

## ***In Situ* Burning of Oil Spills in Ice and Snow**

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### **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 environment. 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-1970's in support of drilling in the Beaufort Sea. This paper serves as a primer on the subject, summarizing the following topics:

- the basic requirements and processes involved with *in situ* burning;
- trade-offs associated with burning in ice;
- how oil spill behaviour in various ice conditions controls *in situ* burning;
- the application of burning in various common ice situations;
- *in situ* burning of oil spills in snow; and,
- general logistical and equipment requirements and constraints.

### **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 very 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.

*In situ* burning is especially suited for use in ice conditions, often offering the only option for removal of surface oil in such situations. Much of the early research and development on *in situ* burning focussed on its application to spills in ice. 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. The use of fire booms to contain oil for burning has been considered for use in broken ice situations since the early development stages of the technology.

*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<sup>3</sup>/hr can be achieved with a fire area of only about 10,000 m<sup>2</sup> 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, 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 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 paper is to review the science, technology, operational capabilities and limitations and ecological consequences of *in situ* burning as a countermeasure for oil spills in ice conditions. The main focus of this section is on marine oil spills. 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 (Buist et al. 1994). 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 3%) 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.

### **Flame temperatures and total heat fluxes**

Flame temperatures for crude oil burns on still water are about 900° to 1200°C (Fingas et al. 1995). 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° to 500°C) but the oil just beneath it is near ambient temperatures. Total heat fluxes generated by an oil pool fire are on the order of 100 to 250 kW/m<sup>2</sup> measured both inside and at the periphery of the fire (SL Ross 1997, Walton et al. 1997). The higher heat flux values are associated with windy conditions that 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, as may be the case in a drifting, broken ice cover, or in melt pools, 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, unemulsified crude oil and diesel fuels is about 3 to 5 mm;
- the minimum ignitable thickness for residual fuel oils, such as Bunker “C” or No. 6 fuel oil, is about 10 mm; and,
- once 1 m<sup>2</sup> 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 to 12 m/s.

- For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water. Some crudes form meso-stable emulsions that can be easily ignited at much higher water contents. Paraffinic crudes appear to fall into this category (Fingas et al. 1997).
- 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.

### **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 to 20 mm in thickness the residue thickness is 1 mm;

- for thicker crude slicks the residue is thicker; for example, 3 to 5 mm for 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 in broken ice conditions 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 to 20 mm thick is a semi-solid, tar-like layer that has an appearance similar to the skin on an old, poorly sealed can of latex paint that has gelled. For thicker slicks, typical of what might be expected in a towed fire boom (about 150 to 300 mm), the residue can be a solid. The cooled residue from thick (>100 mm), efficient *in situ* burns of heavier crude oils can sink in fresh and salt water (SL Ross 1996).

### **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 that is 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 10m, 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**

Although the formation of water-in-oil emulsions is not as predominant a weathering process in spills in ice as it is for spills in open water, emulsions could be formed in some situations (i.e., a sub-sea blowout in broken ice). The processes believed to be involved with *in situ* burning of water-in-oil emulsions are illustrated in Figure 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% to 80% range with some up to 90%. The oil in the emulsion cannot reach a temperature higher than 100°C until the water is either boiled off or removed. The heat from the igniter or from the adjacent burning oil is used first mostly to boil the water rather than heat the oil to its fire point.

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

For stable 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 (Fingas et al. 1997).

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.

## **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 2 to 4 times 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 4 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 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. Safe Approach Distances for *In Situ* Oil Fires**

<b>Exposure Time</b>	<b>Safe Approach Distance for Personnel (fire diameters)</b>
infinite	4
30 minutes	3
5 minutes	2

#### 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 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.*) Smoke particulate is the main concern and is dealt with first in some detail.

### 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  $\mu\text{m}$  in diameter. Health scientists call these PM-10s (*PM stands for*

“*particulate matter*”). PM-10s make up approximately 90 percent of the mass of particulate emitted from an in situ burn. The average particle size of the soot is about 1  $\mu\text{m}$ .

*Health standard.* One exposure standard that exists for PM-10s is the U.S. National Ambient Air Quality Standard (NAAQS) which states that PM-10 exposures of more than 150  $\mu\text{g}/\text{m}^3$ , averaged over a 24-hour 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  $\mu\text{g}/\text{m}^3$ .

**TABLE 2. Airborne Emissions from an *In Situ* Petroleum Fire<sup>a</sup>**

Constituent	Quantity Emitted <sup>b</sup> , kg emission/kg oil burned
carbon dioxide (CO <sub>2</sub> )	3
particulate matter	0.05 - 0.20 <sup>c, d</sup>
carbon monoxide (CO)	0.02 - 0.05
nitrogen oxides (NO <sub>x</sub> )	0.001
volatile organic compounds (VOC)	0.005
polynuclear aromatic hydrocarbons (PAH)	0.000004

- <sup>a</sup> updated from ref. 1 based on Kuwait pool fire (Allen and Ferek 1993) and NOBE data (Ross et al. 1996)
- <sup>b</sup> Quantities will vary with burn efficiency and composition of parent oil
- <sup>c</sup> for crude oils  $soot\ yield = 4 + 3\ lg(fire\ diameter)$ ; yield in mass %, fire diameter in cm (Fraser et al. 1997)
- <sup>d</sup> Estimates published by Environment Canada are considerably lower, ca. 0.2 to 3% for crude oil (Fingas 1998)

*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 140 bbl/hr, concentrations of particulate in the plume near the fire were commonly in the range of 800 to 1000  $\mu\text{g}/\text{m}^3$ , but declined to approximately 150  $\mu\text{g}/\text{m}^3$  within 1.5 hours travel time downwind from the fire. Of particular importance is the fact that PM-10 concentrations beneath the plume, even 150 to 200 feet above the sea surface, never exceeded background levels (30 to 40  $\mu\text{g}/\text{m}^3$ ). Ground-level concentrations beneath a plume from a test burn of crude in Alaska with a burn rate 115 bbl/hr declined from 86  $\mu\text{g}/\text{m}^3$  1 km downwind to 22  $\mu\text{g}/\text{m}^3$  4 km downwind. Measurements of near-ground smoke concentrations under the plume from two even larger diesel fires (428 bbl/hr) in Mobile, AL in 1994 peaked at only 25  $\mu\text{g}/\text{m}^3$  11 km downwind in one case and 15  $\mu\text{g}/\text{m}^3$  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 (McGrattan et al. 1997) 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 10,000 bbl/hr fire to fall below  $150 \text{ } \mu\text{g}/\text{m}^3$  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  $150 \text{ } \mu\text{g}/\text{m}^3$  are much greater than over flat terrain in equivalent meteorological conditions. The distance downwind for the smoke plume to dilute below  $150 \text{ } \mu\text{g}/\text{m}^3$  would range from 1 km over flat terrain in a highly mixed atmosphere (akin to Stability 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

Fingas and Punt (2000) present an empirically-based statistical correlation of concentrations of various emissions of concern downwind from *in situ* burns as a function of fire size. The data was collected in wind speeds of 2 to 5 m/s with no inversions present. Extreme caution must be used not to employ these equations with fire areas outside the sizes for which the data was collected, as the equations “blow up”.

*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 (Walton et al. 1995). In these instances the 150

$\mu\text{g}/\text{m}^3$  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. Estimates for maximum downwind extent of  $150 \mu\text{g}/\text{m}^3$  over complex terrain<sup>a</sup>**

Fire Size (bbl/hr)	Terrain Height (m)	Maximum Distance (km) Downwind for PM-10 Concentration to reach $150 \mu\text{g}/\text{m}^3$ at Ground Level for given Mixing Layer Depth Ranges (m) <sup>b</sup>				
		0 to 100	100 to 250	250 to 500	500 to 1000	>1000
1000	0 to 25 Flat	5	4	3	2	1
1000	25 to 250	10	8	6	4	3
1000	250 to 500	15	12	10	8	5
1000	> 500	20	17	15	12	10

from McGrattan et al. 1997

<sup>a</sup> valid for wind speeds from 1 to 12 m/s

<sup>b</sup> mixing layer depths loosely correspond to atmospheric stability class ranges as follows: Stability Class C  $\approx$  200 to 300 m; Stability Class D  $\approx$  150 to 200 m

*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. 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.

### **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 to 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 semi-solid 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, semi-solid 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, semi-solids or non-sticky 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 to 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 ppb total oil) and were not toxic to bivalve larvae or juvenile fin fish (EVS 1995). 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 (Bleinkinsopp et al 1997).

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 (Moller 1992). In the latter case, an area of the seabed of some 141 km<sup>2</sup> was measurably contaminated with sunken residue (Moller 1992), to the extent that it was abandoned by most local trawl fishermen for a period of two years (Martinelli et al. 1995).

### Precautions and impact mitigation

Burn residues may or may not pose a significant environmental hazard depending on their composition and physical properties. Liquid or semi-solid 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.

## **BURNING SPILLS IN ICE AND SNOW**

In-situ burning has been considered as a primary Arctic spill countermeasure, from the start of offshore drilling in the Beaufort Sea in the mid 1970's. Field trials at that time demonstrated that on-ice burning offered the potential to remove almost all of the oil present on the surface with only minimal residue volumes left for manual recovery (Norcor, 1975). Since then, a great many studies and trials have been undertaken to investigate and document burning of large crude oil slicks (both fresh and emulsified) in open water, slush ice, and broken drift ice and test basins.

### Oil on Water among Broken Ice

In broken ice conditions the use of *in situ* burning is controlled, to some 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 to 3 tenths;
- 3 to 6-7 tenths; and,
- 6-7 to 9+ tenths.

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 can be applied. 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 6-7 tenths is the most difficult from an *in situ* burning perspective. The ice will reduce the spreading and movement of the slick, but not yet to the extent that it is containing the oil. 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. In the highest ice concentrations, the ice floes are touching and contain the oil; if slicks are thick enough they can be burned effectively in these ice concentrations (SL Ross and Dickins 1987; Singaas et al. 1994).

*In situ* burning of oil spilled in broken 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 breakup, there is much less slush and brash ice present, the ice floes are deteriorating and melting, there is 24-hour daylight and the temperatures are warming.

### **Oil on Solid Ice**

In-situ burning is the countermeasure of choice to remove oil pools (created in the spring by vertical migration from an encapsulated oil layer or by drilling into an encapsulated oil lens in the ice sheet) on ice. 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 to 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. breakup, etc.). For areas where the oil surfaces early in the melt, it could be possible to manually flush and/or recover remaining burn residue.

Oil in leads will be herded by winds and currents 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.

### **Oil in Snow**

In the case of oil initially spilled on the ice surface and mixed with snow, burning of oiled snow piles can be successfully achieved even in mid-winter 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. Also, for 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 center of the volcano scraped down to the ice surface. A small amount of promoter is ignited in the center of the pile. The heat from the flames melts the surrounding inside walls of the conical pile, releasing the oil from the snow which runs down into the center and feeds the fire. This technique can generate considerable amounts of melt water, which needs to be managed.

## 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 and fire containment booms.

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 (Buist et al. 1994). The following discusses only technologies that are presently available.

### **Igniters**

These are divided into two types: igniters for use from a vessel or on the ice, 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 (Thornborough 1997). 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.

#### *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 (Figure 3) measures approximately 25 cm by 15cm by 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-volt, 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 seconds 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 seconds with temperatures in excess of 1200°C. During this initial burn, the gelled kerosene begins to burn, producing temperatures of 700° to 800°C. The total burn time for the igniter is about 10 minutes. 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.

*Heli-torch* The Heli-torch (Figure 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.

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 to 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 sub-freezing 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 to 23 m and with speeds of 40 to 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 U.S. Federal Aviation Administration. Recently, the Heli-torch was used in sea trials off the U.K.; part of this trial involved obtaining the appropriate approval to fly the Heli-torch from U.K. authorities.

### **Fire containment booms**

The fire booms that are presently available are summarized below. The available booms are divided into three categories: those constructed of steel, those constructed from fire-resistant fabrics, and those employing active water cooling. It should be noted that many of the booms described below have been tested by the U.S.C.G. for oil containment (Bitting and Coyne 1997) and fire resistance in waves, conducted in the fall of 1997 and the fall of 1998 by NIST, in Mobile, AL (Hiltebrand 1997, Walz 1999).

#### **Steel fire proof booms**

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

*Fireguard boom:* This boom is made of short, rigid flotation units connected by flexible, fabric panels. The floats are made from 2 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 5 bolts. After exposure to fire the asbestos strips and flexible connections panels must be replaced.

*FESTOP boom:* This is a new stainless steel boom produced in France. Little detailed information is available at the present time (Fingas and Punt 2000)

*Pocket Boom:* A large offshore stainless steel boom (the Dome boom -see below) was redesigned to serve as a high-strength, durable burn pocket inserted between two lengths of conventional fabric fire boom. The final design of the Pocket Boom has resulted in considerable cost, weight and size reductions over the original design and a commensurate increase in ease of handling. With a buoyancy-to-weight ratio of 3, a tensile strength in excess of  $1.8 \times 10^5$  N (40,000 lb<sub>f</sub>) and an overall height of 100 cm (39 in.) the boom performs well in its intended operating environment (calm or protected environments with waves up to 1 m [3 ft]) in conjunction with commercially-available fabric fire booms.

Deployment, sea-keeping, towing and retrieval characteristics of the Pocket Boom are all good. Oil containment tests at Ohmsett showed that the boom will contain oil up to the normal limits

(0.4 m/s = 0.75 knots) and can withstand catenary tow speeds up to 1.5 m/s (3 knots) without failure. Exposure to burning oil does not affect the oil containment characteristics of the boom. The boom was exposed to six hours of fire with full-scale heat fluxes: three hours of diesel fires in Mobile, AL (Walz 1999) and three hours of enhanced propane fires at Ohmsett (SL Ross and AFTI 1999). The boom survived this heat insult with only minor damage, none of which would have detracted significantly from its oil containment abilities. The final design of the connector section incorporates modifications to ensure that the boom's service life will be at least 1,000,000 wave cycles. This is equivalent to greater than 45 days at sea in Sea State 3.

*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 (McCarthy 1996) and at OHMSETT in 1996 (Bitting and Coyne 1997). More recently, it has been fire tested by NIST (Walz 1999).

*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. A newer design, called the Pocket Boom, has been developed (see above).

### *Fire-resistant fabric booms*

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

*3M or American Marine 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 non-flammable, 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 foot long segments separated by a metal clamp fastened through the PVC/mesh/NEXTEL “sandwich”. The connector for each 15 m section (consisting of 7 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.

In the summer of 1993, 210 m of the 18" 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 to 3 m/s winds. The first involved 300 bbls of slightly weathered crude oil burned over a 1.5 hour 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 minutes 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 (180 bbls had burned) the boom was again inspected. A prototype section of the boom that incorporated a middle tension member had lost 3 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 minutes exposure to flames. Similar leakage was reported at tests of the latest version of the boom near Seattle in 1995 (McCarthy 1996). 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 minutes each) in 1 to 1.5 m seas. The most recent tests by NIST, showed degradation of the boom during fire testing in a wave tank (Hiltabrand 1997).

*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 hours 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. Recent tests in waves and diesel flames by NIST were curtailed after the first hour of a three hour test protocol (Walz 1999).

*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 hours and peak recorded flame temperatures of 930°C were reached. After 6 hours 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 hour 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 to 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 non-fire proof boom models of similar design. A revised design survived a three-hour diesel fire tests by NIST in 1998, but did suffer degradation above the water-line (Walz 1999).

*Autoboam - Fire Model:* This is a single-point inflatable boom designed for storage and deployment from a reel. It is equipped with a fire-proof cover that protects the individual flotation chambers. It is available in a range of sizes suitable for deployment in rivers to offshore. Little test information is currently available on this boom, although the boom has been exposed to fire at the U.S.C.G. Fire Training Facility in Mobile, Alabama. The boom is claimed to be designed to withstand temperatures in excess of 1093 °C.

#### Water-cooled booms

Three design of actively water cooled booms are available. These depend on ambient water pumped through a series of porous hoses to soak an external covering to protect the internal flotation and structural components from the heat of the fire. The available booms are: an Oil Stop model, one produced by Elastec/American Marine, and a third developed by Environmental Marine Technology Associates. All three have been fire tested in waves (Walz 1999, Stahovec et al. 1999) with the first two passing all tests.

## **OPERATIONAL ASPECTS**

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 an intentional program to burn a thick, uncontained spill in heavy ice concentrations 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 (Buist et al. 1994) and in several *in situ* burning manuals (e.g., Allen 1993, Fingas and Punt 2000).

### **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 to 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 bitts and adequate lengths of tow line (typically 150 m to 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 to 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, nature of spillage to be contained and the prevailing ice conditions 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, such as spills in higher ice concentrations. 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.

U-configurations should be used with 150 m to 300 m of fire boom each. The larger fire containment booms would usually be used during open water conditions, while smaller fire containment booms could be utilized in calmer or ice conditions. Shorter lengths of fire boom may be employed in ice conditions to allow greater manoeuvrability. 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. Water-cooled booms are initially relatively light, but become extremely heavy when soaked. As well, the additional complexity of water filtering and pumping must be accommodated with water-cooled booms. 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 or contact with ice 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 to 8 km/hr or 2 to 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 section 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.

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