FINAL REPORT

TESTS TO DETERMINE THE LIMITS TO *IN SITU* BURNING OF THIN OIL SLICKS IN BROKEN ICE

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and
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SUMMARY

The objective of this research 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 broken ice. The project 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 (3 mm slicks and thinner);
- Mixing energy (calm and low waves to simulate natural mixing of an ice field); and,
- Degree of oil evaporation (weathering).

The small-scale experiments 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, or slush); 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 wave 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 a layer of frazil (also referred to as grease or slush) ice (simulated by using snow in water) for selected degrees of weathering of the various crudes.

The results from this project will be used to propose “rules-of-thumb” for burning thin slicks in broken ice relevant to both existing production fields in Cook Inlet, Alaska as well as to recent and proposed offshore fields (e.g., Northstar and McCovey in Alaska and Sakhalin in Russia) and to existing coastal fields in Prudhoe Bay, Alaska (e.g., Endicott, Pt. McIntyre, Niakuk).

In general, the “rules-of-thumb” for minimum ignitable thickness 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 with gelled gasoline igniters.

It is proposed that the “rule-of-thumb” for oil removal rate for burning thin slicks on broken ice be:

- For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice. Wave action slightly reduces the burn rate on open water, but the halving rule seems to apply in waves as well.

In situ burning oil removal efficiency is related to the initial thickness of the slick and the thickness of the residue remaining after the fire extinguishes naturally. The following is the proposed rule-of-thumb for the residue remaining after thin slicks are burned on broken ice:

- The residue remaining on broken ice in calm conditions is about 50% greater than that on open water or 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 sub-sea leak or blowout 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.

ACKNOWLEDGEMENTS

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DISCLAIMER

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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 broken ice conditions. *In situ* burning may be the only option to quickly remove oil spilled in broken ice. The use of *in situ* burning as a response tool for oil spills in broken 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 are still questions about the limits to ignition and effective burning of spilled oil in broken ice conditions, particularly in fields of broken ice containing significant amounts of brash and slush ice and subjected to wave action. The purpose of this study was to investigate the key factors for burning thin oil slicks in broken ice, including the effects of waves.

1.1 Background

Research in oil spill cleanup in broken ice began in the 1970's. Interest in the subject increased in the early 1980's because of proposals for offshore production in Alaska and Canada, and has become an international subject of R&D with the opening of Russian and Norwegian ice-covered waters for exploitation. Interest in the subject has been rekindled in Alaska with several recent offshore development proposals near Prudhoe Bay. Also, operators of established production facilities in Cook Inlet have an ongoing need to improve their level of understanding of alternative response strategies for spills in broken ice.

The consensus of the research to date on spill response in broken 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 broken 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 broken 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.

The key to the success of an individual burn in a broken 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. In Cook Inlet, brash ice and frazil ice are the forms normally present for most of the year. 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 is appropriate to focus the proposed testing on the ignitability and burnability of oil/brash/slush mixtures in various combinations and situations.

1.2 *In Situ* Burning Fundamentals

The following briefly summarizes the state-of-the-art understanding of *in situ* burning on open water (Buist et al. 1999). There is not sufficient information in the literature to determine similar “rules-of-thumb” for the *in situ* burning of oil spills in broken ice situations, in particular for thinner slicks, in the mm-range, on brash and/or frazil ice that would be typical of oil deposited from blowouts or sub-sea pipeline leaks.

1.2.1 Requirements for Burning

In order to burn oil spilled on water, three elements must be present: fuel, oxygen and a source of ignition. The oil must be heated to a temperature at which sufficient hydrocarbons are vaporized to form a concentration high enough to support combustion in the air above the slick (called the Lower Flammability Limit, LFL). It is the hydrocarbon vapors above the slick that burn, not the liquid itself. The temperature at which the slick produces vapors at a sufficient rate to ignite is called the Flash Point. The Fire Point is the temperature, a few degrees above the Flash Point, at which the oil is warm enough to supply vapors at a rate sufficient to support continuous burning.

1.2.2 Ignition Processes

Ignition of an oil slick and subsequent flame spreading are strong functions of temperature of the slick. If the oil is at a temperature above its Flash Point, ignition is simple and flame propagation is rapid; otherwise ignition and flame spreading will be slower and sometimes difficult.

For an oil slick on water at a temperature below its Flash Point, the igniter must heat the slick surface to above its Flash Point. This problem involves two aspects: heat transfer through the slick and convective motion effects induced in the heated slick (Figure 1-1). When an oil slick on water at a sub-flash temperature is exposed to a radiant heat/ignition source initially, the surface of the slick is heated. As soon as this happens, the warm oil (with a lower air/oil interfacial tension than the colder, underlying oil) begins to flow horizontally away from the heat source. Its place is taken by colder fuel rising up from beneath in convection-induced, gravity-driven flow. It has been shown that this convective flow is decreased with increasing oil viscosity and decreasing bulk oil surface tension; thus, less viscous oils (all other factors being equal) are easier to ignite. In any case, as heat is flowing outward, it is also simultaneously conducted and convected vertically through the oil slick to the underlying water. If the slick is sufficiently thick to insulate itself and allow the surface layer to heat to its Flash Point, the slick will start to burn in the vicinity of the igniter.

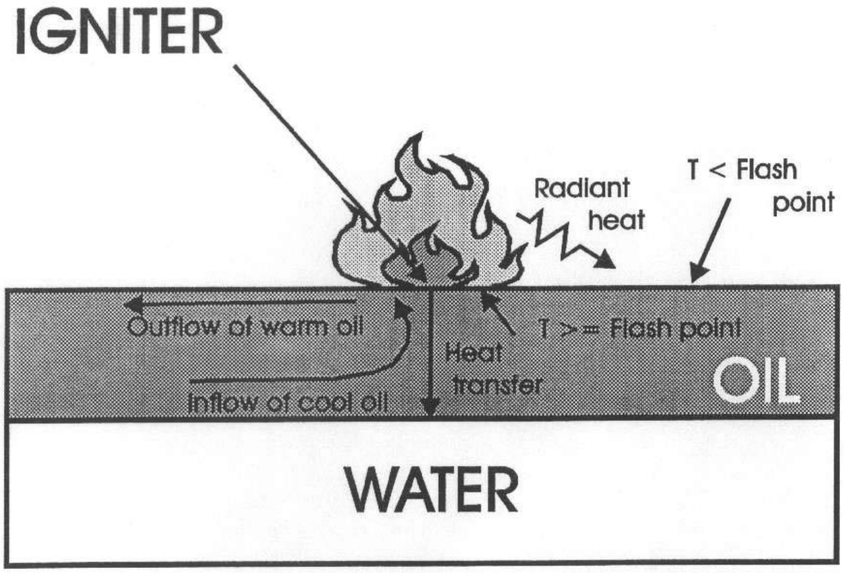


Figure 1-1: Ignition of an oil slick on water.

Extensive experimentation with a variety of oil types, igniters and environmental conditions has confirmed the following “rules-of-thumb” for the ignition of oils on water in relatively calm, quiescent conditions:

- the minimum ignitable thickness for fresh, volatile crude oil on water is about 1 mm;
- the minimum ignitable thickness for aged, unemulsifed crude oil and diesel fuels is about 3 to 5 mm;
- the minimum ignitable thickness for residual fuel oils, such as Bunker “C” or No. 6 fuel oil, is about 10 mm; and,
- once 1 m^2 of burning slick has been established, ignition can be considered accomplished.

Aside from oil type, several factors can affect the ignitability of oil slicks on water. The key parameters are: wind speed and igniter strength; secondary factors include ambient temperatures (primarily water temperature) and waves. The effects of wind speed on the ignitability of oil slicks have been studied both theoretically and experimentally. The maximum wind speed for successful ignition for large burns has been estimated as 10 to 12 m/s (20 to 25 knots). The presence of waves can also prevent the ignition of marginally ignitable slicks.

Flame spreading is a crucial aspect of effective *in situ* burning. If the fire does not spread to cover a large part of the surface of a slick, the overall removal efficiency will be low. There are two ways in which flames spread across a pool of liquid fuel: radiant heating of the adjacent liquid oil warms it to its Fire Point; and, the hot liquid beneath the flame spreads out over the surrounding cold fuel.

As oil evaporation (or weathering) increases, flame spreading velocity decreases. This is because the difference between ambient water temperature and the oil's Flash Point increases, requiring additional heating of the slick to raise the temperature of the surface of the slick. Flame spreading speeds increase with increasing slick thickness due to the insulating effect of the oil layer. For a constant slick thickness and Flash Point, increasing viscosity reduces flame spreading speed. Downwind flame spreading increases with increasing wind speed. This is likely due to the bending of the flame by the wind enhancing heating of the slick. In a wind, flames tend to spread straight downwind from the ignition point without significant crosswind spread. Flame spreading upwind is slow, although the presence of a barrier or edge that provides a wind break can permit rapid upwind or cross-wind spreading. The presence of current and regular waves (or swell) does not seem to affect flame spreading for unemulsified oils, but choppy or steep waves have been noted to curtail flame spreading.

1.2.3 Heat Transfer Back to Slick

Figure 1-2 illustrates the heat transfer processes that occur during the *in situ* burning of an oil slick on water. The rising column of combustion gases carries most of the heat away from the burn, but a small percentage (about 3%) radiates from the flame back to the surface of the slick. This heat is partially used to vaporize the liquid hydrocarbons that rise to mix with the air above the slick and burn; a small amount transfers into the slick and eventually to the underlying water. Once ignited, a burning thick oil slick reaches a steady state where the vaporization rate sustains the combustion reaction, which radiates the necessary heat back to the slick surface to continue the vaporization.

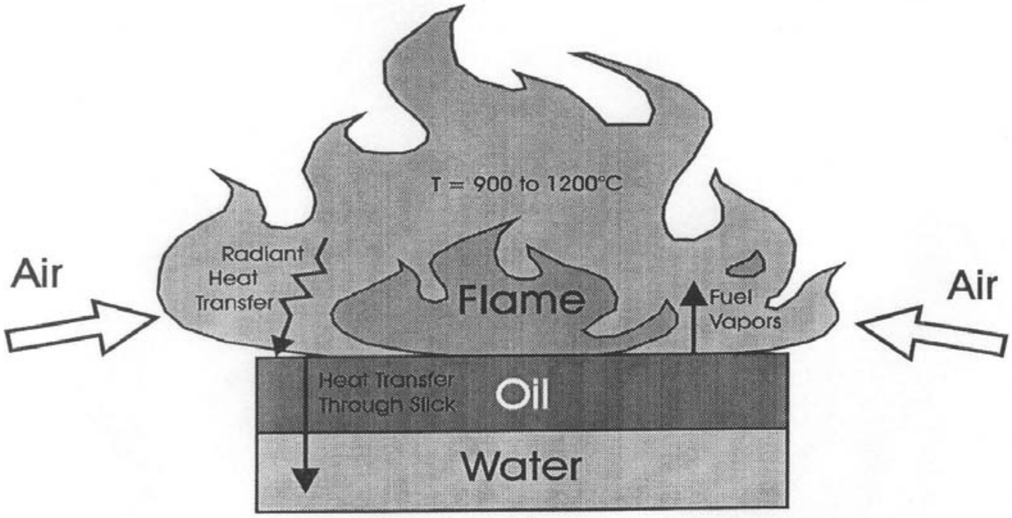


Figure 1-2: Key heat and mass transfer processes during *in situ* burning.

1.2.4 Flame Temperatures and Total Heat Fluxes

Flame temperatures for crude oil burns on still water are about 900° to 1200°C. The temperature at the oil slick/water interface is never more than the boiling point of the water and is usually around ambient temperatures. There is a steep temperature gradient across the thickness of the slick; the slick surface is very hot (350° to 500°C) but the oil just beneath it is near ambient temperatures. Total heat fluxes generated by an oil pool fire are on the order of 100 to 250 kW/m^2 measured both inside and at the periphery of the fire. The higher heat flux values are associated with windy conditions that promote better combustion.

1.2.5 Importance of Slick Thickness

The key oil slick parameter that determines whether or not the oil will burn is slick thickness. If the oil is thick enough, it acts as insulation and keeps the burning slick surface at a high temperature by reducing heat loss to the underlying water. This layer of hot oil is called the “hot zone”. As the slick thins, increasingly more heat is passed through it; eventually enough heat is transferred through the slick to allow the temperature of the surface oil to drop below its Fire Point, at which time the burning stops.

1.2.6 The Vigorous Burning Phase

At the final stages of burning, the “hot zone” approaches the water surface. The temperature of the layer of water directly beneath the slick, no longer insulated by a thick slick, increases. For slicks on calm water with no current, the temperature of the underlying water can increase to the boiling point. When the water begins to boil, the steam vigorously mixes the remaining oil layer and ejects oil droplets into the flames (Figure 1-3). This results in increased burn rate, flame height, thermal radiation output and foaming. This is called the “vigorous, or intense, burning phase”. This phenomenon has not been observed in burns using a towed boom, probably because the water beneath the slick does not stay there long enough to boil.

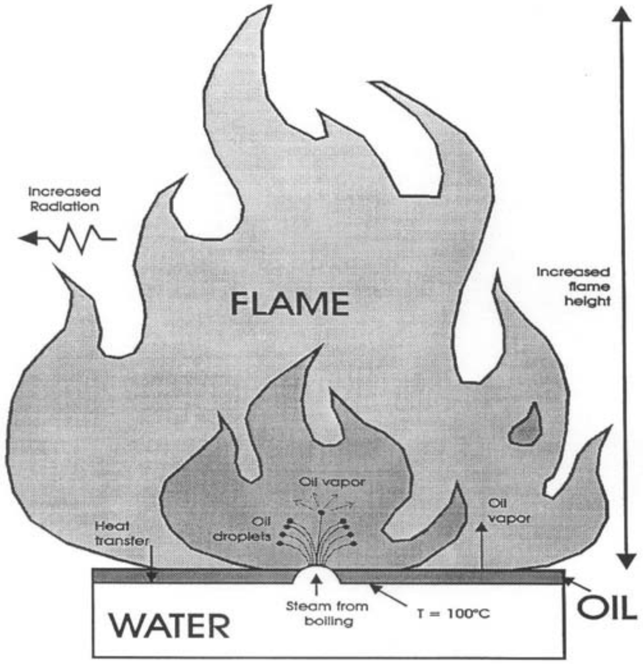


Figure 1-3: Development of the vigorous burn phase.

1.2.7 Oil Burning Rates

The rate at which *in situ* burning consumes oil is generally reported in units of thickness per unit time (mm/min is the most commonly used unit). The removal rate for *in situ* oil fires is a function of fire size (or diameter), slick thickness, oil type and ambient environmental conditions. For most large (> 3 m diameter) fires of unemulsified crude oil on water, the "rule-of-thumb" is that the burning rate is 3.5 mm/min. Automotive diesel and jet fuel fires on water burn at a slightly higher rate of about 4 mm/min. Gasoline and very light fuels can burn at rates as high as 4.5 to 5 mm/min.

1.2.8 Factors Affecting Residue Amounts and Burn Efficiency

Oil removal efficiency is a function of three main factors: the initial thickness of the slick; the thickness of the residue remaining after extinction; and, the areal coverage of the flame. The general rules-of-thumb for residue remaining after a successful burn are described below. Other, secondary factors include environmental effects such as wind and current herding of slicks against barriers and oil weathering.

The following rules-of-thumb apply for the residue thickness at burn extinction:

- For pools of unemulsified crude oil up to 10 to 20 mm in thickness the residue thickness is 1 mm;
- For thicker crude slicks the residue is thicker; for example, 3 to 5 mm for slicks that are initially 50 mm thick;
- For emulsified slicks the residue thickness can be much greater; and,
- For light and middle-distillate fuels the residue thickness is 1 mm, regardless of slick thickness.

Wind and current can herd a slick against a barrier, such as a towed boom, thus thickening the oil for continued burning. As little as a 2 m/s (4 knot) wind is capable of herding oil to thicknesses that will sustain combustion. Indeed, the phenomenon of "uncontained" *in situ* burning is based on the requirement of a self-induced wind (drawn in by the combustion process and the rising column of hot gases), to "herd" and keep an uncontained slick at burnable thicknesses.

Current can also dramatically increase burning efficiency (i.e., reduce the amount of burn residue) by herding burning oil against a barrier, such as an ice edge. The detrimental effects of current can include entrainment of residue beneath a floating barrier as the residue density and viscosity increase during the burn process, and over-washing of the burning slick, causing extinction of the flames. Excessive waves can also have a negative effect on the burning process.

The residue from a typical, efficient (>85%) *in situ* burn of crude oil 10 to 20 mm thick is a semi-solid, tar-like layer that has an appearance similar to the skin on an old, poorly-sealed can of latex paint that has gelled. For thicker slicks, typical of what might be expected in a towed fire boom (about 150 to 300 mm), the residue can be a solid. The cooled residue from thick (>100 mm), efficient *in situ* burns of heavier crude oils can sink in fresh and salt water.

1.2.9 Effects of Emulsification

Emulsification of an oil spill negatively affects *in situ* ignition and burning. This is because of the water in the emulsion. Stable emulsion water contents are typically in the 60% to 80% range with some up to 90%. The oil in the emulsion cannot reach a temperature higher than 100°C until the water is either boiled off or removed. The heat from the igniter or from the adjacent burning oil is used first mostly to boil the water rather than heat the oil to its Fire Point.

A two-step process is likely involved in emulsion burning: “breaking” of the emulsion, or possibly boiling off the water, to form a layer of unemulsified oil floating on top of the emulsion slick; and subsequent combustion of this oil layer. High temperatures are known to break emulsions. Chemicals called “emulsion breakers”, common in the oil industry, may also be used.

For stable and meso-stable emulsions the burn rate declines significantly with increasing water content. The decrease in burning rate with increasing water content is decreased further by evaporation of the oil. The following rules-of-thumb summarize the effect of water content on the removal efficiency of weathered crude emulsions:

- Little effect on oil removal efficiency (i.e., residue thickness) for water contents up to about 12.5% by volume;
- A noticeable decrease in burn efficiency with water contents above 12.5%, the decrease being more pronounced with weathered oils; and,
- Zero burn efficiency for emulsion slicks having water contents of 25% or more. Some crudes form meso-stable emulsions that can burn efficiently at much higher water contents. Paraffinic crudes appear to fall into this category.

Extinction of burning emulsions can be initiated by foaming action of the burning slick. The foaming is likely associated with boiling of water. Burning emulsion slicks may foam and extinguish over one area of their surface, but be re-ignited later by adjacent flames. This can result in sudden and rapid flare-ups of flame near the end of an emulsion burn. Compared with unemulsified slicks, emulsions are much more difficult to ignite and, once ignited, display reduced flame spreading and more sensitivity to wind and wave action.

1.3 Objective and Goals

Objective: The objective of this study was to conduct a focused series of small- and mid-scale experiments to determine the “rules-of-thumb” for the effect of ice concentration, ice dynamics and ice type on the lower limits to ignition, the combustion rate and residue thickness of thinner oil slicks burned on broken ice. The “rules-of-thumb” will be relevant to both existing production fields in Cook Inlet, as well as to recent and proposed offshore fields (e.g., Northstar, McCovey) and to existing coastal fields in the Prudhoe Bay Unit (e.g., Endicott, Pt. McIntyre, Niakuk).

Goals: More specifically, the goals of the work proposed here were to:

1. Conduct a review of the literature on *in situ* burning in broken ice;
2. Perform a series of small-scale scoping burn tests in brash and frazil ice in an indoor tank in order to assist with the design of the larger tests;
3. Develop the test protocols and the test procedures;
4. Conduct mid-scale burns in the Alaska Clean Seas wave tank in Prudhoe Bay; and,
5. Write a technical report and present a technical paper.

2. LITERATURE REVIEW

As the first task of the project, a literature search was completed. A formal computerized search was not undertaken; rather, both the libraries of SL Ross Environmental Research and DF Dickins Associates (both well stocked with the relevant literature sources) were reviewed. A thorough analysis of past work was carried out in order to glean as much information as possible on how to conduct the experiments in a realistic manner.

The review of the literature on *in situ* burning in broken ice revealed three categories of relevant references:

- Tests involving burning oil/snow mixtures;
- Small and mid-scale tests conducted in basins or test pans; and,
- Mid-scale and large-scale tests conducted as part of field trials.

2.1 Burning Oil in Snow

Studies of ignition and burning of oil/snow mixtures were undertaken before research into ISB of oil/ice mixtures began. Because the two are believed to be similar, oil/snow burning studies were reviewed.

The first known parametric tests of oil ignition and burning in snow are reported in Energetex 1981. Two series of tests are discussed:

1. Burns in small pits (100 x 50 x 10 cm) dug in an ice sheet involving pre-mixed blends of either fresh Prudhoe Bay crude or Arctic P40 diesel in snow. The snow content of the mixtures ranged up to 55 to 83% by weight. Ambient temperatures were on the order of 0°C.
2. Burns in small trenches (approximately 150 x 50 x 20 cm) cut in sea ice at McKinley Bay, NWT in the winter of 1979/80 with the same two oil types. The snow content of these mixtures ranged from 26 to 69% by weight. Air temperatures ranged from -31.5°C to 3°C.

The results showed that:

- The maximum snow content (by weight) that could be ignited without a primer was 33% for diesel and 40% for fresh Prudhoe Bay crude. Burn efficiencies for these were in the 70%+ range.
- Air temperatures from -31.5 to +3°C did not appreciably affect the burns.

Nelson and Allen (1982) conducted a series of field tests to burn oil sprayed onto snow at Prudhoe Bay. One cubic metre of fresh Prudhoe Bay crude was sprayed onto 465 m^2 of snow-covered ice resulting in average oil coverage of 2.2 mm. The oiled snow was left undisturbed for 2 weeks at one site and applied just before ignition at another. Oil penetration into the snow was initially on the order of 1 cm. Oiled snow samples indicated a water content of 75 to 90%. Although some isolated oiled snow in depressions did ignite, neither the fresh nor 2-week old oiled snow could be burned efficiently *in situ*. It was necessary to plough the oiled snow into a volcano-shaped pile and ignite the inside: the heat then melted the snow, allowing the oil to run to the center of the pile and feed the fire.

Sveum et al. (1991) report on a series of experiments at Svalbard on burning oil in snow. In these, mixtures of snow and either diesel or fresh Oseberg crude were tested. In the small-scale tests (using about 8 litres of snow), unaided ignition was possible with up to between 25 and 50% snow by volume (approximately 16 and 23% snow by weight). Priming the mixture with fuel was necessary at higher snow contents. The efficiency was uniformly 90% or greater, since once the fire was stared it would melt the snow and release the oil for burning on top of the melt water in the test vessel. Little difference in the results for the two oils was noted. In field tests, a large oiled area used for oil-in-snow spreading experiments was ignited and burned successfully using gasoline as a primer. In some experiments the snow was piled into heaps and in others it was left undisturbed.

2.2 Burning Oil in Broken Ice

2.2.1 Small-scale or Mid-scale Burns in Pans or Basins

The first recorded tests of ISB in broken ice conditions formed part of the "Tier II" demonstrations performed by the Alaskan oil industry in 1983 (Shell et al. 1983, SL Ross 1983). These involved test burns in a pit at East Dock in Prudhoe Bay. For two of the tests large ice blocks mined from the Beaufort Sea were grounded in the pit and Prudhoe crude oil was poured onto the pit water surface, allowed to drift, ignited and burned. For the other two tests, the oil was placed among floating brash ice (40 to 50% coverage of 1 to 5 ft. floes). In the first test with 140 L (36 gallons) of weathered Prudhoe crude the oil spread to cover an area of 90 m^2 (1000 ft^2) with an average thickness of 2.8 mm among the ice and could not be ignited in six attempts. The second free-floating test involved 1 m^3 (288 gallons) of fresh Prudhoe crude spread through 450 m^2 (4900 ft^2) of brash ice with an average thickness of 4.6 mm. This was successfully ignited and burned for 7 minutes free-floating and 23 minutes herded against the downwind edge of the pit. Several subsequent ignitions of herded oil were made after the main fire extinguished. In all, approximately 73% of the initial 288 gallons was burned.

In 1984, 1985 and 1986 burn tests were conducted at Ohmsett inside a wood-boomed area containing large (0.5 x 1 x 0.25 m), tethered, 140-kg freshwater ice blocks (Smith and Diaz 1987). Slightly weathered Prudhoe Bay crude was used. The boomed area was 46.5 m^2.

In the 1984 tests the ice block coverage ranged from 45 to 60%. The average distance between the ice blocks was 20 to 30 cm. Oil was placed on the water between the blocks, with an average thickness of 2 to 4 mm. Three tests were conducted in calm conditions and one in waves. All ignited easily and burned efficiently, with removals of 85 to 95%.

In 1985 and 1986 higher ice concentrations and emulsified oils were tested. With ice block coverage in the 75% to 80% range, fresh and evaporated crudes had burn efficiencies of 60% to 70%, while slightly emulsified crudes were much less burnable (10% to 55% removal, with the lowest efficiency associated with a 18% water-content emulsion).

In 1986, as a small part of a research study to assess ISB of wind-herded oil in various types of leads in an ice sheet, two tests of burning in brash ice were conducted (Brown and Goodman 1986 and 1987). The oil used was a 10% evaporated Norman Wells crude. Breaking up the ice sheet that had grown beneath the oil while it weathered in the lead created the brash ice. The ice pieces were all less than 2 cm in any dimension and were thoroughly mixed into the oil prior to ignition. The presence of brash ice is reported to have:

- Significantly reduced the flame spreading velocity (from 0.07 m/s without ice to 0.03 m/s with brash ice);
- Significantly lowered the oil burning rate (by a factor of about 5); and,
- Somewhat lowered the burn efficiency (from about 85 to 90% to 70 to 80%).

It was noted that brash ice covering <50% of the surface was completely melted during one burn.

In 1992 several mid-scale burn tests were conducted in a rectangular basin cut into the ice sheet on a fjord at Svalbard (Bech et al, 1993). One test involved 4 m^3 of a mixture of fuel oils pumped into 9+ tenths brash ice (a mixture of ice rubble pieces approx. 30 cm (1 ft) in size and frazil ice from blowing snow). The estimated thickness of the oil was 30 mm at ignition. Ignition was accomplished with a small, gelled crude igniter, and a burn efficiency of 90% was obtained with waves (about 40 cm x 4 m) being generated in the basin. Similar tests with 12.5 % and 25% water content emulsions proved extremely difficult to ignite and burn in waves. In calm conditions, with sufficient primer, ignition and burning was achieved but with lower removal efficiencies compared with unemulsified oil. It was concluded that the small ice floes and slush did not negatively affect the burning of the thick oil slicks.

In 1994 a series of experiments on burning crude oil and emulsions in brash ice were carried out in a 15-m diameter circular basin cut in the ice of a fjord at Svalbard (Guenette and Wighus 1996 and, Guenette and Sveum 1994). Fresh, weathered, and emulsified Statfjord crude oil was used. The basin contained slush ice from blowing snow and ice pieces from 0.5 to 3 m in diameter. In a pre-test burn, 200 L of fresh crude was easily ignited and burned in compacted brash ice. The oil initially spread to cover 9 m^2, equivalent to a thickness of 22 mm . At the end of the burn (14 minutes) it had spread to 16 m^2. No removal efficiency was recorded. In the first test, 8 m^3 of fresh crude was placed in the basin with 20% ice cover (most of the ice and slush was submerged by the thick oil) and an initial thickness of 56 mm. This was easily ignited with a simple gasoline-soaked sorbent and resulted in a 99% removal efficiency. The next test involved 6 m^3 of a 50% water-in-18%-evaporated-crude emulsion in 50% ice coverage. This proved very difficult to ignite, eventually requiring 4 m^3 of fresh oil as primer to achieve 75% removal efficiency. The final test involved 2.7 m^3 (30 mm) of 20% water-in-crude emulsion in a 50% ice cover, which was successfully ignited with an emulsion-breaking igniter and gasoline as primer. A 95% removal efficiency was achieved, even in the prevailing 8 to 11 m/s winds, which herded the burning oil and ice against the downwind ice edge.

2.2.2 Field Research Burns

Only one experimental *in situ* burn in broken ice conditions has been reported. In 1986, off the coast of Nova Scotia, three 1 m^3 spills of Alberta Sweet Mixed Blend (ASMB) crude were released and their behavior was monitored. Two of these releases, in brash ice in close pack conditions (9/10ths) were ignited and burned. The oil spread through and saturated the slush and brash over areas of 35 and 36 m^2, equivalent to a thickness of about 30 mm. Several hours after release, each spill was ignited using a burning oil-soaked sorbent. The removal efficiencies (based on timing the area of the burns and using a 2 mm/min regression rate) were 93% and 80%.

2.2.3 Burning Accidental Spills in Broken Ice

The following notes highlight known situations where burning of fuel oil and/or crude was either attempted or carried out successfully during actual response situations with oil in broken sea ice (burns on solid ice were deliberately excluded). This list is not intended to be all-inclusive and only covers incidents that have been reported in detail in the literature:

Tanker Arrow, Nova Scotia, Canada, Feb 1970 (reported in McLean, 1972): Efforts were made to burn oil in the early stages of the spill where oil was congregated in heavy pools against a growing land fast ice edge. Ignition was unsuccessful and further attempts were abandoned. Lack of success was mainly attributed to the cold temperatures, combined with the extremely low volatility of the spilled Bunker C under the prevailing conditions.

Deception Bay Tank Farm, Hudson Strait, Quebec, June 1970 (Ramseier et al., 1973): Spilled oil (diesel and gasoline) from the ruptured tank farm flowed out onto the fast ice and an estimated 50,000 gallons (12% of the spill) became incorporated into a well developed and active tidal crack system (12 to 19 ft diurnal range). Oil pooled in the tidal cracks was successfully ignited and burned. Some emulsification of the oil in the cracks was noted and attributed to the grinding action of the ice motion through the tidal range.

Buzzards Bay Spill, MA, January 1977 (various ref., e.g., Ruby et al., 1977): 81,000 gallons of #2 fuel oil spread and mixed into a dynamic mix of broken pans, rafted sheets and slush. Burning was used with some success at the original site of the barge grounding. Wicking agents soaked with jet fuel were dropped by helicopter into the oil pools. Several thousand gallons (est.) were burned in this manner with fires lasting for up to 2 hours. The burns were not considered totally effective due to a lack of enough large pools to make it worthwhile, inability of the fire to spread naturally along the lightly oiled block and brash ice from one pool to another and the large amount of particulate matter which left a black coating on the ice downwind of the fires.

Imperial St. Clair, Georgian Bay, Ontario, December 1976 (Beckett, 1979): The tanker grounded in area of unstable and shifting new winter ice, losing an estimated 57,000 gallons of diesel fuel and gasoline. Once the vessel was moved from the site, a successful burn was carried out of the diesel fuel that saturated the snow. Air temperatures were around -10°C. Ice conditions were unstable at the time and personnel had safety lines attached. An initial fire started with an oil-soaked rag spread quickly. Further burns were carried out through the winter and into the early melt phase, some by gathering oil-soaked snow into piles on the now stable ice but most with exposed pools during mild periods. One burn covering an area of 10 ft x 100 ft was estimated to have consumed 4,000 gallons. The overall outcome was that an estimated 80 to 95% of the oil lost was evaporated or burned in the original and subsequent burns.

M/T Raphael, 16.11.1969 (Lampela, 2000): The M/T Raphael grounded in Finnish waters of the Gulf of Finland about 30 nautical miles east of Helsinki in the Porvoo archipelago. The Raphael was a single-bottom vessel, and due to the accident about 200 tons of crude oil was released among the ice. The main part of the visible oil (85%) was burned and a significant part was also collected among the ice. Holes were made in order to collect oil from beneath the ice, and the burning was continued when the ice cover began to ablate.

2.3 Oil/Ice Interactions at Freeze-up

The following synopsis covers what is known about likely oil behavior in frazil ice, slush and brash, and is derived from a variety of references.

Oil/ice interactions at freeze-up are heavily dependent on: the stage of ice development; the energy level and nature of interactions between the easily broken new ice forms (frazil, grease, slush, pancakes, nilas etc.); and the oil properties (particularly density and viscosity). It is not useful to characterize the expected behavior of oil in each developing ice type in turn, because a variety of forms typically coexist at the same time within a matter of hours or within a very short distance.

The main factors governing the degree of oil incorporation in porous developing ice forms (slush, grease and frazil) are oil density and turbulence in the upper water column. The tendency for oil to break down into suspended particles is also controlled by the oil viscosity, with the heavier Bunker products more likely to be present as larger particle sizes that are less likely to rise to the surface. This was the case with the Kurdistan tanker incident on the Canadian East coast in 1979 (e.g., Reimer, 1980).

Most of the crude oils from the Prudhoe Bay area will surface quickly through porous developing ice to be concentrated at or near the surface. The density of fresh crude oils produced in the study area are sufficiently low that the oil will surface through buoyant forces, i.e., the density difference between the oil and the ice/water mixture.

In most situations, the turbulent mixing energy in the developing ice field is low compared with open water. In spite of the substantial amount of wave damping in the presence of ice, inter-floe collisions can still create some background turbulence.

An exception to these expected oil behavior patterns could involve a spill of oil that has an opportunity to emulsify before becoming entrained in newly forming ice. Alternatively, oil could become entrained in slush ice close to an ice edge where there is sufficient wave action to provide the necessary mixing energy to drive the oil particles down and maintain the oil at depth within the grease or slush ice.

The presence of any substantial coverage (i.e., 40 percent surface area or more) of any developing ice form more advanced than frazil or grease ice will dramatically limit the spreading of the oil compared with the equivalent spill in open water. In the absence of waves, grease ice will also greatly limit the spreading.

The Norwegian experience in a 1993 experimental spill in broken ice supports the importance of examining the pack geometry on a small scale similar to the scale of the oil patches themselves. Their observations also showed the sensitivity of oil spreading in broken ice to very small changes or shifts in the local degree of ice packing (concentration). In this example, 10 m^3 (157 barrels) of crude oil spread from a starting thickness of 10 cm to 1 cm in 45 minutes after being spilled in 8- to 9-tenths ice. The oil thickness remained constant at just less than 1 cm for four days and then rapidly thinned by another factor of 10 within 24 hours as the ice opened up from 9- to 7.5-tenths (Vefsnmo and Johannessen, 1994).

Another important factor complicating the relationship between ice concentration and oil spreading is the extent of coverage of slush in the water between thicker floes. Ice observations often report only the concentration of solid ice forms, whereas in an oil spill it will be important to obtain accurate information on the state of the water surface between the floes. A heavy layer of slush or grease in the water can significantly slow and limit oil spreading, even in low to moderate solid ice concentrations (less than 5-tenths).

2.3.1 Examples

Oil in developing and broken ice has been observed in a number of spills and field experiments. These observations are important in that they represent actual observations under a realistic range of developing ice conditions. The drawback is that conclusions reached are often specific to the peculiarities of the local area, specific oil type or experimental procedure.

Descriptions of several case studies and tank tests with oil in broken ice are presented below, focusing on spills of lighter fuel oil and crude. For a more complete review of all known laboratory, analytical and field reports, the reader is referred to Dickins and Fleet (1992) and Hollebone (2000).

The following descriptions cover four large-scale spills and experiments:

- Bouchard #65, January 1977
- Experimental Oil Spills in Leads, 1987
- Experimental Oil Spills in Pack Ice, March 1986
- Lab Studies of Dispersion of Crude Oil Within Growing Sea Ice, 1976
- Tank Tests of Oil Spreading in Simulated Broken Ice, 1976

Accidental Spill from the Barge Bouchard #65, January 1977. Number 2 fuel oil, a relatively light, fluid refined product, spilled from a barge and was transported for large distances, dispersed under the ice as leads opened, and incorporated into deformed ice as the leads closed in Buzzards Bay, MA. (Note: This spill provides some of the most detailed observations available for an accidental spill in broken ice.)

The following observations are extracted from Deslauriers and Martin (1978). The ice cover at the time of the spill was half landfast and half broken ice. The broken ice consisted of 75 percent ice floes, along with 25 percent hummocks, pressure ridges and rafted ice. Average ice thickness was 30 cm and the interior salinity of the ice was approximately 4 ppt, somewhat lower but not unlike Arctic sea ice. Strong tidal currents initially transported much of the oil under the ice, where it rose into openings in the ice and was incorporated into rough ice.

A heavy snowfall one week after the spill resulted in the formation of an oil/snow mulch containing about 30 percent oil by volume. Oil weathering ranged from 6 to 47 percent oil volume loss depending on the amount of air exposure. Of the 81,150 gallons spilled, an estimated 45 percent was in pools (contained by the ice) that could be pumped. The remaining 55 percent of the oil contaminated the ice over an area of 23 acres with an average concentration of 0.08 gallons per square foot. Samples of oiled slush ice at the edges of pools in rafted ice showed 30 percent oil by volume.

Welsh et al. (1977) concluded that the oil and water density differences and the ice deformation controlled the dispersion of the oil in the Buzzards Bay spill. Winds were a significant factor in transporting pooled oil over the ice surface. When leads opened in the very close pack ice, the oil was released from under the ice. This oil then became incorporated into the deformed ice when the leads closed again. In some cases, oil was pumped onto the ice surface by this type of action (so called “lead-pumping”).

Experimental Basin Oil Spills in Leads, 1987. Buist et al. (1987) describe the results of a combination of laboratory tank tests of oil in developing ice and outdoor tests in small scale leads cut into a solid sheet of ice. The tank tests involved small ice pancakes about 30 cm in diameter with and without a wave field. Results showed that the amount of oil incorporated into the grease ice in the absence of waves is largely controlled by a combination of the oil’s density and viscosity, the density controlling the relative buoyancy forces between the oil and water/grease ice mixture and the viscosity determining the oil’s tendency to break into particles that are small enough to migrate readily through the porous grease ice. The introduction of wave action into the grease ice field greatly increased the fraction of oil incorporated within the ice vertically as well as increasing the lateral spreading of oil through the slush surrounding the pancake ice. As the ice was allowed to thicken and mature in the cold basin, the amount of oil in the slush steadily decreased. This was likely a result of the damping effects of thicker floe ice on the wave energy in the slush.

Oil spreading on the lead was effectively stopped when it reached the concentrated edge of wind blown ice crystals that naturally accumulate at the downwind end or edge (as occurs naturally in the field). The presence of a wind-herded, thick oil layer significantly reduced the rate of initial ice growth. For example, the unoiled area of the lead formed a 4.5-cm new ice layer within 22 hours, while the oiled section of the lead took 70 hours to reach the same thickness of ice under the oil. A succession of snowfalls and several freeze/thaw cycles over the next few days led to a layered structure of new clean snow on top of a frozen slush/oil crust overlying several cm of water on top of 3 to 5 cm of solid clean ice. Once the oil was sealed with fresh snow, it was isolated from further solar heating and the thaw cycles then stopped. This situation could occur with oil on the ice surface during periods when the diurnal temperatures are oscillating between above and below freezing.

The evaporation rates of the oil did not seem to be greatly reduced by the presence of snow in or on the surface of the oil (see further discussions below of oil weathering at the end of each section describing oil/ice interaction in the different seasons).

Experimental Field Oil Spills in Pack Ice, March 1986. Buist and Dickins (1987) describe the results of three spills of 6 barrels each of crude oil into a variety of pack ice forms ranging 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.

The oil in the first open-pack-ice spill 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 small proportion of the oil was swept as droplets beneath the floes by the relative motion of the ice and water in response to a heavy ocean swell penetrating the ice field. The oil in the first spill mixed with the slush ice, which in turn coated the outer rims of small floes and pancakes with an oil stain. In the other two spills, once the oil spread in the lead to saturate the slush ice above the water surface, it essentially ceased spreading or spread very slowly.

The presence of large amounts of slush in the water effectively stopped the oil from spreading laterally, independent of the surrounding concentrations of the larger and thicker ice forms. In spite of the potential for relatively high turbulent mixing energies in the swell conditions, the majority of the oil remained at or close to the surface. There was no evidence that any significant portion of the spill was driven down or suspended at depth in the slush. No emulsification was observed in spite of the known ability of many crude oils to emulsify in cold water at low sea states. Natural dispersion was occurring with large oil droplets temporarily driven down in the water column but this oil quickly resurfaced.

Lab Studies of Dispersion of Crude Oil Within Growing Sea Ice. Martin et al. (1976) describe the results of a series of spills of diesel fuel and Prudhoe Bay crude into grease ice, slush ice and pancakes grown in an insulated tank in the presence of waves. The grease ice was described as a fluid porous mass of frazil ice crystals up to 12 cm thick. This ice/water mixture was compressed at the crests of the waves and stretched in the troughs. The grease ice was 35 to 45 percent ice by volume and highly porous. Both the No. 2 diesel fuel and crude oil (density 0.893) surfaced almost immediately through the grease ice.

Once the grease ice reached 10 cm in average thickness, the crystals at the surface began to join together in what Martin called “proto” pancakes (clumps of crystals which, although less porous than the grease ice, were still too soft to pick up). These clumps quickly developed into harder, more solid ice pancakes with an average width of 20 cm and an initial thickness of 1 to 3 cm.

These pancakes floated in a thicker layer of grease ice (less buoyant than water). The grease ice created the dish-shaped bottom profile of the pancakes and contributed material to form the characteristic raised edges or rims of the pancakes observed in nature. The result of this profile is that the centers of newly formed pancakes on the surface were below the water line.

These experiments and others (e.g., Metge and Telford (1979), Wilson and Mackay (1987)) show that crude oil spilled into a developing ice field is unlikely to remain suspended or mixed within the slush and grease ice.

Tank Tests Of Oil Recovery Devices in a Simulated Broken Ice Field (Getman and Schultz, 1976): In Phase II of a skimmer test program carried out in an ice model basin, a brief series of spreading tests were conducted to determine the natural equilibrium thickness of oil spilled in broken ice among small ice blocks. Findings showed that this thickness could be highly variable as a function of oil properties, concentration of broken ice and the size distribution of the ice pieces. In tests where the oil was added sequentially, the oil slick tended to increase in thickness rather than surface area after the initial volume was added. The field of simulated broken ice consisted of 95% coverage with ice pieces ranging from small pieces (what they called salt water ice mush) to a maximum of 22x22x10.5 inches. The typical block size was 11x11x10 inches.

2.4 Relevant Ice Conditions

The effect of ice conditions on the ignitability and efficiency of burning is a critical component of the study. As discussed earlier, there is a considerable body of knowledge concerning the burning of oil on solid ice. This study is concerned specifically with the situation where oil is spilled onto the surface of pack ice in its various forms. The definition of pack ice (WMO, 1970) is quite broad, the term being used to describe any area of sea ice other than fast ice (continuous ice cover attached to the shore). New ice forms, which are fractured and mobile at freeze-up in October, constitute one form of pack ice. The remnants of the winter fast ice cover in July are another form of pack ice. Both of these pack ice forms are colloquially referred to as “broken ice” by industry and government agencies in Alaska. Oil spill response strategies during the “shoulder” or transition periods of freeze-up and break-up commonly refer to broken ice. In Cook Inlet, another Alaskan oil production area, broken ice exists throughout the winter (see below).

In natural pack ice (or broken ice), the composition of ice particles and floes, and the degree of compression within the ice field are largely controlled by wind and wave action. The continual changes in composition and compression act to control the porosity of the ice to the oil at any given time and location. The porosity in turn dictates the degree of natural containment offered by the ice in both lateral (spreading), and vertical (mixing) planes to slow or stop the oil spreading. A summary of the range of possible interactions between the oil and ice under these conditions is contained in Section 2.3.

An original purpose of this project was to explore possible differences in burn effectiveness between several distinct types of broken ice. The choice of ice types that can be simulated to some degree in both the laboratory-scale and mid-scale tests was limited and depends on several factors:

- the range in broken ice conditions representative of different offshore areas of interest (see below);
- the scaling consideration of the tank areas relative to the spatial variability of broken ice in the natural environment; and
- the ability to create and maintain a given ice condition without climate control.

The results from this project will be used to create “rules-of-thumb” for burning in broken ice relevant to both existing production fields in Cook Inlet, as well as to recent and proposed offshore fields (e.g., Northstar, McCovey) and to existing coastal fields in the Prudhoe Bay Unit (e.g., Endicott, Pt. McIntyre, Niakuk).

Cook Inlet is exposed to drifting broken ice features with a wide range of thickness through much of the winter. During this time, platforms may encounter large pans of first-year ice interspersed with a range of new ice forms, brash ice and smaller pancakes. Openings between the larger, thicker floes are often choked with a soupy mix of individual plates of ice crystals floating in the water (frazil), combining with ice cakes created through interactions between thicker floes (brash). The frazil ice further coagulates into a “soupy” ice form known as grease. This homogeneous mix of grease/frazil is characterized by a narrow range of fine particle sizes (centimetres or less) and a granular composition. Figures 2-1 and 2-2 show the initial formation of new ice in Cook Inlet in late December, and a slightly later view from January with a mix of new and young ice in broken pans, with both open and ice-choked leads (Photos: Orson Smith, University of Alaska, Fairbanks).

In contrast to Cook Inlet, the Beaufort Sea coast experiences broken ice for two relatively short periods at freeze-up and break-up, and during brief periods in the summer when offshore pack ice can be driven towards the coast. The composition and duration of broken ice in the Beaufort is very different from Cook Inlet.

In early to mid-July the fast ice off Prudhoe Bay fractures into big and vast floes (over 2 km across) that rapidly break down into smaller pieces (Figure 2-3). Over a two- to three-week period, the area from shore to the outer Barrier Islands (Cross and Reindeer) clears of ice except for isolated floes in low concentrations. Further offshore (typically beyond 15 m water depth), significant concentrations of rotting first-year ice persist until the end of July and into early August in many years. Bands and patches of small floes (20 to 100 m across), ice cakes (2 to 20 m across) and brash ice (under 2 m) continue to drift through the deeper water areas (beyond 15 m water depth) during August in many years.

Figure 2-1

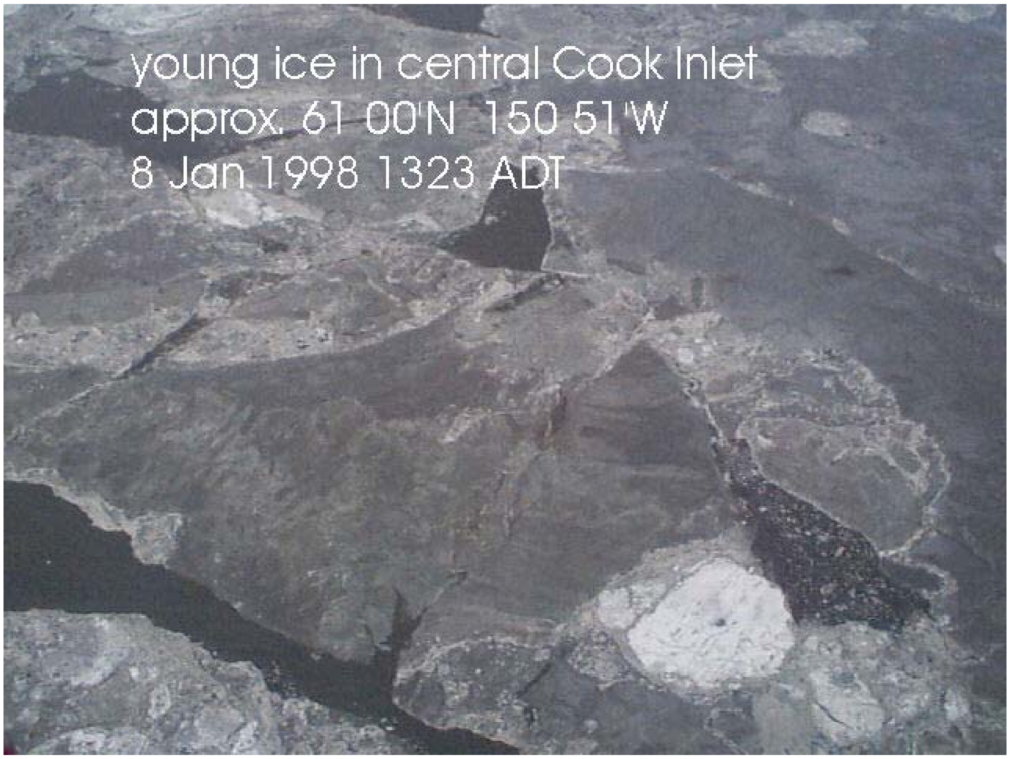


Figure 2-2

Figure 2-3: Break-up conditions around Seal Island in the Alaskan Beaufort on July 8, 1985 (Vaudrey, 2000)

Figure 2-4: Freeze-up around Seal Island in the Alaskan Beaufort in mid-October with moving young ice. The open wake created by the island is covered in a mix of grease and nilas in the center and brash packed into the edges of the lead (Vaudrey, 2000)

Openings between the melting floes at this time of year can contain patches of brash (the wreckage of rotting, larger floes) often driven by the wind against a solid ice boundary or large floe. The overall period of time when broken ice is experienced at break-up ranges from about two weeks at coastal sites such as Endicott or West Dock (PM2), to over three weeks at offshore sites such as Northstar (Vaudrey, 2000).

Oil-ice interaction at freeze-up tends to be a more practical condition to model in a lab at mid-scale. The particle sizes at freeze-up are much smaller on the scale that affects oil spreading, and the ice forms can more likely be accommodated within the dimensions of available test tanks. Beginning in early October, the initial stages of ice formation lead successively to frazil (fine plates of individual crystals suspended in the water), grease ice (soupy layer of coagulated crystals), slush (snow mixed with water appearing much as grease ice) and nilas (the first solid ice form appearing as a thin elastic crust up 10 cm thick). New fast ice (mix of frazil, grease, slush and nilas) in the Beaufort often expands rapidly out from shore (kilometres overnight), and may be interrupted several times by storms, before eventually forming a stable cover.

Conditions following a storm can involve a mix of isolated larger floes (hundreds of metres) separated by brash ice fragments or wreckage from the previous new sheet ice. Depending on the air temperatures at the time, exposed open water starts to fill with a layer of frazil/grease ice almost immediately. With any wave action, this condition often leads to ice pancakes ranging in size from 30 cm to 3 m. (“Pancakes” are circular ice pieces about 10 cm thick, with raised rims resulting from striking one another in a slight swell or wind wave). Figure 2-4 shows ice conditions at freeze-up around an artificial island off Prudhoe Bay.

The overall broken ice period during freeze-up in the Beaufort Sea can range from several weeks or less at coastal sites, to six weeks or more at offshore sites such as Northstar during a mild fall. The young and thin first-year ice (up to about 60 cm thick) remains susceptible to extreme storm events, and it is not unusual to experience localized areas of broken ice into late November or early December at offshore locations (Vaudrey, 2000).

In summary, broken ice in the Beaufort near-shore areas occurs during the relatively brief periods of transition from solid ice to open water or vice versa. This contrasts sharply with Cook Inlet where the extreme tidal variations and dynamic currents keep the ice in a constant state of motion, breaking and freezing as it drifts back and forth up and down the inlet. There is no opportunity to form stable ice in Cook Inlet, and broken ice becomes the normal condition to be dealt with throughout the winter. Similar long-lasting broken ice environments are found in other exploration areas such as offshore Sakhalin Island.

The aim of these tests is to examine oil in a localized portion of a larger broken ice field. As such, the focus is on situations where oil would naturally accumulate together with small ice blocks and/or slush at the downwind side of a lead, or against the upwind side of a much larger floe (Figure 2-4). Under these conditions, the effective ice concentration will always be close to 9/10, with the only openings occurring where randomly shaped ice cakes are imperfectly packed together. Wave action can be transmitted into a compressed ice field from winds acting on open water areas upwind of the ice. These are all conditions that lend themselves to being simulated in a mid-scale test of the scale provided by the ACS wave tank (Section 4.3).

The design phase of the project concluded that there are two commonly occurring, broken ice conditions that can potentially be created in an un-insulated test tank without climate control. These conditions are: (1) a homogeneous mix of frazil, grease and/or slush ice with small particle sizes, and (2) a non-homogeneous mix of brash ice with irregular ice cake sizes ranging from about 10 to 30 cm. Section 4.2 describes how these two forms of test ice were generated and used in the mid-scale tests.

3. SMALL-SCALE LABORATORY BURNS

This chapter describes the small-scale test burns conducted at the SL Ross Laboratory in Ottawa. Four Alaskan North Slope crude oils that could potentially enter the Beaufort Sea were selected for this phase 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.

3.1 Methods

3.1.1 Oil Sample Delivery

Two 19 L (5 gallon) drums of each of the four oils were collected by Alaska Clean Seas and shipped to the SL Ross laboratory in Ottawa. The contents of the two drums of each oil were heated, mixed, co-mingled and split into three aliquots. One aliquot of oil was tested as is (fresh oil). The other two aliquots of each crude oil were transferred into separate containers and artificially weathered prior to testing.

3.1.2 Oil Weathering

Two aliquots of each oil were artificially evaporated to different degrees of weathering. This was accomplished by bubbling air from a small compressor through the oil, which was contained in closed 20 L containers. The vapors were channeled through a pipe in the bucket lid to a fume hood. After an initial period of weathering, the buckets were heated in a water bath to increase the rate of evaporation.

It was desired to achieve the same degrees of evaporation as in previous studies (SL Ross 1994 and 2000) of Alaskan oil properties in order to be able to relate the amount of evaporation to exposure times for real slicks. The bubbling was continued until the desired mass fraction of oil was removed, as calculated using equation 1:

$$f_{\text{removed}} = (M_{\text{current}} - (M_{\text{container}} - M_{\text{sparger}}))/M_{\text{oil,initial}} \qquad \textbf{(1)}$$

where: f_{removed} / mass fraction of oil volatilized

M / mass

Table 3-1 gives the degrees of evaporation achieved for each of the four crudes and their respective densities at room temperature.

Table 3-1: Crude oil evaporation.

<table>
<tr><th><i>Crude Oil</i> | API Gravity</th><th colspan="3"><i>Amount of Evaporation (% mass) | time for a 3-mm slick at 0°C in a 10 knot wind (hr) | Density (g/cm</i>^{3}<i>)</i>*</th></tr>
<tr><td>ANS | 32°</td><td>0 | 0 | 0.861</td><td>10.3 | 1 | 0.888</td><td>16.8 | 3 | 0.899</td></tr>
<tr><td>Endicott | 24°</td><td>0 | 0 | 0.897</td><td>9.1 | 3 | 0.918</td><td>17.4 | 48 | 0.924</td></tr>
<tr><td>Northstar | 42°</td><td>0 | 0 | 0.806</td><td>33.8 | 3 | 0.857</td><td>43.8 | 48 | 0.868</td></tr>
<tr><td>Pt. McIntyre | 28°</td><td>0 | 0 | 0.884</td><td>9.1 | 3 | 0.902</td><td>18.2 | 48 | 0.921</td></tr>
</table>

* measured at room temperature

3.1.3 Small-scale Test Burns

The focus of these tests was on thinner, mm-range slicks (since the literature review had identified that there have been a number of larger experiments with thicker oil slicks) and the oil was spread out on top of the ice (oil released under these ice forms would quickly surface, and in any case be unignitable until it did surface). The parameters that were varied in these burns were: degree of oil evaporation, ice type (open water, brash ice and frazil ice) and mixing energy (calm vs. low waves).

The test matrix 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);
- Burn rate and removal efficiency tests in calm 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; and,
- Burn rate and removal efficiency tests in 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 tests were conducted in a 40-cm diameter steel ring (Figure 3-1) floated in the middle of a 11 m x 1.2 m x 1.2 m (L x H x W) indoor wave tank (Figure 3-2) filled with water to a depth of 85 cm. The smoke from the burns was removed with a 200-m^3/min fan, through a 60-cm flexible aluminum duct that was connected to a fume hood suspended 1 m above the steel ring. Some of the burns were recorded with a video camera. Key parameters for each test were recorded manually.

Two forms of freshwater ice were used for the tests: ice cubes purchased in 2.7-kg bags from a local grocery store (Figure 3-3) to simulate brash ice; and, and ice cubes crushed with a sledgehammer (Figure 3-4) to simulate frazil, or slush, ice. The appearance of each ice type in the ring prior to adding oil is compared in Figures 3-5 and 3-6. At the beginning of the lab test series a few exploratory burns were undertaken to determine the appropriate amounts of ice to

Figure 3-1: Burn ring in wave tank at SL Ross laboratory

Figure 3-2: Wave tank at SL Ross laboratory showing fume hood

Figure 3-3: Ice cubes used for tests.

Figure 3-4: Crushing ice cubes used to simulate frazil, or slush, ice.

Figure 3-5: Ice cubes in burn ring prior to oil addition.

Figure 3-6: Crushed ice in test ring prior to oil addition.

Figure 3-7: Adding Northstar crude to test ring.

Figure 3-8: Spreading Northstar out evenly on ice surface for minimum ignitable thickness test.

add for each test. It was determined that, in order for there to be ice remaining beneath the residue after a 3-mm thick test burn, a 5-cm thickness of ice, corresponding to two bags (either cubes or crushed), had to be placed in the ring.

The temperature of the fresh water in the tank was maintained at 2 to 4°C, despite air temperatures as high as 27°C, by a custom-built chiller, comprised of a 10-kW (3-ton) refrigeration unit supplying two 15-m copper coils immersed in the tank. Tank water was circulated past the coils by a small, electric outboard trolling motor. It is water temperature that primarily controls slick temperature rather than air temperature.

Minimum Ignitable Thickness tests involved pouring pre-weighed 0.5-mm (60 mL) or 1-mm (120 mL) increments of each oil type onto the surface of the ring (containing either ice cubes, crushed ice or open water), spreading the oil out as evenly as possible with a metal blade, then attempting ignition with a propane soldering torch (Figures 3-7 and 3-8). If no ignition was observed, another increment of oil was added and the procedure was repeated. Once a 3-mm thickness was reached, the power of the ignition source was increased by using:

i) one pre-weighed (20 to 30 g) gelled-gasoline igniter;
ii) two pre-weighed gelled-gasoline igniters,
iii) four pre-weighed gelled-gasoline igniters.

Each was initiated with the flame from a propane torch. If the above sequence failed to ignite the slick, then it was deemed unignitable. These tests were conducted in calm conditions only, not in waves.

Burn Rate and Removal Efficiency tests were carried out as follows:

1. If called for, two bags of ice cubes, or crushed ice, were weighed, added to the burn ring, and spread out to form as even a surface as possible.
2. A volume of 370 mL (to form a 3-mm slick) of the candidate oil was measured into a graduated cylinder and weighed (Mettler Toledo 8432 scale).
3. The oil was carefully poured onto the surface of the test ring, then spread out as evenly as possible using a metal blade.
4. Ignition was attempted first with a propane soldering torch flame, then one or more gelled gas igniters (if the test was to involve waves, the initial ignition was with four gelled gas igniters).
5. A stopwatch recorded the following times: initial ignition; 10%, 25%, 50% and 75% flame coverage, full ignition (100% flame coverage); time to the intense (or vigorous) burn phase; 75%, 50%, 25% and 10% flame coverage; and, extinction.
6. If the tests involved waves, the wave generator was activated when the flames reached 50% coverage during ignition.
7. After extinction of the flame, the waves were turned off (if used) and pre-weighed (Fisher XE3100D scale) squares of sorbent were used to recover the residue from the surface inside the burn ring. After use, each pad was shaken to remove as much water as possible. Then the pads were reweighed to determine the mass of residue. In some cases

it was clear that the sorbed oil contained ice particles: in these instances, the sorbent pads were allowed to sit overnight, and reweighed after the ice had melted and the water removed from the recovered oil.

Burn efficiency and burn rate were calculated for each test using equations (2) and (3), 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).

$$\text{Burn Efficiency (mass \%)} = \frac{\text{(Initial Oil Mass - Residue Mass)}}{\text{Initial Oil Mass}} \times 100 \tag{2}$$

$$\text{Oil Burn Rate (mm/min)} = \frac{\text{((Initial Oil Mass/Oil Density)–(Residue Mass/Residue Density))}}{\text{(Burn Area)(Extinction Half-Time - Ignition Half-Time)}} \tag{3}$$

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 lab-scale burns were:

- The accuracy of the scale used to weigh the oil added to the test ring (20 grams in about 300, approximately 6.7%);
- The residue recovery procedure: an analysis of the test data for burns that just barely ignited shows that the largest negative burn efficiency calculated was –6.2%, resulting from a residue weight 20.6 g greater than the weight of oil added.
- 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 about 10%.

3.2 Results and Discussion

In total, 114 40-cm diameter burns were conducted. The data for these may be found in Appendix A.

3.2.1 Minimum Ignitable Thickness

Figures 3-9 through 3-12 show the minimum ignitable thickness determined for the four crude oils.

Figure 3-9: ANS min. ignitable thickness

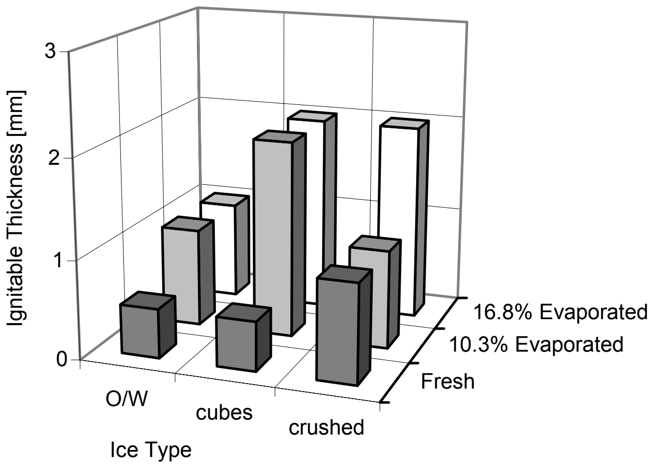


Figure 3-10: Endicott min. ignitable thickness

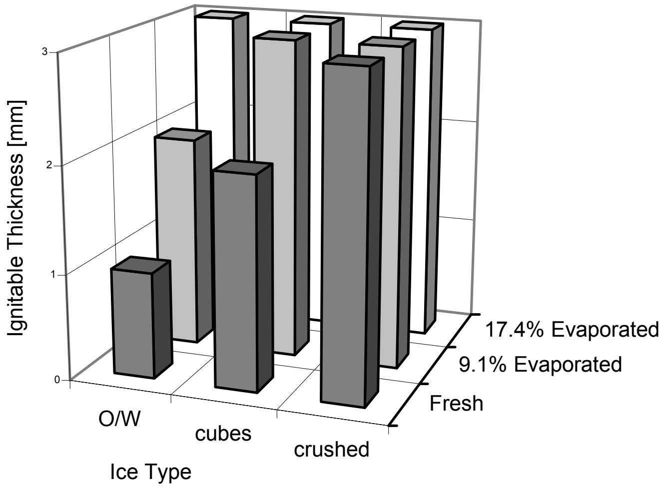


Figure 3-11: Northstar min. ignitable thickness

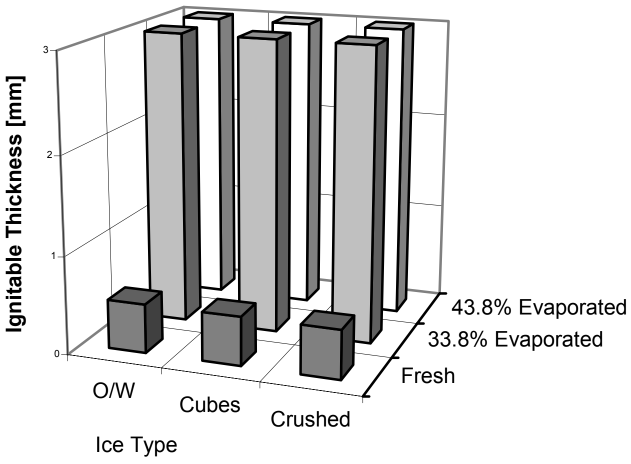
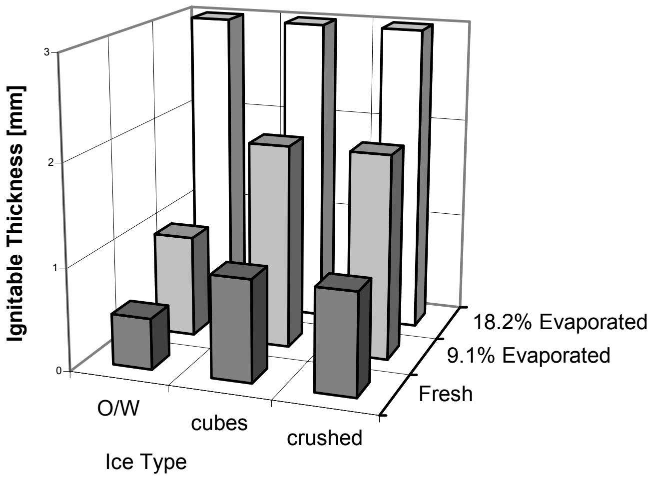


Figure 3-12: Pt. McIntyre min. ignitable thickness



The results for ANS crude (Figure 3-9) show that the minimum ignitable thickness increased with degree of weathering and that the presence of ice also increased minimum ignitable thickness. Fresh ANS, which was a blend of all the crudes produced on the North Slope of Alaska, on cold (approximately 1°C) water is ignitable at 0.5 mm., but needed 1 mm of oil when weathered to 10.3% or 16.8% evaporative loss. On cube ice, fresh ANS was also ignitable at 0.5 mm, but required 2-mm slicks to ignite when evaporated. On crushed ice fresh ANS needed 1 mm to ignite when fresh and 10.3% evaporated, but needed 2 mm when 16.8% evaporated.

Figure 3-10 shows the results for the Endicott crude. Fresh Endicott on cold water is ignitable at 1 mm, but needed 2 mm when evaporated 9.1% and 3 mm when evaporated 17.4%. On ice cubes, fresh Endicott needed 2 mm to ignite when fresh, and 3 mm when evaporated 9.1% and 17.4%. The 17.4% evaporated slick also required the addition of a gelled gas igniter to light. All three degrees of evaporation needed 3 mm of oil to ignite on crushed ice. Again, the 17.4% evaporated slick also required the addition of a gelled gas igniter to start.

The minimum ignitable thickness for Northstar crude is given in Figure 3-11. The fresh crude was ignitable at 0.5 mm on all three substrates; both weathered samples required 3 mm and the application of gelled gas igniters on all three substrates. This was probably due to the high pour point of the oil when weathered. Both weathered samples gelled when coming in contact with the cold water or ice. As such, they did not flow to form a continuous layer on the water or ice, rather they formed congealed lumps, which were too small to allow ignition. The three-mm thickness represents the point at which the oil could be manually spread into a continuous layer that would support combustion.

Figure 3-12 presents the results for Pt. McIntyre crude. The fresh oil on cold water was ignitable at 0.5 mm, but required 1 mm for the 9.1% and 3 mm for the 18.2% evaporated samples on water. On cubes, the minimum ignitable thickness increased from 1 mm for the fresh oil to 2 mm for the 9.1% evaporated sample and 3 mm for the 18.2% evaporated sample. The same results were obtained on the crushed ice. All test slicks were ignitable with the torch only.

The observed trend of increasing minimum ignitable thickness with increasing evaporation is related to the heat and mass transfer processes that control *in situ* burning (e.g., Buist et al. 1994). As described in Section 1.2, ignition of a slick on water is possible when the slick is thick enough to allow the surface of the oil to be heated by the ignition source to a temperature at, or above, the Fire Point of the oil. As crude oil evaporates it preferentially loses its more volatile components and it's Fire Point increases. An evaporated crude oil thus needs to be heated to a higher temperature to sustain combustion and thus, for a given igniter power, requires a thicker layer of insulation beneath it to achieve the higher temperature.

The trend of higher minimum ignitable thickness for slicks on ice, compared with water, probably relates to both the physical characteristics of the ice/oil interface and the rheology of the oil. The data indicate that minimum ignitable thickness was usually higher on ice than on water (except for the very volatile, fresh Northstar crude, where it was the same), but there is no clear effect of ice type. Minimum ignitable thickness was lower on crushed ice than cubes in one case, higher in two cases and the same in eight cases. It is postulated that the rough substrate interface between the oil and ice was more efficient at transferring heat from the oil to the underlying ice (through a larger interfacial surface area compared with oil on liquid water). The solid nature of the substrate would also restrict convective flows within the slick from spreading hot oil out over the surrounding cold oil. The uneven nature of the ice/oil interface also produced an oil slick of varying thickness, with oil pooling in some small areas. Certainly, evaporated oils that gelled when they came in contact with the ice were difficult to spread out evenly over the substrate, which made them generally more difficult to ignite. All the slicks were ignitable at 3 mm using gelled gas igniters typical of what would be generated by a Heli-torch aerial ignition system.

In general, the “rules-of-thumb” for minimum ignitable thickness 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 with gelled gasoline igniters.

3.2.3 Oil Removal Rate

Figures 3-13 through 3-16 give the calculated oil removal rates for each of the lab-scale test burns with the four crude oils.

Alaska North Slope. The calculated burn rates for the ANS crude on water in Figure 3-13 were in the 1.3-mm/min range on calm water and in the 0.9-mm/min range in waves. Previous laboratory burn tests with ANS (SL Ross 1998) have yielded similar results, with burn rates of 1.1 to 1.3 mm/min recorded for slicks of the same diameter and similar thickness (5 mm, instead of 3 mm here) on calm water and 1 to 1.1 mm/min in low waves. The expected average open water crude oil burn rate (a correlation of various researchers results) for a 40-cm diameter burn in quiescent conditions would be 1.1 mm/min (Buist et al. 1994). Note that different researchers calculate or measure burn rate using slightly different bases, thus exact agreement is not expected. In the earlier study, ANS removal rate on open water declined slightly with increasing degree of evaporation of the crude. The data from these ANS burns indicated little dependence of burn rate on evaporation.

The burn rate for ANS on ice cubes and the crushed ice in calm conditions was about half that on open water. This was further evidenced by the much lower flame heights observed, indicative of a reduced fuel supply rate to the combustion zone in the air above the slick. In some of the quiescent burns on ice the heat from the fire would melt the raised surfaces of the ice pieces, allowing the oil to spread more evenly, and thus burn better. As well, particularly on the crushed ice, the heat from the flames would create a thin layer of water trapped on the surface of the ice, which allowed the oil to burn as if it were on water. These phenomena were visually apparent, as the flame height would suddenly increase over an area of the burn ring. If the water drained off the ice surface during this phenomenon, the flame heights would immediately decrease. It is believed to be this phenomenon, combined with the smoother interface with the oil, that resulted in the burns on crushed ice consistently having a slightly higher burn rate than those on cubes in similar conditions.

Burn rates for ANS crude on ice in waves were similarly reduced by about half, compared with open water burns in waves. In the case of the ANS burns on ice in waves there were differences noted between the burns on cubes and those on crushed ice. In waves, the ice cubes tended to move independently, which created a "turbulent" substrate on which the oil was burning; as soon as the waves were started (after the flames, initiated by four gelled-gasoline igniters, reached 50% coverage) the fire would die back almost immediately to a small area adjacent to the igniters. On the other hand, the crushed ice tended to move *en masse* behaving like a small floe rocking in gentle waves. During the course of a burn on crushed ice in waves, the mass would usually break into two or three small "floes" moving independently, which would immediately reduce the flame height (and thus, the burn rate).

Endicott. The burn rates for the Endicott test series are given in Figure 3-14. The quiescent open water burn rate declined from 1.3 mm/min for the fresh crude to 0.95 mm/min for 17.4% evaporated Endicott. This decline was not unexpected for a crude oil burned at this scale (SL Ross 1998, Bech et al. 1992). It may be that Endicott crude, being the oil with the highest density, and thus the greatest proportion of heavier, higher molecular weight components, exhibited this behavior, while the other, lighter oils did not. The burn rates on ice in calm conditions were about 50% of the open water rate, with burns on crushed ice being slightly faster than burns on cubes. The burn rate for these tests also appeared to decline slightly with increasing evaporation of the oil. As with the ANS tests, the quiescent burns on crushed ice resulted in a higher burn rate than the burns on ice cubes.

The open water Endicott burns in waves resulted in reduced burn rates, compared with calm conditions; however, only the burns on ice with fresh Endicott exhibited significantly reduced burn rates compared with the quiescent burns of fresh Endicott on ice. Apparently other unknown factors were controlling the burn rate for the burns on ice in waves for this oil.

Northstar. Figure 3-15 shows the removal rate data for the Northstar crude oil test burns. The burns on open water without waves had burn rates of 1 to 1.2-mm/min. The equivalent burns on ice in quiescent conditions were about half that rate. It was not possible to conclude, for this oil, whether burns on crushed ice were faster than burns on ice cubes.

The presence of waves reduced the Northstar open water burn rate but did not demonstrably reduce the burn rates on ice. Evaporation did not seem to significantly affect burn rate for any of the tests with this oil. It should be noted that both evaporated oils gelled rapidly when poured onto the surface in the burn ring.

Pt. McIntyre. Figure 3-16 gives the burn rate results for the Pt. McIntyre crude. For this oil, the open water burn rates in both calm conditions and waves were nearly identical, 0.9 to 1.1–mm/min. The burn rate on ice data was quite scattered, making it difficult to discern any trends; however, as can be seen on the graph, burn rates on ice were all less than on open water for this oil.

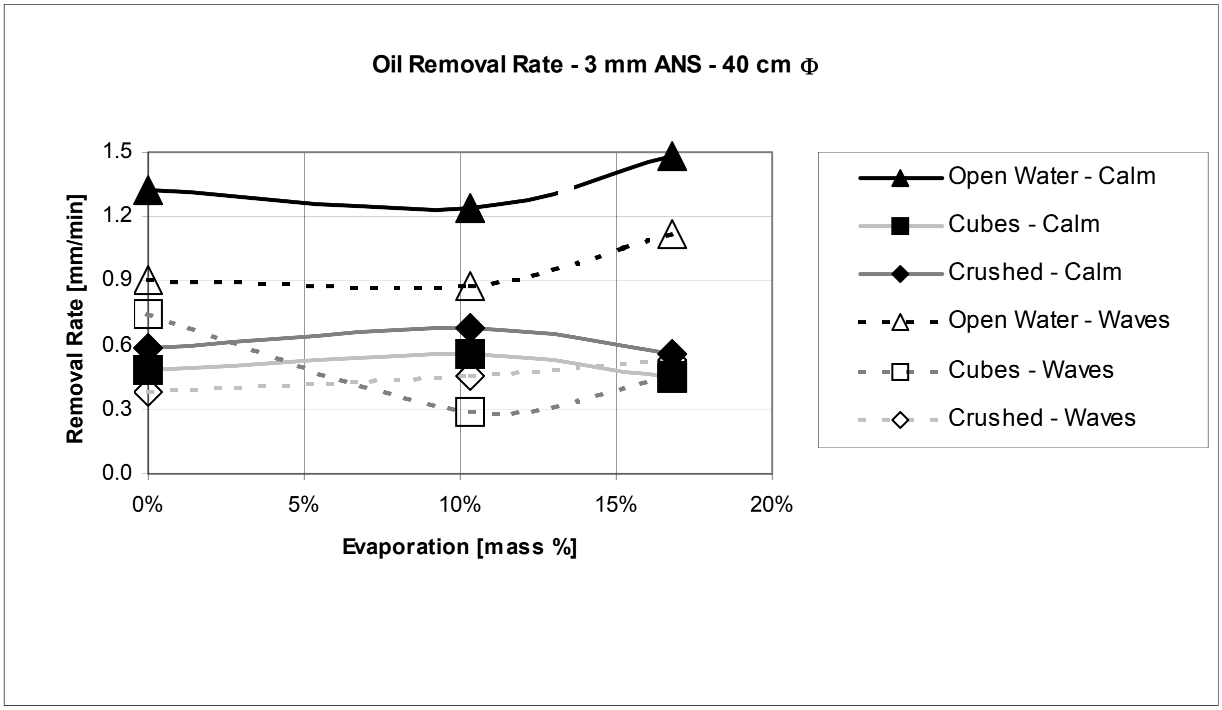


Figure 3-13: Lab-scale oil removal rate results for ANS crude.

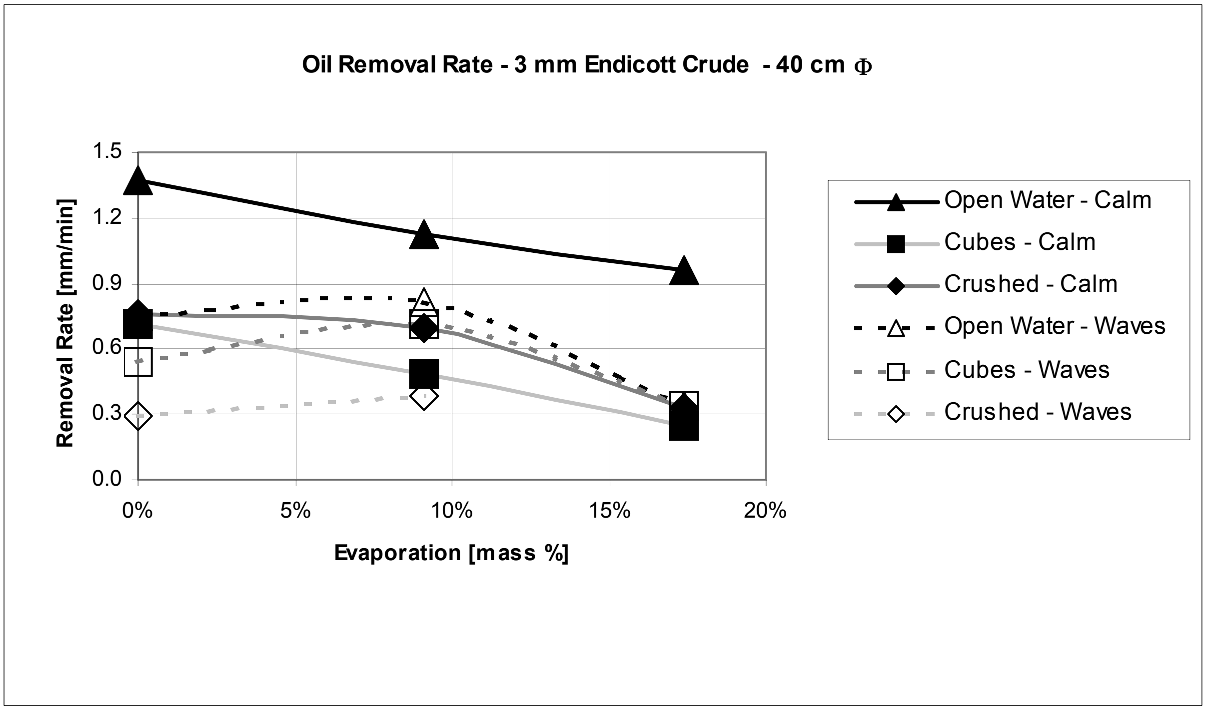


Figure 3-14: Lab-scale oil removal rate results for Endicott crude.

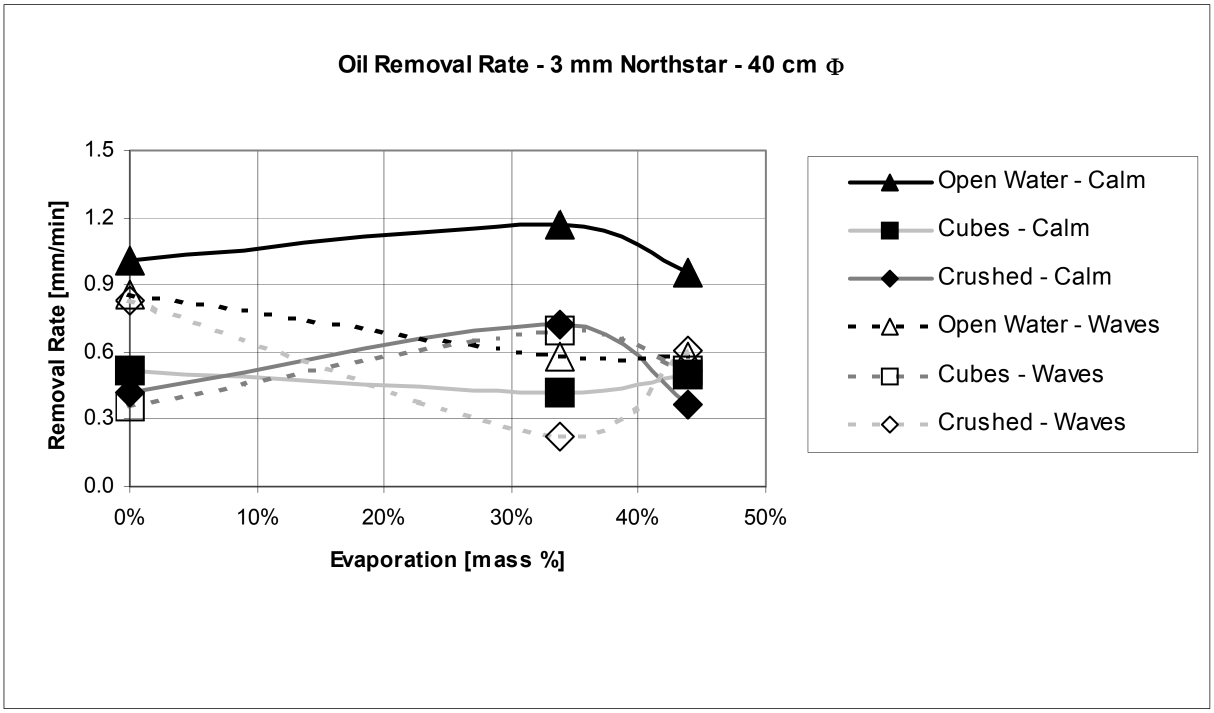


Figure 3-15: Lab-scale oil removal rate results for Northstar crude.

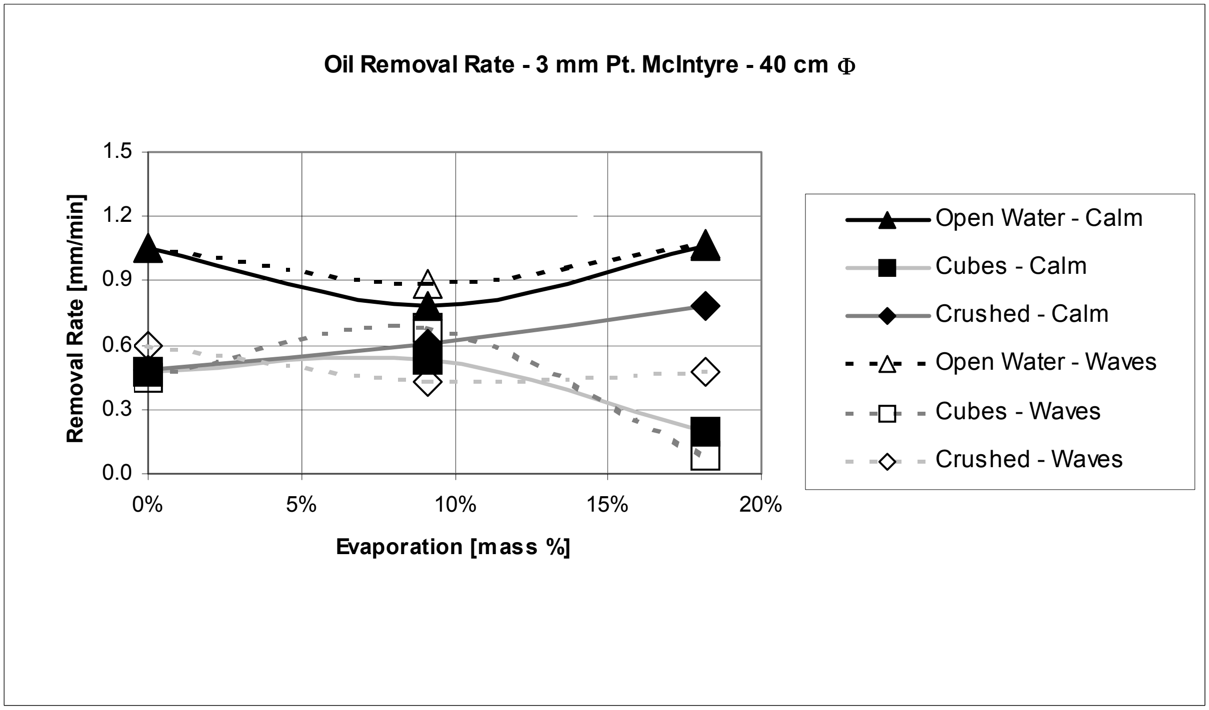


Figure 3-16: Lab-scale oil removal rate results for Pt. McIntyre crude.

3.2.4 Oil Removal Efficiency

Figures 3-17 through 3-20 show the measured oil removal efficiencies for each of the lab-scale test burns with the four crude oils.

Alaska North Slope. The results for the ANS crude burn tests are given in Figure 3-17. The burn efficiencies for the open water tests in calm conditions ranged from 67 to 76%. This corresponds well with the “rule-of-thumb” of 1-mm residue, which would suggest a removal efficiency of 67% for a 3-mm slick. These quiescent, open-water results are also in agreement with those obtained in a previous study with ANS crude (SL Ross 1998). The burns of fresh ANS on the two ice substrates resulted in low efficiencies (this also inexplicably happened for the Pt. McIntyre crude – see Figure 3-20) equivalent to 2 mm of residue remaining. The efficiencies achieved with the two weathered samples on ice were higher because they involved a vigorous burn phase. Discounting the fresh ANS on ice data points, the effect of burning on ice appears to be a slight reduction in burn efficiency, from about 70% to about 60% for the weathered oil on crushed ice (equivalent to leaving a residue of about 1.2 mm), and to about 50% for the weathered oil on cubes (equivalent to leaving a residue of about 1.5 mm). The efficiency reduction is likely due to the colder interface temperature of ice (which cannot be heated above 0°C until it melts), as opposed to water (which can warm to 100°C) resulting in the flames extinguishing sooner and leaving more residue on ice than on water. The differences in the results from the two ice substrates may relate to either substrate interface roughness differences (greater heat transfer to the cube substrate due to its greater area), or the fact that the crushed ice could melt more easily to form pools of melt water retained on the consolidated ice, whereas the cubes could not.

The tests in waves produced oil removal efficiencies consistently lower than those in calm conditions. The burns on open water in waves resulted in efficiencies about 10% to 20% lower than the equivalent tests on calm water, consistent with the results of previous tests (SL Ross 1998). The burns on crushed ice in waves were 35% to 45% efficient, about ⅔rds of those in calm conditions, while the burns on cubes in waves were very inefficient, resulting in removals of only 2% to 20%. This is equivalent to the burns on crushed ice in waves leaving a residue of nearly 2 mm, and the burns on cubes leaving a residue of nearly 3 mm. The crushed ice was able to form a consolidated ice mass for at least a portion of the burn, allowing the oil to burn in a relatively quiescent environment, with perhaps some water between the oil and the ice. The cubes did not consolidate, and tended to move independently in the waves, which would greatly enhance the heat transfer from the oil to the ice below. Both burns on ice substrates exhibited very low flame heights, a strong indication of a low supply rate of fuel vapors due to restricted volatilization of the liquid oil slick.

Endicott. Figure 3-18 shows the efficiency results for the Endicott burns. The results for the quiescent burns on open water show a decline in removal efficiency with increase in evaporation, which has been noted by previous researchers for thin crude oil slicks (Bech et al. 1992). It may be that Endicott crude, being the oil with the highest density, and thus the greatest proportion of heavier, higher molecular weight components, exhibited this behavior, while the other, lighter

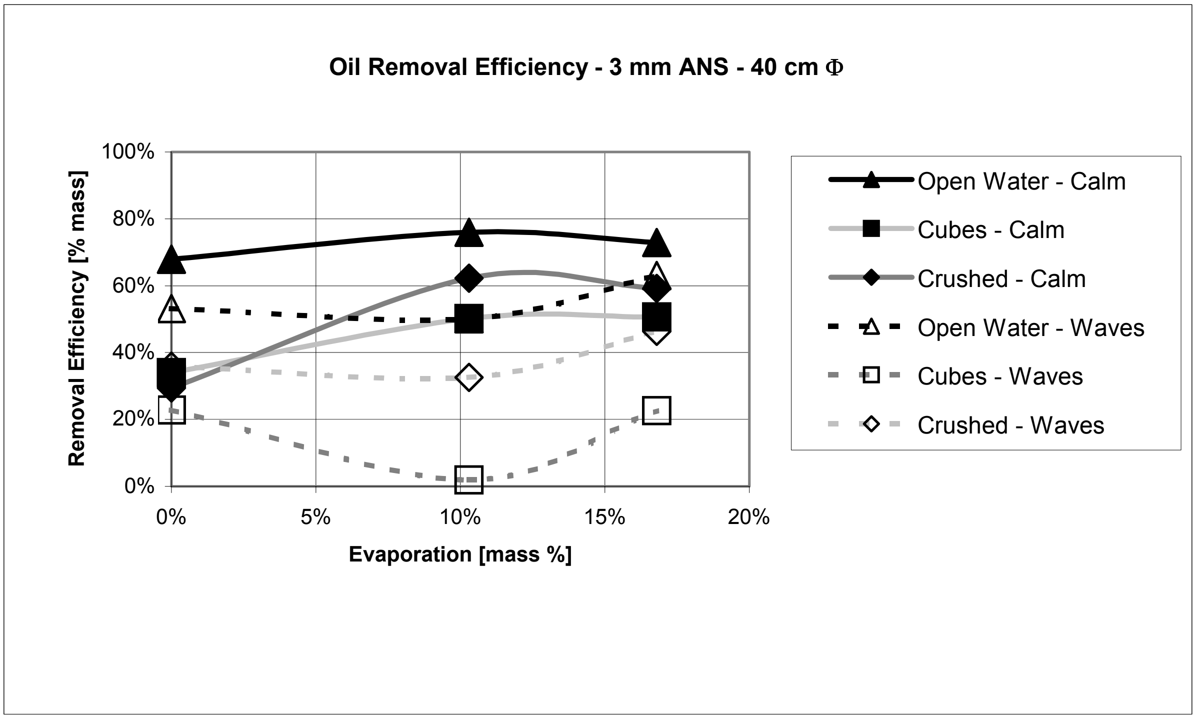


Figure 3-17: Lab-scale oil removal efficiency results for ANS crude.

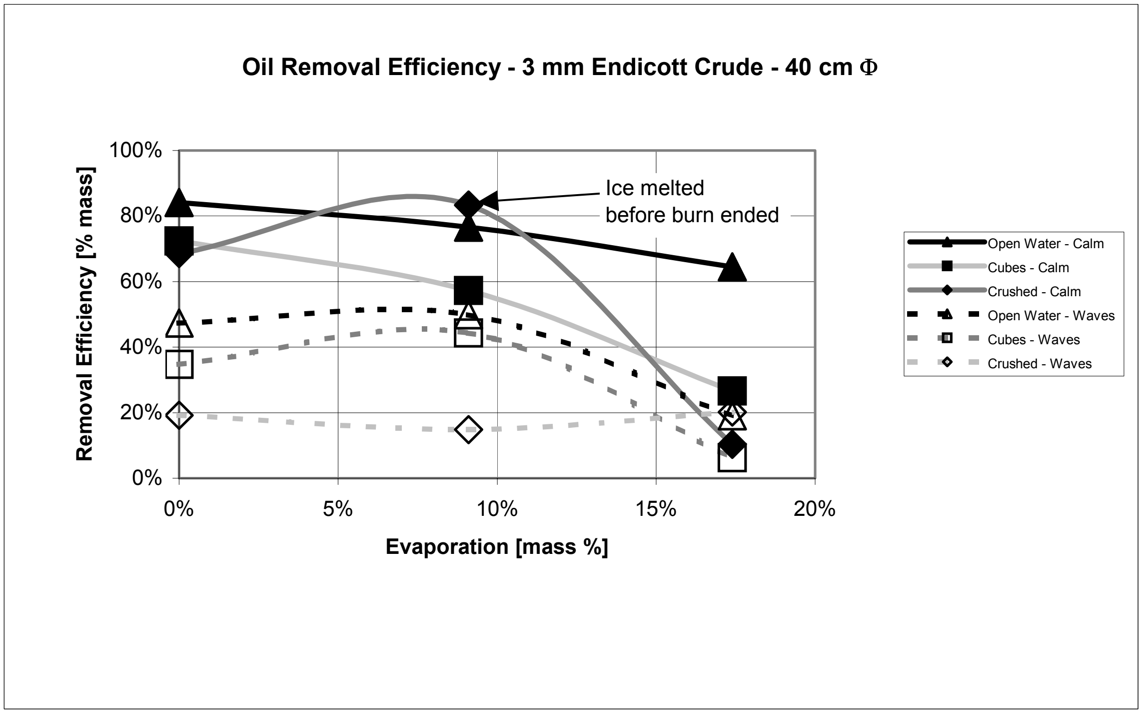


Figure 3-18: Lab-scale oil removal efficiency results for Endicott crude.

oils did not. The burn test with 9.1% evaporated Endicott on crushed ice in calm conditions resulted in the melting of the ice beneath a portion of the slick prior to the end of the test. The flame height increased dramatically at this point, the burn progressed into a vigorous phase, and an unusually high removal efficiency was obtained. The other data points for quiescent burns on ice indicate the same trends noted for ANS crude, reduced burn efficiency on an ice substrate, although the differences between crushed and cube ice is not the same as with the other oils. In waves, the open water burn efficiencies were reduced significantly compared with the calm tests, being consistently nearly 40% less. This would be equivalent to an additional 1 mm of residue. The data for burn tests on ice in waves also indicated a decrease in efficiency compared with the calm tests, although the data is scattered. For the 17.4% evaporated Endicott, all the tests except the open water burn in calm conditions resulted in very poor burn efficiencies, in the 5% to 25% range.

Northstar. Figure 3-19 shows the removal efficiency data obtained from the test burns with Northstar crude. As was the case with the ANS tests, there was little effect of evaporation on the open water quiescent burn efficiency, which ranged from 73% to 79%, equivalent to residue thicknesses of 0.6 to 0.8 mm. This slightly higher range of removal efficiency may relate to the lighter, more volatile nature of Northstar crude, compared with ANS. The burns on ice in calm conditions resulted in reduced burn efficiencies, in the 45% to 55% range on crushed ice and in the 30% to 50% range on cubes. The equivalent increases in residue thickness would be from about 0.6 to 0.8 mm on open water to 1.4 to 1.6 mm on crushed ice and 1.5 to 2 mm on cubes. Wave action further reduced the burn efficiencies. On open water the efficiencies were reduced by 20% to 30%, adding nearly 1 mm to the residue remaining. The reductions in efficiency for burns on ice caused by wave action were relatively smaller, on the order of 10% to 20%, equivalent to adding an additional 0.5 mm or so of residue. The burn efficiencies were lower on cubes in waves than on crushed ice in waves, as discussed above.

Pt. McIntyre. Figure 3-20 presents the results for the Pt. McIntyre crude oil test burns. The open water burn efficiencies in calm conditions showed a slight negative dependence on evaporation and averaged nearly 60%, slightly lower than the ANS and Northstar crudes, probably due to the heavier nature of Pt. McIntyre crude. The burn efficiencies for the burns of fresh oil on ice in calm conditions were both approximately 20%, indicating that the residue remaining was about 2.5 mm. The burn with the 9.1% evaporated oil on cubes was anomalous, with a 48% removal efficiency, in that it involved a vigorous burn phase involving about half the area inside the ring, indicating that the heat from the flames had melted all the ice under the slick in that portion of the slick. The burn test with the 18.2% evaporated oil in calm conditions on cubes did not involve a vigorous phase, and resulted in 14% removal efficiency. Both burn tests with the evaporated oil on crushed ice in calm conditions involved vigorous burn phases, and resulted in removal efficiencies in the range of 50 to 60%.

The removal efficiency results for the open water burns with Pt. McIntyre in waves were almost identical to those obtained in calm conditions. The burns on ice in waves were far less efficient than their counterparts in calm conditions, with the burns on cubes being less efficient than the burns on crushed ice. The burns on ice in waves left residues of 2 to 3 mm, with the amount increasing with increased evaporation of the oil.

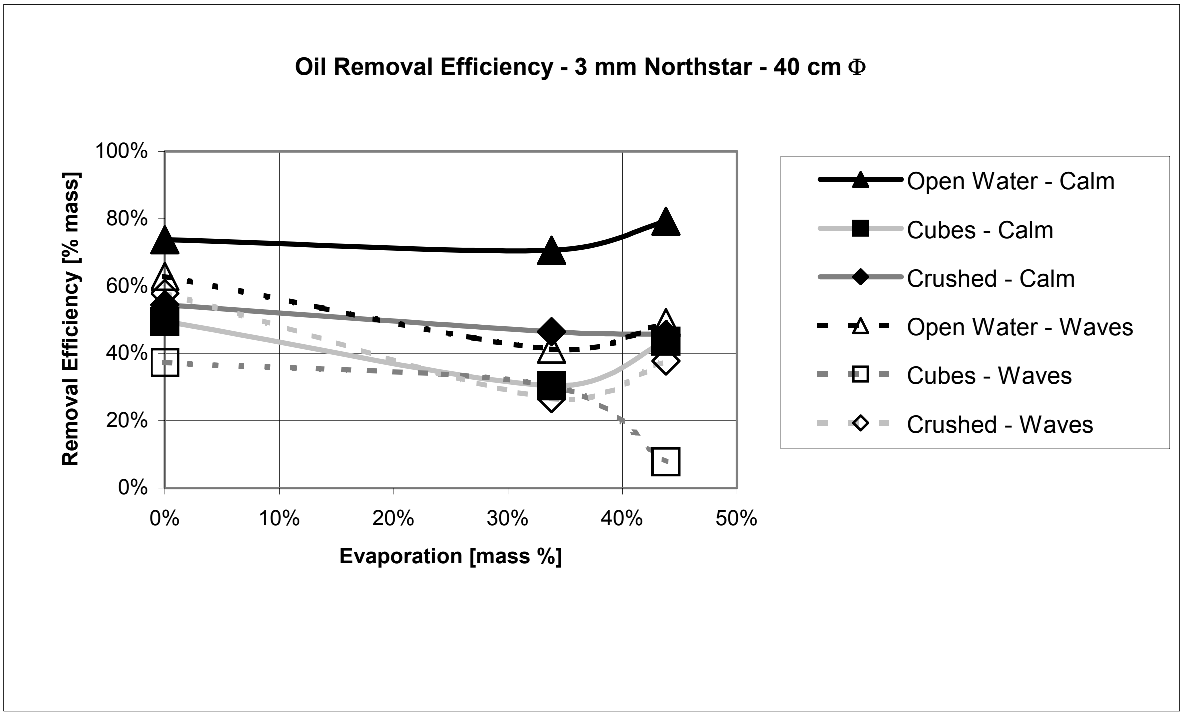


Figure 3-19: Lab-scale oil removal efficiency results for Northstar crude.

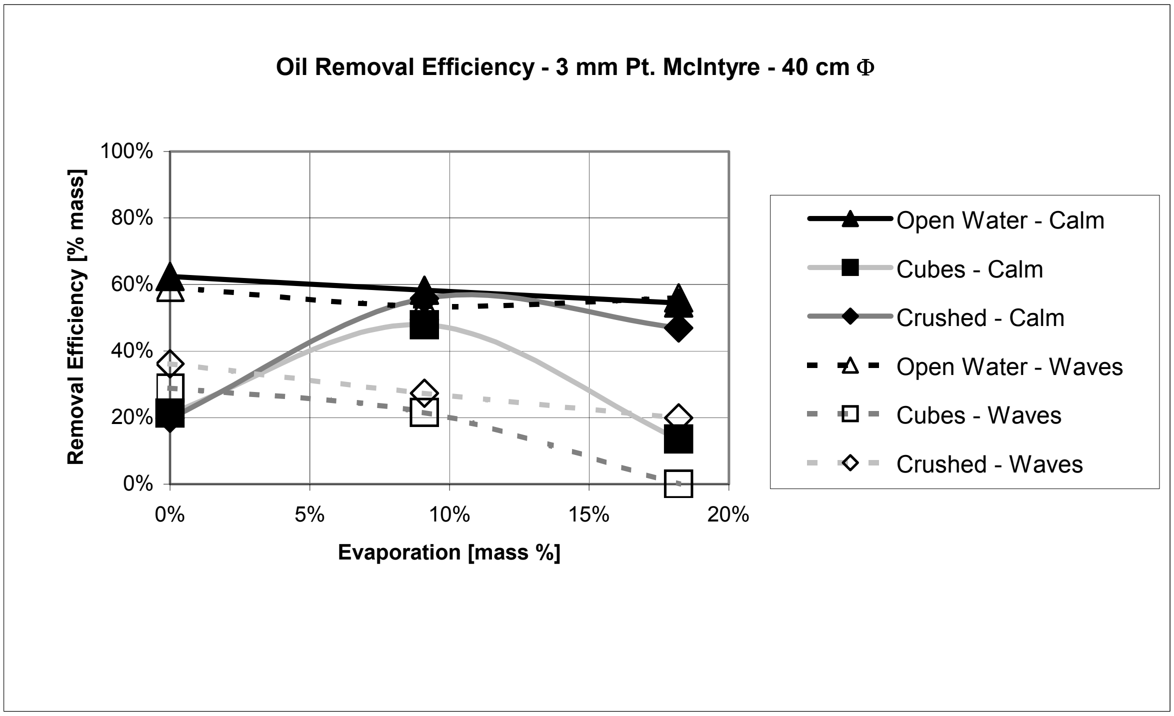


Figure 3-20: Lab-scale oil removal efficiency results for Pt. McIntyre crude.

4. MID-SCALE BURNS AT PRUDHOE BAY

This chapter describes the mid-scale test burns conducted at the BP Fire Training Ground in Prudhoe Bay, AK. The same four Alaskan North Slope crude oils were used for this phase 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.

4.1 Oil Weathering

The oils for the mid-scale tests were artificially evaporated using the same basic technique used for the small-scale tests, except at a larger scale. 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 4-1 shows the degrees of evaporation achieved. The record sheets for the oils can be found in Appendix B. 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 4-1: 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%.

4.2 Test Ice

As described in Section 2.3, the mid-scale tests were designed around two forms of new ice that could be readily simulated under natural field conditions. The rationale behind selecting the general form of test of ice is described in Section 2.3. A number of options were considered for creating the required volume of test ice: for example, growing ice in a series of "Fast Tanks" for harvesting as needed, and possibly collecting natural sea ice from the Arctic Ocean off West Dock, about 10 miles by road from the test site. In the end, the simplest solution was to grow all of the ice in a single large sheet, to be cut and loaded into the tank as needed. This procedure is described below in more detail.

4.2.1 Ice Preparation Procedures

This section describes the proposed field procedures aimed at producing sufficient ice with the desired characteristics to carry out the mid-scale test program. A total of 36 tests were planned: 16 involving burns with 3 mm of each oil in brash ice and 16 involving burns with 3 mm of oil in frazil or slush ice (Section 4.6 describes the full test matrix).

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).

Brash Ice Production The solid ice area needed to generate the necessary volume of brash ice was estimated as 41.4 m^2. This figure was arrived at as a worst-case estimate by multiplying the number of tests planned with this form of ice (18) by the individual test area (approximately 2.3 m^2). In practice, the area of ice required was reduced significantly by allowing a portion of the ice from 13 of the tests to make use of ice remaining from the previous burn (see below).

The ice was started one week ahead of the tests by adding brackish Prudhoe Bay water to a shallow, lined above-ground pit with dimensions of approximately 6.5 m on a side. The pit was located approximately one hundred metres from the wave tank at the fire training facility (Figure 4-9). Warmer than average October temperatures persisted through the entire test program (Appendix D) and slowed the expected ice growth. Several days with colder night-time temperatures prior to the first test, hardened the ice and enabled the harvesting of brash ice to begin on schedule, October 24.

The target ice thickness was reached and held for the entire sheet by freezing the seawater to the bottom (full depth of the pit). The measured thickness of randomly-selected blocks averaged 12.4 cm, with a uniformity within 1 cm. The top 3.8 cm of the ice consisted of snow ice, opaque white in appearance. The central part of the sheet (6.4 cm) was hard sea ice with a normal and distinct vertical crystal orientation. The bottom 2.2 cm of the ice was made up of the soft skeletal layer (individual loose crystals) similar to that found in natural sea ice.

Brash Ice Harvesting, Loading and Consumption Blocks were cut from the main sheet with ice chisels in a 30 cm x 30 cm pattern (Figure 4.2-1). The ice separated cleanly from the liner, aided by the layer of brine solution trapped at the bottom of the ice. Twenty-five blocks were sufficient to fill the burn ring to an ice concentration of 9/10 or more (over 90% coverage by area). Of these, approximately 10 blocks were kept whole (45%), and the remainder divided evenly into two size distributions: 7 to 8 blocks broken into four 15 cm x 15 cm cakes, and 7 to 8 blocks smashed into piece sizes in the order of 5 to 10 cm. Figure 4.2-2 shows the mix of piece sizes resulting after the blocks for one test were prepared prior to loading (see below).

The distribution of ice piece sizes used at Prudhoe was similar to that used recently in larger-scale tank tests at Ohmsett. The relative breakdown of floe sizes for those tests (January 2002) was based on an analysis of photographs of pack ice composition during previous field experiments (Buist et al., 2002).

Figure 4.2-1: Removing 30 cm "brash" ice blocks from the test sheet.

Figure 4.2-2: Final distribution of brash ice piece sizes prior to loading into burn ring.

Sufficient brash for one test was loaded manually into a plastic tote (0.4 m^3 capacity) and slung under the forks of a front end loader for transfer over and up to the side of the tank where it was manually loaded into the burn ring as the appropriate mix of piece sizes (Figure 4.2-3).

After each brash ice burn, it was necessary to make-up some of the ice consumed or depleted by the heat (mostly the smaller pieces). Photographs were taken of each ice sheet before and after the burn. Examples are shown in Figures 4-12 and 4-14. The total ice area required to complete 16 burns with brash ice was 16.4 m^2 , less than half of the area that would have been needed had the full ice sheet been replaced for every burn. By scheduling the test matrix such that groups of burns in similar ice were grouped together, the requirement to fully empty and fill the fire ring with ice was minimized. On average, each burn consumed approximately 25% of the ice in the ring. Following each burn in a consecutive series of brash ice tests, a mix of new ice was added until the composition of ice pieces in the burn ring closely approximated the original composition (first burn of the series).

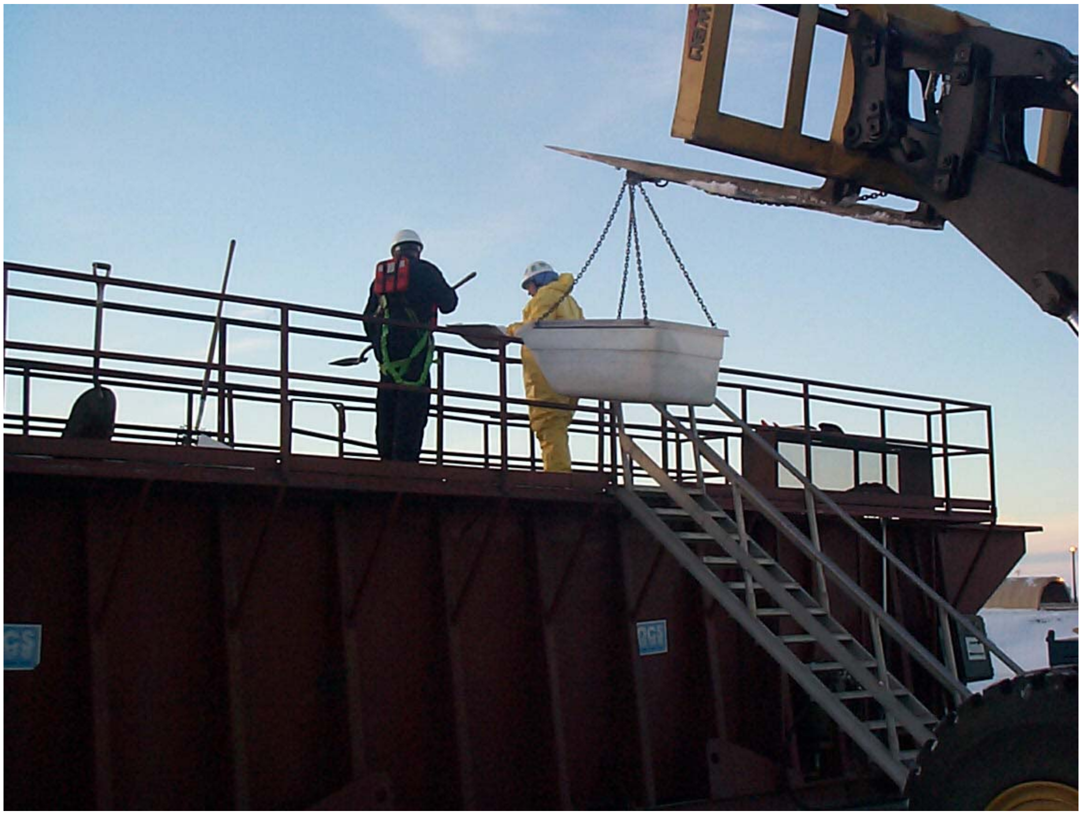


Figure 4.2-3: Brash filled tote being unloaded into the burn ring.

Areas where the oil burned directly on the ice surface were left about 2 to 2.5 cm lower than adjacent unoiled ice. Consequently, the overall thickness of the brash ice was reduced slightly through consecutive burns, reflecting the mix of ice ages and sequential loss in thickness for a percentage of the population of ice pieces making up each burn. This correction is accounted for in the spreadsheet for the mid-scale burns in Appendix D, and amounted to an estimated loss in average ice thickness of approximately 2.3 cm over four consecutive burns in brash ice (from 12.4 to 10.1 cm).

Slush Ice Production The plan for slush ice production was based on harvesting an appropriate volume of snow from around the test site and dumping it directly into the burn ring to simulate slurry of frazil and grease that occurs naturally during freeze-up (Figure 2-3). Based on a typical snow density of 0.35, approximately 2.6 times more snow than ice would be required to form a 12 cm layer of slush within the burn ring. On this basis, the approximate volume of snow required to accomplish the planned 18 tests with slush ice was estimated to be approximately 11 m^3 (386 cubic feet). In practice through grouping of tests and reuse of slush remaining from previous burns, the overall snow volume required was about half that value.

Slush Ice Harvesting, Loading and Consumption Snow was manually loaded into the same plastic totes used to haul the brash ice and slung up to the side of the tank where the snow was shoveled directly into the burn ring. In practice, 1.5 tote loads (0.6 m^3) produced a slush layer 15 to 20 cm thick indicating that the snow density was higher than initially assumed. After the first test it was decided that this was a realistic thickness to use for all of the slush ice burns. Figures 4-15 and 4-17 show the typical appearance of the slush ice in the test ring.

The slush ice thickness was measured before and after each burn, and sufficient make-up snow was added to maintain close to a constant starting slush thickness for each burn. Initially, an additional 1/2 a tote (or 1/3 of the initial snow volume) was required after each burn to maintain the thickness. After the first day, it became necessary to add over half of the initial volume again after each burn to maintain the thickness (reflecting the higher water temperature). The average slush depth over 13 burns was 18 cm (range was from 14 to 20 cm). Refer to Appendix D for the full record of slush thickness.

4.3 The Wave Tank

The burn tests were conducted in a transportable wave tank (Figures 4-1 and 4-2) 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 (Figures 4-3 and 4-4) and passive wave absorbers (Figure 4-5) at the other. With 1.8 m (72") of water in the tank, the wave maker is capable of generating waves with heights to 0.6 m (2') with periods ranging from 1.7 to 3.3 seconds. The corresponding wavelengths are 4.2 to12 m. Small waves with shorter wavelengths are also possible. 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 broken 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 (Figure 4-6). Originally it had been intended to fill the tank with seawater (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 4-7). 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).

Figure 4-1: Transportable wave tank at the Fire Training Ground.

Figure 4-2: View of test burn in tank from lift basket.

Figure 4-3: Wave board and back-wave absorber panels.

Figure 4-4: Electronic control panel and hydraulic drive system for wave board.

Figure 4-5: Wave beach at opposite end of tank.

Figure 4-6: Pump system to feed water to deluge pipes along tank walls (see above picture).

Figure 4-7: Wave tank covered with tarp for night.

Figure 4-8: Warm-up trailer and portable diesel generator.

4.4 Site Layout and Ancillary Equipment

Figure 4-9 shows a schematic drawing of the layout of the major pieces of equipment at the Fire Training Ground. In the foreground of Figure 4-1 can be seen one of the portable diesel-fired forced-air heaters used to warm the tank, the diesel/hydraulic power pack used to drive the wave generator, and the decontamination shelter. In the background of Figure 4-1 is the well-house fire prop on which the portable weather station was placed (at a height of 8.8 m or 29 feet), and the shipping container used for storing and measuring the oil and residue and preparing the gelled gas igniters. On the bottom left of Figure 4-2 is the oily waste container. Figure 4-8 shows the warm-up trailer and the portable diesel electric generator.

Figure 4-10 shows the shipping container and another diesel-fired forced air heater. Figure 4-11 shows the lift used to observe, photograph and video the test burns.

4.5 Gelled Fuel Preparation

Two types of igniters were required for the tests: gelled gasoline and hand-held (Dome) igniters. None of the latter were ultimately required. The detailed procedures for mixing the gelled gasoline are given in Appendix C. Gelled fuel mixing took place just outside the heated, ventilated oil storage/mixing container shown on Figure 4-9 to limit exposure to gasoline fumes (note the drip tray outside the container used for mixing the gelled gas igniters). Only a few litres of gelled gas were mixed each time. Once gelled, the volatility of the gasoline is greatly reduced, and the baggies containing 4 ounces of gelled gas that were used as igniters were prepared inside the container.

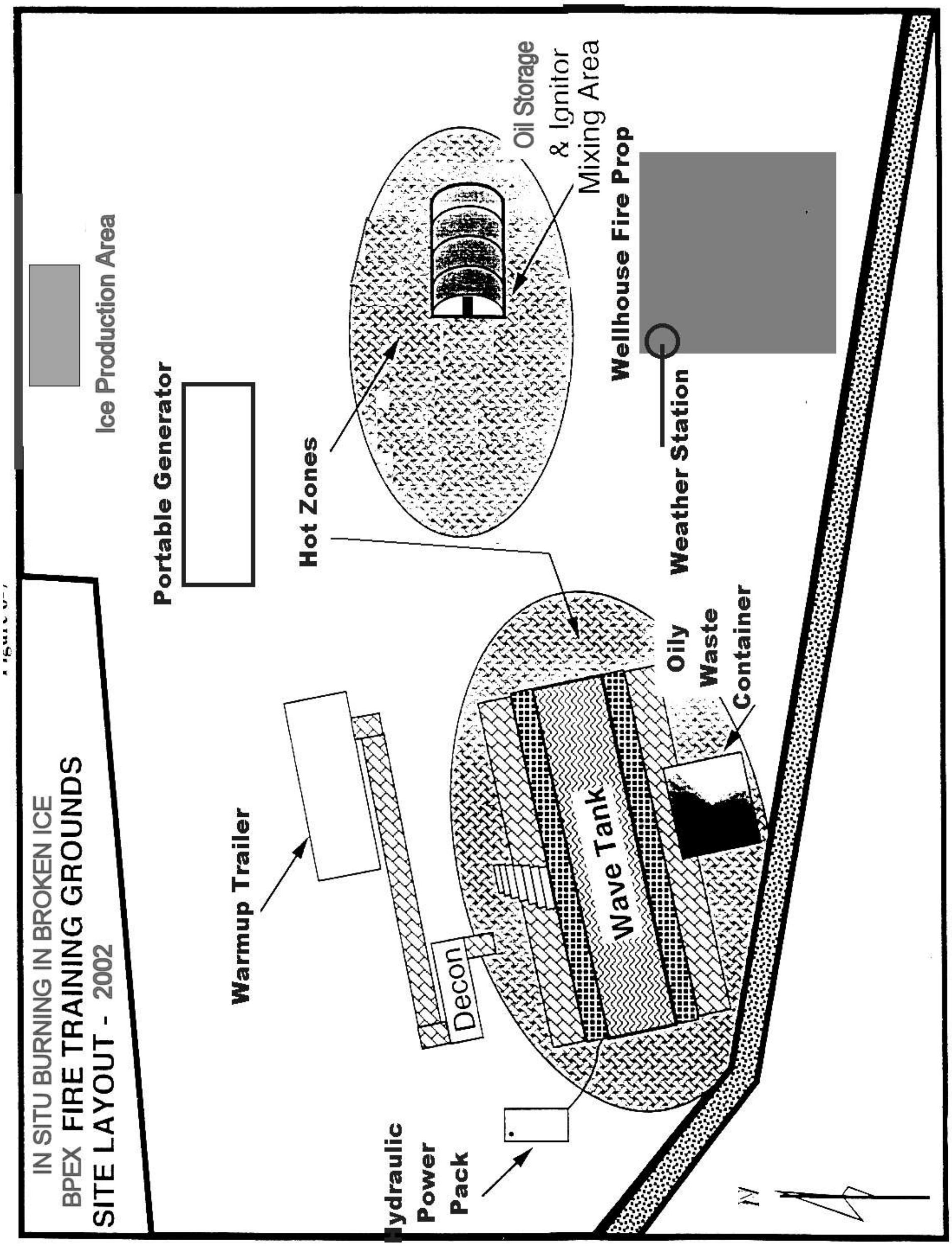


Figure 4-9: Site layout schematic.

Figure 4-10: Container used for oil storage, measurements and gelled gas igniter preparation.

Figure 4-11: Lift used for test photography and video.

4.6 Mid-scale Test Plan

4.6.1 Burn Test Matrix

The mid-scale experimental burns involved contained slicks with a diameter of approximately 1.7 m (5.5 feet). The test program was intended to include ignition and burning tests with four oils (Alaska North Slope, Endicott, Northstar and Pt. McIntyre crudes) in two ice conditions (brash or frazil) with several slick thicknesses (depending on the small-scale tests results), with some tests in waves (long wavelength). A total of 36 tests were planned: 16 involving burns with 3mm of each oil in brash ice and 16 involving burns with 3mm in frazil ice. The equivalent of four tests were to be devoted to determining Minimum Ignitable Thickness (MIT) for each oil in brash and frazil. It was planned that, time permitting; baseline burns on open water (MIT and 3mm in o/w and waves) would also be conducted. The test matrix actually achieved was:

Oil	Percent Evaporated	Brash Ice		Frazil Ice		Minimum Ignitable Thickness		Optional Open Water Burns
		Calm	Waves	Calm	Waves	Brash	Frazil	
ANS	0	✓	✓	✓	✓			✓✓
Endicott	0	✓	✓	✓				✓
	9.4	✓		✓				✓✓
	13.9	✓	✓	✓				✓
Northstar	0	✓	✓	✓	✓		✓	✓✓
	33.8	✓	✓	✓	✓			✓✓
	43.8	✓	✓	✓	✓			✓✓
Pt McIntyre	0	✓	✓	✓	✓			✓

4.6.2 Burn Ring

The burn ring (Figure 4-12) 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.

4.6.3 Burn Test Procedures

Equipment Required

- Wave tank c/w hydraulic power pack, Tioga heaters and fabric cover, deluge piping, hoses and pump
- Front-end loader capable of lifting ice over edge of tank

- Portable weather station
- Digital thermometer
- Stop watch
- Electronic balances (200 and 500 lbs)
- Clear plastic residue bags
- Sorbents for residue recovery/weighing
- Video camera
- 35-mm camera
- Lift for photography and video
- Shovels, rakes and pitchforks for residue recovery
- Propane torch on pole for igniting baggies of gelled gas
- Gelled fuel igniters
- Hand-held igniters
- Empty containers and warmed shipping container for melting ice

The procedures for each test were as follows:

1. Place desired amount of ice type in burn ring (nominally a 10 cm thickness in a 1.7 m diameter ring is 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. Manually spread oil evenly over surface of ice.
4. 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.
5. First, ignition was attempted with the torch alone. Next, a baggie containing 4 fluid ounces of gelled gasoline was used to ignite the slick. The gelled fuel bags were placed on the oil then ignited with a propane torch taped to a pole. 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 the tests involving waves four gelled gas igniters were used.
6. 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).
7. 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).

8. 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.
9. 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
10. The burn efficiency and burn rate were calculated using equations 2 and 3 given in Section 3.1.3.
11. 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 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%.

4.7 Mid-scale Burn Test Results

Complete test results from the mid-scale burns at Prudhoe Bay may be found in Appendix D. The first experiment was intended to be a Minimum Ignitable Thickness test; however, it proved to be impossible to evenly spread a very thin layer of oil over the ice surface in the cold, and further attempts at these tests were abandoned, and the Test Matrix was altered to incorporate open water tests for all the candidate oils.

In total, 42 burns (see Section 4.6.1) were conducted, including the one Minimum Ignitable Thickness attempt. Figure 4-12 shows the burn ring filled with a typical batch of fresh brash ice, Figure 4-13 shows the subsequent burn and Figure 4-14 shows the ice after the residue has been recovered. Figures 4-15 through 4-17 show the same sequence for frazil, or slush, ice. Figure 4-18 shows a typical open water burn.

4.7.1 Oil Removal Rate

Alaska North Slope. Figure 4-19 shows the burn rate data obtained for the fresh ANS crude (recall that no evaporated samples of ANS were tested). The fresh 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 almost the same as 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 4-20 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 at about 20% the open water burn rate (see Section 2.2.1). 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 of the residue combined to result in the 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.

Figure 4-12: Brash ice in ring prior to oil addition.

Figure 4-13: View from lift of test burn on the brash ice.

Figure 4-14: Brash ice after burn and residue recovery.

Figure 4-15: Fresh frazil, or slush, ice in ring prior to adding oil.

Figure 4-16: Test burn on frazil, or slush, ice.

Figure 4-17: Recovering residue from burn ring after burn on frazil, or slush, ice.

Figure 4-18: Typical open water burn test.

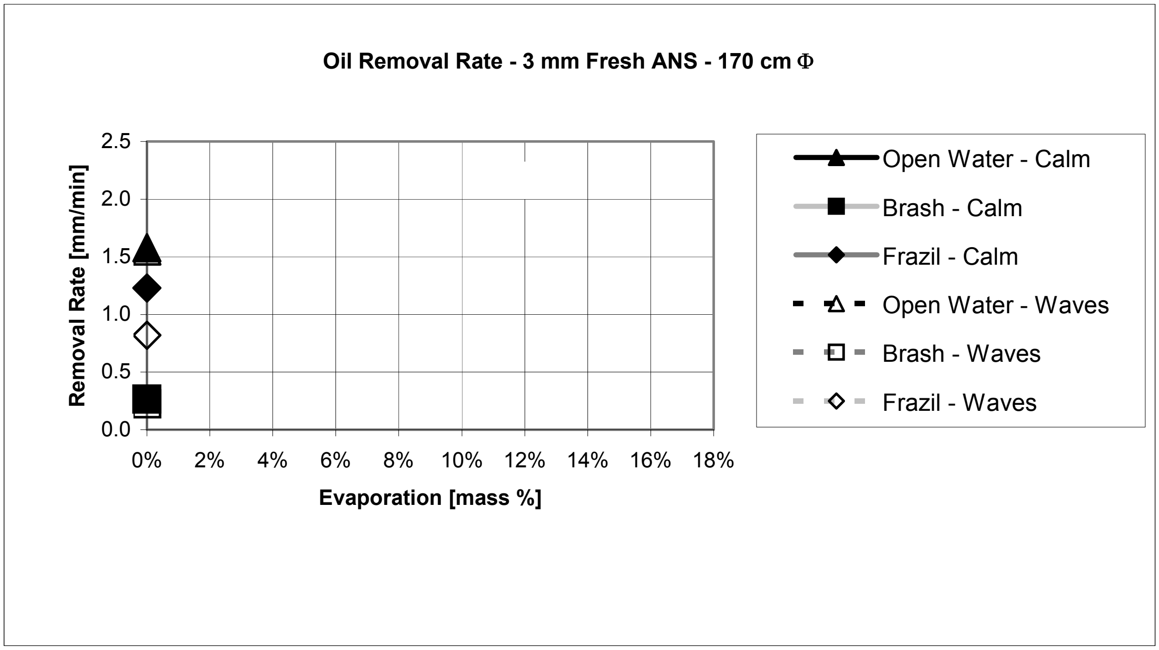


Figure 4-19: Oil removal rate results for fresh ANS test burns.

Northstar. Figure 4-21 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 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 presence of 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. 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 4-22. 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.

4.7.3 Oil Removal Efficiency

Alaska North Slope. Figure 4-23 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). These are broadly consistent with the results for the fresh Endicott, and the lab-scale results.

Endicott. Figure 4-24 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 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

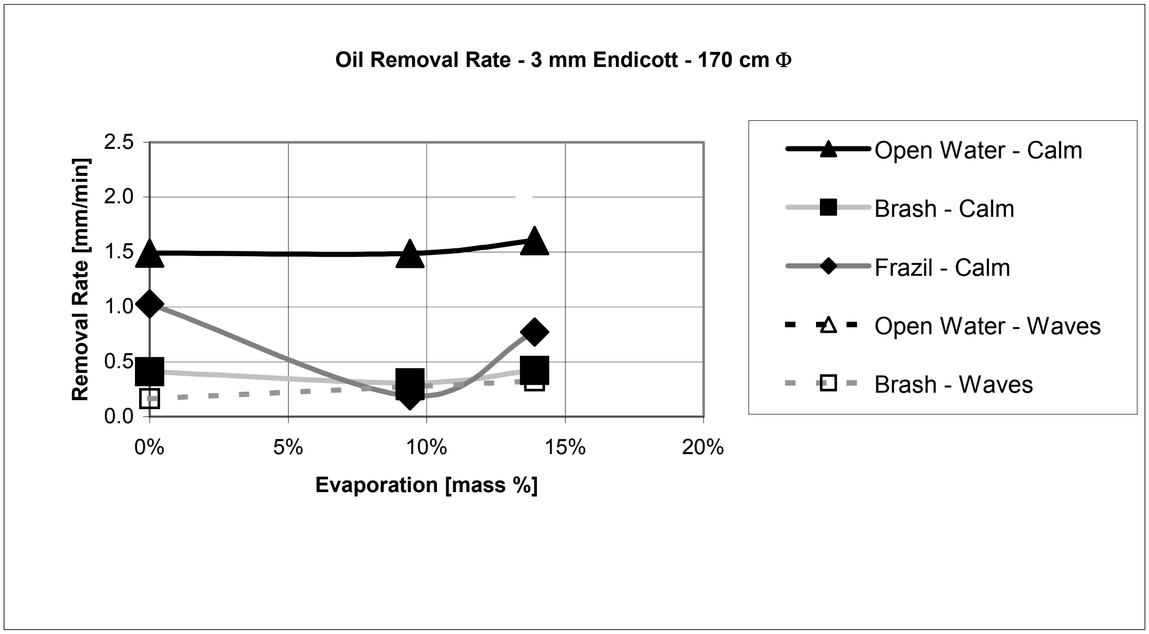


Figure 4-20: Oil removal rate results for Endicott test burns.

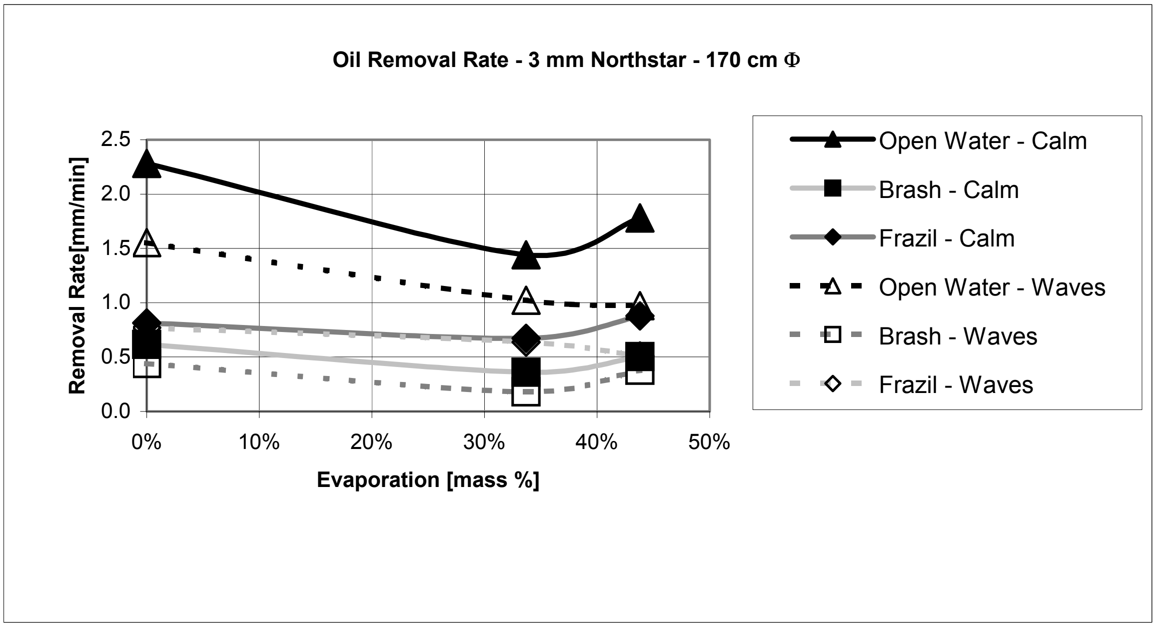


Figure 4-21: Oil removal rate results for Northstar test burns.

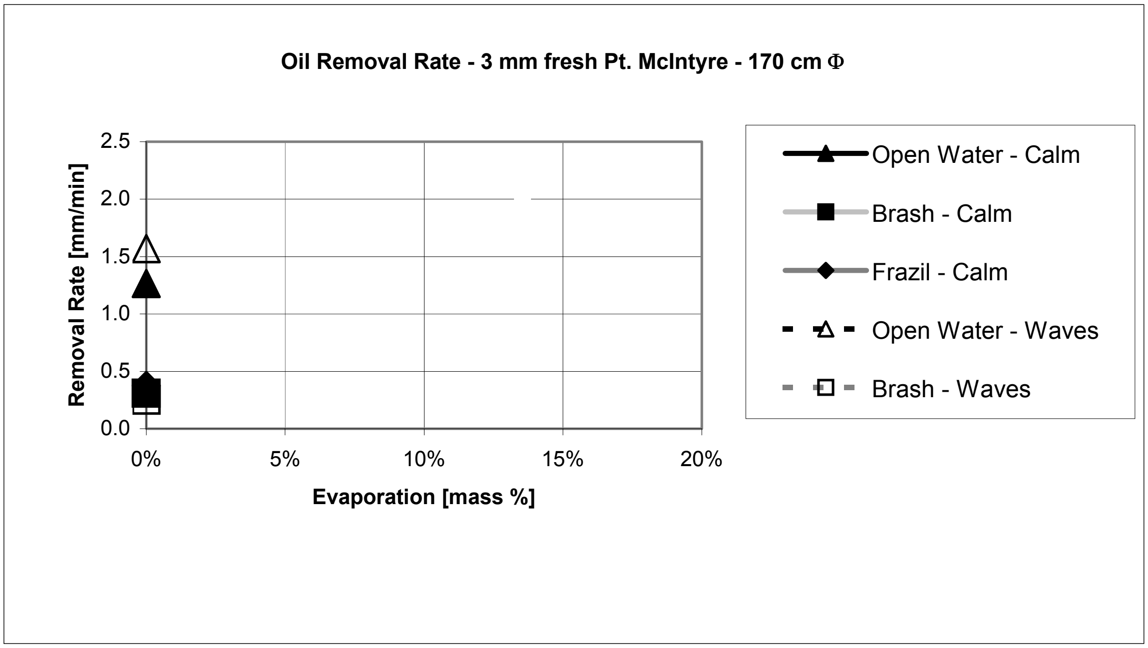


Figure 4-22: Oil removal rate results for fresh Pt. McIntyre test burns.

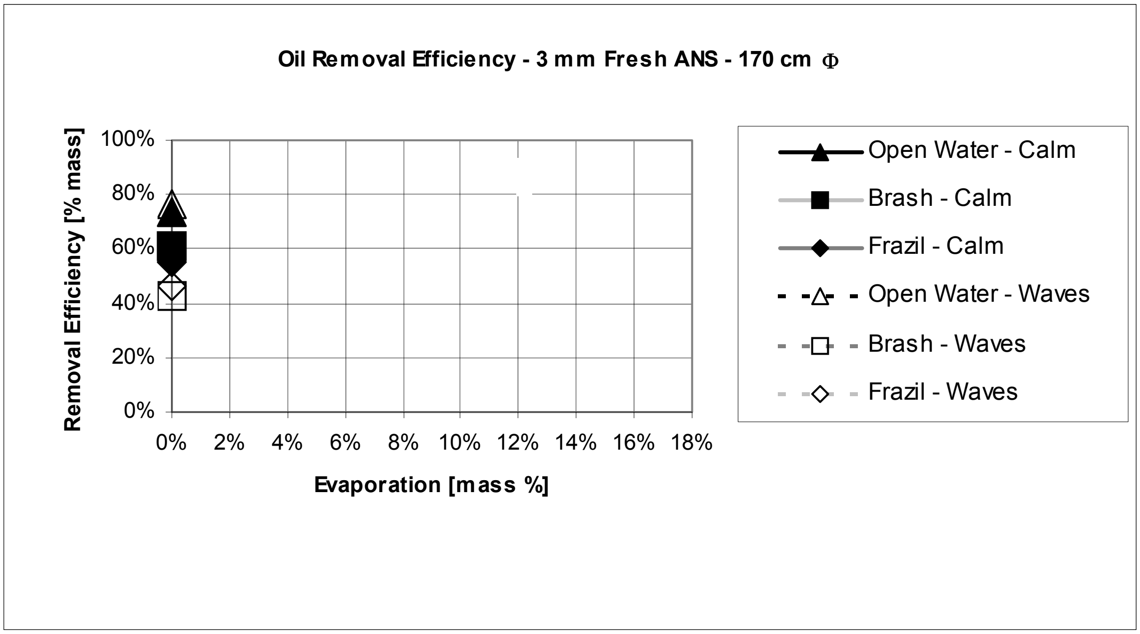


Figure 4-23: Mid-scale burn efficiency results for fresh ANS crude.

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.

Northstar. Figure 4-25 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, slightly less than for the Endicott crude in similar circumstances.

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 4-26 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.

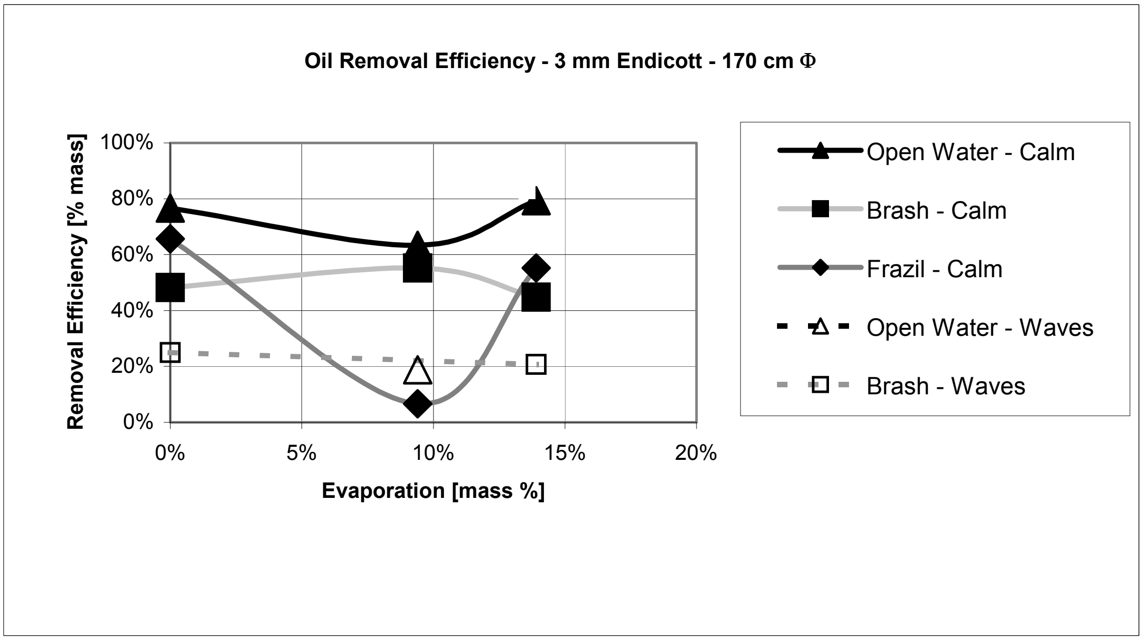


Figure 4-24: Mid-scale burn efficiency results for Endicott crude.

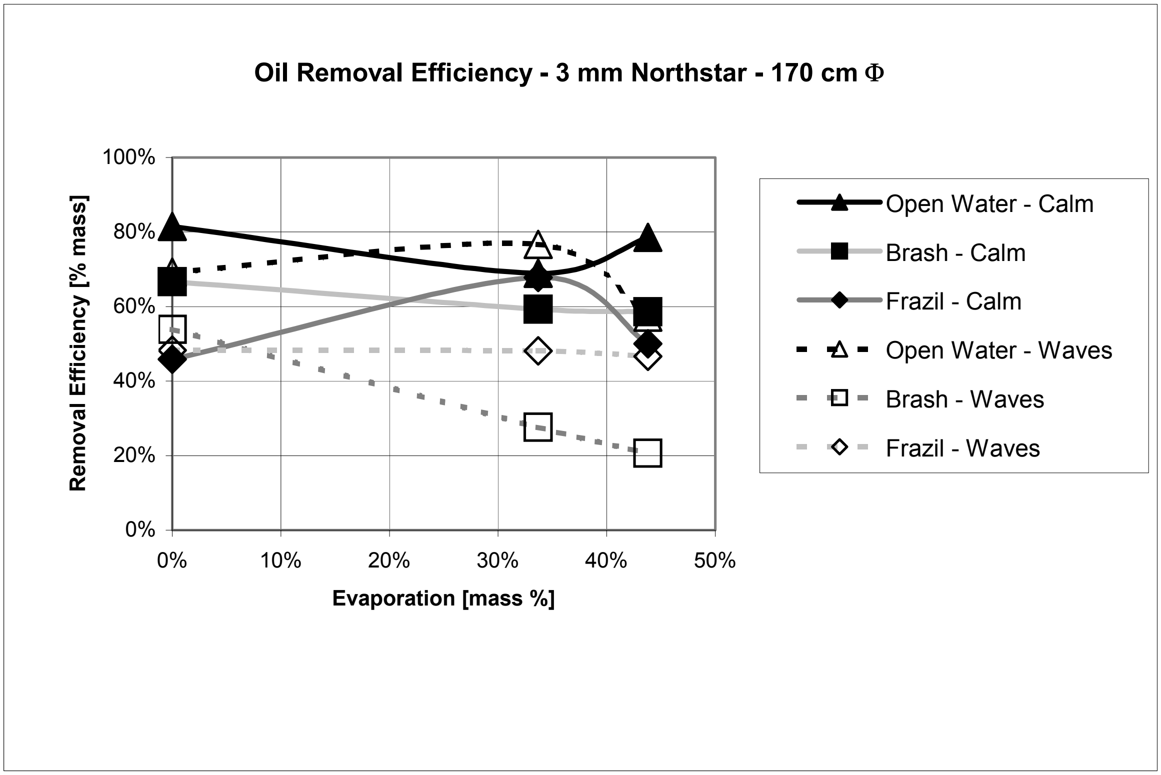


Figure 4-25: Mid-scale burn efficiency results for Northstar crude.

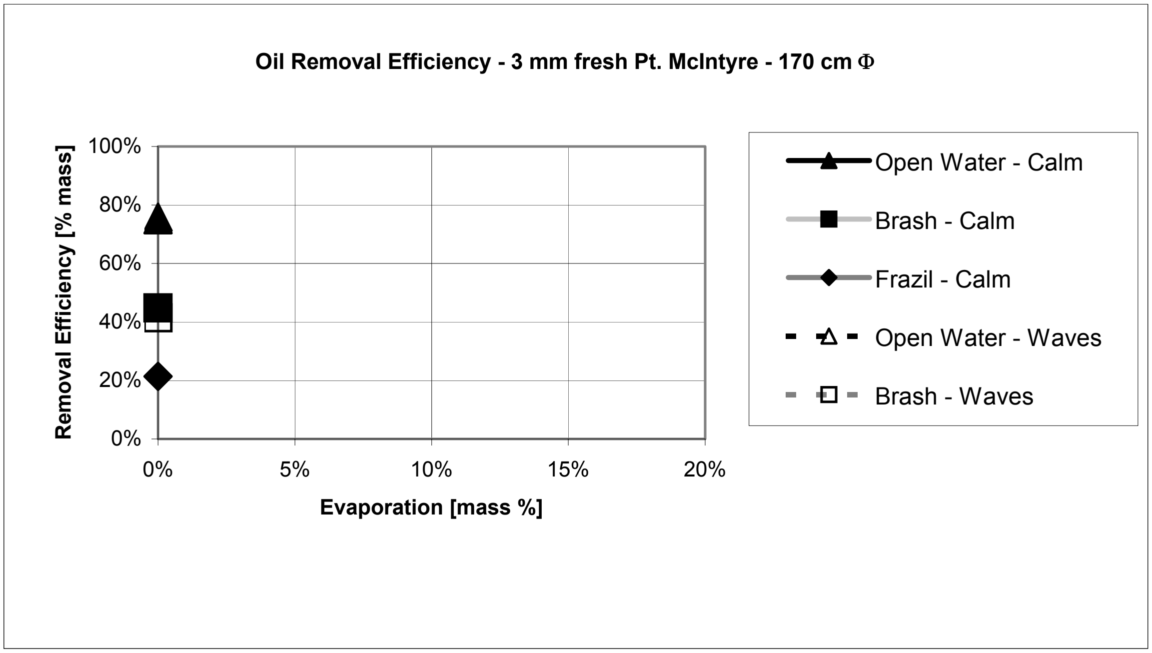


Figure 4-26: Mid-scale burn efficiency results for fresh Pt. McIntyre crude.

5. RULES-OF-THUMB AND BURN PROCESSES

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 of frazil ice. A theory of how the presence of broken ice as a burn substrate affects burn processes is also presented.

5.1 Minimum Ignitable Thickness

Based on the results of the lab-scale tests, shown in Figure 3-9 through 3-12, the "rules-of-thumb" for minimum ignitable thickness for oil slicks on broken 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.

5.2 Oil Removal Rate

Table 5-1 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 broken 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.

5.3 Residue Thickness Remaining

The normal rule-of-thumb for burns 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 broken ice:

- The residue remaining on broken 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

Table 5-1: Summary of all 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

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.

5.4 Burn Processes on Broken Ice

The increase in minimum ignitable thickness for fresh oil on a broken ice substrate and the observed decreases in burn rate and efficiency are believed to be related to the mass and heat transfer processes occurring during ignition and burning.

The trend of higher minimum ignitable thickness for slicks on ice, compared with water, probably relates to both the physical characteristics of the ice/oil interface and their effect on heat transfer, and the rheology of the oil. The test data indicate that minimum ignitable thickness was usually higher on ice than on water but there was no clear effect of ice type. It is postulated that the rough substrate interface between the oil and ice was more efficient at transferring heat from the oil to the underlying ice (through a larger interfacial surface area compared with oil on liquid water). The solid nature of the substrate would also restrict convective flows within the slick from spreading hot oil out over the surrounding cold oil. The uneven nature of the ice/oil interface also produced an oil slick of varying thickness, with oil pooling in some small areas.

The burn rate for thinner slicks is reduced on broken ice likely because the colder substrate and enhanced interfacial area keep the slick colder (Figures 5-1 and 5-2). When a thin slick on water is ignited, almost immediately some of the back-radiated heat begins to warm the underlying water. If the same slick is on ice, the substrate cannot begin to warm until it melts the ice. The colder slick would produce fuel to feed the combustion at a comparably slower rate, which would result in a smaller combustion zone (lower flames) and less heat radiated back to the slick to volatilize liquid oil. The physical differences in the interface created with oil on frazil and brash ice would explain the different burn rates measured for the two substrates. The surface of a frazil ice substrate is relatively smooth and involves smaller ice crystals; the surface of a brash ice substrate is much rougher and involves larger ice forms that would enhance heat transfer into the brash ice, compared with the frazil. The differences in burn rates on ice in waves are also related to the characteristics of the substrates: the frazil ice could consolidate and act as a single mass, keeping the oil in a relatively quiescent situation, whereas the brash ice moved independently with the waves, creating even more heat transfer from the warm oil into the ice, which further reduced volatilization.

Burn efficiencies on broken ice were lower than on water, again probably due to the increased heat transfer from the slick to an ice substrate. An *in situ* oil fire will extinguish when the heat transferred into the underlying substrate cools the surface of the slick below the Fire Point of the burning oil. It is clear from the data that a frazil ice substrate extinguished sooner than a slick on water and a slick on brash ice extinguished sooner than one on frazil ice. Wave action (which would increase heat transfer into the substrate) also caused slicks to extinguish sooner.

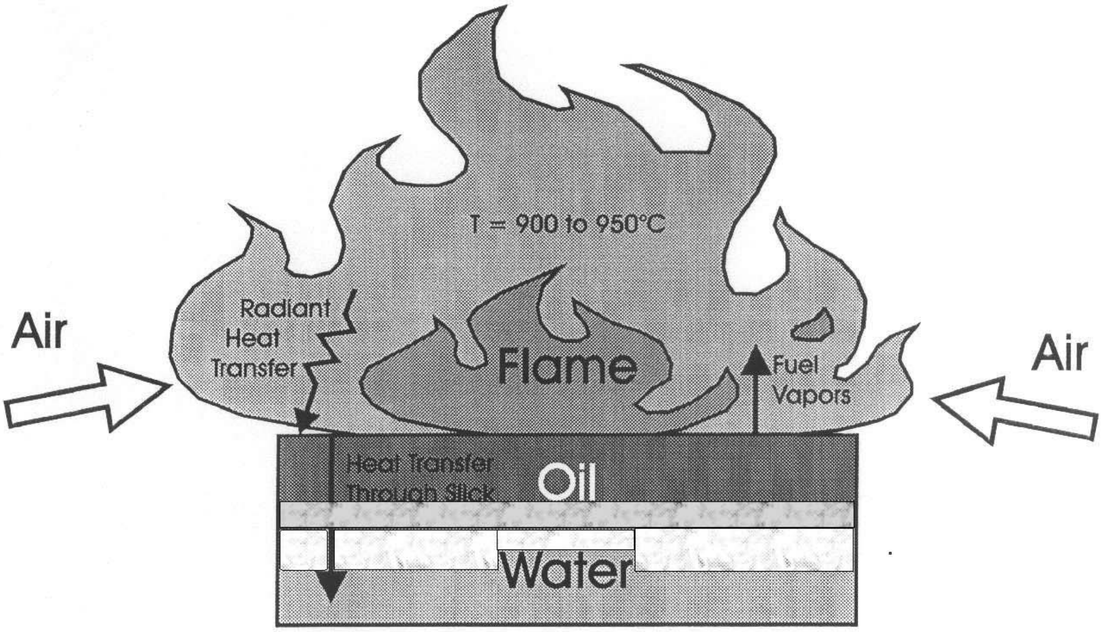


Figure 5-1: Schematic of ISB processes on frazil, or slush, ice.

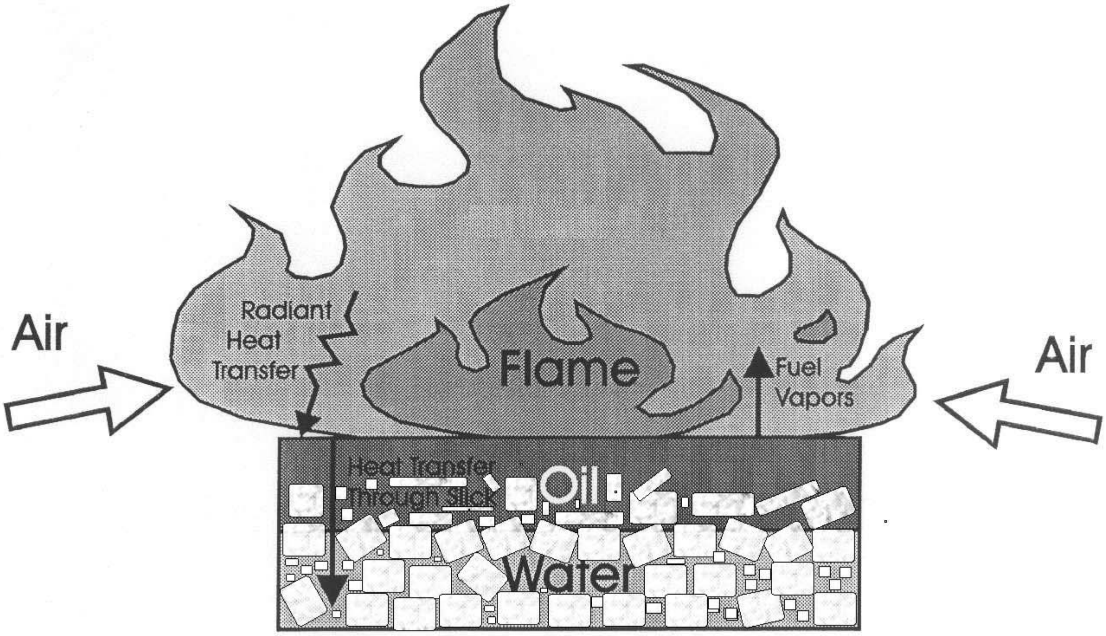


Figure 5-2: Schematic of ISB processes on brash ice.

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APPENDIX A – SMALL-SCALE TEST DATA

Ice Burn Tests

Density

Oil	Weathering F_m	Density (g/cm^3)	@ Temperature (°C)
Endicott1995	0.000	Pretest only	
Endicott2002	0.000	0.897	23.6
	0.091	0.918	23.4
	0.174	0.924	27.3
Northstar2002	0.000	0.806	26.1
	0.000	0.808	23.9
	0.338	0.857	25.0
	0.438	0.868	24.7
ANS2002	0.000	0.861	24.2
	0.103	0.888	23.4
	0.168	0.899	25.5
Pt. McIntyre2002	0.000	0.884	20.1
	0.091	0.902	21.2
	0.182	0.921	20.7

All oils came in two metal cans for each oil
The two were heated to >45°C and part of each was decanted into a third with a small sample kept separate
A can weighs about: 2.35 kg, empty 3.78

	As delivered			After decanting			Net weight: Oil			Total	Density	Litres	Gallons
Can:	#1	#2	#3	#1	#2	#3	#1	#2	#3	Oil	@25°C	Oil	Oil
NorthStar	14.65	13.95	2.28	12.2	10.08	8.44	9.85	7.73	6.09	23.67	0.808	29.29	7.75
Endicott	13.89	15.92	2.27	10.26	10.99	10.71	7.91	8.64	8.36	24.91	0.897	27.77	7.35
ANS PS-1	13.74	15.095	0.98	9.78	10.17	10.06	7.43	7.82	7.71	22.96	0.861	26.67	7.05
Pt. McIntyre	16.48	17.54	0.98	11.79	11.66	11.72	9.44	9.31	9.37	28.12	0.881	31.92	8.44
Chayvo	16.82	16.66	2.35	12.16	11.71	10.97	9.81	9.36	8.62	27.79	0.831	33.44	8.85

				Net weight: Oil			Remaining Oil (Weight)			Remaining Oil (gallons)		
	Weathering Targets											
NorthStar	0.00%	33.80%	43.80%	6.09	7.73	9.85	6.09	5.12	5.54	1.99	1.68	1.81
Endicott	0.00%	9.10%	17.40%	8.64	8.36	7.91	8.64	7.60	6.53	2.55	2.24	1.93
ANS PS-1	0.00%	10.30%	16.80%	7.82	7.71	7.43	7.82	6.92	6.18	2.40	2.12	1.90
Pt. McIntyre	0.00%	9.10%	18.20%	9.31	9.37	9.44	9.31	8.52	7.72	2.80	2.56	2.32
Chayvo	0.00%	9.20%	18.40%	9.36	8.62	9.81	9.36	7.83	8.00	2.98	2.49	2.55

				#3	#2	#1
NorthStar		Target	Needed	6.09	7.73	9.85
	0	2.33	2.33			

Weathering was done in both metal and plastic containers. They have different weights.

Metal:	2.35
Plastic:	0.98

				Weathering Targets						
				Can	Weight			Can	Weight	
	Weathering Targets			#	Initial	Target	Secondary	#	Initial	Target
NorthStar	0.00%	33.80%	43.80%	2	9.77	7.26	6.52	1		1.03
Endicott	0.00%	9.10%	17.40%	3	10.33	9.60	8.94	1	10.14	8.78
ANS PS-1	0.00%	10.30%	16.80%	3	9.58	8.69	8.14	2	10.25	8.92
Pt. McIntyre	0.00%	9.10%	18.20%	3	11.21	10.28	9.35	1	10.67	8.91
Chayvo	0.00%	9.20%	18.40%	3	10.97	10.18	9.38	1		0.43

Weathering started on August 27th. Four spargers with exhaust available, designated A, B, C & D.
A&B are set up for plastic pails, C&D for metal cans.

	A		B		C		D		
	Oil	Target weight	Oil	Target weight	Oil	Target weight	Oil	Target weight	Elapsed
	ANS #1	8.69	PtMc #3	10.28	Endicott #3	9.60	Chayvo #3	10.18	Time
27/08/2002 14:10	9.58		11.21						0:00:00
27/08/2002 14:25	9.18		10.99		10.33				0:15:00
27/08/2002 14:35					10.31		10.97		0:25:00
27/08/2002 14:45	9.04		10.96		10.13		10.66		0:35:00
27/08/2002 15:05	8.96		10.95		10.06		10.40		0:55:00
27/08/2002 15:25	8.90		10.93		10.02		10.29		1:15:00
27/08/2002 15:45	8.81		10.91		9.97		10.19		1:35:00
							Endicott #1	8.78	
27/08/2002 15:55							10.14		1:45:00
27/08/2002 16:15	8.74		10.87		9.90		9.87		2:05:00
27/08/2002 16:30	8.73								2:20:00
27/08/2002 16:55	8.66		10.85		9.84		9.61		2:45:00
	PtMc #1	8.91		Bubbler turned off for night, heat and air on.					
27/08/2002 17:20	10.67								3:10:00
				Bubbler turned back on					
28/08/2002 9:05	10.62		10.61		9.73		9.38		3:10:00
28/08/2002 9:45	10.60		10.60		9.68		9.22		3:50:00
28/08/2002 11:10	10.58		10.595		9.60		9.09		5:15:00
					ANS #2	8.92			
28/08/2002 11:17					10.25				5:22:00
28/08/2002 13:55	10.52		10.51		9.46	removed	8.96		8:00:00
					Northstar #2	started			
28/08/2002 13:55					9.77	7.19			8:00:00
28/08/2002 14:05					9.62				8:10:00
28/08/2002 14:20					9.36				8:25:00
28/08/2002 14:39					9.20				8:44:00
28/08/2002 15:05	10.49		10.50		9.14		8.94		9:10:00
28/08/2002 16:25	10.47		10.48		8.61		8.90	removed for n	10:30:00
							ANS #2	replaced	
28/08/2002 16:25							9.46	8.92	10:30:00
				Bubbler turned off for night, heat and air on.					
29/08/2002 8:55	10.05		10.30		8.27		9.08		10:30:00
29/08/2002 9:30	10.03		10.28		8.15		8.94		11:05:00
			Northstar #1	started					
29/08/2002 9:45			10.90	6.55			8.91		11:20:00
							Endicott #1	replaced	
29/08/2002 9:55							8.90	8.78	11:30:00
29/08/2002 12:25	9.96		10.12		7.78		8.85		14:00:00
29/08/2002 16:05	9.90		9.57		7.51		8.78		17:40:00
							Chayvo #1	8.00	
29/08/2002 16:05							12.16		17:40:00
29/08/2002 16:46	9.75	Air hose	9.46		7.46		11.73		18:21:00
		valve		Bubbler turned off for night, heat and air on.					
30/08/2002 9:05	9.55	turned	9.05		7.42		10.87		18:21:00
30/08/2002 9:55	9.53	off!	9.00		7.33		10.68		19:11:00
30/08/2002 11:25	9.48		8.72		7.28		10.46		20:41:00
30/08/2002 12:55	9.46		8.44		7.23		10.30		22:11:00
30/08/2002 14:35	9.44		8.29		7.19		10.13		23:51:00
30/08/2002 17:00	9.43		8.06				9.95		26:16:00
	Bubbler on this one only.			Bubbler turned off for night, heat and air on.					
31/08/2002 20:20	8.77		7.94	Bubbler and heat off on all			9.75		26:16:00
03/09/2002 9:30			7.87	Heater and Bubbler started			9.70		26:16:00
03/09/2002 16:45			7.65				9.51		33:31:00
04/09/2002 9:15			7.60				9.44		50:01:00

Ice Burn Tests - Endicott

Baseline & Endicott2002 Burns

All waves have the following characteristics:

Height (cm)	Period (s)	Length (m)	Paddle Setting
8	2	2.5	36

MIT = Minimum ignitable thickness

					Ice		Temperature			Oil Added		Residue	Meas.
Test No.	Description	Oil	Weathering (% Mass)	Type	Mass (kg)	Thickness (cm)	T_{water} (°C)	T_{air} (°C)	Volume (ml)	Mass (g)	Thickness (mm)	Mass (g)	Density (g/ml)
PT-1	Pre test, open water	Endicott-95	0.0%	O/W	0	0	3	25	370	330.0	3	55.9	0.897
PT-2	medium cubes	Endicott-95	0.0%	cubes	5.4	5.3	3	25	367	320.0	3	94.3	0.897
PT-3	medium crushed	Endicott-95	0.0%	crushed	5.4	5	3	25	367	320.0	3	184.4	0.897
PT-4	thin cubes	Endicott-95	0.0%	cubes	2.7	2.5	3	21	360	320.0	3	292.4	0.897
PT-5	medium cubes	Endicott-95	0.0%	cubes	2.8	5	3	21	370	320.0	3	113.5	0.897
PT-6	thick cubes	Endicott-95	0.0%	cubes	5.6	8-10	3	21	380	345.0	3	109.4	0.897
PT-7	medium cubes	Endicott-95	0.0%	cubes	2.8	2.5	3	21	370	320.0	3	269.0	0.897
PT-8	thin crushed	Endicott-95	0.0%	crushed	2.82	3	4	23	380	335.0	3	252.2	0.897
PT-9	thick crushed	Endicott-95	0.0%	crushed	8.3	7.5	4	24	380	335.0	3	79.0	0.897
E-1	MIT Fresh on o/w	Endicott2002	0.0%	O/W	0	0	3	23	122	105.0	1	87.0	0.897
E-2	3mm fresh on o/w	Endicott2002	0.0%	O/W	0	0	3	24	367	330.0	3	52.6	0.897
E-3-1	MIT fresh on cubes - no go	Endicott2002	0.0%	cubes	5.9	5	4	24	120	105.0	1	NR	0.897
E-3-2	MIT fresh on cubes - good	Endicott2002	0.0%	cubes	none added	5	4	24	120	105.0	1	157.0	0.897
E-4	3mm fresh on cubes	Endicott2002	0.0%	cubes	E3 + 3.3	5-7	4	24	380	345.0	3	95.1	0.897
E-5	ReE-4 with agitation	Endicott2002	0.0%	cubes	E4 + 2.9	5-7	4	25	380	335.0	3	289.1	0.897
E-6-1		Endicott2002	0.0%	crushed	6	5	4	25	120	105.0	1	NR	0.897
E-6-2		Endicott2002	0.0%	crushed	none added	5	4	25	120	105.0	1	211.4	0.897
E-7		Endicott2002	0.0%	crushed	E6 + 3.2	5	4	25	380	340.0	3	106.7	0.897
E-8-1		Endicott2002	9.1%	O/W	0	0	4	26	120	105.0	1	NR	0.918
E-8-2		Endicott2002	9.1%	O/W	0	0	4	26	120	110.0	1	100.4	0.918
E-9		Endicott2002	9.1%	O/W	0	0	5	26	370	330.0	3	77.3	0.918
E-10-1		Endicott2002	9.1%	cubes	5.94	5	3	24	120	105.0	1	NR	0.918
E-10-2		Endicott2002	9.1%	cubes	none added	5	3	24	120	105.0	1	130.7	0.918
E-11		Endicott2002	9.1%	cubes	E-10 + 2.7	5	3	24	370	340.0	3	145.2	0.918
E-12		Endicott2002	9.1%	crushed	5.6	5	4	24	375	340.0	3	56.8	0.918
E-13-1		Endicott2002	9.1%	cubes	6.3	5	3	24	370	335.0	3	NR	0.918
E-13-2		Endicott2002	9.1%	cubes	none added	4	3	24	none added	0.0	0	186.5	0.918
E-14		Endicott2002	9.1%	cubes	not weighed	5	3	25	370	345.0	3	298.3	0.918
E-15		Endicott2002	0.0%	cubes	E-14 + 5.83	6	3	26	360	325.0	3	212.0	0.897
E-16		Endicott2002	0.0%	cubes	E-15 + 5.7	5+	3	26	730	650.0	6	303.8	0.897
E-17	ReE-16 with enough ice	Endicott2002	0.0%	cubes	10.53	10+	3	26	735	660.0	6	485.6	0.897
E-18		Endicott2002	0.0%	crushed	5.4	5	4	27	370	330.0	3	266.6	0.897
E-19		Endicott2002	9.1%	crushed	E-18 + 5.4	5+	4	27	375	340.0	3	289.7	0.918
E-20-1		Endicott2002	17.4%	O/W	0	0	1	27	120	105.0	1	NR	0.924
E-20-2		Endicott2002	17.4%	O/W					125	110.0	1	NR	0.924
E-20-3		Endicott2002	17.4%	O/W					120	105.0	1	113.5	0.924
E-21		Endicott2002	17.4%	cubes	5.5	5	1	27	367	335.0	3	245.7	0.924
E-22		Endicott2002	17.4%	cubes	E-21 + 5.4	7	2	27	370	340.0	3	318.9	0.924
E-23		Endicott2002	17.4%	crushed	5.4	5	2	27	360	330.0	3	295.8	0.924
E-24		Endicott2002	17.4%	crushed	5.4	5	2	27	370	335.0	3	267.3	0.924
E-25	Open water with waves	Endicott2002	0.0%	O/W	0	0	3	23	367	335.0	3	176.5	0.897
E-26	Open water with waves	Endicott2002	9.1%	O/W	0	0	4	23	367	335.0	3	168.1	0.918
E-27	Open water with waves	Endicott2002	17.4%	O/W	0	0	4	23	367	330.0	3	267.3	0.924
E-28	MIT, 9% on crushed	Endicott2002	9.1%	crushed	5.4	5	2	20	240+120	315.0	3	296.5	0.918

Baseline & Endicott2002 Burns

Test No.	Ignition		Preheat							Ignition		Time to	Intense Burn		
	Source	Amount (g)	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	P_{50} (m:s)	Time (m:s)	Burn Coverage	Waves (m:s)	Time to (m:ss)	Coverage (%)	Time (s)
PT-1	torch								00:00	00:00	100%	No Wave	00:45		01:28
PT-2	torch				00:30	50%	02:00	90%	00:30	03:00	100%	No Wave	03:30		04:27
PT-3	torch				00:00	50%	00:10	75%	00:00	00:30	100%	No Wave	none		02:00
PT-4	torch				00:25	50%	00:57	75%	00:25	01:27	90%	No Wave	none		03:38
PT-5	torch				00:55	50%	01:33	75%	00:55	02:01	100%	No Wave	03:25		04:18
PT-6	torch				02:27	50%	03:42	90%	02:27	03:50	100%	No Wave	05:05		06:15
PT-7	torch				00:42	50%	01:17	75%	00:42	02:53	90%	No Wave	none		04:03
PT-8	torch				00:26	50%			00:26	00:43	100%	No Wave	none		02:06
PT-9	torch				00:04	50%	00:25	75%	00:04	00:39	100%	No Wave	02:10		02:56
E-1	torch								00:00	00:34	100%	No Wave	none		00:55
E-2	1gg	26.0			00:35	50%			00:35	00:52	100%	No Wave	01:14		02:25
E-3-1	torch		Failed												
E-3-2	torch				00:30	50%	01:29	75%	00:30	02:25	90%	No Wave	none		03:37
E-4	1gg	33.1	00:25	25%	02:17	50%	03:10	75%	02:17	04:15	100%	No Wave	04:00		05:30
E-5	gg	NA	01:20	25%	02:10	50%			02:10	03:11	75%	Jiggling	none		06:05
E-6-1	torch		01:23	50%					01:23	01:23	50%		none		01:58
E-6-2	torch		00:42	25%					01:48	01:48	50%	No Wave	none		03:18
E-7	1gg	32.9	00:48	25%	01:07	50%	01:15	75%	01:07	01:22	100%	No Wave	02:50		03:59
E-8-1	torch		Failed												
E-8-2	torch		01:00	75%	stopwatch broke					01:00	100%	No Wave	01:00		02:00
E-9	1gg	23.8	01:30	50%					01:30	02:02	100%	No Wave	02:21		03:30
E-10-1	torch		Failed												
E-10-2	torch		01:05	50%					01:05	01:58	38%	No Wave	05:07	60%	05:30
E-11	1gg	31.7	01:32	50%	02:27	75%			01:32	03:36	100%	No Wave	04:06	100%	05:13
E-12	1gg	21.9	00:55	50%	01:20	75%			00:55	01:51	100%	No Wave	03:06		04:30
E-13-1	1gg	22.4	02:20	25%	03:20	50%	06:10	10%	03:20	07:18	20%	03:20	none		09:32
E-13-2	4gg	96.0	00:38	50%	00:58	75%			00:38	00:58	75%	00:38	none		03:18
E-14	4gg	105.2	00:40	50%	02:42	75%			00:40	02:42	75%	00:46	none		03:48
E-15	4gg	96.2	00:15	50%	00:55	75%			00:15	00:55	75%	00:25	none		03:13
E-16	4gg	108.0	NA						00:25	00:25	100%	00:29	none		NA
E-17	4gg	91.1							00:11	00:11	100%	00:15	none		02:36
E-18	4gg	77.8							00:15	00:15	100%	00:22	none		02:57
E-19	4gg	91.6	00:31	75%					00:31	00:48	100%	00:32	none		02:00
E-20-1	torch		Failed									No Wave	none		
E-20-2	torch		Failed									No Wave	none		
E-20-3	torch								00:00	00:00	100%	No Wave	00:36		01:56
E-21	torch+1gg	18.0	01:58	25%	03:27	75%	04:25	90%	02:27	04:33	100%	No Wave	04:53		06:09
E-22	4gg	77.7	00:44	25%					01:37	01:37	50%	00:46	none		03:57
E-23	torch+1gg	19.2	01:28	25%					01:28	03:33	50%	No Wave	none		04:26
E-24	4gg	65.0	Stopwatch broke, NA								50%		none		NA
E-25	torch		00:00						00:00	00:00	100%	00:19	01:05		02:05
E-26	torch		00:00						00:00	00:00	100%	00:25	01:12		01:55
E-27	torch+4gg	127.8	00:22	50%					00:22	00:29	100%	00:35	01:25		02:30
E-28	torch		00:00	25%	01:44	50%	03:06	75%	01:44	03:06	75%	No Wave	none		03:36

Baseline & Endicott2002 Burns

	Extinction							Burn Calculations					
Test No.	Burn Coverage	Time (s)	Burn Coverage	Time (s)	Burn Coverage	E_{50} (m:s)	Time to 0%	Duration (s)	Rate (mm/min)	Efficiency (%)	MIT [mm]	Time to Waves (m:s)	
PT-1	0%					01:28	01:28	88	1.69	83.05%		No Wave	
PT-2	0%					04:27	04:27	237	0.53	70.53%		No Wave	
PT-3	50%					02:00	03:35	120	0.69	42.38%		No Wave	
PT-4	50%					03:38	04:05	193	0.18	8.63%		No Wave	Tops of cubes melt
PT-5	10%					04:18	04:36	203	0.57	64.53%		No Wave	
PT-6	5%					06:15	06:41	228	0.58	68.29%		No Wave	Cubes have higher freeboard; harder to ignite
PT-7	50%	04:18	25%			04:03	05:59	201	0.23	15.94%		No Wave	
PT-8	75%	02:50	50%	03:04	10%	02:50	03:54	144	0.40	24.72%		No Wave	
PT-9	5%					02:56	03:15	172	0.82	76.42%		No Wave	Layer of water on top of slush ice
E-1	50%					00:55	01:15	55	0.26	17.11%	1.00	No Wave	Only covered 30% of surface when added. Sprea
E-2	50%	02:35	5%			02:25	02:40	110	1.37	84.05%		No Wave	
E-3-1								0		0.00%			1mm didn't ignite, even though only on 30% of th
E-3-2	50%					03:37	03:49	187	0.22	25.24%	2.00	No Wave	Melt to freeboard of cubes. Visually low burn rate
E-4	50%					05:30	06:01	193	0.72	72.43%		No Wave	Only 80% coverage for intense burn. Flames only
E-5	0%					06:05	06:05	235	0.23	13.70%		Jiggling	ReE-4 with agitation. Burned as E-4, except less
E-6-1	50%					01:58	02:30	35		0.00%			Just barely going. Add 1mm and try again
E-6-2	10%					03:18	03:48	90	0.24	-0.67%	3.00	No Wave	Burn OK. Slow spreading by melting ice
E-7	50%	04:10	10%			03:59	04:33	172	0.76	68.62%		No Wave	Good burn
E-8-1								0		0.00%			No ignition with torch. Used torch to spread to 1m
E-8-2	0%					02:00	02:00	120	0.53	53.30%	2.00	No Wave	Good burn. Stop watch broke.
E-9	50%					03:30	03:43	120	1.12	76.58%		No Wave	
E-10-1								0		0.00%			No igniition
E-10-2	50%					05:30	05:46	265	0.47	37.75%	3.00	No Wave	slow burn
E-11	50%					05:13	05:24	221	0.49	57.29%		No Wave	
E-12	50%					04:30	04:50	215	0.70	83.29%		No Wave	Good burn. Areas under slick had no ice after bur
E-13-1	0%					09:32	09:32	372		0.00%		03:20	
E-13-2	50%					03:18	03:46	160	0.71	44.32%	3.00	00:38	Almost all ice melted by end of second burn
E-14	50%					03:48	04:01	188	0.26	13.55%		00:46	Very weak burn away from gg with waves on. Lot
E-15	50%	05:17	10%			03:13	06:16	178	0.54	34.77%		00:25	Weak burn away from gg. Some areas never igni
E-16						NA	NA					00:29	Weak flame when waves on. All ice gone. Scrap
E-17	75%	03:01	50%	03:17	25%	03:01	05:16	170	0.70	26.42%		00:15	ReE-16 with more ice. Weak flame when waves
E-18	75%	03:05	25%			03:00	03:37	165	0.29	19.21%		00:22	Much stronger than with cubes. Ice remaining aft
E-19	75%	02:12	50%			02:12	02:43	101	0.38	14.79%		00:32	Flames weak. Burn appears to subside as ice me
E-20-1								0		0.00%		No Wave	Oil gelled in small slab. Heated to spread to 75%
E-20-2								0		0.00%		No Wave	Same. Spread to 90% cover
E-20-3	50%					01:56	02:05	116	0.96	64.53%	3.00	No Wave	OK, just barely. Problem with recording pre-heat
E-21	50%					06:09	06:26	222	0.25	26.66%	3.00	No Wave	Slow start but eventually burned. Started intense
E-22	0%					03:57	03:57	140	0.33	6.20%		00:46	Oil only burned between four gg pads. Not when
E-23	0%					04:26	04:26	178	0.33	10.36%	3.00	No Wave	No ignition with torch. Slowly ignited around gg s
E-24						NA	NA			20.21%			Stopwatch died. Good flame spread until waves,
E-25	50%					02:05	03:19	125	0.75	47.31%		00:19	
E-26	50%					01:55	02:02	115	0.82	49.82%		00:25	
E-27	50%					02:30	02:52	128	0.34	19.01%		00:35	
E-28	50%					03:36	04:32	112	0.27	5.87%	3.00	No Wave	

Baseline & Endicott2002 Burns

Test No.	Observations:
PT-1	
PT-2	
PT-3	
PT-4	Tops of cubes melt
PT-5	
PT-6	Cubes have higher freeboard; harder to ignite
PT-7	
PT-8	
PT-9	Layer of water on top of slush ice
E-1	Only covered 30% of surface when added. Spread after igniting. Short, weak burn
E-2	
E-3-1	1mm didn't ignite, even though only on 30% of the ring
E-3-2	Melt to freeboard of cubes. Visually low burn rate.
E-4	Only 80% coverage for intense burn. Flames only spread over area with no "cube freeboard"
E-5	ReE-4 with agitation. Burned as E-4, except less powerful flames. Once cubes rose above w/l flames extinguished. May be that there are differences between calm and agitated.
E-6-1	Just barely going. Add 1mm and try again
E-6-2	Burn OK. Slow spreading by melting ice
E-7	Good burn
E-8-1	No ignition with torch. Used torch to spread to 1mm
E-8-2	Good burn. Stop watch broke.
E-9	
E-10-1	No igniition
E-10-2	slow burn
E-11	
E-12	Good burn. Areas under slick had no ice after burn.
E-13-1	
E-13-2	Almost all ice melted by end of second burn
E-14	Very weak burn away from gg with waves on. Lots of ice left after. Some area never ignited.
E-15	Weak burn away from gg. Some areas never ignited. Ice left after
E-16	Weak flame when waves on. All ice gone. Scrap and redo
E-17	ReE-16 with more ice. Weak flame when waves on.
E-18	Much stronger than with cubes. Ice remaining after burn
E-19	Flames weak. Burn appears to subside as ice melts. Because slush begins to mix?
E-20-1	Oil gelled in small slab. Heated to spread to 75% cover
E-20-2	Same. Spread to 90% cover
E-20-3	OK, just barely. Problem with recording pre-heat times.
E-21	Slow start but eventually burned. Started intense phase but stopped after 35 sec. Lots of ice left.
E-22	Oil only burned between four gg pads. Not when ice cubes "surfaced"
E-23	No ignition with torch. Slowly ignited around gg spreading to 50% of slick. Ice remaining.
E-24	Stopwatch died. Good flame spread until waves, then fire reduced to near gg. As gg consumed fire decreases. After waves only covered 50% of slick.
E-25	
E-26	
E-27	
E-28	

Ice Burn Tests - Northstar

NorthStar2002 Burns

All waves have the following characteristics:

Height (cm)	Period (s)	Length (m)	Paddle Setting
8	2	2.5	36

"n/rec"= Not recorded or measured

				Ice			Temperature		Oil Added				Meas.
Test No.	Description	Oil	Weathering (% Mass)	Type	Mass (kg)	Thickness (cm)	T_{water} (°C)	T_{air} (°C)	Volume (ml)	Mass (g)	Thickness (mm)	Residue (g)	Density (g/ml)
NS-1		NorthStar2002	0.0%	O/W	0	0	3	27	120	95.0	1	81.5	0.806
NS-2		NorthStar2002	0.0%	O/W	0	0	3	27	80	65.0	0.66	44.8	0.806
NS-3		NorthStar2002	0.0%	O/W	0	0	3	27	60	50.0	0.5	36.4	0.806
NS-4		NorthStar2002	0.0%	O/W	0	0	3	28	367	300.0	3	78.7	0.806
NS-5		NorthStar2002	0.0%	Cubes	5	5	3	28	367	300.0	3	151.5	0.806
NS-6		NorthStar2002	0.0%	Cubes	5	5	3	28	367	300.0	3	188.2	0.806
NS-7		NorthStar2002	0.0%	Crushed	5.4	5	4	28	360	295.0	3	134.4	0.806
NS-8		NorthStar2002	0.0%	Crushed	5.4	5	4	28	360	295.0	3	124.6	0.806
NS-9		NorthStar2002	0.0%	Cubes	5.4	5	3	24	60	30.0	0.5	n/rec	0.806
NS-10-1		NorthStar2002	33.8%	Cubes	5.4	5	3	24	120	105.0	1	n/rec	0.857
NS-10-2		NorthStar2002	33.8%	Cubes	none added				120	105.0	1	n/rec	0.857
NS-10-3		NorthStar2002	33.8%	Cubes	none added				120	105.0	1	219.1	0.857
NS-11		NorthStar2002	0.0%	Crushed	5.4	5	3	25	60	55.0	0.5	n/rec	0.806
NS-12-1		NorthStar2002	33.8%	Crushed	from NS-11		3	25	240	210.0	2	n/rec	0.857
NS-12-2		NorthStar2002	33.8%	Crushed	none added				120	105.0	1	168.8	0.857
NS-13-1		NorthStar2002	33.8%	O/W	0	0	3	25	120	105.0	1	n/rec	0.857
NS-13-2		NorthStar2002	33.8%	O/W	0	0	3	25	120	105.0	1	n/rec	0.857
NS-13-3		NorthStar2002	33.8%	O/W	0	0	3	25	120	105.0	1	92.7	0.857
NS-14		NorthStar2002	33.8%	Cubes	5.4	5	4	25	367	320.0	3	223.0	0.857
NS-15		NorthStar2002	33.8%	Crushed	5.4	5	4	n/rec	367	320.0	3	235.1	0.857
NS-16-1		NorthStar2002	43.8%	O/W	0	0	4	25	367	325.0	3	n/rec	0.868
NS-16-2		NorthStar2002	43.8%	O/W	0	0			none added			n/rec	0.868
NS-16-3		NorthStar2002	43.8%	O/W	0	0			none added			67.4	0.868
NS-17		NorthStar2002	43.8%	Cubes	5.4	5	4	25	367	325.0	3	183.4	0.868
NS-18		NorthStar2002	43.8%	Cubes	NS-17+ 5.6	5+	5	25	367	325.0	3	299.6	0.868
NS-19		NorthStar2002	43.8%	Crushed	5.4	5	4	25	367	325.0	3	176.8	0.868
NS-20		NorthStar2002	43.8%	Crushed	NS-19+ 5.4	5+	5	25	367	325.0	3	202.5	0.868
NS-21		NorthStar2002	0.0%	O/W	0	0	3	22	367	305.0	3	113.3	0.806
NS-22		NorthStar2002	33.8%	O/W	0	0	3	22	367	325.0	3	191.0	0.857
NS-23		NorthStar2002	43.8%	O/W	0	0	3	22	367	325.0	3	165.4	0.868

NorthSta

Test No.	Ignition		Preheat							Ignition		Time to	Intense Burn		
	Source	Amount (g)	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	P_{50} (m:s)	Time (m:s)	Burn Coverage	Waves (m:s)	Time to (m:ss)	Coverage (%)	Time (s)
NS-1	torch		flashed						00:00	00:00	100%	No Wave	none		01:12
NS-2	torch		flashed						00:00	00:00	100%	No Wave	none		01:09
NS-3	torch		flashed						00:00	00:00	100%	No Wave	none		00:15
NS-4	torch		flashed						00:00	00:00	100%	No Wave	01:21		02:19
NS-5	torch		flashed						00:00	00:00	100%	No Wave	none		03:25
NS-6	torch		flashed						00:00	00:00	100%	00:07	none		04:08
NS-7	torch		flashed						00:00	00:00	100%	No Wave	none		04:22
NS-8	torch		flashed						00:00	00:00	100%	00:12	none		02:19
NS-9	torch		flashed						00:00	n/rec		No Wave	none		
NS-10-1	torch		none							no		No Wave	none		
NS-10-2	torch		none							no		No Wave	none		
NS-10-3	torch +1gg	23.7	01:10	25%	01:34	50%	02:03	90%	02:03	02:12	100%	No Wave	none		04:52
NS-11	torch		flashed						00:00	00:00	75%	No Wave	none		00:21
NS-12-1	torch		none							no		No Wave	none		
NS-12-2	torch+1gg	24.4	01:05	25%	01:19	50%			01:19	01:40	100%	No Wave	none		03:31
NS-13-1	torch		none							no		No Wave	none		
NS-13-2	torch		none							almost		No Wave	none		
NS-13-3	torch		none						00:04	00:07	100%	No Wave	01:13	sporadic	01:56
NS-14	4 gg	96.6	00:17	50%					00:17	00:17	50%	00:28	none		03:42
NS-15	4 gg	93.9	00:23	50%					00:23	00:36	100%	00:27	none		05:14
NS-16-1	torch									no		No Wave			
NS-16-2	1 gg	25.3								no		No Wave			
NS-16-3	4 gg	102.5	none						00:20	00:40	100%	No Wave	01:42		02:53
NS-17	1 gg	22.3	02:50	25%	04:14	50%	05:05	90%	05:05	05:55	100%	No Wave	none		08:09
NS-18	4 gg	83.1	00:35	50%	01:30	25%			01:30	00:35	38%	00:45	none		02:39
NS-19	1 gg	23.9	01:56	25%	02:34	50%	03:23	90%	02:34	03:23	90%	No Wave	none		07:20
NS-20	4 gg	105.7	00:20	20%					00:50	01:25	100%	00:27	none		03:05
NS-21	torch		00:00						00:00	00:00	100%	00:12	02:05	sporadic	02:28
NS-22	torch		00:00						00:00	00:00	100%	00:09	02:04		02:34
NS-23	t+1gg+4gg	138.6	00:00						00:00	00:00	100%	00:12	02:10		02:52

NorthSta

Test No.	e Burn	Extinction								Burn Calculations			MIT	Time to	
	Coverage (%)	Time (s)	Burn Coverage	Time (s)	Burn Coverage	Time (s)	Burn Coverage	E_{50} (m:s)	Time to 0%	Duration (s)	Rate (mm/min)	Efficiency (%)	[mm]	Waves (m:s)	
NS-1		01:12	50%					01:12	01:36	72	0.24	14.21%		No Wave	
NS-2		01:09	100%					01:09	01:09	69	0.25	31.08%		No Wave	Weak flares after flash
NS-3		00:15	100%					00:15	00:15	15	0.82	27.20%	0.50	No Wave	Stopwatch dead. Time
NS-4		02:19	100%					02:19	02:19	139	1.01	73.77%		No Wave	Excellent burn.
NS-5		03:25	50%	03:57	25%			03:25	04:31	205	0.51	49.50%		No Wave	Oil spread around ice
NS-6		04:08	50%					04:08	04:54	248	0.35	37.27%		00:07	Very weak flames in w
NS-7		04:22	50%					04:22	04:39	262	0.42	54.44%		No Wave	
NS-8		02:19	50%					02:19	03:30	139	0.83	57.77%		00:12	Weak flame when wav
NS-9									n/rec	0	0.00	n/rec	0.50	No Wave	Low, weak flames for
NS-10-1										0		0.00%		No Wave	
NS-10-2										0		0.00%		No Wave	
NS-10-3		04:52	50%	05:28	10%			04:52	05:45	169	0.42	30.44%	3.00	No Wave	Good burn. No intense
NS-11		00:21	100%					00:21	00:21	21		n/rec	0.50	No Wave	75% of ice burned for
NS-12-1										0		0.00%		No Wave	
NS-12-2		03:31	50%	05:25	10%			03:31	05:37	132	0.72	46.41%	3.00	No Wave	Oil gelled when added
NS-13-1										0		0.00%		No Wave	
NS-13-2										0		0.00%		No Wave	
NS-13-3	sporadic	01:56	50%					01:56	02:22	112	1.17	70.57%	3.00	No Wave	Oil gelled on hitting wa
NS-14		03:42	25%					03:42	03:58	205	0.70	30.31%		00:28	When waves on, flame
NS-15		05:14	50%					05:14	06:08	291	0.23	26.53%		00:27	Much stronger burn th
NS-16-1										0		0.00%		No Wave	
NS-16-2										0		0.00%		No Wave	
NS-16-3		02:53	50%					02:53	03:27	153	0.96	79.26%	3.00	No Wave	Good burn. Foamy res
NS-17		08:09	50%	08:40	10%			08:09	08:55	184	0.50	43.57%	3.00	No Wave	Very slow start. Ice left
NS-18		02:39	10%					02:39	02:48	69	0.52	7.82%		00:45	Flames died back whe
NS-19		07:20	50%					07:20	07:45	286	0.37	45.60%	3.00	No Wave	Never exceeded 90%
NS-20		03:05	50%					03:05	03:51	135	0.61	37.69%		00:27	Flames not reduced a
NS-21	sporadic	02:28	50%					02:28	02:39	148	0.86	62.85%		00:12	Intense burn was spor
NS-22		02:34	50%					02:34	03:05	154	0.58	41.23%		00:09	
NS-23		02:52	50%					02:52	03:19	172	0.58	49.11%		00:12	Added one gg. No ignit

NorthSta

Test No.	Observations:
NS-1	
NS-2	Weak flares after flash
NS-3	Stopwatch dead. Time estimate. Went out fairly quickly
NS-4	Excellent burn.
NS-5	Oil spread around ice by itself. No intense burn.
NS-6	Very weak flames in waves. Ice cubes surfaced at 4:08, causing immediate drop in flame area to 50% and eventual extinction.
NS-7	
NS-8	Weak flame when waves on
NS-9	Low, weak flames for 20-30 sec. Residue not measured.
NS-10-1	
NS-10-2	
NS-10-3	Good burn. No intense phase. Ice remaining after.
NS-11	75% of ice burned for 21 sec.
NS-12-1	
NS-12-2	Oil gelled when added
NS-13-1	
NS-13-2	
NS-13-3	Oil gelled on hitting water. Very sporatic intense burn. Flaring on extinction.
NS-14	When waves on, flames don't spread from vicinity of gg. Ice left.
NS-15	Much stronger burn than same with cubes
NS-16-1	
NS-16-2	
NS-16-3	Good burn. Foamy residue. Open water around 1 gg after second ignition attempt.
NS-17	Very slow start. Ice left after burn. Residue very waxy-easier to pick up by hand - won't stick to sorbent.
NS-18	Flames died back when waves on.
NS-19	Never exceeded 90% coverage. Ice left after burn.
NS-20	Flames not reduced as much by waves as with cubes. Crushed ice more cohesive
NS-21	Intense burn was sporadic
NS-22	
NS-23	Added one gg. No ignition of oil. Added 4 gg. Flash ignition

Ice Burn Tests - ANS

ANS2002 Burns

All waves have the following characteristics:

Height (cm)	Period (s)	Length (m)	Paddle Setting
8	2	2.5	36

"n/rec"= Not recorded or measured

Test No.	Description	Oil	Weathering (% Mass)	Ice Type	Ice Mass (kg)	Ice Thickness (cm)	Temperature T_{water} (°C)	Temperature T_{air} (°C)	Oil Added Volume (ml)	Oil Added Mass (g)	Oil Added Thickness (mm)	Residue Mass (g)
ANS-1		ANS2002	0.0%	O/W	0	0	5	25	120	105.0	1	85.0
ANS-2		ANS2002	0.0%	O/W	0	0	5	25	60	55.0	0.5	n/rec
ANS-3		ANS2002	0.0%	O/W	0	0	5	25	310	265.0	2.5	102.7
ANS-4		ANS2002	0.0%	cubes	5.7	6	5	25	65	50.0	0.5	n/rec
ANS-5		ANS2002	0.0%	cubes	ANS-4	6	5	25	310	265.0	2.5	208.0
ANS-6	Redone as ANS-12	ANS2002	0.0%	cubes	ANS-5+5.6	5+	5	25	367	315.0	3	n/rec
ANS-7		ANS2002	10.3%	O/W	0	0	3	23	120	110.0	1	93.7
ANS-8		ANS2002	10.3%	O/W	0	0	3	23	60	55.0	0.5	n/rec
ANS-9	Oil added to prev for 3mm	ANS2002	10.3%	O/W	0	0	3	23	310	280.0	2.5	80.7
ANS-10		ANS2002	10.3%	cubes	5.4	5	3	24	367	325.0	3	161.8
ANS-11-1	MIT- 10% on cubes -no go	ANS2002	10.3%	cubes	5.5 + ANS-10	5+	3	24	125	105.0	1	
ANS-11-2	MIT	ANS2002	10.3%	cubes	none added	5+	3	24	120	110.0	1	175.4
ANS-12	R-ANS-6	ANS2002	0.0%	cubes	5.4 + ANS-11	5+	3	24	367	320.0	3	246.9
ANS-13		ANS2002	10.3%	cubes	5.5 + ANS-12	5+	3	25	367	335.0	3	328.6
ANS-14	MIT - fresh on crush	ANS2002	0.0%	crushed	5.4	5	3	22	60	50.0	0.5	n/rec
ANS-15	Oil added to prev for 3mm	ANS2002	0.0%	crushed	none added	5	3	22	310	270.0	2.5	225.9
ANS-16	3mm fresh on crushed	ANS2002	0.0%	crushed	5.4 + ANS-15	5+	3	22	367	325.0	3	208.2
ANS-17	MIT 10% on crushed	ANS2002	10.3%	crushed	5.4+ANS-16	5+	3	22	125	110.0	1	n/rec
ANS-18	Oil added to prev for 3mm	ANS2002	10.3%	crushed	none added	5+	3	22	240	215.0	2	122.5
ANS-19	3mm 10% on crush w/waves	ANS2002	10.3%	crushed	5.4+ANS-18	5+	3	22	367	335.0	3	225.8
ANS-20		ANS2002	0.0%	O/W	0	0	3	22	367	325.0	3	152.3
ANS-21		ANS2002	10.3%	O/W	0	0	3	22	367	335.0	3	167.2
ANS-22		ANS2002	16.8%	O/W	0	0	4	23	120	110.0	1	104.8
ANS-23		ANS2002	16.8%	O/W	0	0	4	23	367	335.0	3	90.8
ANS-24		ANS2002	16.8%	O/W	0	0	4	23	367	340.0	3	125.6
ANS-25	MIT - 17% on cubes	ANS2002	16.8%	cubes	5.4	5	4	23	120+120	230.0	2	192.5
ANS-26		ANS2002	16.8%	cubes	5.45	5	4	23	367	335.0	3	165.4
ANS-27		ANS2002	16.8%	cubes	5.4+ANS-26	5+	4	23	367	330.0	3	255.4
ANS-28		ANS2002	16.8%	crushed	5.4	5	3	18	120+125	220.0	2	189.5
ANS-29		ANS2002	16.8%	crushed	5.4+ANS28	5+	3	18	367	335.0	3	136.8
ANS-30		ANS2002	16.8%	crushed	5.4+ANS29	5+	3	18	367	330.0	3	176.9

[illegible]

[illegible]	Meas. Density (g/ml)	Ignition Source	Ignition Amount (g)	Preheat Time (m:s)	Preheat Burn Coverage	Preheat Time (m:s)	Preheat Burn Coverage	Preheat Time (m:s)	Preheat Burn Coverage	P$_{50}$ (m:s)	Ignition Time (m:s)	Ignition Burn Coverage	Time to Waves (m:s)	Intense Burn Time to (m:ss)	Intense Burn Coverage (%)
[illegible]	0.861	torch		flashed						00:00	00:00	100%	No Wave	none	
[illegible]	0.861	torch		flashed						00:00	00:00	30%	No Wave	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	No Wave	01:05	
[illegible]	0.861	torch		flashed						00:00	00:00	30%	No Wave	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	No Wave	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	00:27	none	
[illegible]	0.888	torch		00:05						00:00	00:00	100%	No Wave	none	
[illegible]	0.888	torch		flashed	small					00:00	00:00	30%	No Wave		
[illegible]	0.888	torch		00:05						00:00	00:00	100%	No Wave	01:11	
[illegible]	0.888	torch		torch moving						00:21	00:42	100%	No Wave	02:45	
[illegible]	0.888	torch		no go							00:00	100%	No Wave	none	
[illegible]	0.888	torch		00:15	25%	00:53	50%	01:21	75%	00:53	02:00	100%	No Wave	none	
[illegible]	0.861	4gg	97.9	00:23	50%					00:23	00:23	50%	00:27	none	
[illegible]	0.888	4gg	88.4	00:31	50%					00:31	00:31	50%	00:42	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	No Wave	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	No Wave	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	00:22	none	
[illegible]	0.888	torch		00:00	75%					00:00	00:34	100%	No Wave	none	
[illegible]	0.888	torch		moved torch around						00:00	00:10	100%	No Wave	02:03	
[illegible]	0.888	4gg	82.0	flashed						00:00	00:21	100%	00:24	none	
[illegible]	0.861	torch		flashed						00:00	00:00	100%	00:17	01:09	
[illegible]	0.888	torch		moved torch around						00:00	00:00	100%	00:15	01:08	
[illegible]	0.899	torch		moved torch around						00:00	00:00	100%	No Wave	none	
[illegible]	0.899	torch		moved torch around						00:00	00:00	100%	No Wave	00:56	
[illegible]	0.899	torch		moved torch around						00:00	00:00	100%	00:16	01:06	
[illegible]	0.899	torch		00:00	25%	00:40	50%	01:03	75%	00:40	01:03	75%	No Wave	none	
[illegible]	0.899	torch		00:00	25%	01:19	50%	02:11	75%	01:19	02:41	100%	No Wave	04:19	
[illegible]	0.899	4gg	84.2	00:44	50%					00:44	00:44	50%	00:56	none	
[illegible]	0.899	torch		00:00	50%	01:11	75%			00:00	01:11	75%	No Wave	none	
[illegible]	0.899	torch		00:00	50%	00:39	75%			00:00	00:57	100%	No Wave	02:35	
[illegible]	0.899	4gg	101.2	00:04	75%					00:00	00:08	100%	00:10	02:12	

[illegible]

	Extinction								Burn Calculations			MIT	Time to	
[illegible]	Time (s)	Burn Coverage	Time (s)	Burn Coverage	Time (s)	Burn Coverage	E_{50} (m:s)	Time to 0%	Duration (s)	Rate (mm/min)	Efficiency (%)	[mm]	Waves (m:s)	
[illegible]	00:33	50%					00:33	01:20	33	0.53	19.05%		No Wave	Short, weak burn.
[illegible]	n/rec						n/rec	n/rec			0.00%	0.5	No Wave	Weak for 30", then out. Very litt
[illegible]	01:37	50%					01:37	01:49	97	1.32	67.91%		No Wave	Lots of minor explosions before
[illegible]	n/rec						n/rec	n/rec			0.00%	0.5	No Wave	Weak for 30", then out
[illegible]	02:36	50%					02:36	03:10	156	0.48	33.97%		No Wave	Ice left after burn
[illegible]	04:56						04:56	04:56	296				00:27	On waves, flames retreated to
[illegible]	00:50	50%					00:50	01:25	50	0.29	14.82%		No Wave	Initially oil only covered 50% of
[illegible]	n/rec						n/rec	n/rec			0.00%	1.0	No Wave	Initially oil only covers 25% of ri
[illegible]	01:54	50%					01:54	02:03	114	1.24	75.91%		No Wave	
[illegible]	03:15	50%					03:15	03:40	174	0.56	50.22%		No Wave	Preheat took some seconds an
[illegible]	no go						no go	no go			0.00%		No Wave	1 mm wouldn't ignite
[illegible]	03:06	50%					03:06	03:53	133	0.24	18.42%	2.0	No Wave	
[illegible]	03:03	25%					03:03	03:38	160	0.74	22.84%		00:27	Flames die down when Waves
[illegible]	03:11	25%					03:11	04:08	160	0.29	1.91%		00:42	Flames don't spread after wave
[illegible]	00:46	0%					00:46	00:46	46		0.00%	1.0	No Wave	Oil pooled, approx. = 30% of ar
[illegible]	01:59	50%					01:59	03:22	119	0.58	29.41%		No Wave	Good, strong burn, ice remainir
[illegible]	03:31	50%					03:31	04:04	211	0.38	35.94%		00:22	Flames die back with waves bu
[illegible]	00:59	0%					00:59	00:59	59		0.00%	1.0	No Wave	Preheated for approx 15 sec, w
[illegible]	02:52	0%					02:52	02:52	172	0.68	62.31%		No Wave	Good burn. Submerged ice rem
[illegible]	02:39	50%					02:39	05:55	159	0.45	32.60%		00:24	Mostly very small burn area afte
[illegible]	01:59	50%					01:59	02:19	119	0.90	53.14%		00:17	
[illegible]	01:54	50%					01:54	02:14	114	0.88	50.09%		00:15	
[illegible]	00:34	0%					00:34	00:34	34	0.25	4.73%	1.0	No Wave	
[illegible]	01:31	50%					01:31	02:08	91	1.48	72.90%		No Wave	
[illegible]	01:48	50%					01:48	02:01	108	1.12	63.06%		00:16	
[illegible]	03:16	50%					03:16	03:37	156	0.26	16.30%	2.0	No Wave	Weak flames. 75% max covera
[illegible]	04:59	50%					04:59	05:11	220	0.45	50.63%		No Wave	All cubes submerged for intens
[illegible]	04:37	0%					04:37	04:37	233	0.46	22.61%		00:56	Flames died back with waves -
[illegible]	01:45	50%	01:56	10%			01:45	02:56	105	0.33	13.86%	2.0	No Wave	Ice remaining
[illegible]	03:20	50%					03:20	03:34	200	0.56	59.16%		No Wave	Good burn, ice remaining after
[illegible]	02:52	50%					02:52	03:20	172	0.53	46.39%		00:10	Good burn. Ice remaining (laste

[illegible]

Test No.	Observations:
[illegible]	Short, weak burn.
[illegible]	Weak for 30", then out. Very little burned, mostly blue flare.
[illegible]	Lots of minor explosions before intense burn.
[illegible]	Weak for 30", then out
[illegible]	Ice left after burn
[illegible]	On waves, flames retreated to edge plus 50% of middle. At end , added 4gg and reignited:ign=50",intense=2'11", ext=2'56". All ice melted. Must REDO.
[illegible]	Initially oil only covered 50% of ring but spread out to 100% on ignition.
[illegible]	Initially oil only covers 25% of ring
[illegible]	
[illegible]	Preheat took some seconds and moving torch. Ice remaining after burn.
[illegible]	1 mm wouldn't ignite
[illegible]	
[illegible]	Flames die down when Waves on. Only burns at edge of ring and between gg. Ice remaining after burn.
[illegible]	Flames don't spread after waves. Only burn around rim and between gg.
[illegible]	Oil pooled, approx. = 30% of area ignited
[illegible]	Good, strong burn, ice remaining after burn. Slush surfaced at 1'59", starting extinction.
[illegible]	Flames die back with waves but not as much as with cubes. Ice remaining.
[illegible]	Preheated for approx 15 sec, weak flame over 75%. Residue left for next test.
[illegible]	Good burn. Submerged ice remaining after burn.
[illegible]	Mostly very small burn area after 2'39". Flames die back when waves hit.
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	Weak flames. 75% max coverage.
[illegible]	All cubes submerged for intense burn. Melts top of cubes and burns there. Only spreads where it can melt ice.
[illegible]	Flames died back with waves - 25% coverage. When cubes act as single mass, can melt areas on top and burn, when mass loosens and cubes surface, flames extinguish.
[illegible]	Ice remaining
[illegible]	Good burn, ice remaining after
[illegible]	Good burn. Ice remaining (lasted for about 1 hr over lunch)

Ice Burn Tests - Pt. MacIntyre

PtMac2002 Burns

All waves have the following characteristics:

Height (cm)	Period (s)	Length (m)	Paddle Setting
8	2	2.5	36

"n/rec"= Not recorded or measured

					Ice		Temperature		Oil Added			Residue
Test No.	Description	Oil	Weathering (% Mass)	Type	Mass (kg)	Thickness (cm)	T_{water} (°C)	T_{air} (°C)	Volume (ml)	Mass (g)	Thickness (mm)	Mass (g)
PM-1	MIT with fresh on water	Point McIntyre 02	0.0%	O/W	0	0	2	19	60	50.0	0.5	n/rec
PM-2	3mm, fresh on water	Point McIntyre 02	0.0%	O/W	0	0	2	19	310	270.0	2.5	120.2
PM-3	3mm, fresh on water w/wave	Point McIntyre 02	0.0%	O/W	0	0	2	19	367	320.0	3	130.7
PM-4	MIT with 9% on water	Point McIntyre 02	9.1%	O/W	0	0	2	20	60+60	100.0	1	n/rec
PM-5	3mm, 9% on water	Point McIntyre 02	9.1%	O/W	0	0	2	20	240+PM-4	215.0	2	131.6
PM-6	3mm, 9% on water w/wave	Point McIntyre 02	9.1%	O/W	0	0	2	20	367	330.0	3	153.7
PM-7	MIT & 3mm with 18% on water	Point McIntyre 02	18.2%	O/W	0	0	2	20	120+120+120	310.0	3	141.4
PM-8	3mm, 18% with waves on water	Point McIntyre 02	18.2%	O/W	0	0	2	20	367	335.0	3	147.5
PM-9	MIT, fresh on cubes	Point McIntyre 02	0.0%	cubes	5.1	5	2	21	65	55.0	0.5	n/rec
PM-10	3mm, fresh on cubes	Point McIntyre 02	0.0%	cubes	none added	5	2	21	310	275.0	2.5	259.4
PM-11	3mm, fresh on cubes w/wave	Point McIntyre 02	0.0%	cubes	5.5+PM-10	5+	2	21	367	330.0	3	234.7
PM-12	MIT, fresh on crushed	Point McIntyre 02	0.0%	crushed	5.4	5	2	21	60	45.0	0.5	n/rec
PM-13		Point McIntyre 02	0.0%	crushed	none added	5	2	21	310	270.0	2.5	252.7
PM-14		Point McIntyre 02	0.0%	crushed	5.4	5	2	21	367	330.0	3	210.8
PM-15	MIT. 9% in cubes	Point McIntyre 02	9.1%	cubes	5.4	5	2	21	120	105.0	1	95.4
PM-16	3mm 9% in cubes	Point McIntyre 02	9.1%	cubes	5.5+PM-15	7+	2	21	367	330.0	3	172.0
PM-17	3mm 9% in cubes w/wave	Point McIntyre 02	9.1%	cubes	5.6	5	2	23	367	340.0	3	266.7
PM-18	MIT for 9% on crushed	Point McIntyre 02	9.1%	crushed	5.4	5	2	23	120+120	215.0	2	222.1
PM-19	3mm for 9% on crushed	Point McIntyre 02	9.1%	crushed	5.4+PM-18	8	2	23	367	330.0	3	146.1
PM-20		Point McIntyre 02	9.1%	crushed	2.7+PM-19	8+	2	23	367	330.0	3	240.0
PM-21		Point McIntyre 02	18.2%	crushed	2.7+PM-20	6+	2	24	240+120	320.0	3	169.8
PM-22		Point McIntyre 02	18.2%	crushed	5.4+PM-21	5+	2	24	367	335.0	3	268.3
PM-23		Point McIntyre 02	18.2%	cubes	5.7	5	2	24	240+120	325.0	3	280.9
PM-24		Point McIntyre 02	18.2%	cubes	5.4+PM-23	5+	2	24	367	330.0	3	350.6

PtMac200

Test No.	Meas.	Ignition		Preheat							Ignition		Time to	Intense Burn	
	Density (g/ml)	Source	Amount (g)	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	P_{50} (m:s)	Time (m:s)	Burn Coverage	Waves (m:s)	Time to (m:ss)	Coverage (%)
PM-1	0.884	torch		moved torch around						00:00	00:00	75%	No Wave	none	
PM-2	0.884	torch		00:00	50%					00:00	00:11	100%	No Wave	01:07	
PM-3	0.884	torch		flashed						00:00	00:09	100%	00:30	01:15	
PM-4	0.902	torch		moved torch around						00:00	00:00	100%	No Wave	none	
PM-5	0.902	torch		moved torch around						00:00	00:13	100%	No Wave	01:33	
PM-6	0.902	torch		flashed						00:00	00:10	100%	00:22	01:27	
PM-7	0.921	torch		moved torch around						00:35	00:35	100%	No Wave	01:20	
PM-8	0.921	torch+1gg	38.4	02:05	25%	02:17	50%			02:17	02:37	100%	02:44	03:20	
PM-9	0.884	torch		flashed						00:00	00:00	50%	No Wave	none	
PM-10	0.884	torch		00:17	75%					00:10	00:52	100%	No Wave	none	
PM-11	0.884	4gg	130.8	00:16	75%					00:10	00:20	100%	00:24	none	
PM-12	0.884	torch		flashed						00:00	00:00	100%	No Wave	none	
PM-13	0.884	torch		flashed(weakly)						00:05	00:11	100%	No Wave	none	
PM-14	0.884	4gg	141.6	flashed						00:05	00:10	100%	00:17	none	
PM-15	0.902	torch		flashed						00:00	00:00	50%	No Wave	none	
PM-16	0.902	torch		01:05	25%	03:30	50%			01:05	03:30	50%	No Wave	05:56	50%
PM-17	0.902	4gg	114.0	00:38	50%					00:38	00:38	50%	00:47	none	
PM-18	0.902	torch		00:26	50%	01:53	75%			00:26	01:53	75%	No Wave	none	
PM-19	0.902	torch		00:30	50%					00:30	01:08	100%	No Wave	02:30	
PM-20	0.902	4gg	n/rec	00:21	50%					00:21	00:28	100%	00:30	none	
PM-21	0.921	torch		00:06	25%	00:35	50%	01:16	75%	00:35	01:16	75%	No Wave	02:13	75%
PM-22	0.921	4gg	138.0	00:34	50%					00:34	00:41	100%	00:43		
PM-23	0.921	torch		00:00	25%	02:37	50%			00:00	02:37	50%	No Wave		
PM-24	0.921	4gg	97.2	00:27	50%	00:40	75%			00:27	00:40	75%	00:40		

PtMac200

Test No.	Extinction								Burn Calculations			MIT	Time to	
	Time (s)	Burn Coverage	Time (s)	Burn Coverage	Time (s)	Burn Coverage	E_{50} (m:s)	Time to 0%	Duration (s)	Rate (mm/min)	Efficiency (%)	[mm]	Waves (m:s)	
PM-1	00:14	50%					00:14	00:14	14		0.00%	0.5	No Wave	Low flame. Ignited but very littl
PM-2	01:50	50%					01:50	02:02	110	1.05	62.44%		No Wave	
PM-3	01:45	50%					01:45	02:02	105	1.05	59.16%		00:30	
PM-4	00:33	50%					00:33	01:20	33		0.00%	1.0	No Wave	22 sec of low, mostly blue, flam
PM-5	02:13	50%					02:13	02:23	133	0.78	58.22%		No Wave	Good burn
PM-6	01:54	50%					01:54	02:07	114	0.89	53.42%		00:22	Good burn. Very waxy residue.
PM-7	02:03	50%					02:03	02:12	88	1.06	54.39%	3.0	No Wave	Three trys at ignition, adding 1
PM-8	03:53	50%					03:53	04:12	96	1.08	55.97%		02:44	Very waxy residue
PM-9	n/rec	50%					n/rec	n/rec			0.00%	1.0	No Wave	Oil was only on 50% of ice. Ign
PM-10	02:04	50%	03:38	25%			02:04	06:44	114	0.48	21.39%		No Wave	Very weak flames. Lots of ice
PM-11	02:38	25%					02:38	03:30	148	0.45	28.88%		00:24	After waves start, burning area
PM-12	00:52	0%					00:52	00:52	52		0.00%	1.0	No Wave	Weak flames over 50% ice are
PM-13	01:48	50%	03:55	25%			01:48	04:41	103	0.48	19.78%		No Wave	Ice remaining after
PM-14	02:15	50%	02:37	25%			02:15	03:05	130	0.60	36.12%		00:17	
PM-15	02:06	0%					02:06	02:06	126	0.16	9.14%	2.0	No Wave	Never burned over more than
PM-16	06:52	25%					06:52	07:07	347	0.53	47.88%		No Wave	Moved torch areound small are
PM-17	03:13	25%					03:13	03:50	155	0.68	21.56%		00:47	No flame spreading after wave
PM-18	02:47	0%					02:47	02:47	141	0.07	-3.30%	2.0	No Wave	Oil was spread out fairly evenly
PM-19	03:23	50%					03:23	03:36	173	0.61	55.73%		No Wave	Ice remaining after burn.
PM-20	02:40	50%					02:40	03:11	139	0.43	27.27%		00:30	Flame coverage retreated to 7
PM-21	02:59	50%					02:59	03:09	144	0.79	46.94%	3.0	No Wave	Would not ignite with 2mm of
PM-22	02:10	25%					02:10	02:22	96	0.47	19.93%		00:43	Flame reduced to 50% of area
PM-23	05:53	25%					05:53	06:07	353	0.19	13.57%	3.0	No Wave	Maximum flame coverage was
PM-24	01:24	25%					01:24	04:38	57	0.09	-6.24%		00:40	Flame reduced to 50% of area

PtMac200

Test No.	Observations:
PM-1	Low flame. Ignited but very little removed.
PM-2	
PM-3	
PM-4	22 sec of low, mostly blue, flame
PM-5	Good burn
PM-6	Good burn. Very waxy residue.
PM-7	Three trys at ignition, adding 120ml each time. Almost didn't ignite on #3. Took a long time with torch. Very waxy residue.
PM-8	Very waxy residue
PM-9	Oil was only on 50% of ice. Ignited. About 30sec of weak flame.
PM-10	Very weak flames. Lots of ice remaining
PM-11	After waves start, burning area = 50%. Flames don't spread in waves. Burning at ring and between gg. Ice remaining after.
PM-12	Weak flames over 50% ice area for 50sec. Used for PM-13
PM-13	Ice remaining after
PM-14	
PM-15	Never burned over more than 50% of ring area
PM-16	Moved torch areound small area to ignite. Flames spread very slowly as top of cubes melted below surface.
PM-17	No flame spreading after waves on. Flame was only between gg at 3:13min
PM-18	Oil was spread out fairly evenly over ring/ice. Minimum: 2mm. Moved torch around to preheat. Flame never spread to more than 75%.
PM-19	Ice remaining after burn.
PM-20	Flame coverage retreated to 75% with waves on. Ice resurfaced at 2:40 causing start of extinction
PM-21	Would not ignite with 2mm of oil. 1mm added and ignited.
PM-22	Flame reduced to 50% of area by 1:03. Ice remaining at end.
PM-23	Maximum flame coverage was 50%. Weak flame. Ice remaining.
PM-24	Flame reduced to 50% of area when waves went on. Then to 25% at 1:24. Burned at 25% til 4:38.

APPENDIX B – MID-SCALE OIL WEATHEREING

OIL DRUM: Endicott #1
Weather to 17.4% which equals total weight of 375.7

DATE	TIME	EMPTY DRUM WEIGHT	WEIGHT	OIL WEIGHT	PERCENT VOLUME REMAINING
8-Sep	1100	47.75	**444.8**	397.05	0
8-Sep	1700	47.75	**442.4**	394.65	99.40%
9-Sep	1730	47.75	**440.35**	392.6	98.88%
10-Sep	1700	47.75	**431.2**	383.45	96.57%
11-Sep	1700	47.75	**427.95**	380.2	95.76%
12-Sep	1700	47.75	**426.95**	379.2	95.50%
13-Sep	1700	47.75	**425.55**	377.8	95.15%
14-Sep	1700	47.75	**420.95**	373.2	93.99%
15-Sep	1700	47.75	**419.05**	371.3	93.51%
16-Sep	1700	47.75	**416.6**	368.85	92.90%
17-Sep	1700	47.75	**413.8**	366.05	92.19%
18-Sep	1700	47.75	**411.9**	364.15	91.71%
19-Sep	1700	47.75	**410.8**	363.05	91.44%
22-Sep	1700	47.75	**408.8**	361.05	90.93%
23-Sep	1700	47.75	**409.6**	361.85	91.13%
24-Sep	1700	47.75	**407.6**	359.85	90.63%
25-Sep	1700	47.75	**406.15**	358.4	90.27%
26-Sep	1730	47.75	**406**	358.25	90.23%
27-Sep	1700	47.75	**404.95**	357.2	89.96%
28-Sep	1700	47.75	**396.05**	348.3	87.72%
29-Sep	1700	47.75	**395.01**	347.26	87.46%
30-Sep	1700	47.75	**393.1**	345.35	86.98%
1-Oct	1700	47.75	**391.7**	343.95	86.63%
2-Oct	1700	47.75	**391.05**	343.3	86.46%
4-Oct	700	47.75	**389.5**	341.75	86.07%
5-Oct	700	47.75	**281.55**	233.8	58.88%
		47.75		-47.75	-12.03%
		47.75		-47.75	-12.03%
		47.75		-47.75	-12.03%
		47.75		-47.75	-12.03%
		47.75		-47.75	

9-20-02 air turned off due to air compressor fire, no measurement taken at this time. Air will be resupplied upon reassembly of compressor hoses and fittings in the next day or two.

Windy conditions on 9-22-02 made it difficult to get an accurate reading - took best reading available

Oil bubbled out of this drum during the day on 10-4. We weighed the drum the following morning and figure we lost 107 pounds of oil.

Weathering process on this drum considered complete.

OIL DRUM: Endicott #2

Weather to 9.1% which equals total weight of 411.

DATE	TIME	EMPTY DRUM WEIGHT	WEIGHT	OIL WEIGHT	PERCENT VOLUME REMAINING
8-Sep	1100	47.75	**447.6**	399.85	0
8-Sep	1700	47.75	**444.1**	396.35	99.12%
9-Sep	1730	47.75	**436.7**	388.95	97.27%
10-Sep	1700	47.75	**433.4**	385.65	96.45%
11-Sep	1700	47.75	**429.3**	381.55	95.42%
12-Sep	1700	47.75	**428.45**	380.7	95.21%
13-Sep	1700	47.75	**427.5**	379.75	94.97%
14-Sep	1700	47.75	**421.2**	373.45	93.40%
15-Sep	1700	47.75	**418.25**	370.5	92.66%
16-Sep	1700	47.75	**413.4**	365.65	91.45%
17-Sep	1700	47.75	**410.05**	362.3	90.61%

Drum sabotaged on 9/18/02 resulting in a loss of 20lbs of oil. Drum capped that date.

Weather process on this drum complete.

OIL DRUM: NorthStar #1
Weather to 33.8% which equals total weight of 303.28

DATE	TIME	EMPTY DRUM WEIGHT	WEIGHT	OIL WEIGHT	PERCENT VOLUME REMAINING
8-Sep	1100	47.75	**433.75**	386	0
8-Sep	1700	47.75	**430.65**	382.9	99.20%
9-Sep	1730	47.75	**424.7**	376.95	97.66%
10-Sep	1700	47.75	**422.25**	374.5	97.02%
11-Sep	1700	47.75	**416.8**	369.05	95.61%
12-Sep	1700	47.75	**416.35**	368.6	95.49%
13-Sep	1700	47.75	**414.25**	366.5	94.95%
14-Sep	1700	47.75	**408.95**	361.2	93.58%
15-Sep	1700	47.75	**398.95**	351.2	90.98%
16-Sep	1700	47.75	**390.85**	343.1	88.89%
17-Sep	1700	47.75	**378.4**	330.65	85.66%
18-Sep	1700	47.75	**370.45**	322.7	83.60%
19-Sep	1700	47.75	**365.3**	317.55	82.27%
22-Sep	1700	47.75	**364.2**	316.45	81.98%
23-Sep	1700	47.75	**362**	314.25	81.41%
24-Sep	1700	47.75	**351**	303.25	78.56%
25-Sep	1700	47.75	**340.5**	292.75	75.84%
26-Sep	1730	47.75	**336.5**	288.75	74.81%
27-Sep	1700	47.75	**321.6**	273.85	70.95%
28-Sep	1700	47.75	**311.9**	264.15	68.43%
29-Sep	1700	47.75	**304.65**	256.9	66.55%
30-Sep	1700	47.75	**304.65**	256.9	66.55%
1-Oct	1700	47.75	**303.75**	256	66.32%
2-Oct	1700	47.75	**303.75**	256	66.32%

9-20-02 air turned off due to air compressor fire, no measurement taken at this time. Air will be resupplied upon reassembly of compressor hoses and fittings in the next day or two.

Air resupplied on 9-22-02

Windy conditions on 9-22-02 made it difficult to get an accurate reading - took best reading available

Heat was applied to both of the North Star drums starting on 9-23-02.

10-3-02 - No weathering was done to this barrel today due to small % left to go.

Weather process on this drum complete.

OIL DRUM: NorthStar #2

Weather to 43.8% which equals total weight of 249.05

DATE	TIME	EMPTY DRUM WEIGHT	WEIGHT	OIL WEIGHT	PERCENT VOLUME REMAINING		
8-Sep	1100	47.75	**405.95**	358.2		0	
8-Sep	1700	47.75	**398.65**	350.9		97.96%	
9-Sep	1730	47.75	**386**	338.25		94.43%	
10-Sep	1700	47.75	**379.8**	332.05		92.70%	
11-Sep	1700	47.75	**369.5**	321.75		89.82%	
12-Sep	1700	47.75	**366.9**	319.15		89.10%	
13-Sep	1700	47.75	**360**	312.25		87.17%	
14-Sep	1700	47.75	**349.65**	301.9		84.28%	
15-Sep	1700	47.75	**338.85**	291.1		81.27%	
16-Sep	1700	47.75	**332.2**	284.45		79.41%	
17-Sep	1700	47.75	**327.3**	279.55		78.04%	
18-Sep	1700	47.75	**323.15**	275.4		76.88%	
19-Sep	1700	47.75	**320.6**	272.85		76.17%	
22-Sep	1700	47.75	**318.6**	270.85		75.61%	
23-Sep	1700	47.75	**319.3**	271.55		75.81%	
24-Sep	1700	47.75	**314.4**	266.65		74.44%	
25-Sep	1700	47.75	**305.1**	257.35		71.85%	
26-Sep	1730	47.75	**301.15**	253.4		70.74%	
27-Sep	1700	47.75	**294.25**	246.5		68.82%	
28-Sep	1700	47.75	**290.55**	242.8		67.78%	
29-Sep	1700	47.75	**289.45**	241.7		67.48%	
30-Sep	1700	47.75	**286.3**	238.55		66.60%	
1-Oct	1700	47.75	**283.85**	236.1		65.91%	
2-Oct	1700	47.75	**283.3**	235.55		65.76%	
4-Oct	700	47.75	**282.8**	235.05		65.62%	
5-Oct	700	47.75	**275.15**	227.4		63.48%	
6-Oct	1700	47.75	**274.5**	226.75		63.30%	
7-Oct	1700	47.75	**272.6**	224.85		62.77%	
10-Oct	1700	47.75	**273**	225.25		62.88%	
11-Oct	1700	47.75	**270.25**	222.5		62.12%	
12-Oct	1700	47.75	**268.95**	221.2		61.75%	
13-Oct							
14-Oct							
15-Oct	1700	47.75	**264.9**	217.15		60.62%	
16-Oct	1700	47.75	**261.05**	213.3		59.55%	
17-Oct	1700	47.75	**257.75**	210		58.63%	
18-Oct	1700	47.75	**254.9**	207.15		57.83%	
19-Oct							
20-Oct	1700	47.75	**249.05**	201.3		56.20%	
21-Oct							
22-Oct							
23-Oct							
24-Oct							
25-Oct							

9-20-02 air turned off due to air compressor fire, no measurement taken at this time. Air will be resupplied upon reassembly of compressor hoses and fittings in the next day or two.

Air resupplied on 9-22-02

Windy conditions on 9-22-02 made it difficult to get an accurate reading - took best reading available

Heat was applied to both of the North Star drums starting on 9-23-02.

10-13 and 10-14 - No measurement taken due to air compressor being down for those days.

APPENDIX C – MID-SCALE TEST PLAN

THIRD DRAFT

TEST PLAN

for

MID-SCALE TESTS TO DETERMINE THE LIMITS TO *IN SITU* BURNING IN BROKEN ICE

October 8, 2002

by

SL Ross Environmental Research Ltd.
and
DF Dickins Associates Ltd.
and
Alaska Clean Seas

Table of Contents

1. Introduction

1.1 Summary

The use of in situ burning as a response tool for oil spills in broken 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 are still questions about the limits to ignition and the most effective means of burning spilled oil in broken ice conditions, particularly for thinner slicks in fields of broken ice subjected to wave action. To date, no experiments have documented the data necessary to answer these questions with any degree of confidence. The purpose of this study will be to investigate the minimum ignitable thickness, the combustion rate, residue amount and the effects of waves for oil burned in situ in broken ice.

This portion of the proposed work entails conducting a series of mid-scale burns in the Alaska Clean Seas (ACS) wave tank at the Fire Training Ground in Prudhoe Bay.

Rather than attempt to scale ice processes to the tank dimensions, the experimental design philosophy is that the tank represents a small portion of a full-scale ice field. The brash and frazil ice used in the wave tank represent a small area of real ice conditions between larger ice features offshore. The test ice fields will be a combination of ice grown either on site in tanks or mined from the Beaufort Sea. The experimental variables are:
X oil type (Alaska North Slope, Endicott, Northstar and Pt. McIntyre crude);
X ice type (brash and frazil);
X initial oil concentration in the ice (3mm slicks and thinner);
X mixing energy (waves to simulate natural mixing of a brash ice field); and,
X degree of oil evaporation.

A total of 36 mid-scale tests are to be carried out in late-October 2002, when freezing conditions exist at the Fire Training Ground in Prudhoe Bay, AK.

1.2 Background

Recent field deployments of skimmers in broken ice conditions in the Alaskan Beaufort Sea have highlighted the severe limitations of containment and recovery systems in broken ice conditions. *In situ* burning may be the only option to quickly remove oil spilled in broken ice. The use of *in situ* burning as a response tool for oil spills in broken 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 are still questions about the limits to ignition and effective burning of spilled oil in broken ice conditions, particularly in fields of broken ice containing significant amounts of brash and slush ice and subjected to wave action. The purpose of this study will be to investigate the minimum ignitable thickness, the combustion rate and residue thickness of oil burned *in situ* in broken ice, including the effects of waves.

Research in oil spill cleanup in broken ice began in the 1970's. Interest in the subject increased in the early 1980's because of proposals for offshore production in Alaska and Canada, and has become an international subject of R&D with the opening of Russian and Norwegian ice-covered waters for exploitation. Interest in the subject has been rekindled in Alaska with several recent offshore development proposals near Prudhoe Bay. Also, operators of established production facilities in Cook Inlet have an ongoing need to improve their level of understanding of alternative response strategies for spills in broken ice.

The consensus of the research to date on spill response in broken ice conditions is that *in situ* burning is a suitable response technique, and in many instances may be the only cleanup technique applicable. An earlier task in this project involved a detailed review of the scientific literature on the subject. A considerable amount of research was done on the potential for *in situ* burning in broken ice, including several smaller-scale field and tank tests and one large field test. Most of these tests involved large volumes of oil placed in a static test field of broken ice resulting in substantial slick thickness 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. Frazil ice is the "soupy" mixture of very small ice particles that forms as seawater freezes.

The key to the success of an individual burn in a broken 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 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. In Cook Inlet, brash ice and frazil ice are the forms normally present for most of the year. 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 is appropriate to focus the proposed testing on the ignitability and burnability of oil/brash/slush mixtures in various combinations and situations.

In open water conditions and on a complete ice cover the "rules of thumb" for *in situ* burning are well known. Extensive experimentation on crude and fuel oils with a variety of igniters in a range of environmental conditions has confirmed the following for relatively calm wave conditions:

- The minimum ignitable thickness for fresh, volatile crude oil on water is about 1 mm;
- The minimum ignitable thickness for aged, unemulsifed crude oil and diesel fuels is about 3 to 5 mm;

- The minimum ignitable thickness for residual fuel oils, such as Bunker “C” or No. 6 fuel oil, is about 10 mm;
- Once 1 m^2 of burning slick has been established, ignition can be considered accomplished.
- The maximum wind speed for successful ignition of large burns has been determined to be 10 to 12 m/s;
- For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water; however, some crudes form meso-stable emulsions that can be easily ignited at much higher water contents;
- If the ambient temperature is above the oil's flash point, the slick will ignite rapidly and easily and the flames will spread quickly over the slick surface - flames spread more slowly over oil slicks at sub-flash temperatures;
- For most large (> 3 m diameter) fires of unemulsified crude oil on water the burning rate is 3.5 mm/min - automotive diesel and jet fuel fires on water burn at a slightly higher rate of about 4 mm/min;
- For pools of unemulsified crude oil up to 10 to 20 mm thick the residue thickness will be 1 mm;
- For thicker crude slicks the residue is thicker (e.g., 3 to 5 mm for an initial slick thickness of 50);
- For emulsified slicks, the residue thickness can be much greater; and,
- For light and middle-distillate fuels, the residue thickness will be 1 mm, regardless of initial slick thickness.

There is not sufficient information in the literature to determine similar "rules of thumb" for the *in situ* burning of oil spills in broken ice situations, in particular for oil mixed with brash and/or frazil ice.

1.3 The Experimental Approach

A series of parametric mid-scale experiments will be carried out in a wave tank in Prudhoe Bay in order to identify the effects of ice concentration, ice dynamics and ice type on the "rules of thumb" for *in situ* burning. For example, what is the minimum ignitable concentration (i.e., thickness) of fresh crude oil mixed with brash ice? Is this the same for frazil ice? How is this affected by wave action? The rules to be determined include:

X minimum ignitable thickness, or concentration (% oil in ice);
X residue amounts (thickness/concentration remaining after extinction); and,
X oil removal rates.

Rather than attempt to scale ice processes to the tank dimensions, the experimental design philosophy will be that the tank represents a small portion of a full-scale lead in an ice field. The brash and frazil ice used in the wave tank would represent a small area of real ice conditions between larger ice features offshore. The final design of the experiments will depend on the results of the series of small-scale scoping burns presently being conducted in Ottawa. These would be used to identify the likely range of ignitable oil concentrations in brash and frazil ice. The mid-scale experimental variables would be:

X oil type (Alaska North Slope, Endicott, Northstar and Pt. McIntyre crudes);
X ice type (brash and frazil);
X initial oil concentration in the ice;
X mixing energy (waves); and,
X degree of oil evaporation.

The 36 burn tests would be conducted inside sections of surplus "Shell" fire boom floated in the tank (Figures 1 and 2). These sections would be designed to contain the test section of ice in the centre of the tank, but not restrict the movement of the ice or the mixing/spreading of the oil with/among the ice. Gelled gas (Heli-torch fuel) and "Dome" hand-held igniters would be used to light the test burns. The tests would involve burns ranging in size up to 60 L. Ignition times, burn rates and burn efficiencies would be measured.

The effect of ice conditions on the ignitability and efficiency of burning is a critical component of the study. The composition of the ice particles and degree of compression in the ice (affected in real time and space by wind and wave action) act to control the porosity of the ice to the oil. This porosity in turn dictates the degree of natural containment offered in both lateral (spreading), and vertical (mixing) planes to slow or stop the oil spreading.

The choice of ice conditions for possible simulation in the outdoor tank depends on several factors:
X the range in broken ice conditions most representative of different offshore areas;
X the scaling consideration of the tank area relative to the spatial variability of broken ice in the natural environment; and
X the ability to create and maintain a given ice condition in an uncontrolled setting.

As described above, the results from this project will be used to create "rules of thumb" relevant to both the existing production fields in Cook Inlet as well as for new and proposed offshore fields (e.g., Northstar) and existing coastal fields in the Prudhoe Bay Unit (e.g., Milne Point).

Cook Inlet is exposed to drifting broken ice features with a wide range of thickness through much of the winter. During this time, platforms may encounter large pans of first-year ice interspersed with slush and brash ice and smaller pancakes. A condition of so called "slush" or brash ice is characteristic of many areas where thicker floes are in constant contact through collision and rotation. This condition leads to a soupy mix of very small ice particles floating in the water, combining the ice remnants ground from the thicker floe interactions with the new frazil ice (fine individual plates of ice suspended in the freezing water). This frazil constantly forms under freezing temperatures and coagulates into an ice form known as grease. The common feature of this elastic ice type is the small particle size (inches or less) and relatively homogeneous granular composition between the ice pancakes.

Figure 1 - ACS wave tank at Prudhoe Bay Fire Training Grounds.

Figure 2 - Burn ring (circle of SWEPI boom) in tank.

The Beaufort Sea near-shore area on the other hand experiences broken ice for two relatively short periods at freeze-up and break-up, and during brief periods in the summer when rotting pack ice may approach the coast. The composition of broken ice in the Beaufort is generally different than Cook Inlet. At break-up, much of the fast ice near-shore melts in place with relatively little movement. Eventually the sheet fractures in an advanced state of decay, leaving drifting ice pans with predominantly open water between. Freeze-up is a more relevant condition in terms of modeling oil-ice interaction at the scale of the tank tests being proposed. Beginning in early October, the new ice sheet often expands rapidly out from shore only to be interrupted by storms and broken-up several times before forming a stable cover. As a result, the broken ice in the Beaufort near-shore areas tends to represent a transition condition between open water and solid fast ice (in contrast to Cook Inlet where the dynamic tidal currents keep the ice in a constant state of motion, breaking and freezing as it drifts back and forth). Beaufort conditions following a storm event may consist of a mix of isolated larger floes (hundreds of feet) separated by brash ice (smaller fragments or wreckage from the previous sheet ice with sizes in the order of a few feet). Depending on the air temperatures the exposed open water between the brash ice features will quickly begin forming frazil/grease ice leading quickly to pancake forms a few feet to tens of feet across.

There are two basic ice conditions which are meaningful in real life and can potentially be created in the tank: homogeneous grease and or slush ice with small particle sizes; and a non-homogeneous mix of brash ice and slush with particle sizes up to about one foot diameter. Given that the tests are simulating only a small slice of a larger broken ice setting it is not meaningful to talk about ice concentration in the sense that ice is usually characterized over large areas. Instead, from the aspect of oil containment and distribution in the ice for burning, it is more relevant to examine the effect of particle size and the interaction of this ice and oil on a small scale in calm and disturbed conditions (waves).

The process of creating a particular ice condition and holding it constant for a period of days with fluctuating temperatures, snow fall, and winds would be impossible. As such, the approach will be to partially insulate or cover the tank sidewalls and, by introducing heat (from one or two Tioga heaters) as necessary, prevent ice from forming on the tank surface while maintaining the water temperature near freezing. Ice will be grown in Fast Tanks set up on site and filled with seawater. Alternatively, it may be possible to collect sea ice from for example the West Dock causeway and transport it back to the tank as required. For each test, a fresh load of ice, of the desired type and thickness, will be placed inside the burn ring. After each test the ice and reside will be removed, and the ice melted to recover any trapped oil, to determine burn efficiency and rate.

Given that shore ice often forms in the Prudhoe Bay area by early October, and that the mean air temperature reaches also reaches the freezing point at this time, a reasonable target to start making ice would be the second week of October. This date may vary by ∀10 days depending on weather conditions.

1.4 The Wave Tank

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 simple, hydraulically-driven wave paddle at one end and passive wave absorbers (Figure 1). With 1.8 m (72") of water in the tank, the wave maker is capable of generating waves with heights to 0.6 m (2') with periods ranging from 1.7 to 3.3 seconds. The corresponding wavelengths are 4.2 to12 m. Smaller waves with shorter wavelengths, for example a 26 cm (10") wave with a period of 1.3 s and a length of 2.6 m, or 8.5', are also possible. The wave absorber design virtually eliminates any reflected waves from the ends of the tank. The tank has been used to conduct experimental *in situ* burns on the North Slope in the past and is fitted with a water deluge system to protect the side walls from heat for this type of testing. Prior to the tests the tank will be checked out and filled with seawater (16,160 gallons) from the processing plant at West Dock.

2. General Information

2.1 Test Locations

The tests will be conducted at the Fire Training Grounds in Prudhoe Bay, AK. Figure 3 is a map showing the location of the Fire Training Ground, ACS' base, BP's Prudhoe Bay Operating Center (PBOC), the Sea Water Treatment Plant at West Dock, East Dock and the airport. Figure 4 shows a general layout of the major pieces of equipment required for the tests at the Fire Training Ground.

2.2 Weather Conditions

The average weather conditions for late October are given in Table 1.

2.3 Project Team

This project is being carried out jointly by SL Ross Environmental Research Ltd. (Mr. Ian Buist, P.Eng.), DF Dickins Associates Ltd. (Mr.David Dickins, P.Eng.) and Alaska Clean Seas (Mr. Lee Majors - Planning and Development Manager). The project is being funded by the Minerals Management Service (Mr. Joe Mullin, COTR) and ExxonMobil Upstream Research Company. (Ms. Charlene Owens).

2.4 Operating Constraints

Burning can take place only in daylight and with winds less than 20 mph.

Table 1 - Climatic Normals[*] for Prudhoe Bay Area

	October 21 to 31
Mean T (°F)	9
Normal Max. T (°F)	10 to 15
Normal Min. T (°F)	0 to 6
Average % POP	45
Average precipitation (in/month)	0.4
Average snowfall (in/month)	8
Avg. Wind Speed (mph)	14
Prevailing Wind	ENE
Hours of Daylight (25th)	8:54 am to 4:20 pm
% visibility < 1/4 mile	3
% visibility < 1 mile	12

[*] Note that recent temperatures have been 5 to 10 °F above normal

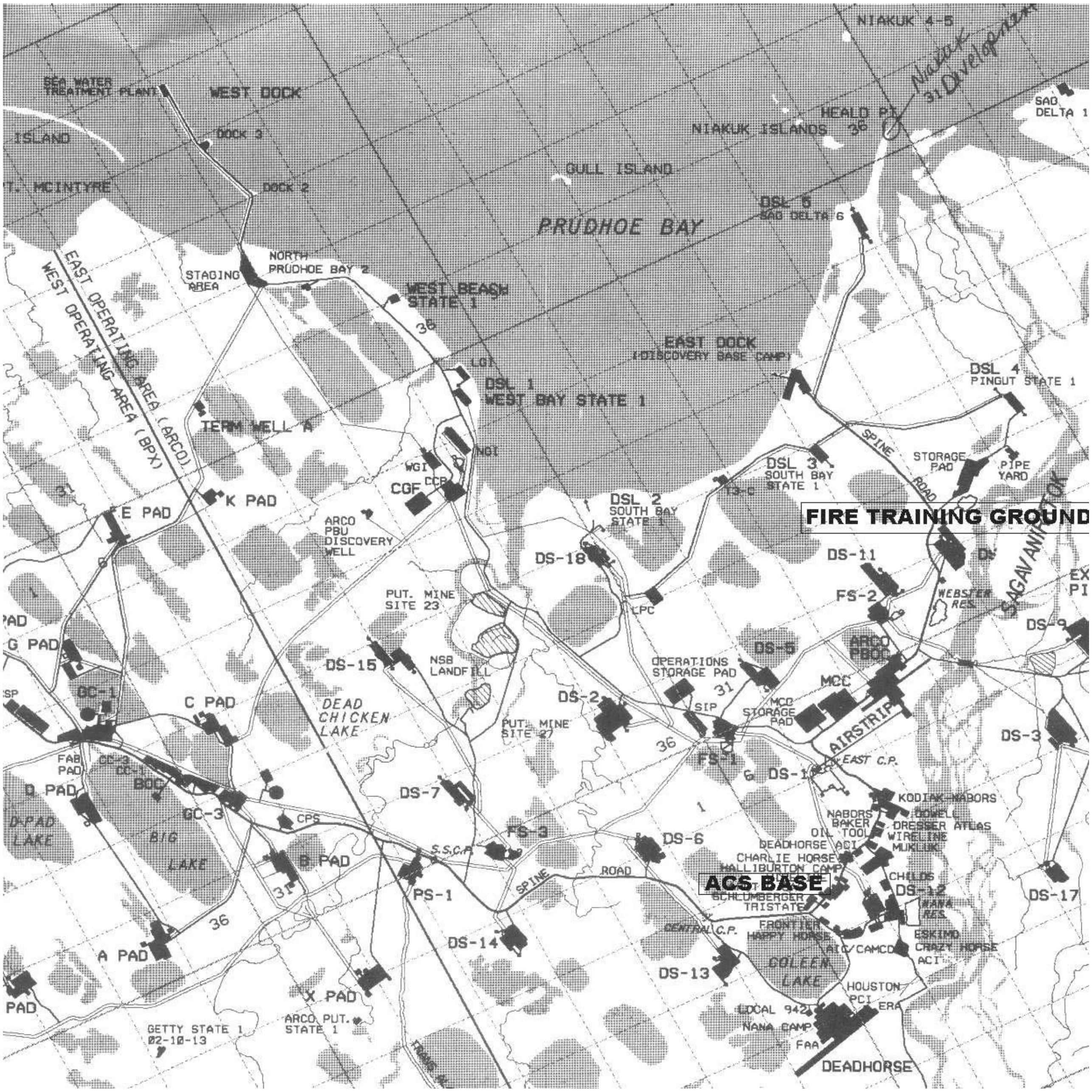

Figure 3 – Area Map

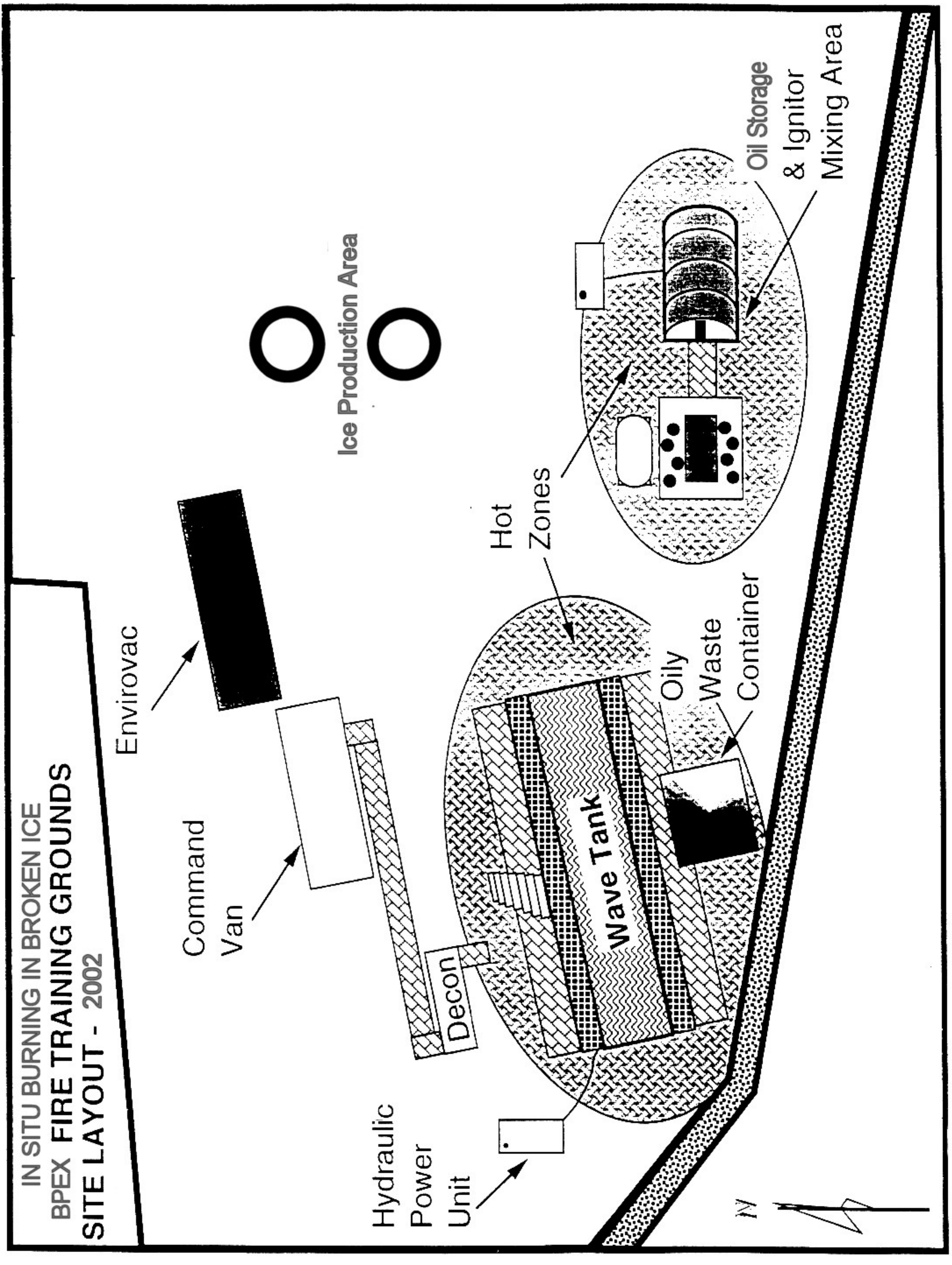

Figure 4 – Site Layout

3.0 Test Plan

3.1 Burn Test Matrix

The experimental burns will involve contained slicks with a diameter of approximately 6 feet. The test program will include ignition and burning tests with four oils (Alaska North Slope, Endicott, Northstar and Pt. McIntyre crudes) in two ice conditions (brash or frazil) with up to three slick thicknesses (depending on the small-scale tests results), with some tests in waves (long wavelength). Two of the oils (Northstar and Endicott) are to be artificially evaporated to two different degrees of evaporation for use in a number of the tests. A total of 36 tests are planned: 16 involving burns with 3mm of each oil in brash ice and 16 involving burns with 3mm in frazil ice. The equivalent of four tests would be devoted to determining Minimum Ignitable Thickness (MIT) for each oil in brash and frazil (these tests are much less effort to conduct, since they usually do not require replacement of the ice after the test and often the oil remaining can be used for a subsequent 3mm test burn). Time permitting; baseline burns in open water (MIT and 3mm in o/w and waves) will also be conducted (again, these are much less effort than the burns in ice). The preliminary test matrix is:

Oil	Percent Evaporated	Brash Ice		Frazil Ice		Minimum Ignitable Thickness		Optional Open Water Burns
		Calm	Waves	Calm	Waves	Brash	Frazil	
ANS	0							
Pt McIntyre	0							
Northstar	0							
	33.8							
	43.8							
Endicott	0							
	9.1							
	17.4							

3.2 Oil Samples and Weathering

The following volumes of oil are required for the tests:
$ Alaska North Slope - 1 full drum
$ Endicott - 3 full drums
$ Northstar - 3 full drums
$ Pt. McIntyre - 1 full drum

Two drums of the Endicott and Northstar are to be artificially evaporated to different degrees of evaporation. The target degrees of evaporation (and the oil types themselves) were chosen because data on their burnability on water already exists for comparison purposes. The equipment and procedures for weathering the oil are described in detail in Appendix 1. Basically, the drum of fresh oil will be placed on a weigh scale and compressed air bubbled through it until it has lost the desired percent of its initial weight. After a period of bubbling, an electric band heater may be used to accelerate the evaporation rate. The weathered crudes will be sealed in the original drums until required for the experiments.

3.3 Ice Preparation

Ice Preparation Procedures

This section describes the proposed field procedures aimed at producing sufficient ice with the desired characteristics to carry out the full sequence of 36 tests. Rather than attempt to scale ice processes to the tank dimensions, the experimental design approach is to consider the tank as a small portion of a full-scale ice field. The brash and frazil ice used in the wave tank are intended to represent a small area of closely-packed (9+ tenths) real ice conditions between larger ice features offshore.

There are two basic pack ice conditions which can potentially be created and added to the tank: homogeneous grease and or slush 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 one foot in diameter. The target ice cover concentrations are 9+ tenths.

The proposed ice preparation plan is based on the following rationale (the exact sequence of may vary according to the weather conditions and the progress of the test program):

Total number of tests	36
Test period	7 days
Maximum expected tests/day after Day 1	6
Number of tests per day with brash ice	3
Number of tests per day with slush	3
Burn/ice area (at 5.6 ft diameter with 9+ tenths)	24.6 square feet
Daily brash ice area needed to provide for 3 tests	75 square feet (approx 8 ft x 10 ft)

Brash Ice Production

The required brash ice (450 square feet [25 ft^2 x 18 brash ice tests total] at a thickness of 4 inches solid ice) will be formed in advance of the tests by using readily available plastic pit liners or drip trays. These trays are already shaped to allow sufficient water to freeze in place. At the air temperatures anticipated for mid-October in the Beaufort Sea, expected growth rates for sea ice on the ocean surface under warmer than average conditions (representing 2002 to date) are in the order of one inch per day. Growth rates will be faster in a closed system with heat transfer in all directions. Care needs to be taken to provide sufficient water in the trays to take-up the salt rejected as the ice forms (in other words, the water depth needs to be at least a few inches deeper than the target solid ice thickness of 4 inches).

Once the Bay water in the trays has frozen solid, the ice will be removed by inverting the trays. The slabs will then be cut into pieces approximately one foot on a side. A portion of the ice will be further broken into smaller pieces prior to adding the ice to the tank. The ice should release cleanly from the plastic surface of the trays due to the layer of liquid slushy brine on the bottom (left from the expulsion of brine beneath the growing ice).

The ice will then be stored outdoors until needed for the tests. If it becomes necessary to stack the ice, plastic separator sheets will be used to prevent the ice blocks from freezing together into a solid mass. This procedure was used successfully for a recent trial with sea ice blocks stored in refrigerated containers at the Ohmsett test facility (January 2002).

Slush Ice Production

The initial test plan proposed using an additional pit or tank to grow frazil, potentially with some form of continuous bubbler agitation. This technique is difficult to control outdoors and may not produce the required granular material. In "real life" slush ice is formed from snow falling on water and then floating as a viscous floating mass. If the tests are conducted as proposed in the third week of October, there is a very high likelihood that snow can be collected naturally and simply dumped as needed into the burn ring each day. Ideally, a snow pile needs to be built-up near the tank ahead of the tests to provide a convenient resource. This is considered a more reliable means of generating a homogeneous small particle size than attempting to grow and maintain frazil in an outdoor tank.

Based on a typical snow density of 0.35, approximately 2.6 times more snow than ice, will be required to form a 4-inch layer of slush ice within the burn ring. On this basis, the approximate volume of snow required to complete 18 tests with slush ice works out to 386 cubic feet (14 cubic yards).

Harvesting and Loading

A small loader with a bucket able to reach directly to the tank edge will be available. Sufficient cut ice for each test can be easily scooped (or moved manually into the loader bucket), lifted up and dumped into the burn ring. Having been stored outdoors for some time prior to the test, the ice will be drained of brine and relatively dry as it is loaded. Wet ice could fuse together and/or immediately stick to the cold steel bucket. To guard against this possibility, it is suggested that the bucket be lined with a Visqueen or poly sheet.

Snow can be gathered from the local area and dumped using the loader. If necessary, additional snow can be recovered from a disused pad or taken from drifts produced normally in the course of general snow clearing around PBU facilities, and trucked to the fire training area.

3.4 Gelled Fuel Preparation

Two types of igniters are required for the tests: gelled gasoline and hand-held (Dome) igniters. The detailed procedures for mixing the gelled gasoline are given in Appendix 3. Gelled fuel mixing will take place in the heated, ventilated oil storage/mixing Conex or tent shown on Figure 4. Only a few quarts of gelled gas will be mixed each time. The actual mixing of the gasoline and gelling agent (requiring 2 to 3 minutes) will take place just outside the tent/Conex to limit exposure to gasoline fumes. Once gelled, the volatility of the gasoline is greatly reduced.

3.5 Burn Tests

3.5.1 Burn Ring

The burn ring (see Figure 2) will be formed using a 20-foot section of the old Shell fire boom formed into a 5.6-foot diameter circle. The burn ring will be held loosely in the center of the wave tank by wires attached to the side of the tank. Sufficient play is required in the attachment wires to allow the ring to move up and down with the waves (18" maximum). As well, in order to facilitate filling the ring with oil, applying igniters and recovering residue, the ring should be easy to move to the side of the tank. When the location of the ring in the tank has been selected, it would be prudent to hang a 15 foot long perforated steel pipe along each side of the tank that sprays water against the inside surface of the exposed wave tank wall to make certain the tank wall does not buckle when exposed to radiated heat. The cooling water should be pumped from the tank itself to prevent depth changes in the tank.

3.5.2 Burn Tests

Equipment Required

! wave tank c/w hydraulic power pack, Tioga heaters and fabric covers, deluge piping, hoses and pump
! front-end loader capable of lifting ice over edge of tank
! portable weather station
! hand-held anemometer
! digital thermometer
! stop watch
! electronic balances (200 and 500 lbs)
! clear plastic residue bags
! sorbents for residue recovery/weighing
! video camera
! 35 mm camera
! fork lift with person-basket or platform/scaffolding for photography and video
! shovels
! butane or propane torch
! gelled fuel igniters
! hand-held igniters
! empty drums and warmed tent or Conex for melting ice

The test plan calls for 36 test burns. The procedures for each test are as follows:

12. Place desired amount of ice type in burn ring (nominally a 10 cm thickness in a 1.7 m diameter ring is 225 L [60 gallons], or 200 kg [450 lbs] of sea ice).
13. Measure oil volume for desired thickness and weigh (nominally, each mm of oil is 2.25 L [0.6 gallons], or 1.9 kg [4.2 lbs]) and add to burn ring using a spill plate.
14. Manually, or with waves, mix oil into ice.
15. After the oil has been added to the ring, and the ring positioned in the center of the wave tank, the wind speed will be recorded using both a hand-held anemometer and the weather station. The temperature of the air and water will also be recorded.
16. For these tests a baggie containing 4 fluid ounces of gelled gasoline will be used to ignite the slick. These gelled fuel bags will be placed on the oil then ignited with a butane torch taped to a pole. For MIT tests, ignition will be attempted with the torch alone until the incremental thickness reaches 3 mm.
17. 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 the settings given in Table 2.

Table 2 - Target Wave Settings for Tests[1]

Steepness	Height (in)	Length (ft)	Period (s)	Waveboard Frequency/Amplitude Settings
0.03	6	15.7	2.0	6.00/0.80

[1] Based on tests in 1997

18. For each burn test the following will be recorded:
    - preheat time - the time from firing 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 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).

19. Each burn will be videotaped, photographed and observed visually from an elevated platform.

20. After each burn, the residue will be allowed to cool. Once cooled, the residue will be collected with a shovel and pre-weighed sorbent sheets and placed in pre-weighed plastic bag(s). If the residue cannot be completely recovered from the ice remaining in the ring, the ice will also be removed and melted to recover any residue. Based on the small-scale tests, it is fairly easy to recover the entire residue from the ice.

21. The residue will then be weighed to allow calculations of burn efficiency and rate. The burn efficiency will be calculated by comparing the weight of the residue with the weight of oil added initially. The burn rate will be calculated by dividing the volume of oil burned by the ring area and the time from full flame coverage (ignition time) to extinction.

22. Once the residue (and ice) is recovered, the ice and oil for the next burn will be added to the ring and the process repeated.

At the end of the tests a photocopy of the Surface Weather Observations sheet for each of the test days will be obtained from the Deadhorse airport.

3.6 Test Schedule

The following is the revised tentative schedule for the tests:

October 14 – install brash ice growth pit(s)/drip trays at Fire Training Ground and test fill
October 19/20 – fill ice growth pits/drip trays with water
October 21 to 23 – equipment deployment and set up at Fire Training ground
October 23 to 29 – conduct 36 test burns
October 30 - demobilize and clean up Fire Training Ground.

A Visitors Day has been tentatively scheduled for Monday, October 28.

4. Safety And Environmental Protection

4.1 Safety

General Information

Site/Area Location: EOA Fire Training Grounds

Purpose: To provide a general site safety and environmental protection plan for use during in situ preparation burning activities.

Summary of Activities

This safety and environmental plan is designed to augment the attached *in situ* burning in broken ice test plan.

Hazard Summary and Evaluation

The following Hazard Analysis and Control Plan is designed to address anticipated exposures during the preparation, testing, and demobilization stages. While this plan has been based upon an extensive pre-job plan of activities and job scope as well as research into similar completed test activities, changes within daily applications may necessitate safety adaptations of controls. As such, this plan will be augmented by daily site safety briefings (ACS Tail Gate Safety Meetings) in order to ensure communication of any changes in identified or anticipated hazards and control options.

Physical Hazards

Slips/Trips/Falls	Dunnage, secondary containment, hydraulic hoses, transfer hoses, securing lines, transitional surfaces, access ways, all walking and working surfaces ***Controls: Continuous housekeeping. Arranging all hoses and lines out of main traffic ways as much as possible. Visibly marking, barricading, or covering of all lines, hose, or obstructions remaining in or adjacent to traffic areas.***
Noise	Hydraulic power equipment, pumps, and heavy equipment. ***Earplugs/muffs will be required during all stages when equipment is being run.***
Pinch Points	Moving parts, moving equipment, connecting transfer hoses, etc. ***Knowledge of equipment-review of systems for personnel not familiar with specific operations. Awareness/communication of potential energy releases and lines of fire. Appropriate work gloves used for task.***

Overhead hazard	Forklift lifting activities, Boom Truck Crane, Drum handling ***Hardhats required for all personnel in the vicinity. One person signalling. Qualified rigger and operator.***
Pressures	Hydraulic hoses, hoses for pumping fluids ***Ensure gauges are properly installed and visible. Ensure that all personnel are familiar with the task sequence of events, along with anticipated pressure ranges and safety ranges. Safety wiring all hose connections, secondary spill containment under all fittings.***
Manual Handling	***Use of mechanical lifting means when necessary, use of additional personal for heavy and or awkward loads, use of proper lifting techniques.***
Fire and Heat	Ignition of Surefire Gelling mixture, in situ burning of crude ***All ignition activities will be conducted using a propane torch securely attached to a 10' extension pole. During all burn activities the minimum safe working/observing distance to the lit oil will be 20 feet. A water deluge system will be used to protect the sides of the tank from overheating. This cooling of metal will provide protection against inadvertent personnel contact with the sides of the tank during post burn data collection activities. ABC type Fire Extinguishers: 300lb and 20lb placed as needed around test tank and at fuel gel mixing location***
Fall From Heights	Video recording of test burn activities, working off of elevated test tank catwalks ***All video recording will be conducted within either a powered man lift or scaffolding platform. Fall protection (harness and lanyard) will be required and provided by ACS if the powered man lift is used. All work conducted on the evaluated test tanks will be limited to the catwalk areas. The perimeter of these working surfaces are protected by top and mid rail restraints.***
Water Hazards	Test tank water levels > 3ft. ***PFD's required on all personnel working on the test tank catwalk***

Chemical Hazards

Inhalation	Smoke (organic and inorganic carbon, respirable fraction) ***The anticipated duration of buns will vary between 10 and 3 minutes for volumes of 17 to 3.5 gallons respectively. All personnel will be placed up wind to the generated smoke plume.***

Aromatic Hydrocarbons (Measured as Benzene and VOC)

Due to the relatively small scale of anticipated volume (17 to 3.5 gallons/test, 5 to 7 tests/day), environmental considerations (outside, natural dilution ventilation) and limited close proximity exposures; inhalation hazards should be viewed as minimum. As such, respiratory protection controls are not anticipated. Periodic environmental sampling however with direct readings to determine Benzene and total VOC will be conducted to verify anticipated atmospheric concentrations.

Engineering abatement measures and respiratory protections required at the following levels: Benzene 0.5 ppm, Total VOC 100 ppm.

Ingestion Hydrocarbon Products

Review the importance of good personnel hygiene especially prior to any hand to mouth activities such as smoking, chewing, or eating. Use of gloves while working to limit contact with product (general work or Nitrile dependant on oil saturation)

Absorption Hydrocarbon Products

While actual physical contact with product throughout the testing protocol should be minimal, chemical protective suits (Saranex or Yellow Tyvek) will be used for tasks associated with potential spill activities. Additionally the use of Nitrile or general work gloves is required depending on task.

ATTACHMENTS:

MSDS Crude Oil
MSDS Surefire Gelling Agent

Wildlife Hazards

Wildlife activities can occur in the vicinity of the fire training grounds.

Fox **-** May be in the area, be cautious, do not feed.
Bears **-** May be in the area, be cautious, do not feed.

Waterfowl **-** Certain species of waterfowl spend time in the waters on the North Slope. They should not pose any hazard in the vicinity of the annex. Most of the birds will have traveled south this time of the year.

Personnel

The buddy system will be observed in the work areas. Buddy system means organizing employees into work groups in such a manner that each employee of the work group is designated to be observed/assisted by at least one other employee in the work group. The purpose of the buddy system is to provide rapid assistance in case of an emergency.

Reporting Unsafe Conditions or Practices

All personnel should be alert to the existence of unsafe conditions or practices that might occur within their area of the operation. Unsafe conditions or practices will be immediately stopped and reported to the designated Site Safety Officer. The Site Safety Officer will evaluate the situation and communicate both the condition and the remedy to all effected personnel. The Site Safety Officer will then take steps to correct the unsafe condition and practice, as appropriate.

If the unsafe condition or practice remains unresolved, the activity is to be eliminated until further investigation.

Everyone has responsibility for their own safety as well as the safety of others, at anytime, anyone can stop the operation for a safety concern.

Emergency Contact Numbers

BP EOA Fire Department	659-5300 or 911
Medical	659-5239 or 911
ACS Base	659-3249 or Radio Channel 65

General Site Procedures and Special Considerations

All personnel are responsible to keep the site clean of debris (trash, food, etc.). Clutter will be kept to a minimum.

If you have any questions regarding the safety during the activities, please contact ACS Safety/Training Department at 907-659-3204.

A Site Safety Officer will be designated each day.

4.2 Environmental Protection and Waste Management

Spill Prevention

All pumping operations and tanks/containers with oil will be located within the containment area comprising the Fire Training Ground. Sorbent material is available and will be utilized on small spills within the containment area.

Waste Management

Contaminated Tyvek coveralls, booties, and gloves will be placed into a oily waste bag and properly disposed of. Used sorbent material will also be placed in oily waste bags separate from the Tyvek coveralls, etc., and properly disposed of.

The crude oil, burn residue and crude oil mixtures with water, glycol, and diesel will be disposed of according to the Alaska Waste Disposal and Reuse Guide.

Pumps, hoses, and other contaminated equipment from the demonstration will be decontaminated at the PEAK wash rack.

Open Burn Approval

This test will be conducted in accordance with the "Open Burn Approval for Fire Training" permit number Y002-NO108 issued to Alaska Clean Seas by the Alaska State Department of Environmental Conservation (ADEC). ADEC will be notified of the test plans prior to commencing burning activities. The following information will be gathered for the annual report to be submitted to ADEC:

a) Date of the Session
b) Number of personnel involved
c) Total burn time for each session
d) Type of fuel used
e) Gallons of fuel used
f) Visual description of smoke transport and dispersal conditions, with approximate wind speed and direction
g) List of complaints received concerning excess odors or smoke, including name, phone number, and any corrective action taken

The Prudhoe Bay Fire Department will also be notified prior to commencing operations.

APPENDIX 1

Crude Oil Weathering Procedures

WEATHERING CRUDE OIL IN DRUMS

The following procedure is to be used to evaporate crude oil in 55-gallon drums for the ISB in Broken Ice tests scheduled for late October 2002. The method is based on weight loss, eliminating the need to correct for different oil temperatures.

EQUIPMENT REQUIRED

- Two 55-gallon drums of fresh Northstar crude
- Two 55-gallon drums of fresh Endicott crude
- One empty 55-gallon drum
- One 500-lb Ohaus electronic scale with digital readout (from LORI skimmer tests)
- Bubbler pipe (A length of ½" copper [or whatever] pipe long enough to reach to the bottom of a 55-gallon drum with a compressed air fitting on one end and an ell with a 6" length of ½" copper pipe on the other. The 6" leg has a 1/8" hole drilled in the top of the pipe every ½".)
- A compressed air supply (a few cfm is enough, i.e., shop air supply or a small electric compressor)
- An electric band heater for the drum.

METHOD

For safety reasons, particularly with the Northstar oil, it would be a good idea to do the evaporation outdoors, or at least in a well-ventilated area, such as the Annex with a door open.

1. Place the empty drum on the scale, with both bungs removed, with the bubbler pipe and record their total tare weight.
2. Place a drum of fresh crude oil on the scale, remove the bungs, insert the bubbler pipe and record the gross weight.
3. The net weight of fresh oil is the gross minus the tare.
4. The target amount of weight loss for each drum is:
   percent loss from Table 1 x net weight of fresh oil / 100
5. Connect the air hose and start bubbling compressed air into the drum through the pipe; adjust the airflow as high as possible, without splashing oil out of the bung holes.
6. Periodically disconnect the air hose and reweigh the drum (the weathering could be done with the drum sitting on the scale, although I don't know whether the scale would turn itself off after a while and require re-zeroing when it turns back on) until the target weight has been lost.
7. Initially, the evaporation will be faster, slowing as time progresses. It would be prudent to weigh the drum every two hours for the first twelve, then every twelve for the next 3 days, then daily thereafter. Do the higher degree of evaporation for both of the crudes first. This will let you review the oil's weathering progress and estimate how long it will take to achieve the lower evaporation target. The two

different crudes will evaporate at very different rates (Northstar much faster than Endicott).

8. If the evaporation rate slows too much, attach the electric band heater to the drum, and warm the contents. This will accelerate the evaporation, so it would be wise to weigh the drum more frequently for a while after turning on the heater. Don't forget to remove the heater for weighing!
9. When the target weight has been lost, remove the bubbler pipe, put the bungs back in, mark the completed drum with the actual percent loss and start on the next drum. Note that, if the band heater is used, it would be a good idea to lave the small bung hole open while the drum cools, to prevent forming a vacuum that crumples the drum.

Table 1 – Evaporation Targets

Crude Type	*Target Weight Percent Evaporated*	
Northstar	33.8%	43.8%
Endicott	9.1%	17.4%

APPENDIX 2

Gelled Fuel Preparation Procedures

Equipment Required

! Porta berm
! plastic pails
! screens
! paint stirrers
! air-powered hand drill
! balance
! graduated pitcher
! gasoline
! fresh ANS crude
! Surefire gelling agent

A gelled fuel mixing area will be set up inside a heated tent or Conex. Small batches of gelled fuel will be mixed here for testing purposes. The amount required for each ignition attempt is 4 fl. oz. Larger volumes of gelled fuel can be prepared in advance and stored for several days. The fuel that will be is:

- gasoline

The procedures followed in mixing the gelled fuel will be:

- the required volume of the gasoline is measured into a plastic pail;
- the desired amount of Surefire gelling agent is weighed into a tared can (see below for recipe);
- the gelling agent is poured through a screen (to prevent lumps of gelling agent falling into the fuel) as the fuel stirred;
- after all the gelling agent had been added, mixing continues until the fuel reaches its final consistency (see below); and,
- then the fuel is poured into baggies or a graduated pitcher for distribution onto the slick.

The recipe for gelled gasoline is 6.75 lbs per drum or 2 oz. per gallon @ 50EF, producing a consistency similar to that of Jello gelatin.

APPENDIX D MID-SCALE TEST DATA

Source: NOAA National Ocean Service

Center for Operational Oceanographic Products and Services Data Disclaimer

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Air Temperature (D1) - Table Key

Date Time	-	Date and time the data were collected
AT	-	Air temperature in degrees Centigrade

Times are on Local Standard Time (LST)

Station No. 9497645 Prudhoe Bay , AK from 20021024 to 20021029

Station D SE Date   Time   AT (°C)

DATE	TIME (LST)	AIR TEMP. (°C)
10/24/02	0:00	-5.9
10/24/02	1:00	-5.7
10/24/02	2:00	-5.7
10/24/02	3:00	-5.8
10/24/02	4:00	-6
10/24/02	5:00	-6.2
10/24/02	6:00	-9
10/24/02	7:00	-8.1
10/24/02	8:00	-7.8
10/24/02	9:00	-7.6
10/24/02	10:00	-5.9
10/24/02	11:00	-5.9
10/24/02	13:00	-8.3
10/24/02	14:00	-8.6
10/24/02	15:00	-8.7
10/24/02	17:00	-9.6
10/24/02	18:00	-9.5

10/24/02	19:00	-8.4
10/24/02	20:00	-11.4
10/24/02	21:00	-12.3
10/24/02	22:00	-11.7
10/24/02	23:00	-12.4
10/25/02	0:00	-12.8
10/25/02	1:00	-13.2
10/25/02	2:00	-13.5
10/25/02	3:00	-14
10/25/02	4:00	-12.7
10/25/02	5:00	-12.3
10/25/02	6:00	-10.6
10/25/02	7:00	-9.7
10/25/02	8:00	-9
10/25/02	9:00	-8.7
10/25/02	10:00	-6.6
10/25/02	11:00	-7.2
10/25/02	13:00	-7.7
10/25/02	14:00	-6.7
10/25/02	16:00	-6.8
10/25/02	17:00	-7.2
10/25/02	18:00	-8.4
10/25/02	19:00	-7.7
10/25/02	20:00	-4.5
10/25/02	21:00	-4.7
10/25/02	22:00	-4
10/26/02	0:00	-3.5
10/26/02	1:00	-3.7
10/26/02	2:00	-3.7
10/26/02	4:00	-4.2
10/26/02	6:00	-4.4
10/26/02	7:00	-4.7
10/26/02	8:00	-4.6
10/26/02	9:00	-4.7
10/26/02	10:00	-4.3
10/26/02	13:00	-5.5
10/26/02	14:00	-5.6

10/26/02	15:00	-11.2
10/26/02	16:00	-9
10/26/02	18:00	-8.2
10/26/02	19:00	-6.9
10/26/02	20:00	-7.2
10/26/02	21:00	-6.4
10/26/02	22:00	-6.1
10/26/02	23:00	-5
10/27/02	0:00	-4.4
10/27/02	1:00	-4.5
10/27/02	3:00	-6.2
10/27/02	4:00	-6.4
10/27/02	5:00	-6.1
10/27/02	6:00	-6.2
10/27/02	7:00	-5.5
10/27/02	8:00	-4.9
10/27/02	10:00	-9.7
10/27/02	11:00	-9.8
10/27/02	12:00	-10.1
10/27/02	13:00	-9.4
10/27/02	14:00	-8.3
10/27/02	15:00	-7.4
10/27/02	16:00	-6.7
10/27/02	17:00	-7
10/27/02	18:00	-7.6
10/27/02	19:00	-7.4
10/27/02	20:00	-6.7
10/27/02	21:00	-5.7
10/27/02	22:00	-4.8
10/27/02	23:00	-3.7
10/28/02	0:00	-2
10/28/02	1:00	-3.4
10/28/02	2:00	-3.9
10/28/02	3:00	-2.6
10/28/02	4:00	-2.9
10/28/02	5:00	-3.9
10/28/02	6:00	-3.2
10/28/02	7:00	-2

10/28/02	8:00	-1.1
10/28/02	9:00	-1.7
10/28/02	10:00	-3.2
10/28/02	11:00	-3.8
10/28/02	12:00	-3.3
10/28/02	13:00	-2.8
10/28/02	14:00	-3.1
10/28/02	16:00	-2.9
10/28/02	17:00	-4.7
10/28/02	18:00	-4.6
10/28/02	19:00	-2.8
10/28/02	20:00	-2.1
10/28/02	21:00	-2.4
10/28/02	22:00	-2.6
10/28/02	23:00	-2.6
10/29/02	0:00	-2.5
10/29/02	1:00	-2.6
10/29/02	2:00	-2.8
10/29/02	3:00	-2.6
10/29/02	4:00	-2.5
10/29/02	5:00	-2.6
10/29/02	6:00	-2.6
10/29/02	7:00	-2.5
10/29/02	8:00	-2.7
10/29/02	9:00	-2.6
10/29/02	10:00	-2.8
10/29/02	11:00	-2.6
10/29/02	12:00	-2.6
10/29/02	13:00	-2.5
10/29/02	14:00	-2.4
10/29/02	15:00	-2.3
10/29/02	16:00	-2.2
10/29/02	18:00	-2.2
10/29/02	20:00	-2.3
10/29/02	21:00	-2.1
10/29/02	22:00	-2.1
10/29/02	23:00	-2.2

Source: NOAA National Ocean Service

Center for Operational Oceanographic Products and Services Data Disclaimer

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* * *

Wind (C1)- Table Key

Date Time - Date and time the data were collected by the DCP
WS - Wind speed is in meters per second
WD - Wind direction in degrees
WG - Wind gust is in meters per second

Times are on Local Standard Time (LST)

9497645 Prudhoe Bay , AK from 20021024 to 20021029

Date	Time	WS	WD	WG
2002/10/24	00:00	0.1	54.0	3.3
2002/10/24	01:00	0.0	53.0	2.0
2002/10/24	02:00	0.0	59.0	1.6
2002/10/24	03:00	0.0	66.0	0.1
2002/10/24	04:00	0.0	99.0	5.2
2002/10/24	05:00	0.0	97.0	1.6
2002/10/24	06:00	0.2	252.0	4.3
2002/10/24	07:00	0.0	267.0	2.5
2002/10/24	08:00	0.0	252.0	0.0
2002/10/24	09:00	0.0	305.0	0.0
2002/10/24	10:00	0.0	23.0	0.0
2002/10/24	11:00	0.0	89.0	0.0
2002/10/24	12:00	0.0	83.0	0.0
2002/10/24	13:00	0.0	158.0	0.0
2002/10/24	14:00	0.0	180.0	0.0
2002/10/24	15:00	0.0	193.0	0.0
2002/10/24	16:00	0.0	127.0	0.0
2002/10/24	17:00	0.0	119.0	0.1

2002/10/24 18:00	0.0	117.0	0.5
2002/10/24 19:00	0.0	118.0	3.4
2002/10/24 20:00	0.0	119.0	0.3
2002/10/24 21:00	1.0	150.0	1.9
2002/10/24 22:00	0.0	142.0	3.7
2002/10/24 23:00	0.0	131.0	3.5
2002/10/25 00:00	0.0	190.0	3.9
2002/10/25 01:00	0.0	204.0	2.7
2002/10/25 03:00	3.7	245.0	3.9
2002/10/25 04:00	0.0	192.0	2.3
2002/10/25 05:00	0.3	232.0	3.5
2002/10/25 07:00	3.9	186.0	4.8
2002/10/25 08:00	4.1	256.0	4.5
2002/10/25 09:00	1.6	222.0	4.0
2002/10/25 10:00	2.2	231.0	5.6
2002/10/25 11:00	5.4	226.0	5.6
2002/10/25 12:00	5.7	276.0	7.2
2002/10/25 13:00	0.0	194.0	4.3
2002/10/25 14:00	0.5	239.0	4.7
2002/10/25 16:00	0.0	138.0	1.4
2002/10/25 17:00	0.0	326.0	2.8
2002/10/25 18:00	0.0	46.0	0.1
2002/10/25 19:00	0.0	83.0	0.1
2002/10/25 20:00	0.3	101.0	4.5
2002/10/25 21:00	0.0	50.0	4.5
2002/10/25 22:00	4.0	77.0	5.3
2002/10/25 23:00	3.6	62.0	5.4
2002/10/26 00:00	5.6	45.0	5.8
2002/10/26 01:00	5.2	44.0	6.8
2002/10/26 02:00	4.6	33.0	7.4
2002/10/26 03:00	7.6	63.0	8.5
2002/10/26 05:00	9.5	76.0	10.9
2002/10/26 07:00	7.1	66.0	8.8
2002/10/26 09:00	4.9	78.0	8.4
2002/10/26 10:00	0.2	99.0	5.4
2002/10/26 11:00	1.7	52.0	2.3
2002/10/26 13:00	0.0	5.0	4.8
2002/10/26 14:00	1.7	0.0	3.6
2002/10/26 16:00	3.4	321.0	5.9
2002/10/26 17:00	2.9	262.0	4.8
2002/10/26 19:00	3.7	262.0	5.9
2002/10/26 20:00	6.4	261.0	7.2
2002/10/26 21:00	6.4	276.0	7.7
2002/10/26 23:00	5.8	252.0	7.4
2002/10/27 00:00	6.4	258.0	8.5
2002/10/27 01:00	5.8	256.0	9.3
2002/10/27 02:00	7.0	260.0	8.2

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2002/10/27 04:00     6.3   269.0     7.4
2002/10/27 06:00     5.4   247.0     7.4
2002/10/27 07:00     4.5   258.0     7.2
2002/10/27 08:00     5.5   237.0     5.9
2002/10/27 09:00     5.2   238.0     6.8
2002/10/27 10:00     5.4   234.0     6.1
2002/10/27 11:00     6.3   238.0     7.8
2002/10/27 12:00     6.8   233.0     7.1
2002/10/27 13:00     7.8   249.0     8.2
2002/10/27 14:00     7.3   256.0     7.8
2002/10/27 15:00     7.0   264.0     7.5
2002/10/27 16:00     4.5   269.0     7.3
2002/10/27 17:00     4.4   256.0     5.1
2002/10/27 18:00     4.0   245.0     5.7
2002/10/27 19:00     5.8   238.0     6.2
2002/10/27 20:00     4.5   262.0     6.4
2002/10/27 21:00     5.0   249.0     7.4
2002/10/27 22:00     4.9   243.0     7.0
2002/10/27 23:00     4.3   236.0     7.5
2002/10/28 00:00     5.6   212.0     6.6
2002/10/28 01:00     8.0   228.0     8.8
2002/10/28 02:00     9.1   229.0    11.2
2002/10/28 03:00     9.9   228.0    11.1
2002/10/28 04:00     8.9   231.0    11.1
2002/10/28 06:00     9.0   248.0    10.6
2002/10/28 07:00     6.7   256.0    10.4
2002/10/28 08:00     6.8   263.0     9.7
2002/10/28 09:00     3.2   256.0     7.7
2002/10/28 11:00     4.8   246.0     7.2
2002/10/28 13:00     0.0   250.0     4.2
2002/10/28 14:00     3.8   250.0     4.5
2002/10/28 15:00     0.0   298.0     4.7
2002/10/28 16:00     0.0   308.0     0.3
2002/10/28 17:00     0.0   230.0     0.1
2002/10/28 18:00     0.0   258.0     3.5
2002/10/28 19:00     0.0   346.0     1.2
2002/10/28 20:00     0.1    51.0     1.1
2002/10/28 21:00     4.7    62.0     4.8
2002/10/28 22:00     5.2    69.0     5.6
2002/10/28 23:00     6.7    52.0     7.2
2002/10/29 00:00     8.5    56.0     9.3
2002/10/29 01:00     9.5    62.0    10.6
2002/10/29 02:00     9.5    60.0    11.8
2002/10/29 03:00    11.3    70.0    13.4
2002/10/29 04:00    12.5    77.0    14.2
2002/10/29 05:00    13.6    72.0    15.2
2002/10/29 06:00    15.0    79.0    17.9
2002/10/29 07:00    15.3    77.0    18.0
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2002/10/29 08:00    15.5    76.0    19.1
2002/10/29 09:00    15.8    68.0    16.9
2002/10/29 10:00    15.9    84.0    19.8
2002/10/29 11:00    15.0    86.0    18.0
2002/10/29 12:00    13.6    89.0    18.4
2002/10/29 13:00    12.5    84.0    16.0
2002/10/29 14:00    13.1    85.0    15.4
2002/10/29 15:00    13.9    86.0    15.7
2002/10/29 16:00    11.3    85.0    14.8
2002/10/29 17:00    11.5    84.0    13.5
2002/10/29 18:00    10.7    90.0    14.4
2002/10/29 19:00    10.8    88.0    13.8
2002/10/29 20:00    10.8   102.0    13.8
2002/10/29 21:00     9.3    90.0    15.1
2002/10/29 22:00    11.0    81.0    13.3
2002/10/29 23:00     9.6    90.0    13.2
```

Mid-Scale Burns

Typical mix all brash ice fields: 45% blocks 1'x1', 28% blocks 6"x6", 27% small pieces under 4"

	Height (inch)	Period (s)	Length (m)	Paddle Setting
All waves have the following characteristics:	6	3.5	N/R	0.8/6.0

				Ice			Temperature				Oil Added			
Test No.	**Description**	**Oil**	**Weathering (% Mass)**	**Type**	**Mass (kg)**	**Thickness (cm)**	**T_{water} (°C)**	**T_{water} (°F)**	**T_{air} (°C)**	**T_{air} (°F)**	**Volume (l)**	**Mass (kg)**	**Thickness (mm)**	**Residue (kg)**
NS-1	24/10/2002	NorthStar2002	0.0%	Snow	22	6-8"	1.8		-7		1.1	0.8	0.5	0.4
NS-2		NorthStar2002	0.0%	Snow	22	6-8"	1.8			21	6.6	4.8	3	2.6
NS-3		NorthStar2002	0.0%	Snow	24	6-9"	1.8			21	6.6	5.8	3	3.0
NS-4		NorthStar2002	0.0%	Brash	10	4.9	1.4			21	6.6	5.4	3	1.8
NS-5		NorthStar2002	0.0%	Brash	9	4.5	1.4			18	6.6	5.2	3	2.4
NS-6		NorthStar2002	33.7%	Brash	9	4.3	1.4			18	6.6	5.4	3	2.2
NS-7		NorthStar2002	33.7%	Brash	8	4	1.5			21	6.6	5.8	3	4.2
NS-8		NorthStar2002	33.7%	O/W	N/A	N/A	1.5			21	6.6	5.8	3	1.8
NS-9		NorthStar2002	33.7%	O/W	N/A	N/A	1.6			21	6.6	6.0	3	1.4
NS-10		NorthStar2002	0.0%	O/W	N/A	N/A	1.6			21	6.6	5.4	3	1.0
NS-11		NorthStar2002	0.0%	O/W	N/A	N/A	1.6		-4.4		6.6	5.2	3	1.6
NS-12		NorthStar2002	43.8%	O/W	N/A	N/A	1.6		-4.4		6.6	5.6	3	1.2
NS-13	25/10/2002	NorthStar2002	43.8%	O/W	N/A	N/A	1.6			19	6.6	5.6	3	2.4
NS-14		NorthStar2002	33.7%	Snow	20	5-8"	4		4		6.6	5.6	3	1.8
NS-15		NorthStar2002	33.7%	Snow	19	4-7"		42			6.6	5.4	3+	2.8
NS-16		NorthStar2002	43.8%	Snow	20	6-7"		42		7	6.6	6.0	3	3.0
NS-17		NorthStar2002	43.8%	Snow	25	6-10"				7	6.6	6.0	3	3.2
NS-18		NorthStar2002	43.8%	Brash	10	4.9					6.6	5.8	3	2.4
NS-19		NorthStar2002	43.8%	Brash	9	4.5					6.6	5.8	3	4.6
ANS-1	27/10/2002 AM	ANS2002	0.0%	Brash	10	4.9		40.9		17	6.6	5.6	3	2.2
ANS-2		ANS2002	0.0%	Brash	9	4.5					6.6	5.6	3	3.2
PM-1		PointMac2002	0.0%	Brash	9	4.3		41.4		19	6.6	5.8	3	3.2
PM-2		PointMac2002	0.0%	Brash	8	4				18	6.6	5.8	3	3.4
PM-3		PointMac2002	0.0%	O/W	N/A	N/A					6.6	5.6	3	1.4
PM-4		PointMac2002	0.0%	O/W	N/A	N/A					6.6	5.8	3	1.4
ANS-3		ANS2002	0.0%	O/W	N/A	N/A				18	6.6	6.0	3	1.6
ANS-4		ANS2002	0.0%	O/W	N/A	N/A				18	6.6	6.0	3	1.4
ANS-5	27/10/2002 PM	ANS2002	0.0%	Snow	22	6-8"		38.8		17	6.6	5.8	3	2.6
ANS-6		ANS2002	0.0%	Snow	24	7-8"		38.8			6.6	5.6	3	3.0
PM-5		PointMac2002	0.0%	Snow	22	5-9"		38.5			6.6	5.6	3	4.4
E-1	28/10/2002 AM	Endicott2002	0.0%	Brash	10	4.9		42		21	6.6	5.8	3	3.0
E-2		Endicott2002	0.0%	Brash	9	4.5					6.6	5.6	3	4.2
E-3		Endicott2002	13.9%	Brash	9	4.3		42.2		17	6.6	5.8	3	3.2
E-4	late morning	Endicott2002	13.9%	Brash	8	4					6.6	5.8	3	4.6
E-5		Endicott2002	9.4%	Brash	8	3.9		40.2		24	6.6	5.8	3	2.6
E-6		Endicott2002	9.4%	O/W	N/A	N/A				24	6.6	6.4	3	5.2
E-7		Endicott2002	9.4%	O/W	N/A	N/A					6.6	6.0	3	2.2
E-8		Endicott2002	13.9%	O/W	N/A	N/A					6.6	5.8	3	1.2
E-9		Endicott2002	0.0%	O/W	N/A	N/A	3.7				6.6	6.0	3	1.4
E-10		Endicott2002	0.0%	Snow	22	6-9"		41.8		24	6.6	6.4	3	2.2
E-11		Endicott2002	13.9%	Snow	25	7-9"				24	6.6	5.8	3	2.6
E-12		Endicott2002	9.4%	Snow	25	7-9"				24	6.6	6.0	3	5.6

Test No.	Meas.	Ignition		Preheat						P_{50}	Ignition		Time to	Intense Burn	
	Density (g/ml)	Source	Amount (oz)	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	Time (m:s)	Burn Coverage	(m:s)	Time (m:s)	Burn Coverage	Waves (m:s)	Time to (m:ss)	Coverage (%)
NS-1	0.806	torch		00:00	25%					00:00	01:30	33%	No Wave	none	
NS-2	0.806	torch		00:00	50%	00:18	75%			00:00	00:30	100%	No Wave	04:20	50%
NS-3	0.806	torch		00:00	50%	00:08	75%			00:00	00:16	100%	No Wave	none	
NS-4	0.806	torch		00:00	75%					00:00	00:18	100%	No Wave	03:04	50%
NS-5	0.806	torch		00:00	75%					00:00	00:15	100%	00:18	none	
NS-6	0.857	torch +1gg	4.0	00:46	10%	01:53	25%			01:53	05:11	50%	No Wave	09:17	
NS-7	0.857	4 gg	16.0	00:43	25%	00:54	50%			00:54	02:11	100%	01:10	none	
NS-8	0.857	1 gg	4.0	01:12	10%	01:30	25%	01:42	50%	01:42	02:17	100%	00:12	hard to tell	
NS-9	0.857	1 gg	4.0	01:09	25%	01:23	50%			01:23	01:30	75%	01:29	03:27	
NS-10	0.806	torch		00:10	25%	00:16	50%	00:20	75%	00:16	00:24	100%	No Wave	01:02	
NS-11	0.806	torch		00:05	25%	00:13	50%			00:13	00:15	75%	00:18	01:35	
NS-12	0.868	2 gg	8.0	00:55	10%	01:24	25%	01:38	50%	01:38	01:49	100%	No Wave	02:09	
NS-13	0.868	2 gg	8.0	01:25	25%	01:41	50%			01:41	01:45	100%	01:49	03:03	
NS-14	0.868	1 gg	4.0	01:12	10%	01:41	25%	02:30	50%	02:30	04:39	100%	No Wave	none	
NS-15	0.857	4 gg	16.0	00:49	25%	01:03	50%			01:03	02:19	75%	01:08	none	
NS-16	0.868	2 gg	8.0	00:50	25%	01:06	50%			01:06	01:41	75%	No Wave	none	
NS-17	0.868	4 gg	16.0	00:59	25%					00:59	02:42	75%	01:23	04:46	
NS-18	0.868	2 gg	8.0	01:12	10%	02:08	50%	02:55	75%	02:08	03:05	100%	No Wave	get from video	
NS-19	0.868	4 gg	16.0	00:50	10%	01:01	25%			01:01	01:15	50%	01:20	none	
ANS-1	0.861	1 gg	4.0	00:38	25%	01:15	50%			01:15	02:14	75%	No Wave	none	
ANS-2	0.861	4 gg	16.0	00:18	50%					00:18	00:34	100%	00:29	none	
PM-1	0.884	2 gg	8.0	00:24	25%	00:50	50%	01:09	75%	00:50	01:35	100%	No Wave	none	
PM-2	0.884	4 gg	16.0	00:14	50%					00:14	00:23	100%	00:22	none	
PM-3	0.884	1 gg	4.0	00:07	25%	00:25	50%			00:25	01:07	100%	No Wave	01:35	
PM-4	0.884	1 gg	4.0	00:00	25%					00:14	00:27	100%	00:28	01:23	
ANS-3	0.861	1 gg	4.0	00:00	25%	00:12	50%			00:12	00:26	100%	No Wave	01:08	
ANS-4	0.861	1 gg	4.0	00:05	25%	00:20	50%			00:20	00:53	100%	00:43	01:22	
ANS-5	0.861	2 gg	8.0	00:20	25%	00:34	50%			00:34	01:20	100%	No Wave	none	
ANS-6	0.861	4 gg	16.0	00:27	25%	00:40	50%			00:40	01:19	100%	00:55	none	
PM-5	0.884	2 gg	8.0	00:29	50%	00:53	75%			00:29	01:21	100%	No Wave	none	
E-1	0.897	2 gg	8.0	00:37	25%	00:48	50%			00:48	01:40	100%	No Wave	03:58	
E-2	0.897	4 gg	16.0	00:40	25%	00:54	50%	01:02	75%	00:54	01:47	100%	01:10	none	
E-3	0.921	2 gg	8.0	00:45	25%	01:06	50%			01:06	01:47	100%	No Wave	03:26	
E-4	0.921	4 gg	16.0	00:42	50%	01:05	75%			00:42	01:05	75%	01:53	none	
E-5	0.918	2 gg	8.0	01:00	25%	01:30	50%	02:00	75%	01:30	02:57	100%	No Wave	05:43	
E-6	0.918	4 gg	16.0	00:40	25%	01:02	50%	01:16	75%	01:02	01:16	75%	01:18	none	
E-7	0.918	2 gg	8.0	00:40	25%	00:55	50%			00:55	01:13	100%	No Wave	none	
E-8	0.921	2 gg	8.0	01:00	25%	01:18	50%			01:18	01:50	100%	No Wave	02:01	
E-9	0.897	1 gg	4.0	00:35	25%	00:50	50%			00:50	01:08	100%	No Wave	none	
E-10	0.897	2 gg	8.0	00:39	25%	01:06	50%			01:06	01:06	50%	No Wave	none	
E-11	0.921	4 gg	16.0	00:42	25%	01:23	50%	01:43	75%	01:23	02:15	100%	No Wave	none	
E-12	0.918	4 gg	16.0	00:47	25%	01:09	50%	02:19	75%	01:09	02:38	100%	No Wave	none	

Test No.	Extinction								Burn Calculations			Time to	
	Time (s)	Burn Coverage	Time (s)	Burn Coverage	Time (s)	Burn Coverage	E_{50} (m:s)	Time to 0%	Duration (s)	Rate (mm/min)	Efficiency (%)	Waves (m:s)	
NS-1	02:00	10%					02:00	07:12	120	0.40	50.00%	No Wave	Calm. Extremely difficult to spread oil over ice evenly
NS-2	01:31	75%	01:49	50%	05:17	10%	01:49	07:37	109	0.81	45.83%	No Wave	Skin of oil over entire slush surface after burn. Intens
NS-3	02:24	50%	05:30	25%			02:24	06:46	144	0.77	48.28%	00:18	Low, weak flame in waves.
NS-4	03:30	50%	04:09	10%			03:30	07:01	210	0.62	66.67%	No Wave	Calm. Good burn. Second intense burn at 3:30
NS-5	04:04	50%	05:23	25%			04:04	06:40	244	0.44	53.85%	00:18	Very low, weak flame when waves on.
NS-6	09:52	25%	11:57	50%	12:43	25%	11:57	13:36	604	0.36	59.26%	No Wave	Burn area never exceded 50% of area but eventually
NS-7	06:49	75%	07:12	50%	07:25	25%	07:12	08:20	378	0.18	27.59%	01:10	Wind calm - 2 mph. Immediate reduction in flames o
NS-8	03:13	50%	03:51	10%			03:13	04:12	91	1.44	68.97%	No Wave	
NS-9	04:36						04:36	04:36	193	1.02	76.67%	01:29	Ring moved to beach end - slightly snagged on pade
NS-10	01:22	50%	01:49	10%			01:22	03:22	66	2.28	81.48%	No Wave	
NS-11	02:03	50%	02:13	25%			02:03	03:03	110	1.55	69.23%	00:18	Flame covers 75% of area towards wave paddle.
NS-12	02:56	50%					02:56	03:04	78	1.78	78.57%	No Wave	Oil gelled over about 50% of ring area.
NS-13	03:31	50%	03:51	10%			03:31	04:24	110	0.97	57.14%	01:49	Slick covers about 50% of ring before ignition. Fire c
NS-14	05:33	50%	06:16	25%	08:15	10%	05:33	08:34	183	0.67	67.86%	No Wave	Low spots only burning
NS-15	04:17	50%	05:29	25%	07:04	10%	04:17	10:04	194	0.64	48.15%	01:08	Oil spread over 50% of ring area initially. Ice moving
NS-16	03:19	50%	03:57	25%	05:05	10%	03:19	06:31	133	1.04	50.00%	No Wave	Skim new ice forming on tank. 75% coverage max.
NS-17	05:15	0%					05:15	05:15	256	0.51	46.67%	01:23	Reweigh of residue not recorded
NS-18	05:53	50%	06:15	25%	09:05	10%	05:53	11:23	225	0.50	58.62%	No Wave	
NS-19	05:53	10%					05:53	08:14	292	0.38	20.69%	01:20	Flames back to 25% when waves on
ANS-1	10:45	75%	12:58	25%			10:45	15:58	570	0.27	60.71%	No Wave	Morning wind at 6-8 mph. Relit last (upwind) 25% at
ANS-2	06:49	50%					06:49	09:02	391	0.22	42.86%	00:29	Very low, weak flames
PM-1	05:15	75%	05:37	50%	06:39	25%	05:37	08:15	287	0.31	44.83%	No Wave	Photo - post burn, pre-residue removal.
PM-2	05:20	75%	05:49	50%			05:49	07:35	335	0.25	41.38%	00:22	Weak burn, low flames. Wind: 8-10 mph
PM-3	02:08	0%					02:08	02:08	103	1.27	75.00%	No Wave	Good burn.
PM-4	01:41	0%					01:41	01:41	87	1.57	75.86%	00:28	Good burn. Wind: 15 mph
ANS-3	01:42	0%					01:42	01:42	90	1.58	73.33%	No Wave	Wind: 11-13 mph
ANS-4	01:55	0%					01:55	01:55	95	1.55	76.67%	00:43	Wind: 10-12 mph
ANS-5	02:03	50%	06:01	25%			02:03	08:56	89	1.23	55.17%	No Wave	Wind: 8-10 mph
ANS-6	02:33	50%	07:44	25%			02:33	13:00	113	0.82	46.43%	00:55	Wind: 0-1 mph.very long extinction burn in two small
PM-5	02:45	50%	04:16	25%			02:45	08:00	136	0.38	21.43%	No Wave	Photo - post burn, pre-residue removal.
E-1	04:33	50%	06:40	25%			04:33	07:48	225	0.41	48.28%	No Wave	Wind: 10 mph
E-2	06:25	50%	06:45	25%			06:25	08:05	331	0.16	25.00%	01:10	low, weak flame
E-3	04:21	50%					04:21	05:35	195	0.42	44.83%	No Wave	Wind: 1-2 mph. Flared up at 5:35. Poppy - micro-exp
E-4	03:46	50%	05:35	25%			03:46	06:27	184	0.33	20.69%	01:53	Wind: 0+. Hydraulic power pack not ready for tests s
E-5	06:51	50%	07:04	25%			06:51	08:10	321	0.31	55.17%	No Wave	Wind 0-3 mph. Second intense burn at 6:51
E-6	04:43	50%	05:39	25%			04:43	09:29	221	0.28	18.75%	01:18	Wind: 3-5 mph. Very low, weak flames.
E-7	02:12	50%					02:12	02:39	77	1.49	63.33%	No Wave	
E-8	02:42	50%					02:42	05:05	84	1.60	79.31%	No Wave	Wind = 0 mph. Microexplosions. Second intense bur
E-9	01:46	50%	02:35	25%			01:46	03:29	94	1.49	76.67%	No Wave	Wind 3-5 mph. Microexplosions. Flared 2 times. Bur
E-10	05:20	25%	06:28	10%			05:20	07:26	254	1.03	65.63%	No Wave	Wind 17-22 mph. Very windy - Gusts necessitated e
E-11	03:04	75%	03:30	50%	04:15	25%	03:30	08:40	127	0.77	55.17%	No Wave	Wind 18-25 mph. Continuing extinction: 10%=5:03; 2
E-12	03:19	50%	04:02	10%			03:19	05:09	130	0.19	6.67%	No Wave	Wind 18-26 mph. Flames downwind only. Reside fro

Test No.	Observations:
NS-1	Calm. Extremely difficult to spread oil over ice evenly, should go with lab data. Small pockets burning for a long time.
NS-2	Skin of oil over entire slush surface after burn. Intense burn: 25% of area, 50% of oil. During extinction, burning only in lower areas. Est. 30% slush eliminated i
NS-3	Low, weak flame in waves.
NS-4	Calm. Good burn. Second intense burn at 3:30
NS-5	Very low, weak flame when waves on.
NS-6	Burn area never exceded 50% of area but eventually burned all of the surface. Spreads upwind around ice blocks. Spreads very slowly - "works" its way over oi
NS-7	Wind calm - 2 mph. Immediate reduction in flames once waves on, then slowly build back up. Weak, low flame.
NS-8	
NS-9	Ring moved to beach end - slightly snagged on padeye - lifted boom at end of burn.
NS-10	
NS-11	Flame covers 75% of area towards wave paddle.
NS-12	Oil gelled over about 50% of ring area.
NS-13	Slick covers about 50% of ring before ignition. Fire covers 75% of ring toward wave paddle.
NS-14	Low spots only burning
NS-15	Oil spread over 50% of ring area initially. Ice moving as one mass in waves at first, then broke into 2, then 3. Ice remaining after burn. Ice remaining after burn.
NS-16	Skim new ice forming on tank. 75% coverage max. Reweigh of residue. Est. close to 70% slush consumed.
NS-17	Reweigh of residue not recorded
NS-18	
NS-19	Flames back to 25% when waves on
ANS-1	Morning wind at 6-8 mph. Relit last (upwind) 25% at 12:35, full coverage of 25% by 12:58, extinguished at 15:56. Brash ice was slushy.
ANS-2	Very low, weak flames
PM-1	Photo - post burn, pre-residue removal.
PM-2	Weak burn, low flames. Wind: 8-10 mph
PM-3	Good burn.
PM-4	Good burn. Wind: 15 mph
ANS-3	Wind: 11-13 mph
ANS-4	Wind: 10-12 mph
ANS-5	Wind: 8-10 mph
ANS-6	Wind: 0-1 mph.very long extinction burn in two small pockets. All ice moving as one mass. Est. 65% slush consumption.
PM-5	Photo - post burn, pre-residue removal.
E-1	Wind: 10 mph
E-2	low, weak flame
E-3	Wind: 1-2 mph. Flared up at 5:35. Poppy - micro-explosions.
E-4	Wind: 0+. Hydraulic power pack not ready for tests so delay in onset of waves. Flames dropped as soon as waves on. Max flame area 75%. 25% of slick area
E-5	Wind 0-3 mph. Second intense burn at 6:51
E-6	Wind: 3-5 mph. Very low, weak flames.
E-7	
E-8	Wind = 0 mph. Microexplosions. Second intense burn at 2:42
E-9	Wind 3-5 mph. Microexplosions. Flared 2 times. Burn duration revised after review of video
E-10	Wind 17-22 mph. Very windy - Gusts necessitated extra g/g. Max area = 50% of slick. Some areas not ignited. Flames travelled Straight downwind from gg - J
E-11	Wind 18-25 mph. Continuing extinction: 10%=5:03; 25%= 6:02, 10%= 7:09 and 0%= 8:40. Very windy. Flames spreading downwind only.
E-12	Wind 18-26 mph. Flames downwind only. Reside from igniter bags remain as a raised area 1 1/2" higher than surrounding frazil ice.