In-situ Burning of Oil

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Executive Summary

In-situ burning is recognized as a viable alternative for cleaning up oil spills on land and water. When performed under the right conditions, in-situ burning can rapidly reduce the volume of spilled oil and eliminate the need to collect, store, transport, and dispose of recovered oil. In-situ burning can shorten the response time to an oil spill, thus reducing the chances that the oil will spread on the water surface or penetrate further into land, thereby aiding in environmental protection. This guide contains a compilation of information about in-situ burning of oil spills and includes the scientific aspects of the burning process and its effects, and practical information about the procedures to be followed and equipment required for carrying out an in-situ burn.

Ignition is easy for volatile oils and is more difficult for heavier oils which require a primer such as diesel fuel for sufficient heat. If not enough vapors are produced, the fire will either not start or will be quickly extinguished. The amount of vapors produced is dependent on the amount of heat radiated back to the oil. If the oil slick is too thin, some of this heat is conducted to the water layer below it. Oil that is completely emulsified with water can be ignited, given that sufficient heat is supplied, typically by burning it alongside un-emulsified oil. Containment of the oil on water may be necessary to carry out in-situ burning as the oil must be thick enough to quantitatively burn. Once burning, the heat radiated back to the slick and the insulation are usually sufficient to allow combustion down to about ½ to 1 mm of oil. The oil burn rate is largely a function of oil type.

The residue from burning oil is largely unburned oil with some lighter or more volatile products removed. When the fire ceases, unburned oil is left that is simply too thin to sustain combustion. In addition to unburned oil, weathered oil is present that has been subjected to high heat. Heavier soot particles are re-precipitated from the smoke plume into the fire and thus become part of the residue. Highly efficient burns of some types of heavy crude oil may result in oil residue that sinks in sea water after cooling.

Burning oil on land or wetlands is a technique that can reduce the environmental impact of oil spills. Burning vegetation is a frequent method of maintaining certain ecosystems and these same ecosystems can be protected from the effects of oil spills using burning. The important factors relating to burning are the water level of wetlands and the moisture content of soils. Burning under the correct circumstances will not affect roots and thus restoration is rapid. Fire breaks are created to avoid spreading of fire to other locations.

Safety in burning is of prime concern. A burn plan and a safety plan must be prepared to encompass the concerns noted in this guide. Training of personnel including a field practice, is essential to ensure safety.

The emissions of burning can be of concern:

**Particulate Matter/Soot** - Burns produce an abundance of particulate matter (soot). Particulate matter at ground level is a health concern close to the fire and under the plume. The particulate concentrations from in-situ oil fires should be monitored in some circumstances.

**Polyaromatic Hydrocarbons (PAHs)** - Oils contain significant quantities of polyaromatic hydrocarbons which are largely destroyed in combustion. The PAH concentrations in the smoke, both in the plume and the particulate precipitation at ground level, are much less than in the starting oil.

**VOCs (Volatile Organic Compounds)** - Many volatile organic compounds are emitted by fires, but in lesser quantity than when the oil is not burning. VOCs are not a significant concern.

**Organic Compounds** - No exotic or highly toxic compounds are generated as a result of the
combustion process. Organic macro-molecules are in lesser concentration in the smoke and downwind than they are in the oil itself. Dioxins and dibenzofurans have not been measured as emissions of oil fires.  

*Carbonyls* - Carbonyls such as aldehydes and ketones are created by oil fires, but do not exceed health concern levels even close to fires.  

*Gases* - Combustion gases such as carbon dioxide, carbon monoxide, and sulphur dioxide are produced by oil fires but are significantly below any health concern level.  

   Overall, emissions are now understood to the extent that emission levels and safe distances can be or fires of various sizes and types.

1 **Introduction**

   In-situ burning is the oldest technique applied to oil spills, especially on land, but is one of the few techniques that has not been used extensively until recently. This is because burning although easy to apply is not well understood. Further, burning oil on water is not intuitive and thus many people did not pursue this course of action.  

   In-situ burning has been used to deal with land spills since there were land spills. There is little documentation on burning on land and this trend still continues. Of the few documented cases, most were successful and resulted in obvious environmental benefits.

2 **An overview of in-situ burning**

   2.1 **Advantages and disadvantages**

      In-situ burning has some distinct advantages over other spill cleanup methods. These advantages include:

      · rapid removal of large amounts of oil from the water surface;
      · significantly reduced volume of oil requiring disposal;
      · high efficiency rates;
      · less equipment and labor required; and
      · may be only cleanup option in some situations, such as oil-in-ice situations.

      The most significant of these advantages is the capacity to rapidly remove large amounts of oil. When used at the right time, i.e., early in the spill before the oil weathers and loses its flammable components, and under the right conditions, in-situ burning can be very effective at rapidly eliminating large amounts of spilled oil, especially from water. This can prevent oil from spreading to other areas and contaminating shorelines and biota. Compared to mechanical skimming of oil, which generates a large quantity of oil and water that must be dealt with, burning generates a small amount of burn residue. This residue is relatively easy to recover or can be further reduced by repeated burns.

      While the efficiency of a burn varies with a number of physical factors, removal efficiencies are generally much greater than those for other response methods such as skimming and the use of chemical dispersants.

      In ideal circumstances, in-situ burning requires less equipment and labor than other techniques. It can be applied in remote areas where other methods cannot be used because of distances and lack of infrastructure. Often not enough of these resources are available when large spills occur. Burning is relatively inexpensive in terms of equipment needed and actually conducting the burn operations.

      In-situ burning also has disadvantages, some of which are:

      · the large black smoke plume created and public fears about toxic emissions to the
· difficulty in igniting the oil in some circumstances;
· oil must be a thicker than about 2 to 3 mm to ignite and burn quantitatively and must usually be contained to achieve this thickness;
· risk of fire spreading to other combustible materials; and
· burn residue sometimes requires collection and disposal.

The most obvious disadvantage of burning oil is the large black smoke plume that is produced and public concern about emissions. Extensive studies have recently been conducted to measure and analyze these emissions. The second disadvantage is that the oil on water will not burn quantitatively or even ignite if not thick enough. Most oils spread rapidly on water and the slick quickly becomes too thin for burning to be feasible. Fire-resistant booms can be used to concentrate the oil into thicker slicks so that the oil can be burned. While this obviously requires equipment, personnel, and time, concentrating oil for burning requires less equipment than collecting oil with skimmers.

And finally, burning oil is sometimes not viewed as an appealing alternative to collecting the oil and reprocessing it for reuse. It must be pointed out, however, that recovered oil is usually incinerated as it often contains too many contaminants to be economically reused.

2.2 The science of burning

The fundamentals of in-situ burning are similar to that of any fire, namely that fuel, oxygen, and an ignition source are required. Fuel is provided by the vaporization of oil. The vaporization of the oil must be sufficient to yield a steady-state burning, that is one in which the amount of vaporization is about the same as that consumed by the fire. Once an oil slick is burning, it burns at a rate of about 1 to 4 mm per minute. This rate is limited by the amount of oxygen available and the heat radiated back to the oil. The oil burn rate is a function of the oil type as well as conditions such as the presence of ice. If not enough vapors are produced, the fire will not start or will be quickly extinguished if it does start. The amount of vapors produced is dependent on the amount of heat radiated back to the oil. The heat radiated back to the pool has been estimated to be about 2 to 3% of the heat from a fire for a pool fire. If the oil slick is too thin, some of this heat is conducted to the water layer below it. Since most oils have the same insulation factor, most slicks must be about 0.5 to 3 mm thick to yield a quantitative burn. Once burning, the heat radiated back to the slick and the insulation are usually sufficient to allow combustion down to about ½ to 1 mm of oil. The basic concepts of burning oil on water are illustrated in Figure 1.

If greater amounts of fuel are vaporized than can be burned, more soot is produced as a result of incomplete combustion, fuel droplets are released downwind or, more typically, small explosions or fireballs occur. The latter phenomenon is often observed when gasoline or light crudes are burning. It has been shown that diesel fuel burns differently than other fuels, with a tendency to atomize, rather than vaporize. This results in an obviously-heavier soot formation. Soot formation occurs by several processes. One common process is the aggregation of molecular species into larger compounds and another process is the partial combustion of fuels such as diesel fuels. Diesel fuels are known to burn with more soot than most other oils. This is for several reasons, diesel fuel and kerosene can form droplets under the influence of heat and these droplets will often only burn partially, leaving partially-burned fuel with carbonaceous material or soot on the outside. Most other fuels will evaporate under the influence of heat and do not form droplets such as diesel, kerosene or jet fuels do.
The amount of oil that can be removed in a given time depends on the fuel and on the area covered by the oil. Most oil pools burn at a rate of about 1 to 4 mm per minute, which means that the depth of oil is reduced by that value of millimeters per minute. As a rule of thumb, oil burn rate is about 2,000 to 5,000 L/m².day. Several tests have shown that this does not vary significantly with oil weathering but varies with oil type. Emulsified oil may burn slower as its water content increases the heat requirement. The burn rates for many crude oils in ice are between 1 to 2 mm/min, typically half of the rate when ice was not present.

The type of oil is relatively unimportant in determining how an oil ignites and burns, except for heavier or emulsified oils. However, heavy oils require longer heating times and a hotter flame to ignite than lighter oils and may often require a primer such as kerosene or diesel.
fuel.

Burn efficiency is the initial volume of oil before burning, less the volume remaining as residue, divided by the initial volume of the oil. Efficiency is largely a function of oil thickness. For example, a slick of 2 mm burning down to 1 mm yields a maximum efficiency of 50%. A pool of oil 20 mm thick burns to approximately 1 mm, yielding an efficiency of about 95%. Other factors such as oil type and low water content only marginally affect efficiency. However, if the oil is contained and moved to the back of the boom as it burns, efficiency can be very high.

Oil that is emulsified with water can be ignited. Once started, it is believed that most emulsions will burn. Boom tows with un-emulsified oil and emulsified oil can be burned by igniting the un-emulsified oil. The heat from burning the un-emulsified oil will start the emulsified oil. Figure 2 shows a fire started on an un-emulsified oil that later spread over the emulsified oil and burned it quantitatively.

![Figure 2 A burn of un-emulsified and emulsified oil. The fire later spread over the red emulsified oil and burned it. (Photo from Elastec/American Marine)](image)

The residue from oil spill burning is largely unburned oil with some lighter or more volatile products removed. When the fire ceases, unburned oil is left that is simply too thin to sustain combustion. In addition to unburned oil, oil is also present that has been subjected to high heat and is thus weathered. Finally, heavier particles are re-precipitated into the fire. Highly efficient burns of some types of heavy crude oil may result in oil residue that sinks in sea water. Figure 3 shows typical residue after an at-sea burn.

Soot is formed in all fires. The amount of soot produced is not precisely known because there is no direct means of measuring soot from large fires. It is believed that the amount of soot is about 0.1 to 3% for crude oil fires and about 1 to 5% for diesel fires. An additional consideration is that the soot precipitates out at a rate equal to approximately the square of the distance from the fire. Thus, a constant percentage of soot for a whole fire may be irrelevant.
The total heat radiated by a given burn has been measured as 1.1 MW/m². Calculation shows that the heat required to vaporize the oil was 6.7 KW/m² and the heat lost from conduction through the slick to the underlying water was 2.5 KW/m². Thermal radiation is important. One test showed burning Alaska North Slope oil showed a heat release rate of 176 KW/m², diesel fuel 230 KW/m², and propane, 70 KW/m². The heat radiated by a liquid propane fire enhanced by air flow and increased pressures was 180 KW/m². The heat flux on booms as a result of these fires was reported as 140 to 250 KW/m² for crude oils, 120 to 160 KW/m² for diesel fuel, 60 to 100 KW/m² for propane, and 100 to 160 KW/m² for enhanced propane burning.

Flame spreading rates have been measured at several fires. Flame spreading rates do not vary much with fuel type, but vary significantly with wind, especially as this relates to up and down wind directions. Flame spreading rates range from 0.01 to 0.02 m/s (0.02 to 0.04 knots). Downwind flame spreading rates range from 0.02 to 0.04 m/s (0.04 to 0.08 knots), and up to 0.16 m/s (0.3 knots) for high winds. Flame spread through vapor clouds can be as fast as 100 km/hour such as would occur at spills of gasoline or similar volatile fuels.

The flame height of a small fire less than 10 m in diameter is about twice that of the diameter of the fire. The flame height approaches the diameter of the pool up to about 100 m in diameter. Thus an estimate of flame height for a fire in a boom with a radius of about 10 to 20 m is about 1.5 times the diameter or 15 to 30 m.

Several workers reported on findings that there is a vigorous burn phase near the end of a burn on water. Significant amounts of heat are transferred to water near the end of a burn when slick thickness approaches 1 mm and this heat ultimately causes the water to boil. The boiling injects steam and oil into the flame giving rise to a ‘vigorous’ burn with the production of steam. This phenomenon occurs only in shallow test tanks because there is little movement of water under the slick to carry the heat away. During burns at sea, no vigorous burning is observed.

2.3 What burns and doesn’t burn
Basically, most oils will burn on water and will burn quantitatively if over about 2 to 4 mm thick. On land or wetlands, the situation is similar, although 1 mm thick oils on grassland can be burned quantitatively. Light and fresh oils will burn readily and can be easily ignited. Heavy oils will require a small amount of primer, such as diesel fuel, to start ignition. Once burning, heavy oils will burn well and even emulsified oil will break down and burn. Table 1 shows the ignition characteristics of various oils. This is independent of whether the oil is on land or on water.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Burnability</th>
<th>Ease of Ignition</th>
<th>Flame Spread</th>
<th>Burning Rate* (mm/min)</th>
<th>Efficiency Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>very high</td>
<td>very easy</td>
<td>very rapid through</td>
<td>3.5 - 4</td>
<td>95-99</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>high</td>
<td>easy</td>
<td>moderate</td>
<td>3 - 3.7</td>
<td>90-98</td>
</tr>
<tr>
<td>Light Crude</td>
<td>high</td>
<td>easy</td>
<td>moderate</td>
<td>3-3.7</td>
<td>85-98</td>
</tr>
<tr>
<td>Medium Crude</td>
<td>moderate</td>
<td>easy</td>
<td>moderate</td>
<td>3-3.7</td>
<td>80-95</td>
</tr>
<tr>
<td>Heavy Crude</td>
<td>moderate</td>
<td>medium</td>
<td>moderate</td>
<td>3 - 3.5</td>
<td>75-90</td>
</tr>
<tr>
<td>Light Fuel Oil</td>
<td>high</td>
<td>medium</td>
<td>moderate</td>
<td>2.5 - 3</td>
<td>80-90</td>
</tr>
<tr>
<td>Weathered Crude Oil</td>
<td>low</td>
<td>difficult, add</td>
<td>slow</td>
<td>2.8 - 3.5</td>
<td>50-90</td>
</tr>
<tr>
<td>Heavy Crude Oil with Ice</td>
<td>low</td>
<td>difficult, maintain heat</td>
<td>slow</td>
<td>2 to 2.5</td>
<td>60-90</td>
</tr>
<tr>
<td>Heavy Fuel Oil</td>
<td>very low</td>
<td>difficult, add</td>
<td>slow</td>
<td>2.5 - 2.8</td>
<td>40-70</td>
</tr>
<tr>
<td>Waste Oil</td>
<td>very low</td>
<td>primer</td>
<td>slow</td>
<td>2 to 2.5</td>
<td>15-50</td>
</tr>
<tr>
<td>Emulsified Oil</td>
<td>low</td>
<td>high heat</td>
<td>slow</td>
<td>1 to 2</td>
<td>40-80</td>
</tr>
</tbody>
</table>

* typical rates only --- to get the rate in Litre/m²/hour multiply by 60
2.4 Comparison of burning to other response measures

In-situ burning is most often compared with the use of dispersants as a countermeasure. Dispersants are chemical spill-treating agents that promote the formation of small droplets of oil that ‘disperse’ throughout the water column. Dispersants contain surfactants, chemicals like those in soaps and detergents, that have both a water-soluble and an oil-soluble component. Surfactants or surfactant mixtures used in dispersants have approximately the same solubility in oil and water, which stabilizes oil droplets in water so that the oil will disperse into the water column. The comparison between dispersion and other countermeasures is poor because the time scales differ widely.

In-situ burning can also be compared to mechanical recovery of oil spills. Mechanical recovery includes the use of booms and skimmers to physically contain the oil and remove it from the water. Booms are limited to waters where the currents, relative to the boom, are less than 0.4 m/s or they must be used in diversionary mode. On the other hand, while recovery using booms and skimmers is slower than removal by in-situ burning or dispersants, the oil is recovered without the potential for air and water pollution. Mechanical recovery works well in sheltered waters such as harbors and marinas where burning should not be conducted, but is impossible in high currents and waves over 2 m.

On land burning has significant advantages over most techniques. Unless the oil is very thick, ability to pump the oil is very limited. Any recovery process that takes a long time will allow oil to penetrate the soil.

In some marine spill situations, the best cleanup strategy involves a combination of mechanical recovery techniques and burning for various portions of a spill. For example, burning can be applied in open water and oil that has already moved closer to shore can be recovered with booms and skimmers. Burning could also be used on open water after the window of opportunity closes for effective use of dispersants. Burning does not preclude the use of other countermeasures on other parts of the slick. When combining different cleanup techniques, the objective should be to find the optimal mix of equipment, personnel, and techniques that results in the least environmental impact of the spill.

Given the major differences between time scales and between the methods, Table 2 shows the estimated differences between among various countermeasures is shown below. The assumptions in this table attempt to equalize the differences between the methods.
### Table 2  Approximate Comparison of On-Water Countermeasures*

<table>
<thead>
<tr>
<th></th>
<th>Light crude</th>
<th></th>
<th>Heavy Crude</th>
<th></th>
<th>Bunker C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hours to</td>
<td>tons/ hour</td>
<td>Hours to</td>
<td>tons/ hour</td>
<td>Hours to</td>
</tr>
<tr>
<td>Brush Drum Skimmer</td>
<td>7.5</td>
<td>8</td>
<td>30</td>
<td>2</td>
<td>75</td>
</tr>
<tr>
<td>Large Weir Skimmer</td>
<td>1.5</td>
<td>40</td>
<td>0.9</td>
<td>71</td>
<td>18</td>
</tr>
<tr>
<td>Dispersants</td>
<td>0.2</td>
<td>75</td>
<td>0.2</td>
<td>47</td>
<td>0.2</td>
</tr>
<tr>
<td>In-situ Burning</td>
<td>0.2</td>
<td>356</td>
<td>0.3</td>
<td>238</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*there are many assumptions in the table including capacities of two average skimmers, dispersant effectiveness, but the burn rate is actual.

- This comparison is for a 150 m boom filled over time with 75 tons of oil.

### 2.5 Applicability of burning to different situations

As no two oil spill situations are the same, it is helpful to look at several possible scenarios when developing response techniques for spill situations. The following specific spill scenarios include: burning on land, burning an oiled marsh, burning at sea, burning in a protected bay, burning on a river, burning in melt pools in the Arctic, and burning in an intertidal zone.

Burning on land or oiled marshes has been carried out extensively in the past and will, no doubt, serve well as a countermeasure in the future. There is an extensive body of knowledge on this application.

The well-known tactic of using towed fire boom at sea to collect and burn oil directly in the boom, has been implemented in practice. As with all booms, this technique has a relative current limitation of 0.4 m/s (0.7 knots) before oil is lost under or over the boom. This can be overcome on the open ocean by towing at the relative velocity, despite the surface current. This means that if the actual current exceeds 0.4 m/s (0.7 knots), the boom tow could be slipping down current. Another limitation of this method is that the fire could propagate to the source of the oil or endanger the tow boats and their crew.

Collecting the oil separately, towing the boom away from a non-burning source, and then burning the oil is another technique. This approach prevents the fire from spreading to the oil source. Another advantage is that the oil can be collected using a conventional boom and then transferred to a fire-resistant boom for actual burning. Since fire-resistant boom is more expensive and harder to deploy than conventional boom, this option has some practical and economic benefits.

Burning oil in ice is a standard method for dealing with oil in ice. The natural containment of ice can serve to thicken oil sufficiently for ignition and burning to take place. This technique has often been used to burn oil spills in the Arctic.

### 2.6 Safety

There are many points of safety that must be considered using in-situ burning. These include, but are not limited to:
• Flash back of burning vapor during ignition,
• Spread of fire beyond the control points,
• Fumigation by smoke of nearby areas during burning,
• Loss of containment of the fire-resistant boom,
• Exposure of people to emissions from the fire,
• Exposure of biota to emissions or fire,
• Issues of safety in marine and airborne operations, and
• Issues in handling the fire-resistant boom.

These issues will be covered in this guide. Precautions have been shown to eliminate injuries during actual burns. An important facet of in-situ burning is to prepare a comprehensive health and safety plan (HASP).

3. Burn emissions

The primary environmental and health concerns related to in-situ burning are the emissions produced by the fire. The measurement of emissions has revealed several facts about the quantity, fate, and behavior of the basic emissions from burning. Overall, emissions are now understood to the extent that emission levels and safe distances downwind can be calculated for fires of various sizes and types. A typical crude oil burn (500 m²) would not exceed health limits for emissions beyond about 500 m from the fire. People and the environment can be protected by ensuring that the burn is kept the minimum distances away from populated and sensitive areas. Figure 4 illustrates the emissions from fires, the important point is that the basic products of combustion of oil are carbon dioxide and water. The remainder emissions are by-products.

![Figure 4 The basic emissions from the burning of oil](image)

3.1 Particulate matter

All burns, especially those of light fuels such as diesel fuel, produce an abundance of particulate matter which is the primary emission from an oil fire that can exceed recommended human health concern levels. Concentrations of particulates in emissions from burning diesel are approximately four times that from similar sized crude oil burns at the same distance from the fire. Particulate matter is distributed exponentially downwind from the fire. Concentrations at ground level (1 m) can still be above normal health concern levels (35 μg/m³) as far downwind as 500 m from a small crude oil fire. The greatest concern is the smaller or respirable particulates. The PM-2.5 fraction (particles of size less than 2.5 μm) is the subject of particular concern at this time. It is important to note that currently the fine particles are coming under
increasing scrutiny as health concerns. Figure 5 shows particles collected on a filter.

Figure 5 Soot particles collected on a normally-white filter. This measuring device was placed under a smoke plume from a test burn.

3.2 Organic compounds

Polyaromatic Hydrocarbons (PAHs) - Crude oil burns result in polyaromatic hydrocarbons (PAHs) downwind of the fire, mostly adsorbed to particulate matter, but the concentration on the particulate matter, both in the plume and the particulate precipitation at ground level, is often an order-of-magnitude less than the concentration of PAHs in the starting oil. This includes the concentration of multi-ringed (5 or 6 rings) PAHs, which are often created in other combustion processes such as low-temperature incinerators and diesel engines. There is a slight increase in the concentration of multi-ringed PAHs in the burn residue. When considering the mass balance of the burn, however, most of the five- and six-ringed PAHs are destroyed by the fire.

Volatile Organic Compounds (VOCs) - Volatile organic compounds are organic compounds that have high enough vapor pressures to be gaseous at normal temperatures. When oil is burned, these compounds evaporate and are burned or released. The emission of volatile compounds was measured at several test burns. The concentrations of VOCs are relatively low in burns compared to an evaporating slick. Concentrations are below human health levels of concern even very close to the fire. VOCs, although present, do not constitute a major human or environmental threat.

Dioxins and Dibenzofurans - Dioxins and dibenzofurans are highly toxic compounds often produced by burning chlorine-containing organic material. Particulates precipitated downwind and residue produced from several fires have been analyzed for dioxins and dibenzofurans. These toxic compounds were at background levels at test fires, indicating no production by oil fires.

Carbonyls - Oil burns produce low amounts of partially-oxidized material, sometimes referred to as carbonyls or by their main constituents, aldehydes (formaldehyde, acetaldehyde, etc.) or ketones (acetone, etc.). Carbonyls from crude oil fires are at very low concentrations and are well below health concern levels even close to the fire.
3.3 Gases

*Carbon Dioxide* - Carbon dioxide is the end result of combustion and is found in increased concentrations around a burn. Normal atmospheric levels are about 300 ppm and levels near a burn can be around 500 ppm, which presents no danger to humans. Concentrations at ground level are as high as 10 times that in the plume and distribution along the ground is broader than for particulates.

*Carbon Monoxide* - Carbon monoxide levels are usually at or below the lowest detection levels of the instruments and thus do not pose any hazard to humans. The gas has only been measured when the burn appears to be inefficient, such as when water is sprayed into the fire.

*Sulphur Dioxide* - Sulphur dioxide, per se, is usually not detected at significant levels or sometimes not even at measurable levels in the area of an in-situ oil burn. Sulphuric acid, or sulphur dioxide that has reacted with water, is detected at fires and levels, although not of concern, the amount corresponds to the sulphur content of the oil.

*Other Gases* - Attempts were made to measure oxides of nitrogen and other fixed gases. None were measured in several experiments. Figure 6 shows an array of measuring devices set up to measure emissions from a test fire.

*Emissions to water* - Studies have shown that there is no measurable quantity of oil released to the oil during burning.

![Figure 6](image)

Figure 6  An array of samplers and instruments used to measure emissions from a test fire

3.4 The behavior and distribution of emissions

The behavior of emissions is an important facet of oil spill burning. The overall emission behavior is illustrated in Figure 7. The most important are the soot particles. Many of these initially rise and then many are precipitated back to the ground. It is estimated that before the plume travels 1 kilometer that half of the particles are precipitated downward. Some particles may stay in the direction of the plume for a long time. The plume itself is not dangerous to humans as long it rises and as long as it does not impact settlements directly such happens in an inversion. Particulate matter also has some organic compounds such as PAHs adsorbed.

Water vapor, one of the main products of combustion, and light gases are distributed widely and soon reach background levels. Carbon dioxide and other heavier-than-air gases rise somewhat and then slowly sink to the ground. Carbon dioxide is one of the major products of oil combustion and is not dangerous to humans. Volatile organic compounds (VOCs) including carbonyls are transported out of the fire and soon dilute to background levels.
3.5 Residue

The residue from burning oil is largely unburned oil with some lighter or more volatile products removed. When the fire ceases, unburned oil is left that is simply too thin to sustain combustion. In addition to unburned oil, oil is also present that has been subjected to high heat and is thus weathered. Highly efficient burns of some types of heavy crude oil may result in oil residue that sinks in sea water after cooling. Figure 8 shows residue from a heavy oil burn.
Figure 8  Residue from this small test burn of heavy oil could be removed in one piece

The residue consists of unburned oil, oil depleted of volatiles, re-precipitated soot, and partially burned oil. It appears to be similar to weathered oil of the same type and is typically viscous and dense. The residue contains a large amount of PAHs, although usually less than the original oil, although it may also contain a slightly higher concentration of metals. There is evidence that the metals contained in the original oil (usually 10 to 40 ppm of vanadium, chromium, and nickel) become concentrated in the burn residue. Several tests have shown that burn residue is less aquatically-toxic than other weathered oils.

3.6 Safe distances

Sufficient data are now available to assemble emission data and correlate the results with spatial and burn parameters. It was found that atmospheric emissions correlated relatively well with distance from the fire and the area covered by the fire. This information was used to develop prediction equations for each pollutant, using the data gathered from about 50 test burns, some of full scale size. Sufficient data were available to calculate equations for over 150 individual compounds and for all the major compound groups. The data were collected with winds between 2 to 5 m/s (4 to 10 knots) and with no inversions present. The prediction equations for several common emission groupings and specific compounds are given in literature referenced in the bibliography.

Safe distances downwind from a crude oil burn (based on PM-2.5 concentrations) were calculated from several test burns and are presented in Figure 9. These safe distances are the distances after which no particulate respirators would be needed. These are applicable to various burn sizes. These are based on actual measurements during which the winds varied from about 2 to 10 m/s (4 to 20 knots). Higher winds could increase these distances somewhat. Lower winds would decrease the distances. These distances are not applicable to situations where there are inversions because the smoke could be forced directly to the ground level. These are applicable
to land burns as well. Specific safety for land burns are discussed in Section 5.3 below.

![Graph showing safe distances for various burn areas](image)

**Figure 9** Safe distances for various burn areas

### 4 Assessment of feasibility of burning

When an oil spill occurs, information must be obtained on the various factors that would influence the decision to burn.

#### 4.1 Decision-making process

When an oil spill occurs, information must be obtained on the spill location, weather conditions, and any other relevant conditions at the site. The necessary questions to be asked before deciding to use in-situ burning are outlined in Figure 10. Depending on the location or jurisdiction, a more detailed process may be required.
4.2 Areas where burning may be prohibited

Burning may be prohibited within a specified distance of human habitation, e.g., within 1 km and within a specified distance of the shoreline, of petroleum-loading, production, or exploration facilities, or of a nature preserve, bird colony, or national or state/provincial parks. Burning may also be prohibited over a marine park or preservation area and over areas designated as military target areas or former areas of munitions dumping.

4.4 Regulatory approvals

The regulatory approvals required for in-situ burning vary among different jurisdictions. In general, the legal constraints and liabilities associated with in-situ burning are not well defined. The situation is made more difficult by the fact that the public is reluctant to accept regulations that allow any kind of burning. The public must be provided with information about
the issues associated with in-situ burning in order to accept allowing it. This information must include a comparison of the risks of burning with the risks associated with other cleanup options, and the results of simply leaving the spilled oil and not treating it at all.

In general, regulatory agencies are most concerned with how the burn will affect air quality. Most jurisdictions stipulate air quality levels that cannot be exceeded no matter what is being burned. Some jurisdictions have modified the air quality limits for special cases, such as in-situ burning of oil during an emergency.

Generally, permission for burning on open water far from land should be obtained from federal authorities, with local and state/provincial authorities being informed. For burning land or marshes, permission for burning should be obtained from local authorities e.g. the municipal/county government and local fire department and then proceed to the state/provincial government. State/provincial government have many provisions for using prescribed burning as a tool to manage land. In-situ burning of oil may fit into these provisions.

Federally, in-situ burning is now included in many contingency plans and the process for permission is included.

4.4 Human health and environmental concerns

The primary environmental and health concerns related to in-situ burning are the emissions produced by the fire. Overall, emissions are now understood to the extent that emission levels and safe distances downwind can be calculated for fires of various sizes and types. People and the environment can be protected by ensuring that the burn is kept the minimum distances away from populated and sensitive areas.

4.4.1 Safety of response personnel

During in-situ burn operations, all response personnel must be fully trained in the operational and health and safety procedures associated with any equipment or operation being used. Personnel involved in the planning stage of the operation and for the deployment of vessels, barriers, and ignition devices must also be well trained. General health and safety guidelines are discussed below. These guidelines should be used to develop site-specific plans once it has been decided that in-situ burning will take place.

4.4.2 Public health

In general, depending on weather conditions, in-situ burning should not be carried out within 4 km of heavily populated areas. Weather conditions to be considered include the presence or absence of an inversion and the wind direction. If no significant air turbulence or ground-level atmospheric inversions occur, burning can be conducted closer to populated areas. In sparsely populated areas, it may be best to evacuate residents close to the burn site. Methods are now available for calculating emission concentrations and safe distances downwind from in-situ oil burns.

4.4.3 Air quality

The major barrier to the acceptance of in-situ burning of oil spills is the lack of understanding of the resulting combustion products and the belief that it is just transferring
pollution to the sky. It should be noted that emissions from oil fires are less than typical emissions from other types of burning, e.g. biomass burning.

Several types of emissions are formed and released when oil is burned. The atmospheric emissions of concern include the smoke plume, particulate matter precipitating from the smoke plume, combustion gases, unburned hydrocarbons, organic compounds produced during the burning process, and the oil residue left at the burn site. Although consisting largely of carbon particles, soot particles contain a variety of absorbed and adsorbed chemicals.

4.4.3.1 Calculation of emission concentrations downwind
Prediction methods have been developed for about 150 chemical groups or substances. These can be applied if there are specific compound concerns as noted in papers in the bibliography.

4.4.4 Water quality
In-situ burning of oil does not release any more oil components or combustion by-products into the water column than are present if the oil is left unburned on the water surface. Water samples from under burning oil have been analyzed and no organic compounds were detected. No PAHs have been detected in water samples from under burning oil. Toxicity tests of the water column were also conducted and no toxicity was found.

The burning process leaves a residue, however, that is primarily composed of oil with little removed other than some of the more volatile materials. The residue contains an amount of PAHs, although usually less than the original oil, although it may also contain a slightly higher concentration of metals. The residue consists of unburned oil, oil depleted of volatiles, re-precipitated soot, and partially burned oil. It appears to be similar to weathered oil of the same type and is typically viscous and dense. Several tests have shown that burn residue is, in fact, much less toxic than weathered oils of the same type.

The density of this residue depends on how heavy the original oil is and the completeness of the burn, although it will never be denser than the heaviest hydrocarbons found in the original oil. A very efficient burn of a heavier crude oil will produce a dense residue that may sink and may pose a threat to benthic species. Sinking is very rare, however, and has been recorded in few burns worldwide. Aquatic toxicity tests performed on samples of residue have shown very low toxicity.

Another concern is that burning will raise the water temperature below the oil, as extreme temperature changes can affect marine species. Measurements during burn trials, however, show no significant increases in water temperature, except during some burns in shallow, confined test tanks. Thermal transfer to the water is limited by the insulating oil layer and is actually the mechanism by which the combustion of thin slicks is extinguished.

4.4.5 Effects on land
There are two major effects of burning on land, that of effects on vegetation and that on the soil itself. These are discussed more extensively in Section 5.3 below.

4.4.6 Effects on birds and animals
Wildlife on land is generally not affected if burning is conducted more than 1 km away from shore or sensitive areas. It has also been observed that birds will avoid the burning site and therefore are unlikely to be affected by the burn. Similarly, marine species should not be affected as the water column normally does not become contaminated and the water temperature does not change within a few centimeters below the slick. Benthic species may be affected by the sinking of heavy burn residue.

During land burns, a variety of birds and animals could be affected by the oil. Nesting birds and burrowing animals, in particular could be affected. Many of these would flee the area once the fire is seen, however, noise and disturbance can be used to cause these animals to flee the area.

4.4.7 Infrastructure concerns
At sea, oil slicks should not be burned close to infrastructure such as buildings, docks, lighthouses, oil platforms, and vessels that originally contained the oil.
On land, oil should not be burned close to infrastructure such as buildings, telephone or hydro poles, or wooden fences.

4.5 Oil properties and conditions
Oil spilled on water undergoes several changes with time. The processes that cause these changes include emulsification, evaporation, oxidation, spreading, dispersion, sedimentation, and dissolution. In order to determine the effectiveness of in-situ burning for a particular oil slick, it is important to understand how these processes change the properties of spilled oil and ultimately affect the oil’s ability to ignite and sustain burning.

4.5.1 Slick thickness
Research has shown that virtually all oils will burn on water if the slick is thick enough. In general, slicks should be 0.5 to 3 mm thick in order to be ignited and to sustain quantitative burning and a burn will be extinguished once the slick becomes less than approximately 0.5 to 1 mm thick. As the slick becomes very thin, the heat generated by burning is lost to the water below the slick, resulting in insufficient available heat to vaporize the constituents of the oil required to sustain combustion. Oil spill containment boom or other containment methods are often used to increase a slick’s thickness on water or to maintain it at the thickness required for burning.
On land, e.g. dry grass, oil can sometimes be ignited at lower thicknesses and the benefits of burning can be achieved.

4.5.2 Oil weathering/volatile content
As a rule, the greater the percentage of volatile compounds in an oil, the more easily it will ignite and continue to burn. It can therefore be difficult to ignite weathered oils and heavy crude oils (No. 5 and above) and higher ignition temperatures, primers and/or longer ignition exposure times may be required. Weathered oils may actually burn with greater efficiency and less soot or smoke than fresh oils.
### 4.5.3 Heavy oils

Heavy oils were once thought to burn poorly if at all, however results in recent years shows that these will burn quite well under most circumstances. Burning tests of bitumen, very heavy oil, along with water have been conducted and shown useful removal potentials.

Heavy oils such as Bunker C burn quite well but yield a highly-viscous residue. This high-viscosity residue has a high asphaltene and resin content. There is no evidence of the presence of soluble components, thus the residue exhibits low aquatic toxicity. Emissions from heavy oil burns show low emissions compared to crude oils and in particular there were few volatiles and few

### Table 3  Burning Properties of Various Fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Burnability</th>
<th>Ease of Ignition</th>
<th>Flame Spread</th>
<th>Burning Rate* (mm/min)</th>
<th>Sootiness of Flame</th>
<th>Efficiency Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>very high</td>
<td>very easy</td>
<td>very rapid - through vapours</td>
<td>4</td>
<td>medium</td>
<td>95-99</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>high</td>
<td>easy</td>
<td>moderate to high</td>
<td>3.5</td>
<td>very high</td>
<td>90-98</td>
</tr>
<tr>
<td>Light Crude</td>
<td>high</td>
<td>easy</td>
<td>moderate</td>
<td>3.5</td>
<td>high</td>
<td>85-98</td>
</tr>
<tr>
<td>Medium Crude</td>
<td>moderate</td>
<td>easy</td>
<td>moderate</td>
<td>3.5</td>
<td>medium</td>
<td>80-95</td>
</tr>
<tr>
<td>Heavy Crude Weathered</td>
<td>moderate</td>
<td>medium</td>
<td>moderate</td>
<td>3</td>
<td>medium</td>
<td>75-90</td>
</tr>
<tr>
<td>Crude</td>
<td>moderate</td>
<td>add primer</td>
<td>slow</td>
<td>2.5 to 3</td>
<td>low</td>
<td>60-90</td>
</tr>
<tr>
<td>Crude oil with ice</td>
<td>low</td>
<td>difficult, add primer</td>
<td>slow</td>
<td>2</td>
<td>medium</td>
<td>50-90</td>
</tr>
<tr>
<td>Light Fuel Oil</td>
<td>low</td>
<td>difficult, add primer</td>
<td>slow</td>
<td>2.5</td>
<td>low</td>
<td>50-80</td>
</tr>
<tr>
<td>Heavy Fuel Oil</td>
<td>moderate</td>
<td>add primer</td>
<td>slow</td>
<td>2 to 3</td>
<td>low</td>
<td>60-90</td>
</tr>
<tr>
<td>Dilbit Weathered</td>
<td>moderate</td>
<td>easy if fresh</td>
<td>moderate</td>
<td>2 to 3</td>
<td>medium</td>
<td>40 -60</td>
</tr>
<tr>
<td>Dilbit</td>
<td>moderate</td>
<td>add primer</td>
<td>slow</td>
<td>2 to 3</td>
<td>medium</td>
<td>50-70</td>
</tr>
<tr>
<td>Bitumen</td>
<td>low</td>
<td>add primer</td>
<td>slow</td>
<td>2 to 3</td>
<td>low</td>
<td>40-70</td>
</tr>
<tr>
<td>Emulsified oil</td>
<td>low</td>
<td>add primer</td>
<td>slow</td>
<td>2 to 3</td>
<td>low</td>
<td>30-70</td>
</tr>
<tr>
<td>Waste Oil</td>
<td>very low</td>
<td>add primer</td>
<td>slow</td>
<td>1 to 2</td>
<td>medium</td>
<td>15-50</td>
</tr>
</tbody>
</table>

*typical rates only --- to get the rate in Litre/m²/hour multiply by 60

PAHs measured in the air. The residues from all the burns were highly viscous. When cooled, all residues were solid and even ‘glassy’ in some cases. Table 3 shows the burning properties of many oils. Figure 11 shows burning bitumen.
4.5.4 Oil emulsification

In general, unstable oil emulsions can be ignited and will sustain burning because the emulsion is quickly broken down during the burning process. By contrast, stable oil emulsions are difficult to ignite because a large amount of energy is required to heat the water and therefore, additional energy is required to vaporize the oil in the emulsion before the burning is sustained. Test burns have shown that once an emulsified oil is ignited and has burned long enough, the heat from the burn breaks down the emulsion and allows the slick to continue to burn. The method that works is to burn emulsified oil alongside the emulsified oil and the heat from burning the un-emulsified oil will breakdown the emulsion and enable burning. This was shown in Figure 2 above.

4.6 Weather and ambient conditions

Weather conditions such as wind speed, gusts, shifts in wind direction, and on water, wave height and geometry, and water currents can all jeopardize the safety and effectiveness of a burn operation. Strong winds can make it difficult to ignite the oil during in-situ burning. Once the oil is ignited, high winds can extinguish the fire or make it difficult to control. In general, oil can be successfully ignited and burn safely at wind speeds less than 20 m/s (40 knots). Tank tests have shown that at wind speeds greater than 15 m/s (30 knots), the flames do not propagate upwind.

The effects of air and water temperatures on the ability to ignite and burn oil slicks is not well documented, however, tank tests have shown that air temperatures of -11 to 23°C and water temperatures of -1 to 17°C did not affect the ability of a slick to burn. While little testing has been done on the effect of rain on burning, rain would probably lower the efficiency of the burn due to
the cooling effect of the water.

At sea, high sea states can make it difficult to contain oil. Waves higher than 1 m can cause the oil to splash over the containment boom. High waves can also contribute to the emulsification of oil, which could make it more difficult to ignite.

Tests in ice-covered areas have shown that ice coverage has a minimal effect on the ability of a slick to burn. In fact, ice is typically used as a natural method to contain oil for burning. There are more on ice situations in a special section below.

Burning can only be done safely at night if oil conditions, weather conditions, and sea conditions are well known. Towing booms at night would be unsafe under most conditions. Burning at night would be a relatively safe choice in the case of a thicker, un-contained spill at sea, especially if the spill is offshore and its extent is well known. Some nearshore spills and spills in marshes have been burned at night, which is a relatively safe practice because the concentrations and location of the oil are known and precautions can be taken to ensure that the fire does not spread to surrounding areas.

5  Burning in Different Circumstances

One important facet of in-situ burning is that it can be applied to burning in several different situations including, on water, on land, on marshes and other areas. These applications will be described below. When an oil spill occurs, the situation is examined and analyzed for possible countermeasures. The type of oil, its thickness, and its state at the time burning could be applied, may be factors.

5.1 Burning on Water

A plan is followed using pre-established scenarios, check lists, and safety procedures. In most cases, containment will be required either because the slick is already too thin to ignite or will be too thin within hours.

The basic processes are shown in Figure 1. Personnel and equipment are transported to the site. In most cases, fire-resistant boom is deployed downwind of the spill and a tow begun. When enough oil collected in the boom, it is ignited using an igniter. The process is illustrated in Figure 12. The boom tow is resumed and continued until the fire is extinguished or the tow is stopped for operational reasons. The burning and progress of the tow are monitored by personnel on aircraft and on a larger ship from which an overview of the slick and conditions is possible. The monitoring crew can also direct the boom tow vessels to slick concentrations upwind. During the burn, monitoring normally includes estimating the area of oil burning at specific time intervals so that the total amount burned can be estimated. The amount of residue is similarly estimated. Particulate matter downwind might be monitored to record the possible exposure levels.
The burn could be stopped in an emergency by releasing one end of the boom tow or by speeding up the tow so that oil is submerged under the water. If the burning stops because there is not enough oil in the boom, the tow can be resumed going downwind and then turning around into the wind before re-igniting. After the burn operation is finished for the day or for the single burn, the burn residue should be removed from the boom. As the burn residue is very viscous, a heavy-oil skimmer may be required if there is a large amount of material. A small amount of residue can be removed by hand using shovels or sorbents.

The burning that took place at the Deepwater Horizon was an example of a successful burn campaign at sea. Indeed, there were about 400 successful burns carried out during the Deepwater Horizon spill and this removed a significant part of the oil on the water. The basic technique was to collect oil in a fire-resistant boom (hereinafter called fire boom) and then ignite the oil and slowly pull the fire boom forward to push the oil to the rear or wait if the winds and currents were doing this. The oil was spotted using a fixed-wing aircraft. Two shrimp boats (about 100 foot long) towed about 150 m (500 ft) of fire boom at about ½ to ¾ knot to avoid loss of the oil through entrainment under the boom. The tow lines were about 100 m (about 300 ft.) for the safety of the tow crews. This is shown in Figure 12. Once sufficient oil had been collected for a burn and marine and air monitoring approved, ignition was requested. A small boat carrying two persons would approach from upwind and an igniter dropped over the edge of the boom. The igniters were made from a plastic jar (about 1 Liter) of gelled diesel fuel, a marine flare and some Styrofoam floats. The flare, once activated burned down to the bottle of gelled diesel fuel, which started burning and acted as a primer to ignite the oil.
Once lit, the heavy, weathered oil would burn until most oil was removed. The burn was monitored from the air by trained observers and from larger vessels in the area. The amount burned was gauged by estimating the burning area in the boom and multiplying by the burning rate.

Many precautions were taken during the burn. Extensive training was given to the crews and several practice sessions were undertaken. Particulate emissions from the burns were monitored.

Oil can also sometimes be burned without containment and by using natural containment features such as oceanic fronts, ice, or shorelines to contain oil.

5.2 Burning without containment

Controlled burning of un-contained slicks is sometimes possible if the slick is thick enough and safety factors are considered. If the oil slick is already fairly thick, it may be advisable to ignite and burn as much of the slick as possible as a first response and then bring in fire-resistant containment booms to thicken the remaining parts of the slick for a second burn.

When burning an un-contained slick, personnel must ensure that there is no direct link between the oil to be burned and the source of the oil, e.g., the tanker or platform on the sea, to prevent the fire from spreading to the source. In the case of the Deepwater Horizon, some of the heavily-weathered oil was ignited without containment. This increased the amount of burns that could be conducted. Figure 13 shows un-contained burning in the vicinity of a contained burn.

Several oil spills or blowouts have accidentally caught fire while un-contained and have burned well. Emulsified oil may stop or retard the spreading of un-contained oil while it burns. In a large burn, large volumes of air are drawn into the fire, which is referred to as a “fire storm”. This may provide enough force to prevent the oil from spreading.

In remote areas, natural barriers such as shorelines, offshore sand bars, or ice can
sometimes be used to contain oil in order to burn it. The shorelines must consist of cliffs, rocks, gravel, or sandy slopes to resist burning and there must be a safe distance between the burning oil and any combustible materials, such as wooden structures, forests, or grass cover. On land, containment generally occurs naturally. Zones of convergence on the sea can also be used to contain oil.

5.3 Burning on land and wetlands

5.3.1 Overview

Burning oil on land is an older and more frequently-used technique than in-situ burning on water. Burning on land involves several different considerations than burning on the sea. First, the effect on soil vegetation is a prime consideration. Certain types of vegetation are very sensitive to fire, others not. Second, the location of the proposed burn should be considered in terms of the burn history or use of prescribed burning in the past in the area. Prescribed burning is extensively used around the world for a variety of purposes including control of vegetative species and removal of fire hazards. Many guidelines exist at state/provincial levels on the use of prescribed burning and these should be consulted for given areas. A third consideration is the exposure of the sub-surface environment to heat as indicated by temperature. This is influenced by soil moisture and depth of oil coverage. This is especially important in terms of plant propagation from roots and tubers. If these are permanently damaged by the fire, then revegetation of the area is very slow or nonexistent. A fourth consideration for burning on land is the amount of oil penetration before and after the proposed fire. If there is little penetration before the fire, then burning is more useful.

In terms of operations, many of the same considerations in this overall burning section apply to land as might apply to burning on water. There are several important differences to consider, however. First, the ease of ignition and oil thickness may not apply if there is combustible material such as dried grass available on the land. Burning in cases where there is dried vegetative material or wood in the target area, is simply a matter of igniting that material. Both the dried vegetative material and oil will burn.

The procedures for lighting a fire on land differ from that on water. First, a firebreak must be established around the entire perimeter of the proposed burn. Sometimes natural barriers, such as rivers, roads, etc. can serve as fire breaks. Once the firebreak is established, one proceeds to the furthermost upwind position and uses an igniter to start the fire. This is typically a drip torch. Once started the fire is monitored, especially close to the firebreaks at the downwind side.

Means should be available to extinguish fires and unwanted fire propagation. This is usually in the form of a fire truck with trained fire-fighters. After the main fire is out, it requires monitoring for several hours until all hot spots are cool and there is no danger of flare-ups.

After the fire is out, the post-burning monitoring should include a walk-through of the area with sampling of the surface. Samples are taken for post analysis, but direct observation is made of the surface layer to observe if oil has been burned, if there is burn residue that interferes with future plant growth and if there was oil penetration into the soil.

5.3.2 Prescribed burns

An important facet of burning oil on land is the burn history of the particular area. If the land is part of a prescribed burn program, the oil burn on land should be tied to the prescribed burn
program. Prescribed burns or sometimes called controlled burns, are carried out frequently in many countries to maintain grasslands, rangelands and wetlands. The purposes of prescribed burns vary from vegetation control, select vegetation species control, habitat maintenance and wild fire prevention and control. There is an extensive body of literature and expertise on prescribed burning which should be harnessed for burning of oil on land.

5.3.3 Special Hazards and Considerations
Burning of oil on land may involve several hazards that one does not encounter during sea burning, for example there is not usually a large fire break and all things in the area may have the potential to burn. Thus, special precautions must be taken to initiate a land burn. The regulation situation is also quite different in that much of the regulation may be at the local level rather than at the federal level.

5.3.4 Assessment of burning
Assessment of the benefits of burning should be considered before planning or proceeding with a land burn. Elements include:

**Health and Safety**
The most important thing about any burn is whether it can be conducted completely safely or not. There is no need to take risks to the burn crew, neighbours or the environment in order to carry out a burn. Considerations should include:
- possible conditions that endanger health
- personal protective equipment availability
- weather forecasts
- predicted smoke volume and movement
- burn area proximity to human habitation and amenities
- ability to ensure that crew members are always in contact and always visible
- training of crew members
- ability to have reliable escape plans
- escape methods and vehicles
- ability to react to emergencies
- ability to deal with out-of-control fires
- knowledge of conditions in the burn area
- proximity of emergency assistance

**Oil Removal Potential**
The potential benefits of removing oil through land burning should be considered. These considerations include the following:
- a thin oil layer on land may not be removed by a fire,
- many fuels will leave residues, which may have to be removed to protect plant life
- a fluid fuel like diesel oil could migrate further and cause ecological problems if it is not rapidly burned,
- an immobile fuel such as Bunker C can readily be burned on land, however depending on
the situation, it may not do ecological harm if left alone,
- a fuel may be made mobile by the heating of the fire,
- the benefits and the liabilities should be weighed.

**Assessment of location**
The feasibility of benefits in burning on land should also be weighted against location.
Locations where burning might be carried out include:
- wetlands
- range lands
- grasslands
- farming areas
- riparian zones
- marshes
- dryland

Locations where oil burning should not be carried out include:
- forests
- taiga
- tundra
- mangrove forests
- wildlife sanctuaries or nature reserves
- urban areas

**Soil heating**
Soil heating can cause damage to the soil structure as well as destroying vegetation by permanently damaging roots and tubers. Research has shown that 60°C is a temperature which can be taken as a temperature above which damage to vegetation occurs. Oil burning on the soil increases the heat flux to the soil. How much oil is present is an important factor. Factors such as soil moisture play an important role. Figure 25 shows a predictor of how far a 60°C temperature profile would penetrate into the soil. This figure shows that moisture content of the soil is an important factor and should be considered in making decisions. Many low shrubs have roots at depths of about 2 to 5 cm. Grass has roots that are quite shallow, 0.5 to 2 cm. Figure 25 can be used to approximately gauge the effects of fire on the vegetation and soil.
Figure 25 A simplified drawing to predict the critical temperature of burning oil pools on different soil moisture contents.

**Smoke control**

The possible impacts of the smoke must be weighed and scenarios developed. Smoke may also be controlled by decreasing the size of the fires and burning in different wind directions. Smoke impact on neighbouring amenities should be considered. Further safe distances as discussed elsewhere in this guide should be followed. Basically, a minimum distance of 1.5 kilometers should be recognized.

**Biota considerations**

There are many considerations regarding biota. If the site is normally a site where prescribed fires are used to maintain the ecosystem, the ecosystem already been considered to a certain degree. The considerations include:
- birds and especially nesting birds
- sensitive plant species
- borrowing and nesting animals
- impact of smoke on neighbouring ecosystems

**Weather conditions**

There are several weather conditions that could prohibit burning:
- high winds (> 40 km/hr)
- a forecast shift in shifting of winds in next 12 hours
- a forecast of an inversion in next 12 hours
- an inversion present now, or
- a forecast of a weather front moving in within the next 12 hours
**Soil conditions**

The soil in the area may be affected by the fire. Consultation should be held with a soil expert in the area. Burning may be accepted if certain restorative measures are implemented. There are soil conditioning options available. The soil could be studied to a depth of 0.5 m and several measurements taken: natural moisture content, grain size distribution, consistency (Atterberg) limits, California bearing ratio (CBR) and unconsolidated-undrained triaxial compression. In the past some studies showed that the crude oil spill and subsequent fire did not have a significant impact on the foregoing soil properties. Further, very little crude oil was observed in the core samples, leading to the conclusion that the fire did not increase oil penetration or increase it significantly in this particular burn.

5.3.5 Planning a burn

Every burn on land or on a wetland such as a marsh should be preceded by both a general plan long in advance and an immediate plan which updates the important conditions in the plan. Figure 26 shows the progression and contents of a burn plan. A generic plan is created for possible areas, which provides the proponent time to research and investigate aspects of the proposed burn. Immediately before the burn, the details are updated to provide the latest information and details.

![Burn Plan](image)

Figure 26 The contents of a typical burn plan

5.3.6 Flooding or raising water levels

One of the techniques that has been applied to land-burning is to spray water on the land
surface. This can help to protect the soil and plant roots as well as to assist in the removal of oil from the land surface. Flooding can also float some of the oil down to lower areas where it can be treated. Wetting grassland, however, can also reduce the potential for the grass to burn and may lower the potential for good oil removal under some circumstances.

5.3.7 Implementing a burn

Each burn should begin with a plan as noted above. There are several important elements and operations that are described below.

**Health and Safety Plan**

The safety plan is an essential part of the main burn plan and should include:

- compliance to the plan
- risks and potential hazards
- remedies for hazards
- necessary conditions before ignition takes place
- personal protective equipment
- weather forecast essentials
- pre-burn and burn patrols
- patrol boundary
- ensuring that crew members are always in contact and always visible
- safety roles of crew members
- escape plans
- escape methods and vehicles
- emergency actions and contacts
- procedures in case fire is out of control
- training of individuals in first aid and rescue
- emergency contacts

**Personal protective equipment**

Every person at the burn site should wear flame resistant clothing, leather boots with metal toes and shanks, safety helmets and leather gloves. All personnel should also wear goggles or a fullface piece respirator with a P100 filter. The latter may be carried along if the person is already wearing goggles.

**Regulatory permission**

Permission to burn on land can be complex. The local level such as local fire department and municipality, country or local authorities are the starting point. State and provincial levels often have plans for prescribed burning and if such is the case for the given area, the burn plan should be coordinated with the prescribed burning plans and regulations in that jurisdiction. It is wise to have the regulatory issues worked out beforehand.

**Fire breaks**

There must be a fire break around any land or wetland burn. These are necessary to protect
the surrounding area from spreading fire. The size of these depends on the wind and the vegetation height. The minimum width is generally 6 m (20 feet). The calculator for calculating the downwind fire break is shown in Figure 27. Since the downwind width of the fire break is more than the minimum upwind distance, the fire area and its fire breaks will form a quadrilateral figure. A typical fire break sketch is shown in Figure 28. The bibliography contains several documents that focus on land burns and fire break design.

There are several types of fire breaks or preparation methods for them:

- burned area
- mowed wet land
- natural
- tilled
- access road, or
- constructed by using a bulldozer, grader, etc.

Figure 27  A calculator for estimating the minimum fire break distances
Figure 28  A schematic of a burn area and the surrounding fire break. The dimensions are exaggerated to emphasize the precautions. In certain situations such as shown in Figure 29, a natural fire break exists.

Figure 29  A burn of oil from a pipeline spilled being burned during the winter, a clearing around the oil and burn creates a fire break.
Evacuation Zone

An evacuation zone must be plotted out and mapped in the same manner as the fire break. This is to evacuate people from the areas surrounding the planned fire. A rule-of-thumb is that the downwind area is evacuated a minimum of 10 times the length of the downwind distance of the fire area or a minimum of 1.5 kilometers (one mile). The upward evacuation distance is the length of this downwind distance of the burn area. The evacuation map will look similar to the fire break map as shown in Figure 28. Before any plans are laid and again before any burns are carried, all people in the area are visited and explanations of the situation given to them.

Fire boss

In many western countries prescribed burning is carried out under the supervision of a trained and experienced ‘fire boss’. These individuals should be engaged to manage any land burn. This will improve the safety and considerations for carrying out land burns. Further a fire boss in a given area has knowledge of local conditions, contacts and considerations.

Smoke management

The possible impacts of the smoke must be determined and considered. Smoke may also be managed by decreasing the size of the fires and burning in different wind directions. Figure 31 shows a typical smoke plume from a land burn.
Hazards in burn area and near burn area
Hazards in or near the burn area include:
- other unintended combustibles
- physical hazards such as debris, barbed wire, etc.
- areas with poor footing, holes or steep slopes
- areas where vehicles may become entrapped.

Ignition plan
The ignition plan should include the method(s) of ignition, the line of ignition and the rate at which this will be ignited. Figure 32 shows the use of a drip torch to ignite a prescribed burn.
Escape plan for burn crew

An escape plan for the burn crew must be in place before considering a burn. In addition, a plan must exist to ensure that during any phase of the burn that all crew are always accounted for and can be contacted at all times.

Plan to deal with escaped fire

A plan and resources must be devoted to the possibility that fire might escape from the planned burn area. This plan should be sufficient to cover the worse case scenario.

Fire monitoring plan

The fire should be monitored visually and with particulate monitors. Photographs using GPS and time annotated photos should be taken. Patrols around the fire break should be conducted, but taken with caution.

Mop up plan

A plan is made to check the burn site after the fire and carry out any cleanup required. This includes wetting down any potential sites that may flare up. Heavy oil burn residue if it suppresses future vegetation growth should be recovered. Soil amendments and re-seeding may be required. Figure 33 shows the results of leaving residue after a land burn.
Figure 33 A burn of oil on land left this residue which many years after the burn, still suppresses vegetation growth.

**Post monitoring plan**

The burn area should be monitored for re-vegetation and re-establishment of the ecosystem for at least 3 years after the burn. Periodic visits a few months after the burn and then annually after that are recommended. If the area is slow to re-establish, then seeding or other forms of amendments may have to be carried out.

**Emergency stabilization plan**

The emergency stabilization plan is related to immediate restorative action that may be required to the burn area considering drainage patterns, soil conditions and vegetative issues. This plan considers only short term and immediate action to stabilize the land situation until further restoration can be carried out or the area recovers naturally.

**Rehabilitation plan**

The rehabilitation plan is a long-term plan (up to 3 or even 5 years) to monitor and restore a given burn area. This includes restoring vegetation, soil or drainage patterns on a longer term. This may include seeding, adding soil conditioners, modifying drainage patterns, etc.

**Equipment and vehicles for fire crew**

Sufficient vehicles should be provided for the fire crew to enable complete redundancy. During the burn itself, at least two individuals should be in each vehicle and their movements must be monitored from a safe location. The crew members should carry equipment that enables them to snuff out hot spots, shovels, rakes and specialized snuffer tools. In addition after burn recovery of oil residue may necessitate recovery tools and disposal containers.
5.3.8 Post burn actions

The burn area should be monitored for re-vegetation and re-establishment of the ecosystem for at least 3 years after the burn. Periodic visits a few months after the burn and then annually after that are recommended. The recovery of the area is monitored. If the area is slow to re-establish, then seeding or other forms of amendments may have to be carried out. The area is surveyed for dense oil burn residue covers. If such residue is found that may inhibit vegetation recovery, it is removed. Figures 34 to 35 show a sequence of photographs from a burn and the post-recovery monitoring.

A report should be prepared on the burn and the subsequent recovery of the area.

Figure 34  Photograph of an oiled area (outlined in yellow) from a pipeline (indicated in red) into a freshwater slough. A fire break consisted of a wet cleared area around the oiled area. The oil was burned on the same day as the release. (Photograph courtesy of Jacqui Michel, RPI)
Figure 35  The oil on the slough from the spill noted in the above figure. (Photograph courtesy of Jacqui Michel, RPI)

Figure 36  The burn residue after the burn of the oil shown above. The residue was removed. (Photograph courtesy of Jacqui Michel, RPI)
5.4 Wetland - marshes

Oiled marshes can be treated with in-situ burning successfully given the same considerations as for land burning as covered in Section 5.3 above. The procedures and cautions are similar as well. The creation of a firebreak may pose a problem as the periphery of an oiled marsh often contains sensitive vegetation and this cannot be destroyed to create a firebreak. One method to create fire breaks is to lower vegetation using air boats and/or wetting down a periphery around the oiled vegetation. Further, the use of fire crews to monitor the burn becomes a necessity.

Several marsh burns have been conducted around the world, including documented burns in Louisiana and Texas. Several cases of burning in marshes are given in the literature. These
burns were largely successful and provided important information on protecting the marsh plants and the best time of year to burn. The roots of marsh plants, which also house the propagation portion of the plants, are sensitive to heat. If burning is conducted at a dry time of year, such as in late summer, these roots could be killed.

Flooding is a useful technique for flushing oil out of a marsh while protecting the roots of marsh plants. This can sometimes be accomplished by putting a berm across the drainage ditches or by pumping water into the high areas of the marsh. Care must be taken to use flood water of similar salinity to that normally in the marsh and to restore the natural drainage in the marsh after the flood. Often marshes cannot be flooded, however, and thus burning could be conducted when the marsh is wet, such as in spring. If a marsh cannot be burned within about one month of oiling, there is usually no benefit to burning because the oil will already have penetrated and severely damaged most of the plant life.

Monitoring after the burn should be carried out to ascertain the effectiveness of the oil removal. Figures 39 to 42 shows sequences from a successful burn of oil in a marsh.

Figure 39  A marsh spill which occurred from an overflow from a settling pond. The cause of the incident related to a hurricane which had passed over this area. This spill was not ignited for 7 to 8 days after the spill. (Photograph courtesy of Jacqui Michel, RPI)
Figure 40  The burn of the marsh shown in the above figure. (Photograph courtesy of Jacqui Michel, RPI)

Figure 41  The surface of the marsh immediately after the burn. Most of the oil is gone and the fate of the vegetation remains to be seen. (Photograph courtesy of Jacqui Michel, RPI)
5.5 Nearshore

Burning can be conducted nearshore if there are no people in the area and there is no danger of the fire spreading to plants on the shore. As these two factors cannot always be guaranteed, nearshore burning is not often conducted. The exception to this is in the Arctic where favorable conditions often exist and where nearshore burning is practiced frequently. Such burns have been very successful, particularly if the oil is contained by the shoreline. If there is also an onshore wind, oil is concentrated against the shoreline.

5.6 Intertidal pools

When oil is stranded in tidal pools formed during low tide, igniting the oil from above using a helitorch or other air-deployable igniter and conducting a burn may be the only viable cleanup solution. It can be dangerous for response personnel to get to the spilled oil either from the shore or the water between tides and such attempts are not recommended. The window of opportunity for burning is quite narrow, however, because of the fluctuations between outgoing and incoming tides. It is also difficult to predict the location of the oil pools and there may not be enough time to conduct aerial surveillance before burning operations. This type of in-situ burn operation would be useful if a spill occurred in an area such as extensive intertidal flats.

5.7 Burning in or on ice

Many burns have been conducted on or among ice floes. The ice serves as a natural barrier to the spreading of the oil. Much of the early burn work was carried out as a countermeasure for oil in ice. There are dozens of research papers on this. Figures 43 and 44 illustrate burning in ice.
Figure 43  Burning an oil spill in ice. In this case the oil is entirely contained by ice rubble.

Figure 44  Burning oil in a lead. This was a test carried out after an oil experiment in pack ice. The oil was compressed by closing conditions in the lead system. The burn was quantitative

5.8 Burning in vessels

There is a special situation if the in-situ burning is to be carried out in a stranded vessel. Safety is, of course, the primary criteria. The oil must be accessible to ignition and accessible to air. Explosives or industrial cutting equipment may be used to allow oil to flow from tanks to spaces where it will be burned and to increase ventilation area. This should be conducted by salvage and explosive experts. Typically, the planned burn would take place in the ship’s hold(s) and explosives would be used to open passage from lubrication and fuel tanks to the hold. Lubrication and fuel tanks generally do not have sufficient exposure to the air to allow for burning. Studies have shown the area of ventilation is a critical regulating factor in the burning of oil directly on ships and in other confined spaces. The rate of burning is generally calculated based on the area of ventilation openings in the case of low wind situations. Studies have shown that top and
side openings combined will yield better ventilation than top openings alone. The presence of two openings allows for air circulation over the area of fire. Small scale studies have shown that a minimum of 10% ventilation is needed to prevent extensive coking. Coking is the formation of coal-like material which can plug ventilation openings. The 10% ventilation refers to the area of ventilation compared to the surface area of oil available to burn. An area of more than 20% ventilation has been shown to result in little coking during test burns. External winds assist in providing additional ventilation, despite the semi-closed conditions that may exist. One study showed a threefold increase in burn rate with wind increase from 0 to 11 m/s.

During the burn process, some localized oil may become super-heated. When the heating is sufficient, flash evaporation of a component of this oil may occur and the surrounding boiling oil can erupt upwards towards the top ventilation port. This could result in oil being splashed onto other parts of the vessel or sea.

The safety of the proposed operation should be the primary consideration. The vessel should be stable and relatively stationary during the preparation and burn phases. The operation should only be contemplated if the operation will not result in flashback to other sources of fuel. The fire should be prevented from spreading to other combustible material in the area, including trees, docks, and buildings.

Preparation of the vessel for burning by using explosives and subsequent burning of the oil will weaken the ship’s structure. Burning in ships should be considered only if there is no potential for future salvage of the vessel or if the trade off between future salvage potential and removing the oil is favorable. The use of preparation and burning may weaken the structure sufficiently to result in breakup of the vessel. A breakup may result in the release of oil. Salvage experts and experts on ship design should be consulted, before proceeding with the preparation for ignition and burn. Salvage experts should also be consulted after the burn regarding options to deal with the remaining vessel. The vessel may not be seaworthy, towable or even in condition to allow ship-breaking in place.

Figure 45 A controlled burn of the remaining oil in a ship wreck. The wreck was prepared for this burn using explosives.
6 Equipment for burning - selection, deployment, and operation

6.2 Oil containment and diversion

6.2.1 Fire-resistant booms

The biggest concern with containment booms for in-situ burning is the ability of the boom’s components to withstand heat for long periods of time. Fire resistant booms have been tested for fire resistance and for containment capability and designs are modified in response to test results.

The different types of fire-resistant boom are water-cooled booms, stainless steel booms, thermally resistant booms, and ceramic booms. Fire-resistant booms require special handling, especially stainless steel booms, because of their size and weight. Thermally resistant booms are similar in appearance and handle like conventional booms, but are built of many layers of fire-resistant materials. The types of fire-resistant boom are shown in Figure 46.

Fire-resistant booms manufactured today are generally designed to survive several burns at one site, but are then disposed of or refurbished. A standard has been devised by ASTM to test the durability of fire-resistant booms for in-situ burning. The standard is a minimum 5-hour test involving three 1-hour burning periods with two 1-hour cool-down periods between the burning periods. Booms are tested in a test tank with oil or diesel fuel. Oil is pumped into the center of the boom at a predetermined rate and is burned. The oil is continuously fed into the boom for 1 hour and then is shut off allowing the burn to die out. The boom then cools for 1 hour and is tested for two additional 1-hour burn/1-hour cooling sessions. At the start of the third burn, oil is pumped into the boom to test for gross leakage. Several booms have been tested in this manner.

The containment behaviors of the fire-resistant booms currently on the market were evaluated in a test tank and compared with previous at-sea performance results. These studies determined the tow speeds at which the booms first began to lose oil (“first loss”) and the speed at which a continuous, significant loss occurs (“gross loss”). It also determined the rate of loss of oil at specific tow speeds and the tow speed at which the boom physically failed, i.e., became submerged or suffered structural damage. The following are the conclusions of these tests.

– In terms of oil containment, the performance of the fire-resistant booms was similar to conventional booms, with first losses occurring at tow speeds of 0.44 to 0.52 m/s (0.85 to 1.0 knots) in calm waters. These losses were relatively unaffected by regular waves and were reduced slightly by short-crested waves.

– The physical failure of fire-resistant booms was also similar to that of conventional booms with critical tow speeds between 1 and 1.5 m/s (2 and 3 knots).

– The critical tow speeds determined during the at-sea tests were lower by 0.25 to 0.75 m/s (0.5 to 1.5 knots) than the critical tow speeds determined during tank tests.

– From the limited data available from the in-tank and at-sea tests, an increase in the buoyancy-to-weight ratio of the boom appears to increase the boom’s ability to contain oil at higher than normal tow speeds.

The fire-resistant booms currently on the market are described in Figure 47. Detailed specifications for these booms can be found on the manufacturer’s web sites.
6.2.2. Conventional booms

Conventional booms cannot usually be used to contain burning oil as the construction materials either burn or melt, compromising the boom’s ability to contain the oil. Conventional booms can be used to corral a slick and contain it until a fire-resistant boom can be obtained. Logs or other floating material can sometimes be used as temporary booms. In narrow rivers, dams can be constructed across the upper layer of water to contain or divert the oil for burning.
6.2.3 Boom configurations and towing

The size of boom required for an in-situ burn depends on the amount of oil to be burned. Generally, the oil in the boom should fill no more than one third of the area of the catenary, the typical shape that a towed oil boom takes. If the boom is too long, it will be difficult to control and the stress on the boom may be too great. If the boom is too short, the catenary may not be large enough to contain the burned oil. In general, the length of boom used ranges from 150 to 300 m (500 to 1000 feet). Most commercial booms come in standard lengths of 15 or 30 m (50 or 100 feet). Figures 48 and 49 show some boom-towing configurations. The overall height of the boom should be equal to the maximum expected wave height (short period waves, not swell) from peak to trough.

An important factor when containing oil is the direction and speed at which the boom is being towed. The distance from the burn to the tow vessels should be far enough that the burn does not pose any danger to the tow vessel or personnel onboard the vessel. Temperature profile tests performed during the burns and test trials showed that the air and water temperature ahead of the burn levels off very quickly. Therefore, unless the tow line was very short (only a few meters), the heat from the fire would not be an issue. As well, since the boom is being towed upwind, the smoke from the burn should not reach the tow vessels.
Tow lines from tow boats should generally be at least 75 m (150 feet) long such as shown in Figures 2, 48 and 49. The boom must always be towed into the wind so that the smoke will go behind it. As tow speeds are measured relative to the current, the boom may have to be towed very slowly or even downwind to maintain a low enough speed relative to the current while towing into the wind. If the boom is towed too slowly, however, the burn will begin to move up towards the end of the boom. Booms should never be filled more than 2/3 to avoid fire from spreading out the front of the boom.

In general, the boom must be towed at a speed of less than 0.4 m/s (0.7 knots) relative to the current in order to prevent the oil from splashing over the boom or becoming entrained beneath the boom. The towing speed may have to be increased periodically if the burn begins to fill more
than two-thirds of the boom catenary. If contained oil does become entrained in the water column below the boom or splash over the boom, it will resurface or pool directly behind the apex of the boom. This oil could be reignited by burning oil inside the boom or by oil that splashes over the boom.

Another important factor in ensuring that the oil is properly contained for burning is the configuration of the boom. Booms can be towed in various configurations, depending on the equipment available and the weather and sea state conditions. The various conventional configurations for towing oil spill booms are shown in Figure 50.

![Figure 50](image)

Figure 50  Tow configurations that can be used to tow fire-resistant boom (Figure courtesy of Environment Canada)

The standard configuration is a length of fire-resistant boom connected with tow lines to two vessels at either end of the boom to tow the boom in a catenary or U shape, as shown in Figure 50 (a). A tether line or cross bridle is often secured to each side of the boom several meters behind
the towing vessels to ensure that the boom maintains the proper U shape, as shown in Figure 50 (b). This tether line or cross bridle is very useful in maintaining the correct opening on the boom tow as well as preventing the accidental formation of the J configuration. The tether line can also be attached to the vessels as shown in Figure 50 C. The advantage of this method is that boat operators can detach the tether line very quickly in case of an emergency.

When using the standard U configuration, it can be difficult to ensure that the two towing vessels maintain the same speed. To overcome this problem and to increase control over the boom configuration, three vessels can be used as shown in Figure 50 (d). One vessel tows the boom by pulling from the center using tow lines at each end of the U, while the other two vessels pull outward from the ends of the boom to maintain the U shape.

If the oil is near shore, a boom or booms can be used to divert it to a calm area, such as a bay, where the oil can be burned. An example of this method using two booms is shown in Figure 50 (e). Diversion booms must be positioned at an angle relative to the current that is large enough to divert the oil, but not too large that the current would cause the boom to fail. The boom must be held in place either by anchors, towing vessels, or lines secured to the shoreline.

In nearshore situations, anchors can be used to secure booms in a stationary position. It is important, however, that a proper anchor is used particularly in high currents, to ensure that the boom will stay in place for the duration of the burn. Various types of anchors suitable for anchoring containment booms are available.

### 6.2.4 Deployment of boom for in-situ burning

The deployment procedures for fire-resistant containment booms depend on the type of boom used. The water-cooled booms are either inflatable or flexible in some way and, therefore, they can be stored on and deployed from a reel. However, these booms sometimes require a large flat area for the proper installation of the water-cooling equipment as the boom is removed from the reel. Stainless steel booms and thermally resistant booms are rigid and therefore must be stored in sections in a container and also require a large flat area to lay out and connect the sections. Because of their rigidity and weight, a winch or crane is normally required to assist in deploying and recovering these booms.

After floating in the water for some time, containment boom may become waterlogged making it much heavier than when it was deployed. The vessel used to recover the boom must therefore be stable enough to handle this weight, especially if a crane or winch is being used.

Because of the added difficulty in handling some fire-resistant booms, they may be damaged during deployment and recovery. Care must be taken to ensure that the boom is moved slowly and handled carefully. For example, the cinch and choker attachment of a crane can damage a boom and it is therefore better to use a web belt to lift the boom. It is also much easier to deploy and recover the boom if a powered reel is used. Figures 51 to 54 show boom deployment methods.
Figure 51  Deployment of a boom from the rear of a supply vessel. This is a common way to deploy boom (Photo courtesy of Elastec / American Marine Inc.)

Figure 52  Deployment of a boom by a straight line tow. The boom could have been deployed from a dock or a ship (Photo courtesy of Elastec / American Marine Inc.)
Containment boom normally comes in sections that are joined by a connector. Many of the commercially available fire-resistant booms are equipped with standard connectors or to accommodate adapters that fit such standard connectors. These connectors allow different types of booms to be joined easily and securely. In any case, if more than one type of boom is used for containment, the connectors on these booms should be checked first to ensure that they can be properly joined.

If a burn is to be performed nearshore, i.e., within 5 km, the boom can be deployed from shore and then towed out in a straight line. It is for this reason that the ASTM standard for fire-resistant boom indicates that a fire-resistant boom section that is at least 150 m (500 foot) long
must be able to withstand towing in a straight line at 2.5 m/s (5 knots) for a period of 2 hours. A straight-line tow is shown in Figure 52.

If the burn is to take place too far from shore for the boom to be deployed from the shoreline, the boom must be deployed from a vessel. Again because fire-resistant boom is quite cumbersome, a large deck area is normally required for boom deployment.

The following is a typical procedure for deploying boom in open water from a vessel using a standard U configuration.

- The deployment vessel situates itself far enough downwind from the oil so that there is enough time to deploy the boom before approaching the oil.
- The deployment vessel aligns itself so that its bow is facing upwind.
- Before the first part of the boom is deployed from the deck, a tow line for the towing vessel is attached to the end.
- The boom is deployed off its stern so that the wind causes the boom to trail behind the vessel.
- When the last section is deployed, the end of the boom is attached with a tow line to the deployment vessel, which can become one of the towing vessels. If another tow vessel is to be used, this tow vessel picks up the tow line from the deployment vessel.
- The tow line at the other end of the boom is then attached to a second towing vessel.
- The second towing vessel heads upwind until the proper U configuration is formed.

If a tether line or cross bridle is used across the opening of the U (see Figures 50 (b), ©, and (d)), this line should be attached to the end of the boom or tow line closest to the deployment vessel before the last section is deployed. Once the U is formed, a third vessel will have to bring this line across to the other end of the boom or tow line and connect it. If, as is shown in Figure 50 (d), a third tow vessel is used for stability, the tow lines for this third vessel should also be attached as the boom is deployed and then attached to the third vessel, which then situates itself in-between and ahead of the other two tow vessels. Figures 55 and 56 show a fire-resistant boom towed as in Figure 50 (c).

Figure 55  A side view of a three vessel and bridle tow system (Photo courtesy of Environment Canada)
The method for deploying diversion barrier in a river (see example in Figure 50 (e)) is very different from deploying containment boom in a U configuration in the open ocean. The boom must be held in place at an angle relative to the current that is large enough to divert the oil, but not too large that the current would cause the boom to fail. The boom must, therefore, be secured in place either with lines to the shoreline or towing vessels, or by anchoring the boom on the river bottom. Unless the boom can be fixed to both shorelines, it is more secure to use anchors. In fact, two anchors placed in series are usually required to prevent the boom from moving in high current situations. The proper deployment of anchors in order to hold boom can be difficult, as they must be deployed systematically in order to properly set in the river bottom. The anchors should be securely in place before the boom is deployed.

6.3 Ignition devices for on-water burns

A variety of ignition devices or methods, both commercial and non-commercial, have been used to ignite oil slicks, although the methods of igniting oil on water have not been well documented. Many of the methods used are modifications of ignition devices used for other purposes.

In general, an ignition device must meet two basic criteria in order to be effective. It must apply sufficient heat to produce enough oil vapors to ignite the oil and it must be safe to use. Safety issues to be considered when operating ignition devices are outlined in a subsequent section.

Research has shown that to a certain extent the thicker the slick, the more easily and quickly it will ignite. The main factor, the lighter, i.e., more volatile or less weathered the oil, the more easily it will ignite. For heavy oils, more heating time is required to produce enough ignitable vapors. It is suggested that for heavy oils, a primer, preferably diesel fuel or kerosene is used to soak in the oil for a few minutes before applying an igniter.

As discussed above, unstable emulsions can be ignited, but may require additional energy before burning is sustained. Stable emulsions can be very difficult to ignite because the water in the oil acts as a heat sink and a high amount of energy is required to heat the water and vaporize
the oil before burning can be sustained. It is best to burn emulsions alongside un-emulsified oil. This was shown in Figure 2.

Commonly-available devices, such as propane and butane torches, have been used in the past to ignite oil slicks. They are more effective on thick slicks, however, as torches tend to blow the oil away from the flame on thin slicks, thus hampering ignition. Weed burners have also been suggested as an ignition device for in-situ burning.

6.3.1 Helitorches

Helitorch devices are sophisticated commercial devices sometimes used for igniting oil slicks. These are helicopter-slung devices that dispense packets or globules of burning, gelled fuel and produce an 800°C flame that lasts up to 6 minutes. This type of igniter was designed for the forestry industry and is used extensively for forest fire management. Two helicopter-based systems suitable for igniting in-situ burns are the Simplex Helitorch manufactured by Simplex Manufacturing of Portland, Oregon and the Universal Drip Torch available from several suppliers. The latter is frequently used for land and forest burns. These helicopter-borne devices are shown in Figures 57 and 58.

Figure 57  A Helitorch emptying its tank on a slick which it had lit earlier. The torch normally puts out a smaller amount of burning fuel (Photo courtesy of Environment Canada)

Figure 58  A helicopter-borne drip torch igniting a prescribed burn

The fuel used in the helitorch system is a mixture of a powdered gelling agent with either
gasoline, or a diesel/gas mixture. SureFire, an aluminum soap, is the most commonly used gelling agent. Alumagel is another type of gelling agent that was used to make Napalm for military purposes. It is currently available only through military surplus. The SureFire powder is more readily available and gels faster than Alumagel. An improved version of SureFire gell, known as SureFire II, is now available. SureFire and SureFire II are available from Simplex Manufacturing in Portland, Oregon.

When preparing to operate a helitorch, the gelling agent and fuel must be mixed in a secure area well away from any ignition sources. The first step is therefore to set up a mixing area where the fuel is mixed with the gelling agent and a loading area where the barrels are loaded onto the helitorch system. These two areas should be at least 30 m apart and 150 m away from the helipads and helicopter refueling areas. They should also be well away from any ignition sources and upwind from the burn area. These areas must be used solely for the work associated with the helitorch and should not be combined with other helicopter operations or other work associated with the burn. No personnel other than the helitorch crew should be allowed in these areas unless authorized by the Helitorch Supervisor.

The mixing of gelling agent and fuel, the loading of the fuel, and the hookup of the helitorch to the helicopter should be done on land unless the burn site is too far from land for the helicopter to ferry the helitorch, i.e., more than 20 km. In this case, the fuel and agent should be mixed at a land-based site and the barrels of gelled fuel should be stored on a ship in an area approved for fuel storage. This area must be above deck in a contained, ventilated area, well away from any ignition sources. A loading area should be set up on the ship, where the barrels of gelled fuel will be loaded onto the helitorch system and hooked up to the helicopter. In this case, any preliminary testing and preparations for the ignition procedure should be done at a land base.

The fuel is mixed with the gelling agent directly in the specialized barrels that come with the helitorch unit, using the raised hatch opening in the barrel. The required ratio of gelling agent to fuel depends primarily on the type of fuel and the air temperature. In general, the lower the flash point of the fuel, the less gelling agent is required.

The amount of fuel needed to ignite an oil spill is primarily related to the number of slicks and the degree of weathering of the oil. The amount of ignition fuel is not related to the amount of oil to be burned. The volatility of the type of ignition oil used and the temperature may also affect the amount of gelled fuel required. It should also be noted that the amount of gelled fuel dropped depends on the individual operator, since not every operator holds down the ignition switch for the same amount of time.

Using the carrying handles on the barrel, the barrel containing the gelled fuel is transported to the loading area and attached to the helitorch frame or ignition system. The complete system is then attached to the helicopter using slinging cables. The electrical connection runs along one of these cables. For ignition purposes, the torch can be hooked up at right angles to the frame so that the pilot can see the ignition head. If the unit is being transported a long distance, however, it should be hooked up parallel to the frame to reduce the drag on the unit and conserve the helicopter’s fuel. Before the ignition preparation begins, the helicopter should set down on a helipad on a ship near the site to change the position of the torch to be perpendicular to the frame. Before the helitorch is deployed, wind conditions are checked so the pilot can approach the burn from an upwind or crosswind direction. Water currents are also checked to ensure that the
burning gel will not drift towards any vessels involved in the burn operation. A test drop can be carried out. If this indicates that the gelled fuel is igniting and falling properly, the pilot positions the helicopter over the desired location, fires the torch on a slow pass, and then leaves the area. If igniting a fuel with a high flash point, the pilot may have to hover over the burn area and release multiple balls of burning fuel to concentrate the fire in one location.

6.3.2 Non-commercial ignition devices

Simple ignition methods such as oil-soaked paper, rags, or sorbent have been used to ignite oil at actual and test spills. It should be noted that diesel oil is much preferable to and safer than gasoline for soaking materials or as a base for the gelled fuels in hand-held igniters because diesel burns slower, making it safer and supplying more pre-heat to the slick.

As noted earlier, ignition of heavier oils is best carried out using a primer such as diesel fuel, and a small wick such as a piece of cardboard or sorbent. This enables a start similar to lighting a candle. The flames will then spread to the un-primed oil nearby. An illustration of such an ignition is given in Figure 59. In large scale heavy oil ignition might be accomplished by applying a bit of primer and then using the helitorch. Use of a gelled fuel igniter is inadequate to directly ignite heavy fuels without the use of a primer.

Figure 59 Hand ignition of a small test burn of a heavy oil. This was carried out using a small amount of diesel fuel and a cardboard wick

A variety of hand-held igniters have been devised for igniting oil slicks. These are meant to be thrown into a slick from a vessel or helicopter. These devices often have delayed ignition switches to allow enough time to throw the igniter and, if required, allow it to float into the slick. These igniters use solid propellants, gelled fuel, gelled kerosene cubes, reactive chemical compositions, or a combination of these, and burn for 30 seconds to 10 minutes at temperatures from 1,000 to 2,500°C.

A hand-held igniter was used during several in-situ burning tests. This igniter consists of a 1-L Nalgene bottle filled with gelled gasoline or diesel fuel. The gel was made by mixing 1 L of gasoline with 0.01 kg of SureFire fuel gelling agent. A variant on this is to use diesel fuel.
bottle and a standard 15-cm marine hand-held distress flare are secured side-by-side within two polystyrene foam rings. The flare is lit and thrown into the slick, where it burns for approximately 60 seconds before melting the plastic bottle and lighting the gelled gasoline which in turn lights the oil. Figure 60 shows the construction of this type of device. A similar device was used to ignite the burns at the Deepwater Horizon spill. Gelled diesel fuel was used in this set of burns. Such devices, which are relatively easy to make and to deploy, are shown in Figures 61 and 62.

Figure 60  Illustration of the construction of one type of ignition device (Photo courtesy of Environment Canada)

Figure 61  Photograph of one of the igniters used during the Deepwater Horizon spill. This is similar to that illustrated in Figure 60 except that diesel fuel was used instead of gelled gasoline
6.4 Igniters for land burns

The hand-held, helitorch or one of the noncommercial ignition devices can be used for land or marsh burning. There are also hand-held drip torches available for igniting land burns such as illustrated in Figure 32. Caution must be exerted in igniting materials at close proximity, especially if there are volatile components. Gasoline or light crudes should not be ignited at close proximity. Further it should be noted that the spread of fire through a vapor cloud can be as fast as 50 m/s (100 knots).

6.5 Treating agents

Work has been done to investigate the use of chemical additives to enhance burning. There are a number of agents that can be used, however, none of these is readily available or has proven to be effective for the task. Agents include emulsion breakers, ferrocene, combustion promoters, and sorbents.

Emulsion breakers and inhibitors are formulated to break water-in-oil emulsions or to prevent them from forming. They have not been used extensively in field trials and rarely in actual spills. Some information is available on specific formulations of these agents, but the formulations vary extensively.

Herding agents have been tested to thicken oil for burning in pack ice. Outdoor tests showed that the herders were effective at reducing the slicks to burnable areas in pack ice. Herders work in calm conditions and that a wind of 1.5 m/s may be sufficient to overcome the effect.

Ferrocene is a chemical that can reduce or eliminate soot production from burns. Tests have shown that ferrocene, if it can be mixed with the oil, is highly effective at percentages from 1 to 2%. The problem with ferrocene is that it is more dense than oil and water so it must be pre-mixed just before burning, which is very difficult to do outside a pan test burn. Ferrocene may be encapsulated so that it does float and even be added to the fire once in progress. This is not an established process.
In the past, several combustion promoters, usually agents that would act as both a wicking agent like a sorbent and an auxiliary fuel, have been tested and shown to be marginally useful. None of these agents is currently available. Some have suggested that such agents may be useful in burning un-contained slicks, but further research is required on these agents before they can be applied to actual in-situ burn situations.

Sorbents such as peat moss have proven useful in burning by acting as wicking agents. It was shown that such agents could reduce the minimum burning thickness and increase the efficiency of a burn. Sorbents may allow un-contained burning to be conducted in marginal conditions, but again more research is needed.

6.6 Support vessels/aircraft for at sea burning

Vessels and aircraft play an important role in a successful in-situ burn operation. Vessels are required to bring equipment and personnel to the burn site, to tow booms, and to carry monitoring equipment. Barges and small boats may also be required for standby fire safety operations, monitoring, recovering residue, and for storing equipment and residual oil. Tug boats may be required if a tanker must be moved away from the burn area.

A sufficient number of vessels must be available to transport and deploy the length of containment boom required at the burn site. The vessels must have a large enough deck to carry the boom as well as any equipment and materials required for handling the boom. They must also be able to move steadily at a slow speed (<0.5 m/s (1 knot)) and have bow-thrusters for easy maneuvering and to quickly move in reverse if required. When containment booms are used in open water, two vessels are required to carry, deploy, recover, and tow each end of the boom, depending on the configuration. Such tows are shown in Figures 2, 48 and 49.

For safety reasons, any vessels used in a burn operation must be large and stable enough to carry the necessary equipment in all possible sea states including storm conditions. A vessel with an onboard crane and one or more tugger winches is recommended for handling equipment on deck and for recovering oil from the water. A burn monitoring vessel is shown in Figure 49. Separate, smaller tow vessels can be used to tow the boom.

Fixed wing aircraft and/or helicopters may also be required to perform surveillance of the spill site, carry monitoring equipment, and perform ignition and extinguishing operations. An aerial view of a burn is invaluable such as shown in Figure 49. For safety reasons, twin engine helicopters are recommended for helitorch operations. If a single-engine helicopter must be used, it should be equipped with floats to allow emergency landing on the water. This is not a requirement for twin engine helicopters.

For all aircraft operations, reliable air-to-ground communications are essential to coordinate operations. During helitorch operations, this includes communications between the base ship, the helicopter, and the fire-boom deployment vessels. A safety standby boat having communications with the helicopter may also be desirable under certain circumstances.

Any vessel used as a floating base for helicopter operations must have a heli-deck with a nearby fuel storage area and be equipped for onboard firefighting operations. If using a helitorch or other helicopter-deployed igniter, and the distance from shore is too far for safe helicopter transit from a land base, another vessel may be required to store the gelled fuel and for helitorch refueling operations.
When burning against a shoreline without the use of deflection or containment booms, only one helicopter is required to carry the helitorch and conduct ignition operations. If booms are needed, vessels or aircraft will be required to transport the equipment to the site. Vessels and aircraft may not be needed to hold the boom in place, however, as this can be done with anchors.

A vessel with a low freeboard to allow for easy access to the water surface is recommended for recovering oil residue using skimmers. A barge or landing craft used in conventional oil spill response is ideal for access to the water surface. The amount of residue that can be recovered will depend on the displacement of the boat used and the size of tank and cargo that can be safely carried on deck.

7 Monitoring the burn for safety and control reasons
7.1 At Sea Burns

Each burn requires monitoring from the air and from a larger ship. The purpose of the monitoring is to:
- Ensure the safety of the crews working on the fire,
- Monitor the fire to ensure it does not spread or go out of control,
- Guide the ignition,
- At sea, to provide direction to the tow crews to ensure that the burn rate is satisfactory, if the fill of the boom is proceeding to the tow lines, the tow rate needs to be increased, and vice versa. If the oil is starting to come out the apex, the tow needs to be stopped,
- The area burning and times that this area is burning, needs to be recorded to establish an amount burned. This can be done directly on nomograms such as in Figure 63 below,
- Watch for danger of any type and take action as necessary, and
- If necessary activate the extinguishing plan.

![Figure 63](image)

An organization structure should be in place to ensure that there is a good communication and reporting procedure for burns at sea. Monitoring should be planned with back-up plans for
eventualities. Roles might include ‘burn commander’, ‘aerial spotter’, ‘surface spotter’, ‘ignition crew’, ‘tow boat operator’, etc. A good defined structure and communication plan will ensure the safety of all concerned.

The specific safety monitoring targets at sea from both a larger ship and an aircraft include:
- The ignition of the oil, safety of the igniter and the spread rate of the flame
- The movement of the fire and oil inside the boom. If the fire spreads rapidly forward toward the tow boats, the speed of the tow may have to be increased and vice versa. If the flame is spreading to slicks near the tow lines, for safety purposes, the tow may have to be increased to the point where the fire is extinguished.
- Particular attention must be paid to the distance between the flame and the front of the fire-resistant boom.
- Attention must also be paid to the rear of the tow, often oil that is on fire is deposited behind the fire-resistant boom. These burning oil spots should be extinguished if they move further than about 10 m from the boom tow or if they threaten to ignite other slicks in the area. If left behind the boom, these fires usually burn out.
- The speed of the tow must always be monitored for the above reasons as well as for practicality of efficient burning. If there are no slicks directly ahead of the tow, the tow might have to be stopped to allow removal of oil in the boom before proceeding for another slick. Caution should always be taken if there are slicks directly in front of the tow, so that these are not ignited, endangering those on the tow vessels.
- All personnel and vessel locations close to the burn should be monitored.
- The direction of the smoke plume and its proximity to human habitation should be monitored.
- Communication with the larger monitoring vessel on the surface should be coordinated.

The operational targets for monitoring burns at sea using aerial observation include:
- Times, positions and other data on towing, ignition, length of time of burns and specific areas of burns,
- Area of burns using a template such as shown in Figure 63. Areas should be recorded for each area at approximately 10 minute intervals, and
- Photographs at intervals using a camera that has time and GPS stamps.

The operational targets for the ship-borne observer include:
- Times, positions and other data on towing, ignition, length of time of burns and specific areas of burns,
- Positions of vessels at time intervals of about 30 minutes, and
- Photographs at intervals using a camera that has time and GPS stamps.

7.1 On-land Burns
Each burn requires monitoring from the air and from a vantage point. The purpose of the monitoring is to:
• Ensure the safety of the crews working on the fire,
• Monitor the fire to ensure it does not spread or go out of control,
• Guide the ignition,
• Record the area burning and times that this area is burning. This can be done directly on a burn chart such as in Figure 28 above,
• Watch for danger of any type and take action as necessary, and
• If necessary activate the extinguishing plan.

An organization structure should be in place to ensure that there is a good communication and reporting procedure for burns at sea. Monitoring should be planned with back-up plans for eventualities. Roles include ‘Burn Boss’, ‘ignition crew’, etc. A good defined structure and communication plan will ensure the safety of all concerned.

The specific safety monitoring targets on land from an aircraft include:
• The ignition, safety of the person performing the ignition and the spread rate of the flame,
• The movement of the fire the burn area,
• Particular attention must be paid to the fire spread at the boundaries of the intended burn area,
• All personnel and vehicles close to the burn should be monitored,
• The direction of the smoke plume and its proximity to human habitation should be monitored, and
• Communication with the ground crews should be coordinated.

The operational targets for monitoring burns on land using aerial observation include:
• Times, positions and other data on ignition, flame spread, and specific areas of burns,
• Area of burns using a template such as shown in Figure 28. Areas can be recorded for each area at approximately 10 minute intervals, and
• Photographs at intervals using a camera that has time and GPS stamps.

The operational targets for the land vantage-point observer include:
• Times, positions and other data on ignition, flame spread, and specific areas of burns,
• Positions of personnel and vehicles, and
• Photographs at intervals using a camera that has time and GPS stamps.

8 Health and safety precautions during burning

8.1 Worker health and safety precautions

To protect the health and safety of workers involved with in-situ burning, a thorough health and safety plan must be established and be well understood by all personnel involved before the operation begins. As with any operation in which health and safety are issues, workers are responsible for their own safety and for the safety of their co-workers. To assist in the development of proper health and safety plans for in-situ burning, much of the information required can be obtained from firefighting associations.
8.2 Ignition operation safety
The following are some general safety issues that relate to ignition devices.

- The operators must fully understand the operational and safety instructions for the specific device being used. This includes understanding the safe operating procedures, training requirements, disposal requirements for spent igniters, and requirements for retrieving and handling igniters that misfire,
- The device should be protected against accidental activation,
- Hand-held igniters should have a delay mechanism that postpones the ignition of the device for at least 10 seconds from the time of activation. This delay allows time to activate and throw the device and for it to float into the slick,
- For helitorch systems, specific helicopter safety precautions must be followed, as well as the specific precautions for helitorch systems, and
- Any device deployed from a helicopter should not require the use of open flames or sparks within the aircraft.

8.3 Preventing unwanted ignition and secondary fires
Once the operation begins, the burn must be closely monitored to allow response personnel to determine if the burn situation must be reassessed, the plan needs to be modified, or the burn must be controlled or terminated. If on the sea, surveillance of the burn area should be arranged to provide such essential information to the tow operators including the approximate thickness and frequency of slicks in the path of the boom tow or containment area, the precise direction of the smoke plume, the area of oil burning, and whether this is increasing or decreasing. If on land, surveillance of the area around the burn, before, during and after the burn is essential.

At sea, two surveillance tactics should be considered - aerial surveillance and surveillance from a larger vessel. The increased visibility from aircraft, particularly helicopters, ensures the safety of the burn operation. However, a larger vessel not only provides a good view of the tow operation from the surface but can also be equipped with extra fire monitors for firefighting capability. This vessel also provides a means of rescue if one of the tow vessels fails.

Any potential difficulties in a burn operation, such as encountering thick burnable slicks that could burn out of control, should be anticipated and avoided. The fire could propagate ahead of the tow vessels or to amenities that can be burned. Other difficulties that should be avoided are the loss of significant amounts of burning oil behind the boom. These burning patches could also cause problems downwind. This can be avoided by having an extra fire-resistant boom downwind to catch any burning patches or vessels with fire monitors to extinguish external burning oil.

Flames spread very rapidly through vapors - as fast as 100 m/s or 200 knots. If burning a highly volatile oil such as a fresh, very light crude, gasoline, or mixtures of these in other oils, vapor flame spread could occur and cause serious injury. This is referred to as vapor flashback. This can only be avoided by carefully assessing the properties and characteristics of the oil to be burned. If burning these very light mixtures, it must be ensured that no people are in the area. These circumstances are rare because normally, by the time responders have reached an oil spill, the volatile fraction of the oil has been removed. In any case, all burn personnel should be familiar with the hazards and with the difference between the speed of flames spreading on a pool and through a vapor cloud.
Burning should not be attempted on a slick that could flash back to the source of the spill such as a tanker or towards populated areas. This can usually be prevented by removing or isolating the source from the part of the slick to be burned or separating manageable sections of the slick with containment booms and burning these sections within the boom well away from the main source of the slick. In tanker spills, the source can be moved away using tug boats which can be brought to the site more quickly than containment booms. When this is not possible, containment booms can be used to isolate the main part of the slick from the source. Precautions must also be taken to prevent the fire from spreading to nearby combustible material such as grass, trees, docks, buildings, and operational vessels.

Perhaps the best way to prevent unwanted or uncontrollable burns is to carve off a manageable section of oil from a large slick and pull it well away from the main slick or other combustible material before igniting it. This oil can be collected using conventional booms and then transferred to fire-resistant booms in an area where it is safe to burn. If oil is close to shore, deflection booms can be used to deflect oil toward a calm area such as a bay where it can be safely burned. Exclusion booms could be used to keep oil away from areas where it is not wanted. A number of techniques can be applied to prevent secondary fires, fire spreading to unwanted areas, and flashback of the fire to workers. If a boom is used, it must be towed properly. It is important to recognize that a boom fails when towed at a speed faster than about 0.4 m/s (0.8 knots) and that the boom should always be towed into the wind. On most oil slicks, flames will not spread across an oil slick at a rate faster than about 0.2 m/s (0.4 knots). Thus, in a typical situation in which the boom is steadily towed at least at the flame-spreading speed, flames will not reach the boom tow vessels, even at low winds. Caution should be taken, however, because winds can change rapidly. Burns should not be conducted if the tow boats are actually in thick oil or could pass through it.

Operators of a boom tow should be knowledgeable about how to control the area of the burn by increasing or decreasing the tow speed. At excessive tow speeds, the oil will be lost through the boom apex as a result of boom failure, entrainment under the boom, or loss over the top of the boom. At a towing speed that is too slow, the oil, and therefore the fire, will slowly spread to the boom opening, towards the towing vessels. The movement of oil back and forth in the boom is also influenced by the amount of oil encountered. If more oil is encountered than can be burned in the area of the boom, measures will have to be taken to prevent the fire from spreading towards the tow vessels. If no safe action is possible, the fire may have to be extinguished or the boom tow dropped.

Once the oil is burning, extinguishment may not always be straightforward or easy. Several tow control methods have been suggested to extinguish the fire within a towed fire-resistant boom at sea. The first method is to release one end of the boom tow and let the oil spread until it is too thin to burn. Secondly, if the tow speed is increased to greater than containment velocities (0.4 m/s or 0.8 knots), oil will submerge under the boom and the fire is often extinguished. Since this method may be hard to carry out, it is not suggested as the primary technique. Another method is to slow down the towing rate thereby reducing the encounter rate.

It is recommended that fire extinguishing equipment be available during the burn. At sea, one dedicated fire extinguishing vessel should be positioned beside the boom containing the burn. During burn operations at sea, those who must be near the burn such as the tow-boat operators can
be protected by ensuring that fire monitors of sufficient capacity are available. These monitors can
be left on to ensure they are ready if needed. Extra fire monitors and experienced crews should be
available on the surveillance vessel to assist if a fire spreads. The fire can also be extinguished by
using a firefighting foam made for liquid fuel fires. To ensure safety, at least two of these
extinguishing methods should be ready at a burn site. When burning is done close to shore or on
land, fire trucks and crews can be stationed at strategic points on land to fight unwanted secondary
fires.

8.4 Exposure of personnel to burning operations

Crews in vessels involved in tow operations are in danger of being exposed to fire or
flames if the fire should move up the boom. This could occur if thick patches of oil are
encountered and the flame spreads along this thicker patch. The flame velocity is about 0.02 to
0.16 m/s. The flames would not spread towards the tow vessels if the boom is moving at a speed of
at least 0.4 m/s (0.8 knots) in an upwind direction. Because winds can change rapidly, however,
this fact should not be taken as an assurance of safety. In highly variable winds, caution must be
taken to ensure that thick concentrations of oil are not encountered at low boom-tow speeds.

On land, a similar situation can be encountered. The flame spreading rate is also about 0.02
to 0.16 m/s, however in winds this can increase. On land, fires can move very rapidly if there is
combustible material such as trees and grass available. A fire break should always be made in the
area in advance of ignition. Workers must avoid downwind locations even if there is a fire break
between them and the fire.

Any crews working alongside the burn could be exposed to high concentrations of
particulate matter, if the wind changes and blows towards them. For this reason, operational
vessels at sea should not operate behind the tow boat positions. On land, crews should stay upwind
of the burn at all times possible.

Helitorch personnel are not directly exposed to the dangers of burning operations other
than being exposed to small amounts of vapors from the fuel used for gelling. If necessary,
respirators can be used to minimize this exposure. The helitorch operator in the helicopter is not
physically exposed to any dangers, other than those normally associated with flying.

When booms and other equipment are handled, the appropriate personal protective
equipment must be worn. This includes safety boots, hard hats, goggles, neoprene gloves, life
jackets, chemical-resistant clothing, and foul weather gear.

8.5 In-situ burn training

All personnel involved in a burn in most jurisdictions must complete a 12 to 40-hour haz-
mat course. Such training is illustrated in Figure 64. Personnel involved in a burn should be
familiar with the technology and procedures in this section. Training should involve simulated
burns in the planned setting.

It is recommended that experienced boom operations staff attend at least a one-day course
on the use of booms for in-situ burning and that an additional day be spent on practicing towing
booms and releasing oil from booms such as might be required in an emergency. Personnel who
are not totally familiar with boom deployment and operations should spend at least one week in
training and practice.
All members of the helitorch operating team require extensive training. Only a highly experienced lead person, such as the helitorch supervisor, should be used to provide training. Operators and ground support personnel should generally participate in at least three days of training including several practice runs.

Land burn operation training is covered in Section 5.6 above.

8.6 Vessel safety

The size, structure, and navigational equipment of any vessels used in an at-sea oil burn must be suited to the wind, sea state, carrying requirements, and visibility conditions expected during the burn operation. For operations on the open water, vessels should have a reliable positioning system, such as GPS, backup GPS, working radar, working depth sounder, HF radio, VHF radio, and satellite telephone.

Under the typical federal laws, each vessel is legally required to have the appropriate safety equipment in accordance with the size and type of vessel and the type of operation being undertaken. This includes life boats, life rafts, life-saving rings, flares, firefighting equipment, life jackets, survival suits, and navigation lights. Any vessel chartered should possess a valid coast guard inspection certificate. A check by a qualified ship surveyor is recommended before chartering a vessel.

8.7 Land burning safety considerations

Burning on land requires that reliable vehicles be available to operate in the area, and also to escape if necessary. The fire break requires monitoring to ensure there is no breach of that line. At least one fully-equipped fire truck should be on scene with a backup supply of water. Larger fires would require more fire trucks. A large land burn should also be monitored from the air with good communications to all ground crews.

8.8 Establishing safety zones

An important part of the safety program for an in-situ burn operation is establishing minimal safety zones. This has been accomplished in several ways including the use of values that are larger than the measured hazardous distances, as shown in Table 4, and by the use of smoke plume modeling. For burning on land or wetlands, one can use the largest distances shown in Table 4 or 1.5 kilometers as a minimum.
Smoke dispersion modeling has been used frequently in the past decade to establish safe zones and obtain permits for large industrial sources. Specialized models have been developed that can also be applied to in-situ burning. Although models are not intended to replace monitoring, they provide an important tool for assessing the impact of smoke both before and after a burn. Models have also been used to prepare tables of safe distance predictions for typical fires.

Table 4 Safe Distances for a Crude Oil-filled Catenary Boom

<table>
<thead>
<tr>
<th>Metric Units</th>
<th>Boom size - 150 m - 50 m opening</th>
<th>200 m - 66 m opening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burn Area (m²)</td>
<td>Safe Distance (m)</td>
</tr>
<tr>
<td>3/4 three quarters</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>5/8 five eighths</td>
<td>43</td>
<td>46</td>
</tr>
<tr>
<td>1/2 one half</td>
<td>34</td>
<td>44</td>
</tr>
<tr>
<td>3/8 three eighths</td>
<td>26</td>
<td>41</td>
</tr>
<tr>
<td>1/4 one quarter</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
<td>1/8 one eighth</td>
<td>9</td>
<td>32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>U.S. Customary Units</th>
<th>Boom size - 500 foot - 166 foot opening</th>
<th>700 foot - 233 foot opening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burn Area (square feet)</td>
<td>Safe Distance (ft.)</td>
</tr>
<tr>
<td>3/4 three quarters</td>
<td>165</td>
<td>156</td>
</tr>
<tr>
<td>5/8 five eighths</td>
<td>137.5</td>
<td>149</td>
</tr>
<tr>
<td>1/2 one half</td>
<td>110</td>
<td>142</td>
</tr>
<tr>
<td>3/8 three eighths</td>
<td>82.5</td>
<td>132</td>
</tr>
<tr>
<td>1/4 one quarter</td>
<td>55</td>
<td>122</td>
</tr>
<tr>
<td>1/8 one eighth</td>
<td>27.5</td>
<td>102</td>
</tr>
</tbody>
</table>

* safe distances are typical downwind distances where fine particulates (2.5 µm) are less than the prescribed level (<35 µg/m³)

The side distances in a constant wind are estimated to be 1/10 of these values. The values for diesel or diesel-like crude oils are 8.5 times the crude oil values

It is important to recognize the limitations of each type of hazard zone estimation. Differing weather conditions can change the concentrations of particulate matter dramatically. In some cases, the plume drops to ground level. Weather officials should be consulted for possible wind changes, atmospheric inversions, and other factors that can change the trajectory and impact of the plume.

9 Monitoring and sampling for emissions

Monitoring the emissions during an in-situ burn operation can provide continuous feedback as to whether the burn is progressing properly and safely. A well planned monitoring program, in which data are recorded before, during, and after a burn, will also help answer any questions that come up after a burn operation is completed. It is generally recommended that, if possible, the following sampling and monitoring be performed for any in-situ burn operation:

- Real-time monitoring of PM-2.5 particulate matter downwind - a minimum sampling requirement,
- Real-time monitoring of volatile organic compound (VOCs) downwind,
Soot sampling for analysis for organic compounds and polyaromatic hydrocarbons (PAHs),
Monitoring of combustion gases, and
Residue sampling for analysis for organic compounds and PAHs.

If it is determined that burning can be done safely and will likely result in the least overall environmental impact, operations should not be delayed because of monitoring and sampling.

The minimum monitoring and sampling should include:

- Visual monitoring of the smoke plume, its trajectory and its possible impacts to humans or sensitive environments. Time and physical locations should be documented.
- Monitoring of 2.5 µm particulates downwind of the burn at receptor height 1.5 m (5 ft.) and at between 1 to 3 kilometers downwind of the burn at the receptor height at any potential human impact locations.

Monitoring could be extensive for primarily scientific reasons. Environmental agencies may be interested in conducting extensive monitoring and sampling such as shown in Figure 6 or Figure 65.

Figure 65   Extensive monitoring carried out for scientific purposes at a test burn
9.1 Visual monitoring

Visual monitoring is not as effective as monitoring using instruments. Obviously, gases and light concentrations of particulate matter cannot be seen. The trajectory of the smoke plume can be observed, however, and its passage over land, population centers, and other points of concern can be noted, timed, and recorded. This information is necessary if there is ever a question of exposure to emissions after an in-situ burn incident. The prime areas of deposition should be surveyed after a burn to check for soot deposits. If soot is found, it should be sampled for possible analysis if necessary.

9.2 Real-time monitoring

In general, real-time monitoring of emissions should be performed downwind of the fire and at a point closest to populated areas. Studies of the emissions from in-situ oil burns indicate that the main public health concern is particulate matter in the smoke plume as this is the first emission that normally exceeds recommended health concern levels.

For monitoring of particulate matter, it is generally accepted that the concentration of small respirable particles having diameters of 2.5 µm or less (PM-2.5) should be less than 35 µg/m³ for a 24-hour period. This is the standard set out by several national authorities.

The devices currently used to carry out real-time monitoring of particulates are the Dustrak, MiniRAM and DataRAM aerosol monitors, which are capable of detecting the PM-2.5 particulates emitted by a burn. A cluster of similar instruments is shown in Figure 66. It is important to note that the concentrations of particles downwind are very variable over time. A reading can be over the recommended maximum value one instant and then at baseline values the next. Furthermore, the background values must be measured and subtracted from the current value. As both the MiniRAM and DataRAM measure humidity as particulate (which it is), the instructions state that these instruments should not be used in locations where there is high humidity. This certainly applies to locations on boats and near the sea. Experimentation has shown that high humidity can lead to readings as much as five times the maximum exposure value, although the data can be corrected for this. In both cases, the real-time value on the instrument is noted only for interest. The instrument readings should be electronically recorded and averages calculated from the recorded and corrected data.

The second emission of concern is polyaromatic hydrocarbons or PAHs on the particulate matter. Volatile organic carbons or VOCs are a tertiary concern. There are no reliable real-time or near real-time methods for monitoring PAHs. There are many methods for sampling particulates using pumps and filter papers, however, and some portable devices are also available. Real-time monitoring of VOCs can be done, but the measurement is fraught with difficulties and inaccuracies. VOCs are sampled in many ways, however, the use of evacuated metal cylinders, known as Summa canisters, is easy and yields accurate results.

9.3 Monitoring combustion gases

Combustion gases include carbon dioxide, carbon monoxide, sulphur dioxide and nitrogen oxides. Since only carbon monoxide would be of concern in a petroleum fire, it could easily be monitored. Significant amounts of carbon monoxide would only be formed during an inefficient burn such as a smoldering fire with poor ventilation. Figure 67 shows aerial collection of gases and
particulates.

Figure 66 A cluster of real-time particle monitoring instruments being tested in the field.

Figure 67 Use of a model helicopter to collect samples of combustion emissions. This method is useful for scientific purposes. For practical purposes sampling should be carried out at the human receptor height of 1.5 m (5 feet).

9.3 Sample collection and analysis

There are several methods for collecting and analyzing samples to be used for evaluating the effectiveness of in-situ burning. Not all these methods will be required in an actual emergency burn situation, but depending on the circumstances, regulations, and/or the specific operational plan, some or all of them may be required. There is literature listed in the bibliography which gives more specific procedures for sampling particulate matter.

10 Final disposition of residue

The oil residue left after a burn is usually a heavy, tar-like material which is very viscous and adhesive, similar to a highly weathered oil. The greater the burn efficiency, the higher the density and viscosity of the residue. The burn residue from some types of oil may sink in the water column. This behavior should be determined in advance for common crude and bunker oils being transported in the waters of concern. Figure 68 shows the residue from a burn.
Figure 68  The residue from a 50-ton burn. This amount of residue was estimated to be 20 kg or about 0.05 % of the starting oil.

The decision to recover the residue mechanically or leave it to break down naturally depends on the total volume of the residue, whether the residue is dense enough to sink, and where it is expected to go if left alone. Other considerations include the immediate availability of equipment and personnel who may be deployed in other recovery efforts. On land residue is readily recovered using mechanical means.

At sea, residue is best recovered using a vessel with low freeboard which provides easy access to the water surface. A barge or landing craft used in conventional oil spill response is ideal for this purpose. The amount of residue that can be recovered will depend on the displacement of the vessel and the size of tank and other equipment that can be safely carried on the deck. Figure 69 shows the collection of burn residue using sorbents. Depending on sea conditions and the dimensions and displacement of the barge, such a vessel could carry an estimated 1 to 5 tons of residue.

Recovering residue is simplified if the recovery vessel can be operated from a shore base. The vessel can be launched from shore and the recovered residue can be removed using a vacuum truck on shore. If the residue is too viscous to remove using vacuum devices, it can be removed manually. When conducting a burn on the open ocean, launching and retrieving a boat to recover residue can be difficult. Unless the burn site is within reasonable distance of shore, the residue recovery vessel must be deployed from one of the larger vessels towing the fire boom. This vessel must be equipped with a suitably-sized crane to launch and retrieve the residue boat and have enough tankage or deck space to hold the recovered residue.

Transferring the recovered residue to a larger vessel could be difficult, especially if the larger ship has a high freeboard. The residue tanks should therefore be carried on the ship with the lowest transfer height. Residual oil can also be collected in a backup boom and recovered using sorbents or skimmers suitable for use with heavy oil. Depending on the volume, the residue can be recovered or transferred using either a vacuum suction system or a submersible pump or it can be manually transferred with shovels and buckets.
Residual oil can also be collected in a backup boom and recovered using sorbents or skimmers suitable for use with heavy oil. Depending on the anticipated volume and properties of the residue, the collected residue could be transferred using either a vacuum suction system, a submersible pump such as the many heavy oil pumps now available, or manually using shovels and buckets.

Another option is to herd the residue into one area using pumps or water hoses deployed from a small boat. Once herded, it may be possible to re-ignite the residue or to ignite it with newly collected oil to further reduce the volume of residue to be recovered.

11 Equipment availability and checklist

Before starting any in-situ burn response operation, it must be ensured that all the required equipment is available. To assist in determining the type and specifications of the equipment that may be required for a burn operation, an equipment checklist has been included in Table 5 for at sea burning and Table 6 for land/marsh burning.
### Table 5

**Burn Equipment Checklist for at Sea Burns**

<table>
<thead>
<tr>
<th>Vessels and Aircraft</th>
<th>General Supplies</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Tow vessels</td>
<td>- Burn plan</td>
</tr>
<tr>
<td>- Command vessel</td>
<td>- Safety plan</td>
</tr>
<tr>
<td>- Surveillance aircraft</td>
<td>- Radios</td>
</tr>
<tr>
<td>- Helicopter for igniter</td>
<td>- Contact lists</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety Equipment</th>
<th>Helitorch Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Fire pump for each tow boat</td>
<td>- Helitorch unit</td>
</tr>
<tr>
<td>- Fire hoses</td>
<td>- Helicopter harness</td>
</tr>
<tr>
<td>- Fire nozzles</td>
<td>- Fuel gellant</td>
</tr>
<tr>
<td>- Fire extinguishers</td>
<td>- Fuel mixture</td>
</tr>
<tr>
<td>- First aid kits</td>
<td>- Fire extinguishers</td>
</tr>
<tr>
<td>- Fire blankets for tow boats</td>
<td>- Hard hat</td>
</tr>
<tr>
<td>- Extra radios</td>
<td>- Gloves</td>
</tr>
<tr>
<td></td>
<td>- Goggles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Containment Equipment</th>
<th>Monitoring Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Full length of fire-resistant boom</td>
<td>- RAM and/or Dustrac</td>
</tr>
<tr>
<td>- Extra lengths</td>
<td>- PAH Sampling pump/filters</td>
</tr>
<tr>
<td>- Towing paravanes</td>
<td>- Summa cannister</td>
</tr>
<tr>
<td>- Towing cables</td>
<td>- Recording notebook, pens</td>
</tr>
<tr>
<td>- Bridles</td>
<td></td>
</tr>
<tr>
<td>- Attachment shackles</td>
<td></td>
</tr>
<tr>
<td>- Anchors - if needed</td>
<td></td>
</tr>
<tr>
<td>- Equipment for backup boom if needed</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ignition Equipment</th>
<th>Personal Protection Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Hand-held igniters</td>
<td>- Respirators</td>
</tr>
<tr>
<td>- Helitorch and accessories</td>
<td>- Boots, gloves</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Residue Cleanup Equipment</th>
<th>Personal Cleanup Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Sorbents</td>
<td>- Sorbents, rags, towels</td>
</tr>
<tr>
<td>- Shovels or bailers</td>
<td>- Citrus cleaner</td>
</tr>
<tr>
<td>- Drums or other recovery collection containers</td>
<td>- Garbage bags</td>
</tr>
<tr>
<td>- Heavy oil skimmer - if necessary</td>
<td>- Soap, warm water</td>
</tr>
<tr>
<td>- Pumps and hoses for skimmer</td>
<td>- Extra clothing</td>
</tr>
</tbody>
</table>
Table 6

Burn Equipment Checklist for on Land Burns

<table>
<thead>
<tr>
<th>Vehicles and Aircraft</th>
<th>General Supplies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational vehicles</td>
<td></td>
</tr>
<tr>
<td>Backup Vehicles</td>
<td></td>
</tr>
<tr>
<td>Surveillance aircraft</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire pump for each vehicle</td>
</tr>
<tr>
<td>Fire hoses</td>
</tr>
<tr>
<td>Fire nozzles</td>
</tr>
<tr>
<td>Fire extinguishers</td>
</tr>
<tr>
<td>First aid kits</td>
</tr>
<tr>
<td>Fire blankets for vehicles</td>
</tr>
<tr>
<td>Extra radios</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fire Break Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural tiller (or)</td>
</tr>
<tr>
<td>Dozer/gradedr</td>
</tr>
<tr>
<td>Shovels and rakes</td>
</tr>
<tr>
<td>Water, pumps, hoses</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fire Snuffing Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shovels and rakes</td>
</tr>
<tr>
<td>Snuffers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ignition Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand-held igniters</td>
</tr>
<tr>
<td>Driptorch and accessories</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Residue Cleanup Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorbents</td>
</tr>
<tr>
<td>Shovels or bailers</td>
</tr>
<tr>
<td>Drums or other recovery collection containers</td>
</tr>
<tr>
<td>Heavy oil skimmer - if necessary</td>
</tr>
<tr>
<td>Pumps and hoses for skimmer – if necessary</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Visual Monitoring Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Note books</td>
</tr>
<tr>
<td>Binoculars</td>
</tr>
<tr>
<td>Camera, annotated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission Monitoring Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAM(s) and/or Dustrac(s)</td>
</tr>
<tr>
<td>PAH Sampling pump/filters</td>
</tr>
<tr>
<td>Summa canister(s)</td>
</tr>
<tr>
<td>Recording notebook, pens</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Personal Protection Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respirators</td>
</tr>
<tr>
<td>Boots, gloves</td>
</tr>
<tr>
<td>Special clothing</td>
</tr>
<tr>
<td>Hard hats</td>
</tr>
<tr>
<td>Goggles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Personal Cleanup Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorbents, rags, towels</td>
</tr>
<tr>
<td>Citrus cleaner</td>
</tr>
<tr>
<td>Garbage bags</td>
</tr>
<tr>
<td>Soap, warm water</td>
</tr>
<tr>
<td>Extra clothing</td>
</tr>
</tbody>
</table>
12 Post-burn actions

12.1 Follow-up monitoring

The site must be surveyed immediately after the burn to ensure that no burning materials remain in the area. On sea, this could include thick patches of escaped oil, parts of the boom, or burning organic matter. After this immediate surveillance, the residue should be recovered quickly before it sinks. Areas where residue may have sunk should be carefully documented as this could adversely affect the benthic environment. The area should be surveyed and the amount of unburned oil remaining should be estimated. This amount of residue is important in estimating the overall mass balance. On land, priority is given to finding and quenching hot spots. Areas where there are significant amounts of oil remaining should be marked for further disposition.

Analysis of particulate matter, PAHs, and VOCs at the downwind locations should be completed if these were sampled and these results included in the final burn report. In the case of the VOCs, a background sample must be collected on a day when burning is not taking place and when the wind is blowing in a similar direction as that on the day of the burn.

A report on the actions taken during the burn should be prepared at this time to ensure that others can learn from the burn and that a good record is maintained if there are any questions on efficiency or other issues.

12.2 Estimation of amount burned and burn efficiency

At sea, the area of oil burning inside a boom was recorded using a drawing similar to that in Figure 70. The time that this was burning was also recorded. These can be used to calculate the amount of oil burned. The area can be calculated from Figure 70 using Table 7. This will yield an area time the time. The rate of burning is dependent on the oil and conditions to a certain degree. Burn rates are found in Table 3. The procedure is this: Using the charts of the fills recorded during the burn, one estimates the fill area using Table 7. Then multiplying the time that burning took place for this fill level times the burn rate for that type of oil from Table 3, one gets the amount of oil burned. All times and boom fill amounts are calculated this way and then summed. The final result is then the amount of oil estimated to be burned. Burned oil volume calculation is simply the following formula:

\[ \text{Burn Volume} = \text{Area} \times \text{time} \times \text{rate} \times \text{conversion factor} \]

Where the conversion factor for metric units is 0.001 to give volume in m³ and In U.S. Customary units is 0.0006 to yield volume in barrels (area in square feet but burn rate in mm/min.).

Example: During the example burn, nomograms of the type in Figure 70 showed that for 21 minutes that there was a burn of approximately ½ of a 150 m boom filled with medium crude oil. From Table 7 we find that the area is about 1220 m² and from Table 3 that the burn rate is about 3.5 mm/min. Then the amount is burned is 1220*21*3.5*0.001 or 89.7 m³ (560 barrels).
Table 7 Fill to Area Conversions for a Crude Oil-filled Catenary Boom

<table>
<thead>
<tr>
<th>Metric Units</th>
<th>Boom size - 150 m - 50 m opening</th>
<th>Burn Area</th>
<th>200 m - 66 m opening</th>
<th>Burn Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>Length (m)</td>
<td>width (m)</td>
<td>(m²)</td>
<td>Length (m)</td>
</tr>
<tr>
<td>3/4 three quarters</td>
<td>51</td>
<td>48</td>
<td>2020</td>
<td>68</td>
</tr>
<tr>
<td>5/8 five eighths</td>
<td>43</td>
<td>46</td>
<td>1610</td>
<td>57</td>
</tr>
<tr>
<td>1/2 one half</td>
<td>34</td>
<td>44</td>
<td>1220</td>
<td>45</td>
</tr>
<tr>
<td>3/8 three eighths</td>
<td>26</td>
<td>41</td>
<td>860</td>
<td>35</td>
</tr>
<tr>
<td>1/4 one quarter</td>
<td>17</td>
<td>38</td>
<td>530</td>
<td>23</td>
</tr>
<tr>
<td>1/8 one eighth</td>
<td>9</td>
<td>32</td>
<td>220</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>U.S. Customary Units</th>
<th>Boom size - 500 foot - 166 foot opening</th>
<th>area</th>
<th>700 foot - 233 foot opening</th>
<th>area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>Length (feet)</td>
<td>width (feet)</td>
<td>area (square feet)</td>
<td>Length (feet)</td>
</tr>
<tr>
<td>3/4 three quarters</td>
<td>165</td>
<td>156</td>
<td>21000</td>
<td>231</td>
</tr>
<tr>
<td>5/8 five eighths</td>
<td>137.5</td>
<td>149</td>
<td>16800</td>
<td>193</td>
</tr>
<tr>
<td>1/2 one half</td>
<td>110</td>
<td>142</td>
<td>12700</td>
<td>154</td>
</tr>
<tr>
<td>3/8 three eighths</td>
<td>82.5</td>
<td>132</td>
<td>9000</td>
<td>116</td>
</tr>
<tr>
<td>1/4 one quarter</td>
<td>55</td>
<td>122</td>
<td>5500</td>
<td>77</td>
</tr>
<tr>
<td>1/8 one eighth</td>
<td>27.5</td>
<td>102</td>
<td>2300</td>
<td>39</td>
</tr>
</tbody>
</table>

*safe distances are typical downwind distances where fine particulates (2.5 µm) are less than the prescribed level (<35 µg/m³)

The side distances in a constant wind are estimated to be 1/10 of these values. The values for diesel or diesel-like crude oils are 8.5 times the crude oil values.

Burn efficiency is measured as the percentage of oil removed compared to the amount of residue left after the burn. The burn efficiency, E, can be calculated by the following equation, where \( V_{oi} \) is the initial volume of oil to be burned and \( V_{of} \) is the volume of residual oil remaining after burning:

\[
E = \frac{V_{oi} - V_{of}}{V_{oi}} \quad (2)
\]

In this equation, the initial volume of oil, \( V_{oi} \), can be estimated in a number of ways. If the spill source is known, as in the case of a vessel or storage depot, the volume spilled can be estimated from the tank size and the amount of oil remaining in the tank. In the case of an offshore rig, the pumping rate can be used to estimate the initial volume. If the source is unknown or the volume of oil released from the source cannot be estimated, the volume of the slick can be estimated either visually using objects of known dimensions, e.g., response vessel or containment boom, or using timed overflights, aerial photographs, or remote sensing devices. This area together with an estimate of the average thickness of the oil, performed either visually, can then be used to estimate the volume of the slick. In the case of burning at sea using a containment boom, the amount burned versus an estimate of the residue can constitute the inputs to equation (2).

Spills on land or marshes cannot be estimated by the above methods since much of the material burned maybe vegetation.
Figure 70  Chart used to record and estimate boom area burning
13 Acknowledgments

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