min after ignition. The waves drove the oil to the north side of the test area. The slick was ignited on the south (downwind) side and did not burn intensely until reaching the north side with the thicker slick of oil. Some burning oil escaped over the north side of the boom during this test.

The slick burned for 9 min 40 s. The weight of the oil residue indicated a percentage burned of 85; however, 10 percent (of the distributed oil weight) was retrieved outside the boomed area. This oil may not have burned to the extent of that contained within the boom. The actual percentage burned within the test area is estimated to be between 90 and 95 percent.

Calculations

Measurements and calculations indicated average ice channel widths, total ice surface area, total oil surface area, average oil slick thickness, percent ice cover, flame spreading rate, and percentage burned by mass. To determine average ice channel width prior to ignition for each test, the ice and boom were traced from a single frame display on the color TV monitor screen. Knowing the dimensions of the boomed area, a scale was derived. Measurements were made directly from the video tracing for the ice channel width values. Ice channel widths were summed and averaged separately for those measured north to south and those measured east to west.

Total oil and ice surface areas were obtained by making a photocopy of the video tracing, cutting the copy along the test area perimeter, and weighing the cut-out on a Mettler H31 analytical balance. The ice blocks were then cut and weighed, as well as the remaining paper to check the mass balance. Using the percent weight of the ice and oil of the total test area, oil and ice surface areas were determined. Average oil slick thickness was calculated by the total oil surface area and the volume of oil used.

Percent ice cover was calculated by average ice channel widths, number of ice blocks, and total ice surface area. First, average ice block dimensions were calculated from the number of blocks and surface area assuming the length of the blocks remained twice that of their width during melting. Percent ice cover in the center of the pack was calculated as shown below:

$$\text{Percent ice cover} = \frac{W_{BL} \times L_{BL}}{(W_{BL} + W_{E/W}) \times (L_{BL} + W_{N/S})} \times 100 \text{ percent}$$

Where:

$W_{N/S}$ = average ice channel width in the north-south direction
$W_{E/W}$ = average ice channel width in the east-west direction
W_{BL} = average ice block width
L_{BL} = average ice block length

Flame spreading rate was determined from the overhead video recording. A transparent grid sheet with scaled increments of 0.3 m was overlaid on the video monitor, and when a segment showed the spreading of the flame clearly, the starting point and ending point were marked. Elapsed time was derived from the time-date display on the video screen. Since flame spreading was clearly visible during measurement, flame spreading rates were always measured as flames spread against the strongest winds.

Percentage of test oil burned by mass was determined by calculatig initial oil weight and weighing the oil residue. Initial oil weight was calculated by specific gravity and oil volume. Initial oil volume was measured with a precision of ± 4 L.

Discussion

Laboratory test data exhibited several trends in burn behavior with respect to water temperature. Burn rates were consistently higher in room temperature tests compared to tests performed on cold (<6.5° C) water. Percentage burned was also higher in warmer water. Burn time did not vary significantly with variations in water temperature, but it did increase, as expected, with increase in slick thickness. The fumed silica wicking agent appeared to increase burn efficiencies on room temperature water. On cold water the wicking agent did not appear to aid in oil removal.

No trends can be derived from the tank work since only four tank tests were carried out, but comparing the tank test to laboratory data illustrates a scaling consideration. Percentage burned in the laboratory was determined by volume. Percentage burned in the tank was determined by mass. Assuming an increase in specific gravity in the burn residue compared to that of the oil initially used, the value for percentage burned by volume will be higher than that for percentage burned by mass for the same burn. Laboratory results on cold (<6.5° C) water ranged from 30 to 50 percent burned by volume. Tank test results ranged from 85 to 95 percent burned by mass, indicating a substantial increase in burn efficiency in the larger scale tank tests. This owes to a change in heat transfer "regimes". It has been shown that various regimes of heat transfer depend on pool diameter in burning.[1,4] Below a 1.0-m pool diameter, various modes of heat transfer are postulated to occur. Above a 1.0-m pool diameter, however, burn rates have been found to remain fairly consistent. Wakiyama *et al.* report that a pool 1 to 2 m in diameter should model the kind of turbulent burning rate that occurs when oil spills burn.[10] So, although the laboratory work does not correspond to the tank burns, the tank test results are considered useful in predicting results on a still larger scale.

In-place burns of Prudhoe Bay crude oil performed during a Shell Oil Company demonstration yielded burn efficiencies of 55 to 85 percent.[7] In a subsequent study, burning efficiencies for pooled oil in ice were predicted to range between 80 and 90 percent. In evaluating in-place burning of pooled oil, burn efficiencies obtained were 90 to 95 percent,[8] and > 95 percent.[5] In another study fresh crude oils were burned in a 1-m square yielding burn efficiencies of 93 and 94 percent by mass.[9] Thus, most of available data on burning pooled oil slicks agree with the OHMSETT burn tests that burn efficiency is 85 to 95 percent. The minimum slick thickness needed to support combustion as determined in the OHMSETT laboratory corresponded with that determined during the demonstration by Shell Oil.[7]

Summary

The burn efficiencies of the tank test burns (85 to 95 percent removed by mass) of Prudhoe Bay crude oil fall within the ranges determined in previous pooled oil burn demonstrations and studies.[3,5,6,7,9] The regular wave generated did not significantly inhibit flame from spreading to the entire test area under the ice cover conditions tested.

Minimum slick thickness to support combustion on cold (< 6.5° C) water is 2.5 mm for the Prudhoe Bay crude oil used in testing, as shown in the laboratory results, in agreement with a previous study.[7] Laboratory results are inconclusive regarding the increase in burn efficiency from a wicking agent. Laboratory results indicated two trends in burn behavior: percentage of oil burned decreases with decrease in water temperature, and burning rates decrease similarly. The burn efficiencies attained during laboratory tests were much lower than those attained during tank tests because of a scaling factor, according to the work of Babraukas and Wakiyama.[1,10]

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