IN-SITU BURNING FOR OIL SPILLS IN ARCTIC WATERS: STATE-OF-THE-ART AND FUTURE RESEARCH NEEDS

STEPHEN POTTER[†] & IAN BUIST
SL Ross Environmental Research, 200-7 17 Belfast Rd.,
Ottawa, Ontario, Canada K1G 0Z4

Abstract. *In-situ* burning is one of the few practical options for removing oil spilled in ice-covered waters. In many instances *in-situ* burning, combined with surveillance and monitoring, may be the only response possible. As with all countermeasures in any environment, the suitability of burning a particular spill depends on the characteristics of the spilled oil and how the oil behaves in the particular ice conditions. There is an extensive body of knowledge concerning *in-situ* burning of oil in ice situations, beginning with laboratory, tank and field studies in the mid-1970s in support of drilling in the Canadian Beaufort Sea. *In-situ* burning research has been conducted primarily in Canada, Norway and the United States. This paper serves as a review of the subject, incorporating recent research results, summarizing the following topics:

- The basic requirements and processes involved with *in-situ* burning
- Trade-offs associated with burning in ice-covered waters
- How oil spill behavior in various ice conditions controls *in-situ* burning
- The application of burning in various common ice situations and
- Key equipment requirements.

Keywords: *in-situ* burning, oil spill response, arctic

[†] To whom correspondence should be addressed. E-mail: Steve@slross.com

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1. Introduction

The use of *in-situ* burning as a spill response technique is not new, having been researched and employed in one form or another at a variety of oil spills since the late 1960s. *In-situ* burning is especially suited for use in ice conditions, often offering the only practical option for removal of surface oil in such situations. Much of the early research and development on *in-situ* burning focused on its application to spills on and under solid sea ice. Most recently, the research has addressed burning spills in loose pack ice. In general, the technique has proved very effective for thick oil spills in high ice concentrations and has been used successfully to remove oil resulting from pipeline, storage tank and ship accidents in ice-covered waters in Alaska, Canada and Scandinavia (Buist *et al.*, 1994; Guénette, 1997).

Although there have been numerous incidents of ship and oil well spills that inadvertently caught fire, the intentional ignition of oil slicks on open water has only been seriously considered since the development of fire-resistant oil containment booms beginning in the early 1980s.

The development of these booms offered the possibility of conducting controlled burns in open water conditions. *In-situ* burning operations using these booms have been conducted at three open water spills in North America in the 1990s: a major offshore tanker spill, a burning blowout in an inshore environment, and a pipeline spill into a river. The new generations of fire containment booms presently available commercially represent a mature technology: the best have been subjected to standardized testing that verifies their suitability and durability.

In-situ burning of thick, fresh slicks can be initiated very quickly by igniting the oil with devices as simple as an oil-soaked sorbent pad. *In-situ* burning can remove oil from the water surface very efficiently and at very high rates. Removal efficiencies for thick slicks can easily exceed 90%. Removal rates of 2,000 m^3/h can be achieved with a fire area of only about 10,000 m^2 or a circle of about 100 m in diameter. The use of towed fire containment boom to capture, thicken and isolate a portion of a spill in low ice concentrations, followed by ignition, is far less complex than the operations involved in mechanical recovery, transfer, storage, treatment and disposal. If the small quantities of residue from an efficient burn require collection (research indicates that burn residue is of low acute toxicity to marine organisms, but may smother benthic resources if it sinks), the viscous, taffy-like material can be collected and stored for further treatment and disposal. There is a limited window of opportunity for using *in-situ* burning with the presently available technology. This window is defined by the time it takes the oil slick to emulsify; once water contents of stable emulsions exceed about 25%, most slicks are unignitable. Research has shown how it may be possible to overcome this limitation by spraying the slick with demulsifying chemicals.

Despite the strong incentives for considering *in-situ* burning as a primary countermeasure method, there remains some resistance to the approach. There are two major concerns: first, the fear of causing secondary fires that threaten human life, property and natural resources; and, second, the potential environmental and human-health effects of the by-products of burning, primarily the smoke.

The purpose of this paper is to review the science, technology and ecological consequences of *in-situ* burning as a countermeasure for oil spills in ice conditions. The main focus is on marine oil spills; however, spills in snow are also covered (since many spills on ice will inevitably involve snow). Much of the content of this chapter is adapted from: an in-depth review of *in-situ* burning produced for the Marine Spill Response Corporation (MSRC) (Buist *et al.*, 1994) summarized and updated for IUPAC (Buist *et al.*, 1999) and the USCG In-situ Burn Operations Manual (Buist et al., 2002). Interested readers are encouraged to refer to the original reports for fully referenced details of the sum-mary presented here. The MSRC report is available from the American Petroleum Institute in Washington, DC and the USCG Manual is available from the USCG R&D Center in Groton, CT. Both documents are contained on a CD produced by NIST for MMS that contains a large number of the key references on *in-situ* burning (Walton and Mullin, 2003).

2. The Fundamentals of *In-Situ* Burning

2.1. REQUIREMENTS FOR IGNITION

In order to burn spilled oil, 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 support combustion in the air above the slick. 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. The essential elements of a burning pool of liquid are:

- That the liquid is heated to its Fire Point.
- Once at its Fire Point, the liquid evaporates quickly.
- Vapors from the liquid burn in the air above the pool.
- Air for combustion is drawn in by the plume of rising combustion gases.

2.2. 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 drop the temperature of the surface oil below its Fire Point, at which time the burning stops.

2.3. EFFECT OF EVAPORATION ON SLICK IGNITION

Extensive experimentation on crude and fuel oils with a variety of igniters in a range of environmental conditions has confirmed the following "rules-of-thumb" for relatively calm, quiescent conditions:

- The minimum ignitable thickness for fresh crude oil on water is about 1 mm.
- The minimum ignitable thickness for aged, unemulsified crude oil and diesel fuels is about 2–5 mm.
- The minimum ignitable thickness for residual fuel oils, such as IFO 380 (aka Bunker "C" or No. 6 fuel oil) is about 10 mm.
- Once a 1 m^2 of burning slick has been established, ignition can be considered accomplished.

2.4. OTHER FACTORS AFFECTING IGNITION

Aside from oil type, other factors that can affect the ignitability of oil slicks on water include: wind speed, emulsification of the oil and igniter strength. The maximum wind speed for successful ignition of large burns is 10–12 m/s. For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water. Some crudes form meso-stable emulsions that can be easily ignited at much higher water contents. Paraffinic crudes appear to fall into this category.

Secondary factors affecting ignitability include ambient temperature and waves. 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.

2.5. 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.

2.6. EFFECTS OF EMULSIFICATION

Although the formation of water-in-oil emulsions is not as dominant a weathering process with spills in ice as it is for spills in open water, emulsions could be formed in some situations (i.e., a subsea blowout). Emulsification of an oil spill negatively affects *in-situ* ignition and burning. Emulsion water contents are typically in the 60–80% 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 adjacent burning oil is used 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. Surface-active chemicals called “emulsion breakers”, common in the oil industry, may also be used.

For stable emulsions the burn rate declines significantly with increasing water content, with 25% water content being the upper limit for effective burning for most emulsions. (There are exceptions: some crudes form meta-stable emulsions that can be burn at much higher water contents. Paraffinic crudes appear to fall into this category).

3. Environmental and Human Health Risks

This section describes the main risks associated with *in-situ* burning of spills and the safety measures used to overcome these risks. Much of the material in this section was developed for open water burn operations with towed fire boom, but is also applicable to burns in ice-covered waters. Humans and the environment may be put at risk by:

- The flames and heat from the burn
- The emissions generated by the fire and
- The residual material left on the surface after the fire extinguishes.

3.1. FIRE AND HEAT

Flames from *in-situ* burning pose a risk of severe injury or fatality to both responders and wildlife. The threat is obvious and needs no elaboration. This section, then, focuses on the problem of the heat radiated by the burn. Risks exist both in normal operations and abnormal conditions such as tow vessel breakdown and boom failure. The risk to spill responders at the spill site is the main concern because the risks to the general public will be eliminated through the use of an exclusion zone surrounding the spill site.

3.2. EFFECTS OF HEAT ON SPILL RESPONDERS

In-situ burning of oil produces a large amount of heat that is transferred into the environment through convection and radiation. About 90% of the heat generated by *in-situ* combustion is convected into the atomsphere. The remainder is radiated from the fire in all directions, but there is most concern with heat radiated towards responders, causing heat exhaustion and burns to unprotected skin. Of lesser concern is heat transferred downward which might affect water column resources. The potential for causing injury to exposed workers is a function of both the level of incident radiation and the duration of exposure. Wood will char if positioned about half a fire diameter from the edge of an oil burn. The "safe approach distance" to an *in-situ* oil fire for a person is from two to four times the diameter of the fire depending on the duration of exposure. Conservatively, it is assumed that the safe approach distance to the edge of an *in-situ* oil fire is approximately four fire diameters.

It is important to recognize that the oil contained in a towed boom is relatively thick in the early stages of a burn and that this thick-ness is maintained through towing. If the towing were to stop or slow, or the boom were to break, this thick layer would spread quickly to cover an area several times that of the boomed oil. This will increase the fire diameter, the heat flux from the fire, and the need for workers to move further from the fire to avoid discomfort.

3.3. ENVIRONMENTAL EFFECTS OF HEAT

Heat from the flames is radiated downward as well as outward and much of the heat that is radiated downward is absorbed by the oil slick. Most of this energy is used to vaporize the hydrocarbons for further burning, but a portion of the heat is passed to the underlying water. In a towed-boom burn or in a stationary boom situation in current, the water under the slick does not remain in contact with the slick long enough to be heated appreciably. However, under static conditions (the slick does not move relative to the underlying water – for example in a melt pool) the upper layer of the underlying water may be heated in the latter stages of the burn. In a prolonged static burn, the top few millimeters of the water column may be heated to near boiling temperatures, but the water several centimeters below the slick has been proven to be unaffected by the fire. As a result, the environmental impact of the heat from an *in-situ* burn is likely to be negligible.

3.4. AIR EMISSIONS

The smoke plume emitted by a burning oil slick on water is the main concern. The concentrations of smoke particles at ground or sea level are of concern to the public and they can persist for a few miles downwind of a burn. The smoke plume is composed primarily of small carbon particles and combustion gases. Smoke particles cause the greatest risk in a plume. Carbon smoke particles are responsible for providing the characteristic black colour of the plume rising from a burn. The smoke is unsightly but more important; the smoke particles can cause severe health problems if inhaled in high concentrations. Smoke particulates and gases; however, are quickly diluted to below levels of concern. The amounts of PAHs in the smoke plume are also below levels of concern. Approximately 5–15%, by weight, of the oil burned is emitted as smoke particles.

Descriptions of the constituents of the smoke plume and their dissipation under various conditions can be found in Buist *et al.* (1994). Suffice to say here that although the smoke that is generated can be a dramatic and visible effect from any large *in-situ* burn, the smoke plume is sent high in the air by the hot combustion gases, such that sea-level concentrations of soot are below levels of concern from 3 to 6 km (2–4 nautical miles) downwind.

3.5. BURN RESIDUE

As a general rule of thumb, the residue from an efficient burn of crude oil on water is environmentally inert. More specifically, the potential environmental impacts of burn residues are related to their physical properties, chemical constituents and tendency to float or submerge. Correlation between the densities of laboratory-generated burn residues and oil properties predict that burn residues will submerge in sea water when the burned oils have:

- Initial density greater than 0.865 g/cm^3 (API gravity less than about 32°) or
- Weight percent distillation residue (at >540°C) greater than 18.6%.

Burn residues usually submerge only after cooling. Based on modeling the heat transfer, it is likely that the temperature of a 1-cm thick burn residue will reach that of ambient water within approximately 20–30 min. Even for thicker slicks, it is likely that this cooling would occur within approximately 2 h.

Physical properties of burn residues depend on burn efficiency and oil type. Efficient burns of heavier crudes generate brittle, solid residues (like peanut brittle). Residues from efficient burns of other crudes are described as semi-solid (like cold roofing tar). Inefficient burns generate mixtures of unburned oil, burned residues and soot that are sticky, taffy-like or liquid. Burns of light distilled fuels result in a residue that is similar to the original fuel but contains precipitated soot.

4. Burning Spills in Ice and Snow

In-situ burning has been considered as a primary Arctic spill countermeasure since before the start of offshore drilling in the Canadian Beaufort Sea in the mid-1970s. Field trials at that time demonstrated that on-ice burning offered the potential to remove almost all of the oil present on the surface of landfast ice with only minimal residue volumes left for manual recovery. This area of research culminated in 1980 with a full-scale field research program on the fate and cleanup of subsea oil well blowouts under landfast sea ice.

4.1. SPILLS IN ICE

Research in oil spill cleanup in pack, or broken, ice also began in the 1970s. Interest in the subject increased in the early 1980s because of proposals for offshore production in Alaska and Canada, and has become an international subject of R&D with the opening of Russian ice-covered waters for exploitation and the future potential for drilling in Norwegian ice-covered seas. 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).

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; SL Ross and DF Dickins, 2003). 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.

4.2. OIL ON WATER AMONG PACK ICE

In pack ice conditions the use of *in-situ* burning is controlled, to a large degree, by the concentration and types of ice present. In general, the applicability of burning can be divided into three broad ice concentration ranges:

- Open water and ice up to 3 tenths
- Between 3 and 7 tenths and
- Greater than 7 tenths.

In ice concentrations greater than 7/tenths, the ice will effectively contain the oil; if slicks are thick enough they can be burned effectively without additional containment (SL Ross and DF Dickins, 1987). In the lowest range, the oil's spread and movement will not be greatly affected by the presence of the ice, and open water *in-situ* burning techniques may be possible. This would generally involve the collection of slicks with fire boom operated by tow vessels, and their subsequent ignition. The ice concentration range from 3 to 7 tenths is the most difficult from an *in-situ* burning perspective. The ice will reduce the spreading and movement of the slick, but not sufficiently to allow burning without additional containment. The deployment and operation of booms in this ice concentration would be difficult, if not impossible. Untended booms could be deployed into the ice by helicopter, but the amount of oil that could be collected by this technique is unknown.

An important area of recent and ongoing research has been the use of chemical herding agents to thicken oil for burning. For oil slicks in ice concentrations of 1–7/tenths, the oil will likely spread out to an unburnable thickness, and it will be difficult or impossible to use containment booms to thicken the oil. The concept here is to apply a chemical herding agent to the water surrounding a thin slick; the herding agent causes the slick to contract and thicken such that burning may be possible. These were investigated for open water conditions in the 1970s, and small-scale tests in ice showed promise as long as the oil was fluid (i.e., above its pour point).

Over the last three years, testing has been done at increasing scales, culminating in an outdoor near-full scale test in Alaska in 2006. In general terms, the tests have involved spilling oil in a range of ice types and concentrations, allowing the oil to spread to an equilibrium (i.e., non-burnable) thickness, then applying herder to the perimeter of the oil slick. Within a few minutes, the herding agent caused the slick to contract to cover a much smaller area, and consequently, a much greater thickness. The technique appears to have considerable promise, and further full-scale field tests are planned for the future.

In-situ burning of oil spilled in pack ice during break-up will likely be easier than in the same ice concentration during freeze-up. In fall, the sea is constantly freezing, which generates significant amounts of slush ice which can severely hamper containment and thickening (naturally, or with booms) of slicks for burning; it is dark for much of the day, and it is cold, and only going to get colder with the onset of winter. During break-up, there is much less slush and brash ice present, the ice floes are deteriorating and melting, there is 24-h daylight and the temperatures are warming.

4.3. OIL ON SOLID ICE

In-situ burning is the countermeasure of choice to remove oil pools on ice (created in the spring by vertical migration from an encapsulated oil layer or by drilling into an encapsulated oil lens in the ice sheet). There is a high degree of knowledge on the ignition and burning of oil on melt pools. For large areas of melt pools, helicopters deploying igniters would be used to ignite individual pools of oil. For smaller areas, manual ignition techniques could be employed.

Wind will generally blow oil on melt pools to the downwind ice edge, where it will be herded to thicknesses of approximately 10 mm. Individual melt pool burn efficiencies are thus on the order of 90%. The overall efficiency of *in-situ* burning techniques in removing oil from the ice surface ranges from 30% to 90%, with an average in the 60–70% range, depending on the circumstances of the spill (e.g., melt pool size distribution vs. igniter deployment accuracy, film thickness, degree of emulsification, timing of appearance vs. break-up, etc.). For areas where the oil surfaces early in the melt, it could be possible to manually flush and/or recover remaining burn residue.

Winds and currents will herd oil in leads to the downwind edge, where it can be ignited and burned. In leads where a current herds the oil against an edge, very high removal efficiencies can be obtained.

4.4. OIL IN SNOW

In the case of oil spilled on the ice surface and mixed with snow, burning of oiled snow piles can be successfully achieved even in mid-winter Arctic conditions. Oiled snow with up to 70% snow by weight can be burned *in-situ.* For higher snow content mixtures (i.e., lower oil content), promoters, such as diesel fuel or fresh crude, can be used to initiate combustion. For the lower concentrations of oil in snow, the technique of ploughing oiled snow into concentrated piles may be the only way of achieving successful ignition and burning. In many cases, waiting for the snow to melt could result in thin oil films incapable of supporting combustion and spread over a large ice area. For this technique, the oiled snow is scraped into a volcano-shaped pile, with the centre of the “volcano” scraped down to the ice surface. A small amount of promoter is ignited in the centre of the pile. The heat from the flames melts the surrounding inside walls of the conical pile, releasing the oil from the snow that runs down into the centre and feeds the fire. This technique can generate considerable amounts of melt water, which needs to be managed.

5. Technologies for Conducting *In-situ* Burns

A variety of methods are available to ignite an oil slick, including devices designed or modified specifically for ISB as well as simple, ad-hoc methods. Successful ignition of oil on water requires two elements:

- Heating the oil to its fire point, such that sufficient vapors are produced to support continuous combustion
- Providing an ignition source to start burning.

For light refined products, such as gasoline and some un-weathered crude oils, the flash point may be close to the ambient temperature and little if any pre-heating will be required to enable ignition. For other oil products, and particularly for those that have weathered and/or emulsified, the flash point will be much greater than the ambient temperature and substantial pre-heating will be required before the oil will ignite. The choice of one igniter over another for a given application will depend mainly on two factors:

- Degree of weathering or emulsification of the oil, which will dictate the required energy level of the igniter
- Size and distribution of the spill, which will determine the number of ignitions required to ensure an effective burn.

5.1. HELI-TORCH

The Heli-torch was originally developed as a tool for burning forest slash and for setting backfires during forest-fire control operations. It was adapted for use in ISB in the mid-1980s and found to be an effective system for igniting spilled oil. The Heli-torch has been tested extensively, used in a number of field trials, and refined considerably over the years, resulting in its being viewed as the igniter of choice for ISB.

The Heli-torch emits a stream of gelled fuel, typically gasoline that is ignited as it leaves the device. The burning fuel falls as a stream that breaks into individual globules before hitting the slick. The burning globules produce a flame that lasts for several minutes, heating the slick and then igniting it. The globules' burn time depends upon the fuel used and the mixing ratio of the fuel and gelling powder. Although gasoline is the fuel typically used, alternatives such as diesel, crude oil, or mixtures of the three fuels have been found to produce a greater heat flux, and they should be considered for highly weathered oils and emulsions that may be difficult to ignite.

5.2. HANDHELD IGNITERS

A variety of igniters have been developed for use as devices to be thrown by hand from a vessel or helicopter. These igniters have used a variety of fuels, including solid propellants, gelled kerosene cubes, reactive chemical compounds, and combinations of these. Burn temperatures for these devices range from 650°C to 2,500°C and burn times range from 30 s to 10 min. Most hand-held igniters have delay fuses that provide sufficient time to throw the igniter and to allow it and the slick to stabilize prior to ignition.

5.3. AD-HOC IGNITERS

For small, contained spills, simple ad-hoc techniques can be used to ignite the oil. For example, propane- or butane-fired weed burners have been used to ignite oil on water. As weed-burners or torches tend to blow the oil away from the flames, these techniques would only be applicable to thick contained slicks. Rags or sorbent pads soaked in fuel have also been successfully used to ignite small spills. Diesel is more effective than gasoline as a fuel to soak sorbents or rags because it burns more slowly and hence supplies more pre-heating to the oil.

Gelled fuel can also be used without the Heli-torch as an ad-hoc igniter. This was the method used for the test burn during the Exxon Valdez spill in 1989. Gasoline and gelling agent were mixed by hand in a plastic bag, and then the bag was ignited and allowed to drift into the slick contained within a fire-resistant containment boom.

5.4. IGNITION PROMOTERS

Ignition promoters are used to increase the ignitability of an oil slick or to promote the spreading of flame over the surface of a slick. Petroleum products, such as gasoline, diesel, kerosene, aviation gasoline, and fresh crude oil, have all proved effective as ignition promoters. Of these, the middle distillates, such as diesel and kerosene, are preferred because they burn more slowly and produce a higher flame temperature. Crude oil is also very effective as it contains a mixture of com-ponents.

Emulsion-breaking chemicals can also be considered as ignition promoters. The concept is to apply the chemical to emulsified oil to break the emulsion *in-situ*, thus increasing the likelihood of successful ignition. Large-scale tests have proven the feasibility of this approach and research to include emulsion-breaking chemicals in the fuel of the Heli-torch system has been undertaken. There are presently no demulsifiers on the U.S. approved list of chemicals for oil spill use; however, their use as combustion promoters (which are permitted) is not specifically excluded. Most of the demulsifiers and other ignition promoters will be consumed in the resulting fire.

When using an ignition promoter, it is important to distribute the promoter over as large an area as possible. Simply pumping it onto one location of the slick will create a thick pool of the promoter in one area and it will not promote ignition effectively.

5.5. FIRE-RESISTANT BOOM

To achieve an effective burn in lower ice concentrations, boom is required to create and maintain an oil thickness that will burn efficiently. The two main requirements for a fire-resistant boom are to provide oil containment (floatation, draft, and freeboard) and to resist fire damage. This section provides a brief description of the main types of fire-resistant boom. Additional detailed specifications are provided in the USCG Manual for products that are commercially available in the United States and that have been involved in recent fire-resistance testing.

Two main methods of providing fire resistance are used. Passive or intrinsically fire-resistant boom uses fire-resistant materials such as ceramic fibres or stainless steel. The active method keeps the boom materials within an acceptable range of temperatures by supplying coolant (usually water) to surfaces of the boom. Other ad-hoc methods of containment are also described at the end of this section.

A number of booms have been tested at the Oil and Hazardous Materials Simulated Environmental Test Tank (Ohmsett) and have been found to have similar containment limits as conventional boom, with first-loss tow speeds in the range of 0.85–1.0 knots when towed in calm water in a U-shape. Due to the weight of materials used for fire-resistance, the weight per unit length is generally much higher and the buoyancy-to-weight (b/w) ratio is much lower than for conventional booms of a similar size. Their lower b/w ratios mean that they are generally not applicable for high sea states. Fire-resistant booms often require special handling, partly due to their higher weight and due to the use of materials that are less rugged than those used in conventional booms.

Tests to confirm fire resistance have been performed in recent years and the American Society for Testing and Materials (ASTM) International has developed a standardized test (F 2152). The test comprises three 1-h burn cycles separated by two 1-h cool-down cycles during which the boom is exposed to waves. The test is designed to simulate the stresses that a boom would receive in a typical burn scenario, where the boom is used alternately to collect oil and then contain it during a burn. A heat exposure is specified to simulate the effects of a crude oil fire; in the test either burning diesel or using a specially designed propane system that is available at Ohmsett and provides an equivalent heat can supply the specified heat. Booms are judged to have passed the test if they survive and can contain oil at the conclusion of the cyclic heat exposure.

Based on these tests, there is recognition that many fire-resistant booms have a limited life when exposed to fire, which means that an extensive ISB operation will require the periodic replacement of boom, depending on the intensity and duration of the burn.

References

Bech, C., Sveum, P. and Buist, I., 1993, The Effect of Wind, Ice and Waves on the *In-Situ* Burning of Emulsions and Aged Oils, in: *Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar*. Environment Canada, Ottawa, Ontario, Canada, pp. 73 5–748.

Brown, H.M. and Goodman, R.H., 1986, In Situ Burning of Oil in Ice Leads, in: *Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar.* Environment Canada, Ottawa, Ontario, Canada, pp. 245–256.

Buist, I., McCourt, J., Potter, S., Ross, S. and Trudel, K., 1999, In Situ Burning. *Pure Appl. Chem.* **71**(1) 43–65.

Buist, I., Coe, T., Jensen, D., Potter, S., Anderson, L., Bitting, K. and Hansen, K., 2002, *In-Situ Burn Operations Manual.* U.S. Coast Guard Research and Development Center, Groton, CT.

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

Guénette, C.C., 1997, *In-Situ* Burning: An Alternative Approach to Oil Spill Clean-up in Arctic Waters, in: *Proceedings of the Seventh (1977) International Offshore and Polar Engineering Conference*, pp. 587–593.

Guénette, C.C. and Wighus, R., 1996, In Situ Burning of Crude Oil and Emulsions in Broken Ice, in: *Proceedings of the 19th AMOP Technical Seminar.* Environment Canada, pp. 895–906.

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

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

SL Ross Environmental Research Ltd. and DF Dickins Associates Ltd, 1987, *Field Research Spills to Investigate the Physical and Chemical Fate of Oil in Pack Ice.* Environmental Studies Research Funds Report no. 62. ESRF. Calgary.

SL Ross Environmental Research Ltd. and DF Dickins Associates Ltd., 2003, *Tests To Determine The Limits To In-situ Burning Of Thin Oil Slicks In Broken Ice.* Report to MMS and ExxonMobil Upstream Research. Herndon, VA.

Smith, N.K. and Diaz, A., 1987, In-Place Burning of Crude Oils In Broken Ice, in: *Proceedings of the 1987 Oil Spill Conference.* American Petroleum Institute, Washington, DC, pp 383–387.

Walton, W.D. and Mullin, J.V., 2003, *In-situ Burning of Oil Spills: Resource Collection.* National Institute of Standards and Technology. Gaithersburg, MD.