In situ burning*

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INTRODUCTION

The use of *in situ* burning as a spill response technique is not new, having been researched and used for a variety of oil spills since the late 1960s. In general, the technique has proved effective for oil spills in ice conditions and has been used successfully to remove oil spills in ice-covered waters resulting from storage tank and ship accidents in Alaska, Canada and Scandinavia.

Although there have been numerous incidents of vessel oil 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 boom 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 spills in the last decade: a major offshore tanker spill, a burning blowout in an inshore environment, and a pipeline spill into a river.

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 2000 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, 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, the viscous, tar-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 is ongoing to overcome this limitation.

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 objective of this chapter is to review the science, technology, operational capabilities and limitations and ecological consequences of *in situ* burning as a countermeasure for oil spills on water. The main focus of this section is on marine oil spills in open water conditions. The use of *in situ* burning for spills in ice conditions is dealt with in another chapter. Much of the content of this chapter is updated from an in-depth review of *in situ* burning produced for the Marine Spill Response Corporation (MSRC) in 1994 [1]. Interested readers are encouraged to refer to the original report for fully referenced details of the summary presented here. The MSRC report is available from the American Petroleum Institute in Washington, DC.

THE FUNDAMENTALS OF *IN SITU* BURNING

Requirements for ignition

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 support combustion in the air above the slick. It is the hydrocarbon vapours above the slick that burn, not the

liquid itself. The temperature at which the slick produces vapours 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.

Heat transfer back to slick

Figure 1 illustrates the heat transfer processes that occur during the *in situ* burning of an oil slick on water. Most heat from the burn is carried away by the rising column of combustion gases, but a small percentage (about 1%) radiates from the flame back to the surface of the slick. This heat is partially used to vaporize the liquid hydrocarbons which 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.
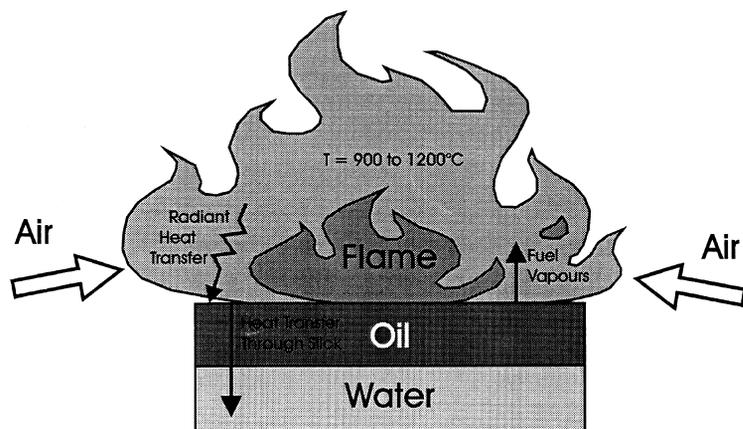

Fig. 1 Key heat and mass transfer processes in *in situ* burning.

Flame temperatures and total heat fluxes

Flame temperatures for crude oil burns on still water are about 900–1200 °C [2]. But 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 (350–500 °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 100–250 kW/m^2 measured both inside and at the periphery of the fire [3,4]. The higher heat flux values are associated with windy conditions which promote better combustion.

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.

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. This results in increased burn rate, flame height, radiative output and foaming. This is called the 'vigorous 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.

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, volatile crude oil on water is about 1 mm;
- the minimum ignitable thickness for aged, unemulsifed crude oil and diesel fuels is about 3–5 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 m² of burning slick has been established, ignition can be considered accomplished.

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. Secondary factors include ambient temperature and waves.

- The maximum wind speed for successful ignition of large burns has been determined to be 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 [5].
- 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 subflash temperatures.

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.

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 10–20 mm in thickness the residue thickness is 1 mm;
- for thicker crude slicks the residue is thicker; for example, 3–5 mm for 50 mm thick oil;
- 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 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. 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 10–20 mm thick is a semisolid, 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 150–300 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 (6).

Flame spreading

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 spreading out over the surrounding cold fuel.

As oil evaporation (or weathering) increases, flame spreading velocity decreases. This is because the difference between ambient 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. 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.

Flame heights

Flames from large oil fires are obscured by the thick, black smoke produced, making it difficult to estimate flame heights. However, the best available data suggests the following rules-of-thumb:

- For small and medium fires having diameters less than 10 m, fire heights are twice the fire diameter;
- For larger fires the ratio declines, approaching a value of one for very large fires.

Effects of emulsification

The processes believed to be involved with *in situ* burning of water-in-oil emulsions are illustrated in Fig. 2. Emulsification of an oil spill negatively affects *in situ* ignition and burning. This is because of the water in the emulsion. 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 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
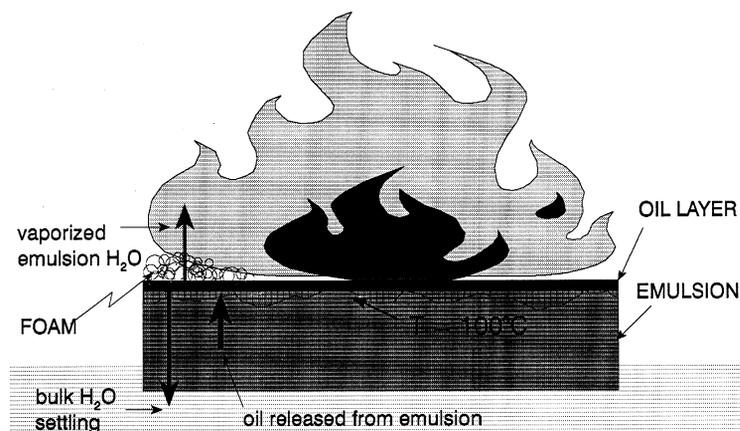

Fig. 2 Emulsion burning processes.

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 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 effect of water content on the removal efficiency of weathered crude emulsions can be summarized by the following rules-of-thumb:

- little effect on oil removal efficiency (i.e. residue thickness) for low 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 be burn efficiently at much higher water contents. Paraffinic crudes appear to fall into this category [5].

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 to unemulsified slicks, emulsions are much more difficult to ignite and, once ignited, display reduced flame spreading and more sensitivity to wind and wave action.

TECHNOLOGIES FOR CONDUCTING *IN SITU* BURNS

This section deals with the technologies available for *in situ* burning. Specific pieces of equipment are documented in the categories of igniters, fire containment booms, and additives. The latter category includes ignition promoters, burn promoters, wicking agents and smoke suppressors.

Numerous variations of the above technologies have been researched, developed and tried on spills in the past, and most of these have had limited success or are no longer available for one reason or another. These obsolete systems are discussed in detail in the larger MSRC report [1]. The following discusses only technologies that are presently available.

Igniters

These are divided into two types: igniters for use from a vessel or from shore, and igniters for use from helicopters.

Surface-deployed igniters

Both portable propane or butane torches, or weed burners, and rags or sorbent pads soaked in diesel have been used successfully many times in the past to ignite oil slicks on water. Propane torches tend to blow thin oil slicks away from the flames and are best utilized on thick, contained slicks. Diesel is the best fuel to soak sorbents or rags for use as igniters; gasoline results in a less powerful flame and can be dangerous to handle.

A variation on this kind of sorbent igniter was used in experiments in the 1980s and involved sorbent wrapped around a short length of Ethafoam (a type of styrofoam) log, dipped in diesel or crude oil, and then sprayed with dimethyl ether (also known as starter fluid). This ignited easily and burned for a long time, even in choppy wave action.

At the *Exxon Valdez* spill a plastic bag containing gasoline gelled with 'Surefire' gelling agent was used successfully to ignite oil during an *in situ* test burn. The contents of the bag were mixed by hand, placed on the water surface, ignited and then allowed to drift from the tow boat into the contained oil in the fire containment boom being towed behind. The manufacturer of the Heli-torch now offers a more sophisticated version of this approach, consisting of a plastic bottle with a marine flare attached to it with foam floatation collars [7].

The manufacturer of the Heli-torch also produces a surface-deployable version called the Groundtorch. The device consists of a storage drum and pump connected to a hand-held 'wand' for

application of the burning gelled gasoline. The development of a sophisticated hand-held igniter by the US Navy has been recently reported [8].

Aerially deployed igniters

There are two aerially deployed igniter systems that are currently available for use on oil spills. These are the Dome igniter and the Heli-torch igniter.

Dome igniter. The igniter (Fig. 3) measures approximately 25 cm × 15 cm × 10 cm and weights about 500 g. The unit consists of a wire-mesh fuel basket with solid propellant and gelled kerosene slabs suspended between two metal floats. The Dome unit is intended as a hand-thrown device. The fuse wire is started with an electric ignition system consisting of a 12 V, spill-proof battery with a gel electrolyte and a heater element. This provides sufficient heat to activate the igniter's fuse wire within two seconds of contact. Once started, the 25 cm-long safety fuse allows 45 s of delay for throwing the igniter and allowing it to settle within the target oil slick. Once ignited the solid propellant burns intensely for about 10 s with temperatures in excess of 1200 °C. During this initial burn, the gelled kerosene begins to burn, producing temperatures of 700–800 °C. The total burn time for the igniter is about 10 min. The relatively long burn-time for the igniter helps get the slick lit even if winds temporarily separate the igniter from the heaviest concentrations of oil. Upon completion of the burn, all of the metal components of the igniter remain on the surface of the water and attached to the two floats.
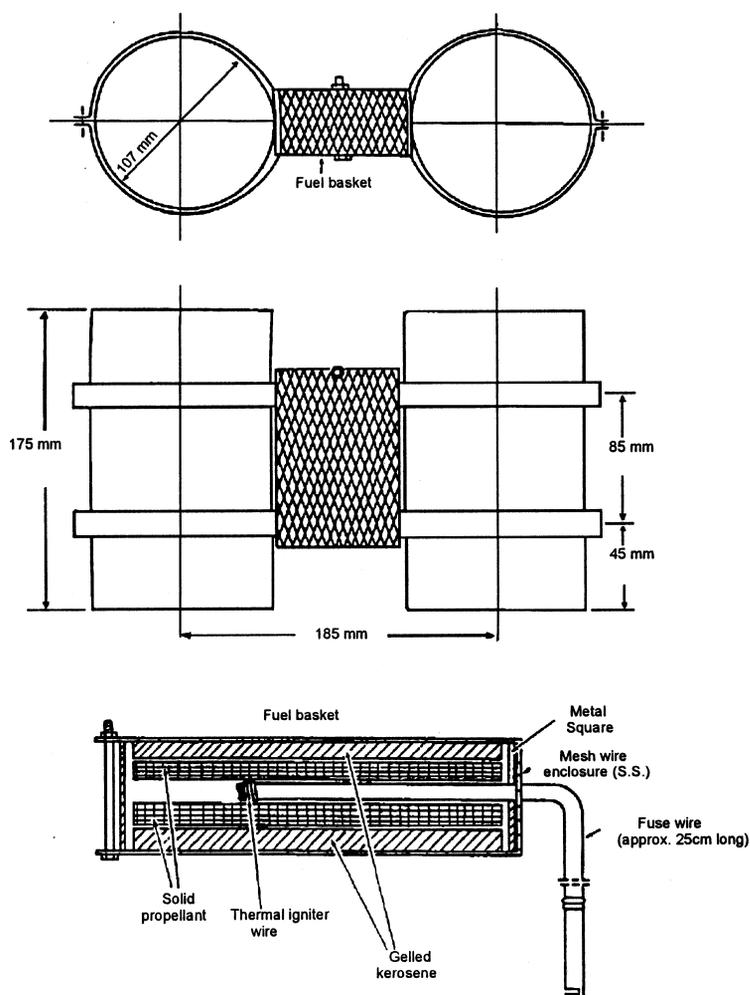
Fig. 3 Basic design and internal components of the Dome or Energetex igniter (adapted from [1]).

Heli-torch. The Heli-torch (Fig. 4) is a field-proven, helicopter-deployable, gelled fuel igniter commonly used for burning forest slash and for setting backfires during forest fire-control operations. Three models are available with gelled-fuel capacities of 110, 210 and 1100 L. Of these, the 210 L model has been most extensively tested for use on oil spills. The ignition system is a self-contained unit consisting of a gelled-fuel drum, pump, and motor assembly slung beneath a helicopter and controlled with an electrical connection from the Heli-torch to a panel in the cockpit. The fuel is pumped upon demand to a positive-control shut-off valve and ignition tip.
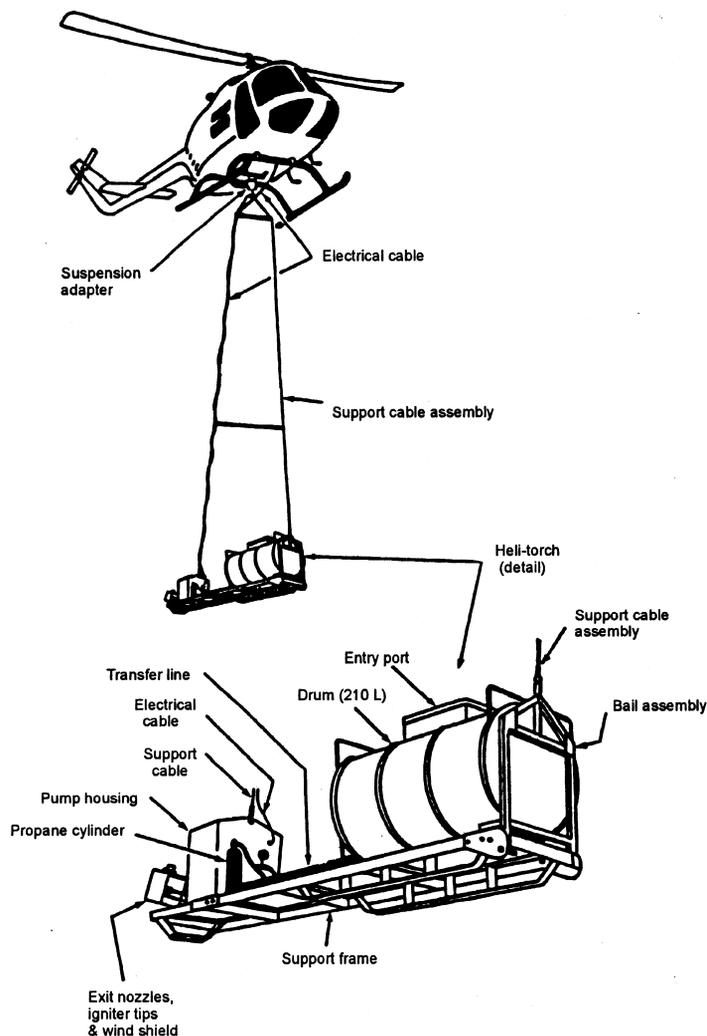
Fig. 4 Heli-torch components and support systems.

The gelling mix used to thicken the gasoline (or diesel in some cases) is a fine powder that produces a smooth, viscous gel when mixed with liquid fuel. When ratios of 1.8–2.7 kg of product to 210 L of fuel are used, adequate viscosities can normally be achieved within a matter of minutes at room temperature. At subfreezing temperatures, twice the amount of product is needed. The gelling mix is normally poured through the entry port of the Heli-torch fuel storage drum, which is equipped with a hand crank for mixing. As it exits one or more nozzles, the gelled fuel mixture is lit with electrically fired propane jets. The burning gel falls as a highly viscous stream and quickly breaks up into individual globules before hitting the ground. Experience has shown that the Heli-torch should be flown at altitudes of 7–23 m and with speeds of 40–50 km/h. The suggested altitude range is to provide accuracy during the release, to reduce the loss of gelled fuel while burning in the air, and to prevent the blowout of smaller globules on the surface by down-wash when the helicopter is flying at low speeds. The Heli-torch ignition system is

approved by the US Federal Aviation Administration. Recently, the Heli-torch was used in sea trials off the UK; part of this trial involved obtaining the appropriate approval to fly the Heli-torch from UK authorities.

Fire containment booms

The fire booms that are presently available are summarized below. The available booms are divided into two categories: those constructed of steel and those constructed from fire-resistant fabrics. Details of boom characteristics are provided in the MSRC report [1]. It should be noted that many of the booms described below are in the process of being tested by the USCG for oil containment [9] and fire resistance in waves (conducted in the fall of 1997 in Mobile, AL). All five booms that were fire tested leaked [10].

Steel fire proof booms

The first three steel booms are commercial products (Fireguard, Sandvik and Spilltain) and the next two (Dome and Merkalon) are not but their designs are available for construction.

Fire-guard boom. This boom is made of short, rigid flotation units connected by flexible, fabric panels. The floats are made from two square tubes of AG-3 (a grade of galvanized steel) that is 2 mm thick. These are attached to either side of a 3-mm thick plate of AG-3 that serves as sail and skirt. To minimize heat transfer the floats and vertical plate are separated by a 1-cm gap and the connections between the two are insulated with asbestos strips. The design draft and freeboard have been calculated so that there is sufficient heat transfer to the water at 1300 °C to ensure that the boom does not melt. The connectors consist of stainless-steel mesh enclosed in a 3 ply asbestos fabric coated with a sacrificial PVC covering. Stainless steel cables, top and bottom, carry tension loads, not the flexible panels. Each unit (float + connector) is 5 m long. Each section is apparently connected by means of five bolts. After exposure to fire the asbestos strips and flexible connections panels must be replaced.

Sandvik steel barrier. This product consists of sheets of cold-rolled stainless steel supported by pontoons of welded stainless steel cylinders. The boom sections are connected by a bolt joint arranged so the boom, according to the manufacturer, can move freely and follow waves. The manufacturer claims that the product has performed as a conventional containment boom for seven years without maintenance.

Spilltain boom. This product is a resurrection of an older design produced by Bennet Pollution Controls in the early 1980s. The present version consists of galvanized steel floats (foam-filled) supporting sheets of galvanized steel connected with a piano-type hinge. The boom was fire and tow tested in the Seattle area in 1995 [11] and at OHMSETT in 1996 [9]. Further details of the design, were not available at the time of writing.

Dome stainless steel boom. This boom, developed by Dome Petroleum Ltd. from the late 1970s to the early 1980s, is large and heavy, in order to meet its design criteria of long-term deployment offshore and resistance to ice impacts. Each section (flotation unit plus connector unit) weighs 210 kg and is 2.7 m long, has a draft of 1.2 m and a freeboard of 0.6 m. The boom has been tested extensively for fire-resistance, oil-containment performance in wind and wave conditions, and durability in offshore waters.

The boom's design consists of two units, the flotation and the connector. The flotation unit is constructed of Type 310 stainless steel with a steel sail and skirt attached. Each flotation unit incorporates a drain plug and wax-plugged vent pipe (for the release of over pressure air during burning and the ingestion of cold air during cooling). The connector units consist of a pleated, thin gauge 321 stainless steel sheet through which passes a universally jointed box beam. This design is necessary to avoid the self-abrasion problems associated with mineral-based fire-resistant cloth when wetted and the stress cracking problems associated with simpler steel connector designs. The deployment and retrieval of this boom is a cumbersome process.

An internationally funded, joint industry/government program to re-engineer this boom into a smaller, easier to handle product is underway. The concept is to produce a highly durable boom that can be used as a burn pocket between two 'arms' of conventional fabric-based fire boom.

Fire-resistant fabric booms

The following four fire containment booms constructed with fire-resistant fabrics are commercially available.

3M fire boom. This boom is the most tested and advanced of the fabric booms. It consists of high temperature resistant flotation sections constructed of a 3M patented ceramic foam. This material is stable at temperatures up to 1100 °C. The float core sections are held together with stainless steel knitted wire mesh. These 2 m long flotation sections are laid end to end and surrounded by a continuous blanket of 3M NEXTEL fibres. These nonflammable, poly crystalline, metal oxide fibres are designed for applications at temperatures up to 1400 °C. The NEXTEL layer is wrapped with another layer of stainless steel mesh. This entire package is covered with a sacrificial layer of PVC which extends below the flotation to form a skirt and double-layered pocket for a galvanized chain tension member. Short, stainless steel seaming bars rivetted through the layers underneath the flotation are used to hold the package together. Individual flotation sections are contained in 7 ft long segments separated by a metal clamp fastened through the PVC/mesh/NEXTEL 'sandwich'. The connector for each 15 m section (consisting of seven segments) is a stainless steel plate quick connector.

This product has evolved since the mid 1980s as a result of improvements made after a large number of tests. After several successful tests in quiescent waters in the late 1980s, the boom was put to real use during the response to the *Exxon Valdez* spill in March 1989. Subsequent experimental programs from July 1990 to May 1991 involving quiescent salt water tank tests led to further design modifications to the boom.

More recently, in the summer of 1993, 210 m of the 18 ft version was used to contain the burning oil in trials conducted 45 km offshore of St. John's, Newfoundland. Two discrete burns were conducted in 1 m waves and 2–3 m/s winds. The first involved 50 m^3 of slightly weathered crude oil burned over a 1.5-h period. At the end of the burn, the stainless steel in the boom showed signs of fatigue and some of the NEXTEL fabric was missing; however, the boom was considered fit enough for a second burn. One hour and 15 min into the second burn several flotation sections from the boom came loose, oil began to leak and the oil pumping was stopped. After the fire had stopped (30 m^3 had burned) the boom was again inspected. A prototype section of the boom that incorporated a middle tension member had lost three flotation sections and a number of other sections were completely missing NEXTEL fabric near the vertical stiffeners. It is presumed that the combined action of heat, saltwater and wave action were to blame for this self abrasion problem.

In 1994, an earlier version of the Fire Boom was used to contain thick slicks of burning ANS oil and emulsions in a water-filled pit on the North Slope. In each of three burns the oil began to leak through the fabric after about 5 min exposure to flames. Similar leakage was reported at tests of the latest version of the boom near Seattle in 1995 [11]. No leakage was reported during test burns offshore England in the spring of 1996. At these tests the boom was reported to survive two short burns (of about 15 min each) in 1–1.5 m seas.

Sea curtain fireguard: This boom is designed to be reel-able and self-inflating. As the boom is drawn off the reel a stainless steel coil springs from a flattened position to a helical position thus providing flotation and freeboard. The flotation section consists of high temperature, closed cell foam protected by Thermoglas fabric. The coil supports a double layer of Thermotex coated with a sacrificial abrasion resistant coating; this coating will burn away at 300 °C. The skirt is constructed of a heavy-duty polyurethane coated polyester. Ballast and tensile strength are provided by a galvanized high test chain in a pocket at the bottom of the skirt. Tow tests have shown that new boom has good towing and wave riding characteristics at speeds up to 0.5 m/s.

The boom has been burn-tested in quiescent, freshwater and saltwater conditions and containment testing has been conducted in a wave tank. After a one-hour exposure to maximum flame temperatures of 900 °C the yellow sacrificial coating discoloured to a pale green and were noticeably more brittle than the rest of the boom. However, even after 24 h of exposure to flames, and despite serious embrittlement of the Thermotex fabric and damage to the inner layer's sacrificial coating, the boom shape, freeboard and configuration were still satisfactory. Design changes in 1992 proved unsatisfactory in test burns, and the manufacturer has returned to the original design with an enhanced thermal resistant coating on the covers and additional thermal protection for the internal float system.

Pyroboom: This fence type boom consists of a sail constructed of Fibrefrax fabric, supported by Inconel wire mesh and coated with silicone rubber bonded to a PVC coated fabric skirt. A chain in a pocket at the bottom of the boom is provided for ballast and tension carrying (this replaces the lead ballast on earlier versions). Flotation is provided by a series of stainless steel hemispheres bolted together above and below the waterline. The floats are filled with a high temperature-resistant, closed cell foamed glass.

The boom has been the subject of both fire tests in quiescent conditions and towing and containment tests in a wave tank. The fire tests lasted 24 h and peak recorded flame temperatures of 930 °C were reached. After 6 h exposure, the boom still contained oil and remained flexible, although the upper few centimetres of the sail were degraded, with several small holes where the internal Inconel wires were exposed. During the remainder of the 24 h-test the boom continued to contain the burning oil without loss of freeboard. At the end it was found that the baked silicone rubber and fabric in the upper area of the boom was very susceptible to abrasion, although from the waterline to a height of 10–12 cm the combination of silicone and burned oil residues had created a flexible and impermeable barrier protecting the boom. Although there were indications of some melting of the foam inside the floats, it was minimal and did not result in any loss of freeboard during the tests.

Subsequent towing resulted in significant oil simulant losses at tow speeds above 0.35 m/s; the design has been subsequently modified to include a more flexible skirt which is reported to have performed well during tests along with nonfire proof boom models of similar design.

Autoboom—fire model: Little information is currently available on this boom. No details on construction materials or test results have been supplied by the manufacturer, although the boom has been exposed to fire at the USCG Fire Training Facility in Mobile, Alabama. The boom is claimed to be of the pressure inflated (7 kPa) variety designed for deployment from a reel or compact storage without a reel.

Additives

A variety of additives to assist *in situ* burning have been developed and tested over the years. These can be categorized into three major groups: ignition promoters (or primers), combustion promoters (including wicking agents) and smoke suppression additives.

Ignition promoters

Ignition promoters are defined as substances added to an oil slick in order to increase its ignitability or to promote spreading of flame over the surface of unignited oil. Several products have been considered over the years, but petroleum products themselves have proved to be the most reliable and effective ignition promoters for *in situ* burning. Examples include gasoline, diesel, kerosene, aviation gasoline, and even fresh crude oil. The middle distillates (diesel, kerosene, etc.) are considered better ignition promoters than the lighter petroleum products (gasoline, etc.) for three reasons:

- the use of the lighter products poses a significant safety hazard due to their high volatility;
- the lighter products evaporate faster than middle distillates which results in faster cooling of the underlying oil slick; and
- the flame temperature is higher with middle distillates.

Crude oil, with its wide range of components, is probably the best ignition promoter. With viscous oil slicks it is necessary to spray the promoter over an area of the slick; pumping oil onto one point only will result in a localized, thick, pool of fuel.

Combustion promoters

Combustion promoters can be defined as substances that are added to a slick to increase the oil removal efficiency by burning. These substances usually act as either a wick or an insulator between the slick and the water substrate, or a combination of the two. The following substances have been tried in the past but are now considered unsuitable: SeaBeads, Cab-o-Sil, Aerosil, Tullanox, Fibreperl, Ekoperl, Wonderperl, Vermiculite and straw.

The one natural product that has proved effective in the past is peat moss. Peat moss was used in 1968 at the cleanup of the *Raphael* spill off the coast of Finland. Responders used 300 bales of peat moss

soaked with 10 400 gallons of fuel oil and petrol to burn 90% of the spilled oil trapped in ice. Tests with peat moss soaked with diesel oil as a combustion promoter for crude oil fires have shown that oil removal efficiencies of 80–95% were obtained with peat loadings of 3–5% by weight and diesel loadings of 1%. Of all combustion promoters, only peat moss with diesel fuel is recommended, primarily due to its low cost and ready availability. Due to anticipated problems with application over large areas it should be considered for use on smaller spills where it can be manually applied.

Sorbent products as wicking agents

A variety of manufactured sorbents have been used successfully as wicking agents, including Saneringsull and polypropylene sorbent sheets and pads. Their use is restricted to smaller spills where access is available for manual application of the sorbent.

Emulsion breakers

The idea of applying emulsion breakers to a slick to break the emulsion *in situ*, remove water, and extend the 'window-of-opportunity' for successful ignition of the slick is being actively researched with several crudes. Recent large-scale tests in Alaska, the UK and Norway indicate that the technique shows great promise. The effectiveness of the technique is highly oil-specific and surfactant-dependant.

Smoke suppressants

The beneficial effects of adding certain organo-metallic compounds to fuels to reduce smoke has been recognized since the early 1960s. The compounds that have been studied include derivatives of barium, manganese, iron, lead, copper, magnesium, nickel, cobalt and boron. Of these, the compound that has been researched the most for oil spill use is ferrocene and its derivatives.

Ferrocene is an orange-coloured, crystalline solid that is insoluble in water and slightly soluble in hydrocarbons (up to about 2% to 4% by weight). Its density is greater than that of water. It is relatively nontoxic and is thus attractive for use on marine spills. Ferrocene is used commercially as a fuel additive for many applications, including in rocket propellant to promote more efficient burning and as a smoke suppressant in diesel fuel and heating oils to reduce particulate emissions to regulated levels. Tests with ferrocene on *in situ* burning have shown that 90–95% reductions in soot production can be realized with the addition of 2% by weight ferrocene to the oil.

The problems with ferrocene powder include its high cost, that it dissolves slowly in oil, and its density exceeds that of water. This makes it difficult to mix into an oil spill, and if the powder misses the slick it sinks. Over 30 organic derivatives of ferrocene have been tested to overcome this problem. The derivatives tested tend to be liquids at room temperature and are much more soluble in oils than the parent ferrocene.

It is reported that the latest ferrocene hybrid, RMS 9757, reduces soot up to 70% at dose rates of 0.5 wt% ferrocene equivalent, is easily applied as a liquid concentrate that can be sprayed onto a slick, and dissolves quickly. Research on ferrocene has recently been shelved due to the technique's high cost and a lack of interest in its use.

OPERATIONAL ASPECTS

This section briefly summarizes how *in situ* burning operations could be applied to an oil spill, what resources are required and the capabilities and limitations of *in situ* burning operations. It should be recognized that operational experience with controlled *in situ* burning in open water conditions is extremely limited. The method has only been used at an actual offshore spill once, and only on a trial basis, at the *Exxon Valdez*. *In situ* burning with fire booms has also been applied successfully at two inshore spills: once in response to a burning blowout and once to burn oil from a pipeline leak in a river. Thus, many of the suggested techniques in this section have been extrapolated from knowledge gained from small tests of *in situ* burning or derived from experience with conventional spill containment operations. As knowledge of controlled burning increases through R & D and actual use, the concepts presented here will undoubtedly be expanded, revised or even rejected. As such, the aspects of *in situ* burning discussed here should be considered a 'work-in-progress' only.

Scenarios for use

There are two basic scenarios for the application of controlled *in situ* burning in spill response operations: the 'batch' mode and the 'continuous' mode. The 'batch' mode consists of six discrete steps: (i) oil is collected in a section of fire-resistant boom towed by two vessels until the back third of the boom is filled; (ii) the filled boom is manoeuvred to a safe distance crosswind; (iii) the contained oil is ignited; (iv) the oil is burned and then extinguishes; (v) the residue is collected, if necessary and the boom inspected for damage, and replaced if necessary; and, (vi) the boom is manoeuvred back into the slick to begin collecting the next batch of oil. In the 'continuous' mode the fire-resistant boom is positioned a safe distance down drift from a continuing oil leak, such as a blowout, and oil is burned continuously or intermittently as it accumulates in the back of the boom. An alternative to controlled burning is the ignition of uncontained oil slicks that are thick enough to support combustion.

Capabilities and limitations

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 $2000\,m^3/h$ can be achieved with a fire area of only about $10\,000\,m^2$ or a circle of about $100\,m$ in diameter. In actual operations, however, other factors can determine the overall removal rate and efficiency.

The oil removal rate for the 'batch' mode is constrained by the rate at which the towed boom can encounter oil (estimated from the tow speed—a maximum of $0.35\,m/s$, the width of the mouth of the boom and the average thickness of the slick through which the boom is being towed); and, the time required to manoeuvre the boom to a safe area, ignite and burn the oil, recover the residue, inspect and perhaps replace the boom, and return to the oil collection area. A recent analysis of this approach [12] concluded that although small *in situ* burning systems (consisting of $150\,m$ of fire-resistant boom towed by two fishing boats) could remove significant amounts of oil from the sea surface, they could not match the capacity of a large, offshore rated containment and recovery operation. The oil removal rate for the 'continuous' mode is constrained by the rate at which the boom system collects the leaking oil and the ability to keep the boom on station in the oil slick.

Although there are few data on the effects of sea state on *in situ* burning, what little experience exists suggests that the sea-state limit for effective burning is from 1 to 2 m significant wave height or less. Of course, burning will not be effective if the fire boom fails to hold oil in these sea conditions.

Winds of approximately 30–40 km/h are considered to be the upper limit for ignition of oil pools in the absence of waves. These constraints reflect both the current state-of-the-art in proven ignition and fire containment booms systems, as well as the environmental conditions under which most oils will be quickly weathered beyond a combustible state.

Another important environmental factor controlling burning is the presence of good visibility. For a safe and effective burn to take place it should be possible to see (i) the oil to be collected, (ii) the vessels towing the fire containment booms, and (iii) the proximity of the intended burn location relative to the spill source, other vessels in the area, and other potentially ignitable slicks. As a guide, VFR flying conditions (greater than 4 km visibility and a minimum 300 m ceiling) could be used. If helicopters are to be used, VFR flying conditions must exist both at the site and at the helicopter base. If burning is to be conducted at a remote, fixed, continuous source of spilled oil (e.g. an offshore blowout), it may be feasible to burn spilled oil safely at or near the source during limited visibility conditions (e.g. less than VFR flying conditions, dusk, dawn, etc.).

Resources necessary for a burn

This section summarizes the resources that are generally required to carry out a safe and effective controlled burn: trained personnel, vessels and aircraft, and fire containment boom and igniters. It is recognized that certain types of burning may not require all of these resources. For example, a situation involving accidental burning of oil following a ship accident would not require igniters to start the burn process; and, an intentional program to burn a thick, uncontained spill would not involve fire proof boom. The requirements for trained personnel, and greater detail on the various planning aspects of a burning operation are given in the MSRC report [1] and in several *in situ* burning manuals [e.g. 13].

Vessels and aircraft

It is important that all vessels used during offshore burning operations have sufficient power to pull the size and length of fire containment boom being considered. Vessels with twin variable-pitch propellers are generally preferred; and powers in the 100–150 kW (150–200 hp) range are generally sufficient for boom tow boats. Large vessels (e.g. 45 m to 60 m supply vessels) make ideal platforms for large containment booms and recovery systems, although such vessels are often over-powered for the needs of pulling boom. Experience has shown that small towing boats in the 8 m to 12 m range are usually much better for controlling a simple track-down and collection operation, particularly when towing speeds need to be maintained for extended periods at 0.4 m/s or less. This size of towing boat can often be transported to the burn area with a larger vessel and deployed and recovered from the larger vessel. Regardless of the size of vessel selected, it is important that its propulsion system permit the vessel to maintain steerage at speeds in the 0.4 m/s and lower range. All vessels should be equipped with explosimeters.

Vessels used for the towing of fire containment boom need to be equipped with properly positioned tow-posts or bits and adequate lengths of tow line (typically 150–250 m). The tow lines need to be strong enough to accommodate the maximum drag forces that would likely be experienced during the towing of boom in open water conditions.

Vessels should also have space to carry fire containment booms to the burn site and space to deploy them. The size and weight of the boom must conform to the deck space and safe load-carrying capacity of each vessel. When the boom-towing boats are too small to carry the entire boom on deck, the fire containment booms may be pulled in a straight-line tow (typically at speeds of about 9–18 km/h), or the boom can be transported to the oil collection area with the aid of an additional vessel or barge. In some cases, helicopters may be used to transport boom from shore or from a vessel to the spill site.

With respect to aerial support operations, helicopters will provide an effective platform not only for the possible transport of boom and personnel, but for the release of igniters onto the oil to be burned. Helicopters will also be of value for the spotting of oil slicks, the directing of vessels to the heaviest concentrations of the spill, and the monitoring of burn effectiveness and smoke plume transport and dispersion. Because of the diversity of tasks for which helicopters may be used and the distances that may have to be travelled offshore, it is important that the type and size of aircraft, the number of engines, and the need for pontoons be properly considered.

It should be recognized that while aircraft will usually play a key role during burning operations, there will be potential burn situations where controlled burning could be initiated without them. For example, as long as surface operations are located a safe distance from property and other vulnerable resources, boats could begin to concentrate and ignite oil with hand-held igniters released from one of the boom towing vessels.

Fire booms and igniters

From an operational standpoint, it is the specific location and nature of spillage to be contained that will determine the type, size, length and mode of deployment of fire containment boom required. The location and nature of the spill, together with the boom deployment mode will then determine the best type of igniter and the most appropriate scheme for igniting the contained oil. It is important to remember that certain spill scenarios may not require the use of fire containment booms for the effective burning of large quantities of spilled oil. In such situations, extra safety precautions may be necessary to avoid unexpectedly large initial burn areas and harmful exposure levels.

When spilled oil has spread to thin layers covering large areas, fire containment boom will be required to concentrate the oil to thicknesses that will support combustion. If there is a chance that burning could spread to oil outside the towed boom configuration, the contained oil should be towed and ignited well away from the main slick.

Should a tanker accident involve spillage without fire, fire containment boom could be used to collect oil in one or more U-configurations and then be towed to a safe location for ignition. If oil is already burning at the source, this mode of controlled burning should be considered if it is impractical or unsafe to burn near the stricken vessel.

During burning operations on the leeward or downstream side of an already burning tanker, it may be impossible to deploy fire containment booms immediately at the spill source. In such a situation, it may only be necessary to periodically release igniters into any unignited oil as it concentrates under the influence of wind and current eddies in the lee of the burning tanker. If safe to do so, it may be possible to position fire containment booms on the leeward side of the spill in order to thicken and burn oil before it spreads downstream.

In all of the above three examples the fire containment boom in U-configurations should be used with 150–300 m of each boom. The larger fire containment booms would usually be used during open water conditions, while smaller fire containment booms could be utilized in calmer or protected waterways. When wind and sea conditions require the use of large fire containment booms configurations, each U-configuration could be established with a short length of the large boom forming the apex, and with medium-sized boom serving as the deflection boom forward along each leading side of the 'U'. In this situation care must be taken to ensure that the connection point between the two boom sizes can withstand the extra loads imposed by the differing wave response characteristics of each boom type. Where it is safe to do so (i.e. in situations where the oil is too thin to burn except where it is thickened within the apex), conventional boom could even be used to deflect oil directly into the fire containment boom portion of the U-configuration.

Some fire containment booms are heavy and difficult to handle, but are also durable and able to survive burning in an offshore marine environment for long periods. These are typically metal booms. Others are lighter and easier to handle and deploy but are not designed for long-term deployment offshore or long-term exposure to fire. These usually employ fire-resistant, mineral-based fabric and ceramics. It is important for planners and field personnel to anticipate the full range of constraints that may be imposed on the burning operation because of a boom's particular weight and handling requirements. With proper training, experience has shown that fire containment booms can be deployed quickly and used in the same manner as most comparably sized conventional booms. If the fire containment boom is subsequently not used for the combustion of oil, it can be recovered, cleaned and stored for use again at a later time.

When fire containment boom is used to contain burning oil, there will almost always be some degree of thermal stress and material degradation with time. Some fire containment booms have been constructed of materials designed to strongly resist the effect of fire (e.g. steel). Other fire containment boom designs have outer coverings that protect the more fragile underlying material from abrasion during handling and storage, but are destroyed during the early phase of a burn. The underlying materials are refractory in nature and designed to withstand the effects of burning and to remain intact for subsequent burns over a period of several hours. Wave action may accelerate the degradation of these boom types. The actual number of times that a fire containment booms can be used will vary from one product to another and from one application to another. Repeated use will clearly depend on the intensity and duration of the burns, the sea conditions at the time of burning and the manner in which the boom is handled during and between each burn. As with some conventional booms, the extent of use and the degree of damage will likely make it cost-effective to discard the boom upon completion of use, rather than attempting to clean and restore it.

When using fire containment booms for multiple burns, the boom should be inspected (at least along segments exposed to the most thermal stress) for any significant breaks, tears, or deterioration which could result in mechanical failure or loss of containment. Any damaged sections should be repaired or removed and replaced as necessary. If it is necessary to tow used fire containment booms of the sacrificial-coating type to a new site for additional burns, care should be taken to avoid any excessive speeds (more than 4–8 km/h or 2–4 knots) even in a straight-line tow. This is because exposed areas where the protective outer cover has burned away will experience more drag and be less resistant to abrasion. Even with metal boom, care should be used in transporting and reusing the boom due to the cumulative effects of mechanical and thermal stress upon its components.

This chapter has described several devices for igniting spilled oil. Of these, the Heli-torch is the most cost-effective, reliable and flexible system for the aerial application mode. Because of the quantity of gelled fuel that can be carried, it is possible to release ignition fuel as individual ignition points or in a continuous mode. With the Heli-torch operated from a hovering position, it is possible to create very large initial ignition areas for difficult-to-ignite weathered or partially emulsified oil layers.

In spill situations where a helicopter's staging area is distant from the proposed burn region, it may be advisable to locate nearby temporary landing sites where the helicopter could set down between ignitions. A single drum of gelled fuel within the Heli-torch would normally be large enough to support the ignition of numerous individual burns. During an extensive ongoing burn operation it may be helpful to move backup Heli-torches, fuel, mixing facilities and gelling agent to forward landing sites in order to avoid delays because of long transit distances to the primary staging location. Ships with appropriate heli-decks may also be used, if the transport and mixing of the gasoline-based Heli-torch fuel is allowed onboard.

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. 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.

Fire and heat

Flames from *in situ* burning poses a risk of severe injury or death 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 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.

Effects of heat on spill responders

In situ burning of oil produces large amounts of heat which is transferred into the environment through convection and radiation. About 90% of the heat generated by *in situ* combustion is convected into the atmosphere. 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 is from two- to fourfold the diameter of the fire depending on the duration of exposure, as shown in Table 1. Conservatively, it is assumed that the safe approach distance to the edge of an *in situ* oil fire is approximately four fire diameters**.**

Table 1 Safe approach distances for *in situ* oil fires

Exposure time	Safe approach distance for personnel (fire diameters)
Infinite	4
30 min	3
5 min	2

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 thickness 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. (Table 1).

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) the upper few inches of the underlying water may be heated in the latter stages of the burn. In a prolonged static burn, the upper few millimetres of the water column may be heated to near boiling temperatures, but the water several inches below the slick has been proven to be unaffected by the fire. The Alaska Regional Response Team, in their assessment of the impacts of *in situ* burning, has recognized that this heating may eliminate the small life forms that exist in the surface layer of water, but have concluded that the areas involved are small and that the lost biota will quickly be replaced, with negligible overall impact. The conclusion is that the environmental impact of the heat from an *in situ* burn is negligible.

Air emissions

Table 2 shows the components of the smoke from an *in situ* burn and their approximate proportions. (Recognize, however, that the composition of burn emissions varies with the type of oil burned and the size of the burn.) Each component in the table is treated separately below. Smoke particulate is the main concern and is dealt with first in some detail. Following this are brief discussions of the other emissions of lesser concern.

Table 2 Airborne emissions from an *in situ* petroleum fire*

Constituent	Quantity emitted† (kg emission/kg oil burned)
Carbon dioxide (CO_2)	3
Particulate matter	0.05–0.20‡
Carbon monoxide (CO)	0.02–0.05
Nitrogen oxides (NO_x)	0.001
Volatile organic compounds (VOC)	0.005
Polynuclear aromatic hydrocarbons (PAH)	0.000004

* Updated from [1] based on Kuwait pool fire [14] and NOBE data [15].
† Quantities will vary with burn efficiency and composition of parent oil.
‡ For crude oils *soot yield* = $4 + 3$ log (*fire diameter*); *yield* in mass %, *fire diameter* in cm [16].

Smoke

The main concern. Carbon smoke particles are responsible for providing the characteristic black colour of the plume rising from an *in situ* burn. The smoke is unsightly, but more important, the smoke particles can cause severe health problems if inhaled in high concentrations. Of particular concern are persons with special sensitivities, such as the very young, the very old, pregnant women, and persons with asthma, pulmonary and vascular diseases. In addition, they serve to carry other adsorbed toxic materials (e.g. PAHs) deep into the respiratory tract. Smoke particulate are also of concern because they obstruct visibility and hence may pose a safety hazard to operators of ships, aircraft and motor vehicles in the immediate vicinity of the fire.

Particle size, PM-10. Smoke particles are formed as a result of the agglomeration of tiny specks of unburned carbon. The particles vary greatly in size. From a health perspective the focus is on those particles that are small enough to be inhaled into the lungs, that is, those smaller than 10 μm in diameter. Health scientists call these PM-10s (PM stands for 'particulate matter'). PM-10s make up approximately 90% of the mass of particulate emitted from an *in situ* burn The average particle size of the soot is about 1 μm.

Health standard. One exposure standard that exists for PM-10s is the US National Ambient Air Quality Standard (NAAQS) which states that PM-10 exposures of more than 150 μg/m^3, averaged over a 24-h time period, can cause mild aggravation of symptoms in persons with existing respiratory or cardiac

conditions, and irritation symptoms in the healthy population. However, *in situ* burn experts, health experts and regulators, in the absence of any data, have agreed to adopt a more conservative standard for *in situ* burning requiring that concentrations averaged over one hour should not exceed 150 $\mu g/m^3$.

Measurements and models of PM-10. Particulate concentrations in the plume are greatest at the burn site, but decline with increasing distance from the burn site primarily through dilution, dispersion and fallout, but also through washing out by rain and snow.

At a large *in situ* burn experiment that took place in the summer of 1993, concentrations of particulate matter were measured in the smoke plume and elsewhere. At the Newfoundland Offshore Burn Experiment (NOBE) burns, with an average burn rate of 23 m^3/h, concentrations of particulate in the plume near the fire were commonly in the range of 800–1000 $\mu g/m^3$, but declined to approximately 150 $\mu g/m^3$ within 1.5 h travel time downwind from the fire. Of particular importance is the fact that PM-10 concentrations beneath the plume, even 50–70 m above the sea surface, never exceeded background levels (30–40 $\mu g/m^3$). Ground-level concentrations beneath a plume from a test burn of crude in Alaska with a burn rate 20 m^3/h declined from 86 $\mu g/m^3$, 1 km downwind, to 22 $\mu g/m^3$ 4 km downwind. Measurements of near-ground smoke concentrations under the plume from two even larger diesel fires (70 m^3/h) in Mobile, AL in 1994 peaked at only 25 $\mu g/m^3$ 11 km downwind in one case and 15 $\mu g/m^3$ 11 km downwind in the other.

Concentrations of PM-10 in a smoke plume are not easy to predict because they are a function of many factors including soot yield, fire size, burn efficiency, distance downwind from the burn, terrain features and atmospheric conditions (e.g. wind speed). To help decision makers, computer models have been, and continue to be, developed to predict the concentration of soot particles in an *in situ* burn smoke plume as a function of altitude and distance from the fire. Such models can be of assistance in deciding whether or not to initiate an *in situ* burning operation when close to populated areas.

As an interim measure, until such time as these computer models become widely available, general examples can be used as guides. A technique has been presented [17] for roughly estimating the maximum distance downwind over complex terrain for the ground level concentration of soot under plumes from *in situ* burns to dilute and disperse below a given concentration. The table is based on analysing the results of many runs of the ALOFT-CT computer model, developed by the U.S. National Institute for Standards and Technology to predict smoke plume dispersion from *in situ* burns. The distance beyond which the soot concentration falls below a given level depends mainly on the terrain height and the mixing layer depth relative to the elevation of the burn site, with wind speed being the next most important factor. Table 3 lists the approximate distances downwind over land for the ground-level PM-10 concentrations from a 1700 m^3/h fire to fall below 150 $\mu g/m^3$ for various terrain heights in winds from 1 to 12 m/s. It can be seen that if the plume passes over highly elevated terrain the distances for the ground-level concentrations of PM-10 to decrease below 150 $\mu g/m^3$ are much greater than over flat terrain in equivalent meteorological conditions. The distance downwind for the smoke plume to dilute below 150 $\mu g/m^3$ would range from 1 km over flat terrain in a highly mixed atmosphere (akin to Stability

Table 3 Estimates for maximum downwind extent of 150 $\mu g/m^3$ over complex terrain*

Fire size (m^3/h)	Terrain height (m)	Maximum distance (km) downwind for PM-10 concentration to reach 150 $\mu g/m^3$ at ground level for given mixing layer depth ranges (m)†				
		0–100	100–250	250–500	500–1000	>1000
1700	0–25 Flat	5	4	3	2	1
1700	25–250	10	8	6	4	3
1700	250–500	15	12	10	8	5
1700	>500	20	17	15	12	10

From [17].
* Valid for wind speeds from 1 to 12 m/s.
† Mixing layer depths loosely correspond to atmospheric stability class ranges as follows: Stability Class C ≈200–300 m; Stability Class D ≈150–200 m.

Class A) to 20 km over mountainous terrain in a very stable atmosphere (akin to Stability Class F). Low mixing layer depths, associated with Stability Classes E and F conditions, generally only occur at night. As a general rule a downwind distance of 5 km over water bodies and flat terrain is used as the zone of concern.

Sampling strategies. In some jurisdictions, real-time environmental sampling for PM-10 is prescribed. Sampling devices for measuring particulate matter in the plume that can be rapidly deployed by a helicopter have been developed [18]. In these instances the 150 μg/m^3 ground level concentration level should be considered a conservative, general guideline. If it is exceeded substantially over some time, terminating the burn could be decided. However, if the trend is for ground level PM-10 readings to be less than the limit, with only occasional readings at higher levels, there is no reason to believe that the nearby population would be seriously threatened (Table 3).

Threat to and safeguards for workers. Exposure concentrations in the immediate vicinity of the fire will usually exceed public health standards both in-plume and at ground level, but are within acceptable levels according to industrial safety standards (see Table 4).

Table 4 Summary of exposure threshold standards for constituents of burn emissions

Compound	Industrial Standards* (mg/m^3)		Public Health Standards† (mg/m^3)		
	TLV-STEL	TLV-TWA	1-h	24-h	Annual
Carbon dioxide	54 000	9000	none	none	none
Carbon monoxide	–	55	none	none	
Nitrogen oxides	9.4	5.6	0.25‡	–	0.05
Sulfur dioxide	13	5.2	0.2–0.4	0.14	0.03
PAH	–	0.2	–	–	–
Particulate§	7	3.5–10§	–	0.15	0.05

* TLV-STEL are short-term exposure limits (usually 15 min); TLV-TWA are the time-weighted average (usually 24 h).
† Based on US Federal or state public Health Standards unless otherwise specified.
‡ Based on the standard for California.
§ Threshold limits for particulate were taken from a number of standards: Public health standards are base on US Federal and state standards for PM-10s; TLV-TWA values based on values for 'Particles Not Otherwise Specified' (= 10 mg/m^3) or carbon black (3.5 mg/m^3); and TLV-STEL values based on values for carbon black (7 mg/m^3).

In any case, safeguards are required to protect workers. These should include:

1　*Screening process.* It is important to screen potential workers in the burning operation for conditions such as asthma that would make them sensitive to elevated concentrations of particulate in the air.

2　*Respiratory protection.* Respiratory protection, eye protection and protective clothing should be available for all personnel involved in the burning operation.

3　*Effects on visibility.* The precaution is to contact local authorities to notify them of the potential visibility problem and identify the area(s) potentially affected. Notify local air traffic control, vessel traffic control, police, fire and transport authorities.

Gases

Unlike particulate matter, the gases emitted during an *in situ* burn operation do not represent a serious threat to safety or human-health, primarily because the concentrations at which they are of concern are much higher than those for the particulate soot. The concentrations of the gases fall below these levels of concern in very short distances downwind of a burn; much shorter than the distance for the soot concentration to fall below 150 μg/m^3. A brief summary of each gas is presented below.

Carbon monoxide. Approximately two to five percentage by weight of crude oil consumed during *in situ* burning is converted to carbon monoxide. Industrial exposure standards are: the threshold limit value (TLV-TWA) is 50 p.p.m. (or 55 mg/m^3) averaged over 8 h.

Measurements of CO made at several burn tests show that at ground level, 30 m downwind of a *in situ* oil fire, ambient concentrations of CO were at or near background levels or were below the limits of detection of the instruments. This suggests that there is little risk of effects from CO at ground level. Routine monitoring might be warranted on vessels immediately involved in the burn and in residue collection. Respiratory protective equipment should be on hand for emergency use.

Volatile organic compounds. Volatile organic compounds, VOCs, are a mixture of the lighter, lower molecular weight hydrocarbons. These compounds are released into the air during oil spills, whether burning is used or not.

During any petroleum spill, the lighter, more volatile components of the oil evaporate quickly, causing elevated concentrations of VOCs in the air downwind of the slick. This process is rapid and much of this material is lost from the slick within the first 24–48 h. If the oil spill is ignited and burned, these compounds are consumed by the fire. During the Mobile mid-scale burns, VOC concentrations at ground level, within 30 m downwind of the fires, averaged approximately $2 \, mg/m^3$ during the burns with peak average (Table 4) concentrations reaching $10 \, mg/m^3$. At 60 m downwind, average concentrations were $0.8 \, mg/m^3$, with peaks to $1.5 \, mg/m^3$, well below the safety standard for exposure to such vapours.

Carbon dioxide. Carbon dioxide (CO_2) a colourless, nonpoisonous gas, is the most abundant product of *in situ* burning. CO_2 concentrations within the smoke plume are likely to be well above background. Concentrations at ground level at 30 m from mid-scale fires averaged from 100 to 1100 p.p.m. above normal background levels of about 330 p.p.m., with peaks from 200 to 1100 p.p.m. above background, which are well below the hazardous levels.

Sulfur dioxide. Sulfur dioxide (SO_2) is a minor product of oil spill fires. Its concentration in the smoke is dependent on the amount of sulfur in the oil. Measurements of SO_2 taken 30 m downwind of mesoscale burns show that peak levels ranged from below detection limits to 1.2 p.p.m., well below levels of concern.

Nitrogen oxides. Nitrogen oxide (NO_x) gases are present in only small amounts in emissions from oil fires. During mid-scale test burns, concentrations of NO_x at ground level downwind of the fire were below the limits of detection and levels of concern.

Comparison with other sources. The emissions measured from the NOBE burn have been compared with emissions from other sources. The rate that CO_2 was emitted from the test was equivalent to a 1 hectare forestry slash burn; the rate of CO emission was equivalent to a 0.1-ha slash burn or 2400 wood stoves. The SO_2 emission rate was equivalent to an average coal-fired power plant. The emissions of soot particles were equivalent to a 3.5-ha slash burn or 58 000 wood stoves.

Polynuclear aromatic hydrocarbons

Polynuclear aromatic hydrocarbons (PAHs) are of interest because certain PAH compounds, such as benzo[a]pyrene, benzo[k]flouranthene and chrysene are known or are suspected to cause cancer. PAHs are present in small, but varying amounts in petroleum oils, burn residue and in the smoke. The ambient concentrations of particle-bound PAH in 'clean' air near the fire are on the order of a few $\mu g/m^3$ (based on data from the Mobile mid-scale burns and NOBE). Concentrations measured at ground level near the fire appear to be well below accepted workplace exposure standards, and hence the risks to spill workers would appear to be low. A detailed assessment of the carcinogenic and toxic hazards posed by PAH in emissions from *in situ* burn fires [19] has suggested that risks of adverse effects to the public are well below the level of concern when population centres are at least 5 km downwind of the fires. The only known potential effect of soot on the environment is that it may be mutagenic. In a detailed assessment of the ecological risks associated with *in situ* burning [20] it was concluded that under practically all combinations of physical conditions and ecological receptors, the preferred decision would be to burn a spill.

Burn residue

This section deals with the residue remaining following a burn. This residue will be much reduced in volume from the amount of oil at the beginning of the burn; and, it will be altered in terms of the chemical

composition and physical properties and possibly the fate of the oil (i.e. the residue may sink rather than float). The environmental risks associated with burn residue will depend on its fate. Residue that floats may continue to pose a threat to wildlife and shorelines. Residue that submerges may pose a threat to benthic communities. Both may still pose some risk of toxicity or contamination to water column dwellers.

Chemical composition

Crude and refined oils contain a broad range of hydrocarbons. Crude oils contain the broadest range of compounds from the lightest alkane to the heaviest asphaltene, while refined products such as diesel fuel or residual fuel contain a narrower range of components. During an *in situ* burn, both light and heavy components of the oil are combusted, but the lighter, lower-boiling-point (LBP) hydrocarbons are preferentially removed and the heavier, higher-boiling-point (HBP) components are concentrated in the residue. Therefore the residue remaining at extinction will differ in composition and properties from the parent oil. In laboratory test burns of thick slicks (50–150 mm) of crude oils, the residues remaining following natural extinction of the burn were completely stripped of lower boiling point compounds and were largely depleted of middle boiling range hydrocarbons. Thus, burn residues can be expected to be depleted of the more volatile, lower boiling point fraction which includes many of the more toxic and hazardous components of crude oils (benzene, naphthalene, benzopyrenes). Hence, burn residues should be less toxic than the parent oils and therefore less hazardous.

In general terms, the precise chemical composition of the residue will depend on the composition of the parent oil, the degree of weathering, and the efficiency of the burn. Several studies have shown that the levels of PAH's in residue from burns of relatively thin slicks are greater than in the parent oil, by as much as 40%. Considering the volume reduction accomplished by *in situ* burning, the total amount of PAHs remaining in the residue is a fraction of what was in the slick before ignition.

Physical properties

The physical properties of burn residues are important from the perspectives of both their environmental fate and effects and their recoverability. Three properties are critical: state, density, and stickiness.

State. The state of burn residue is important because it determines the amenability of the residue to collection and removal by mechanical means. Liquid residues could be removed by conventional methods used to recover spilled oil. Solid or semisolid residues will require specially designed recovery methods, including manual methods.

Stickiness. Stickiness is important from an environmental point of view because of the potential for affecting marine wildlife. Liquid or sticky, semisolid residues pose environmental risks that are similar to those posed by the parent oil, in that by adhering to birds' feathers they affect the birds either by disrupting the waterproofing of their plumage or through chemical toxicity if ingested while preening. Residues from crude oils are likely to be either sticky, semisolids or nonsticky solids, depending on factors such as the extent of weathering of the oil prior to the burn and the efficiency of the burn. Residues from light and middle distillate fuel oils are similar to the parent oil.

Density. Density of burn residue is important because it determines whether residues will float or sink. Experience to date is that most residues are less dense than water when the fire extinguishes and float at the surface for a time, but residues of many oils may sink as they cool. The potential for sinking is important from both environmental and cleanup points of view. From an environmental point of view, the potential for sinking is regarded as a disadvantage, because of concern over potential effects of the sunken residue on the seabed community. It is for this reason that burning has been prohibited near coral reefs in some jurisdictions. The potential for residue sinking is a serious problem for responders if the residue must be collected, because it means that all residues must be collected soon after the fire extinguishes itself while the residue is still warm and buoyant.

The likelihood that residue from *in situ* burning will sink is only poorly understood. Early *in situ* burning studies with relatively thin slicks (i.e. 10–20 mm) suggested that the residues would be more dense than the parent oils, but would probably float, even in freshwater. However, recent experience with real spills of heavy oils suggests that burn residues of these crude oils will sink, even in salt water.

Preliminary laboratory tests suggest that residues from efficient burns of thick slicks of many heavier crude oils may sink in both salt and fresh waters.

Environmental risks from burn residues

The chemical toxicity of burn residues appears to be low. In tests conducted at NOBE water taken from beneath the oil slick contained only low concentrations of hydrocarbons (<13 p.p.b. total oil) and were not toxic to bivalve larvae or juvenile fin fish [21]. More recently, Environment Canada scientists developed methods for conducting toxicity tests on water-accommodated fractions from burn residues. Results showed that these water-accommodated fractions were not toxic to a variety of standard test organisms, including sea urchin gametes and three-spine sticklebacks [22].

Some of the environmental risks associated with sinking residues have been demonstrated in actual spills; the M/T *Honan Jade* (South Korea, February 1983) and the M/T *Haven* (Italy, April 1991). In the former case, sunken residues disrupted crab mariculture operations [23]. In the latter case, an area of the seabed of some 141 km^2 was measurably contaminated with sunken residue [23], to the extent that it was abandoned by most local trawl fishermen for a period of two years [24].

Precautions and impact mitigation

Burn residues may or may not pose a significant environmental hazard depending on their composition and physical properties. Liquid or semisolid residues should be collected because they may pose a threat to wildlife and property. Residues that show signs of sinking should be collected out of concern for the benthic environment, mariculture installations and demersal fisheries. Indeed, current thought is that all residues, regardless of properties should be collected. There is insufficient information on the potential effects of residues on sea bottom communities at the present time to suggest intentionally allowing residue to escape and sink.

SUMMARY

In summary, there are several incentives and disincentives for the use of *in situ* burning as an oil spill countermeasures tool.

Incentives

Simple logistics. 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. The use of towed fire containment boom to capture, thicken and isolate a portion of a spill, followed by ignition is far less complex than the operations involved in recovery, transfer, storage, treatment and disposal. If the small quantities of residue from an efficient burn require removal, the viscous, tar-like material can be collected and stored for further treatment and disposal.

High removal rate. The burning rate of thick (10 mm or more), large (3-m diameter or more) slicks of relatively fresh crude oil has been measured to be in the range of 3.5 mm/min. Thus, removal rates of 2000 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.

High removal efficiency. The volume of oil eliminated depends on the original thickness and type of oil, which is commonly burned down to a thickness ranging from 1 to 10 mm. Burning can result in an efficiency of removal of 90–99%.

Versatility. In situ burning can be used on fresh water or salt water; on lakes, streams, and oceans; onshore; or on wetlands/marshes with only a few centimetres of water. Burning can be used on calm water and in sea conditions approaching a Beaufort scale wind force of 4–5. The burning of spilled oil can be used under tropical and arctic conditions, and is particularly effective in ice conditions.

Disincentives

Despite the strong incentives for considering *in situ* burning as a primary countermeasures 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.

Flashback and secondary fires. If oil on water is at a temperature near or above its flash point, ignition of the oil will result in very rapid spreading of the flame. In cases where a large amount of volatile oil is spilled, a cloud of vapours can collect near the source in calm wind conditions and may represent a fire hazard. In such cases, care must be taken to isolate the portion of the slick to be burned from other areas of the slick. It is understandable that tanker and petroleum facility owners and personnel have serious reservations about *in situ* burning of oil spills: fires are one of the greatest fears that exist in the tanker and the offshore oil and gas industries and major efforts are dedicated to fire prevention. The fire and heat pose risks that are real, acute and potentially life-threatening, even in burn situations that are under control. The risks to responders are mitigated through the implementation of an exclusion zone around the fire itself that protects responders from radiated heat. The exclusion area extends 3–4 fire diameters from the edge of the fire. Surface vessels should be excluded from this zone under all but emergency conditions.

Combustion products. In situ burning of oil slicks on water can be described as 'starved combustion' in which not enough air (oxygen) is drawn into the fire to burn the fuel completely to carbon dioxide and water vapor. As a result, *in situ* burning produces a large, dense, black plume of smoke rising from the fire. Smoke and burn emissions can pose risks both in the immediate vicinity of the fire and at a distance. Although the emissions include a variety of toxic substances, most, including PAHs, appear to pose little genuine risk. The exception is the smoke itself. Smoke particles are of concern for at least two reasons: disruption to visibility and threat to human health. Smoke disrupts visibility, which is important to persons operating aircraft, surface vessels and motor vehicles on high speed motorways. When burning is used it is important to notify air traffic controllers, vessel traffic control systems and local police of the potential hazard to visibility. The health threat to workers on site is avoided by their wearing appropriate respiratory equipment when required. The threat to the general population is avoided by ensuring that no PM-10 concentration greater than 150 $\mu g/m^3$, averaged over one hour, is produced by the smoke plume at any populated locations downwind of the burn. This is best accomplished by ensuring adequate separation (5 km in most cases) between *in situ* burning operations and population centres and that appropriate meteorological conditions for plume dispersion exist and are predicted to last.

The future

In situ burning is a potentially valuable tool for oil spill response. If used prudently, it can make a significant contribution as one facet of an overall spill response operation. For spills in ice-covered waters it may be the only removal option. Although a considerable body of knowledge exists on the use and impacts of *in situ* burning, continued research is warranted, particularly on: the use of emulsion breakers to extend the window-of-opportunity; developing better, longer-service-life fire containment booms; verifying smoke plume computer models and confirming their capabilities to model complex terrain effects; and, research the behavior, properties and potential effects of the residue from large burns of thick slicks of crude oil.

Most importantly, *in situ* burning needs to be used on real spills; it is only through operational usage that practitioners will gain the knowledge to ascertain the place of burning in an overall oil spill response.

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