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In-situ Burning: A Cleanup Technique for Oil Spills

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In-Situ Burning:
A Cleanup Technique for Oil Spills

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- To promote the development of bilateral and regional cooperative agreements on emergency planning through joint government/industry cooperation.
- To provide guidance to assist industry's efforts in being proactive in the prevention of oil spills.

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ABSTRACT

In-situ burning is recognized as a viable alternative to mechanical methods for cleaning up oil spills on water, and in near shore areas, wetlands, and other land situations. When performed properly and 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 and thereby protecting aquatic biota. Such rapid removal of oil can also prevent the oil from reaching shorelines, which are difficult to clean and where the greatest environmental damage caused by oil spills occurs.

What remains after an in-situ burn are burn by-products such as carbon dioxide, water, some smoke particulate, and unburned oil in the form of residue. Sufficient information is now available to predict levels of emissions from the fire and to calculate safe distances downwind from the fire. It may be necessary to contain the oil in order to carry out in-situ burning as the oil must be thick enough to burn - a minimum of 2 to 3 mm. Even if containment is necessary, however, in-situ burning requires less equipment and personnel than mechanical methods of oil spill cleanup.

This document provides guidance on decision-making for in-situ burning of oil spills. It contains a compilation of information about in-situ burning of oil spills and includes the scientific aspects of the burning process and its effects, examples from the extensive research into in-situ burns, and practical information about the procedures to be followed and equipment required for carrying out such a burn.

EXECUTIVE SUMMARY

While in-situ burning of oil spills has been tried over the past 30 years, it has only recently been accepted as an oil spill cleanup option in some countries. The lack of acceptance and implementation of burning as a cleanup option is largely because both the combustion products resulting from the burning of oil and the principles governing the combustibility of oil on water are poorly understood. This report provides basic information on these two major topics as well as practical advice on how to conduct burns.

The two essential physical concepts associated with burning are the minimum amount of vapors required above the oil slick, which is often simplified to a minimum thickness of about 2 to 3 mm, and the fixed burn rate. The burn rate is about 3.75 mm/min for a lighter crude oil and about 1 mm/min for heavier oil. Fuel, oxygen, and an ignition source are required. Fuel is provided by the vaporization of oil, which 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 a light crude oil slick is burning, it burns at a rate of about 3.75 mm per minute, which means that the depth of oil is reduced by 3.75 mm per minute. This rate is limited primarily by the amount of oxygen available. As a rule of thumb, the burn rate for light crude oil is about 5,000 L/m^2 per day. Typical crude oil burn at about half this rate, and heavier oils burn at a rate of about 1,200 L/m^2 per day.

The oil burn rate is a function of the area covered by the oil because of the physics of a burn, that is, the volume does not affect the amount burned in a given time, only the area burned. 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. Since most oils have about the same insulation factor, most slicks must be about 2 to 3 mm thick to be ignited and yield a steady-state burn. Once burning, the heat radiated back to the slick and the insulation are usually sufficient to allow burning down to about 1 mm of oil. 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, and small explosions, or fireballs, may occur.

Studies conducted in the last 10 years have shown that the type of oil is relatively unimportant in determining how an oil ignites and how efficiently it burns. Heavy oils, however, require longer heating times and a hotter flame to ignite than lighter oils. Heavier oils have also been shown to burn at a lower rate and at only about 70% efficiency. It is uncertain whether oil that is completely emulsified with water can be ignited, although oil containing some emulsion can be ignited and burned. Burn efficiency is the initial volume of oil before burning, less the volume remaining as residue, divided by the initial volume of oil. Efficiency is largely a function of oil thickness.

The residue from burning oil is largely unburned oil with some lighter or more volatile products removed. When the fire stops, unburned oil is left that is simply too thin to sustain combustion. In addition to unburned oil, oil that has been subjected to high heat is also present and is thus weathered. Finally, heavier particles are re-precipitated from the smoke plume back 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. Floating residue can be recovered using methods similar to those used for recovering very heavy oils. Small amounts of residue can be recovered by hand, using shovels and sorbents.

Fire-resistant containment booms may be needed to concentrate the oil to thicknesses that will burn well and efficiently. The types of these booms currently available include: water-cooled booms, stainless-steel booms, thermally resistant booms, and ceramic booms. Most fire-resistant booms, especially stainless-steel booms, require special handling because of their size and weight.

Fire-resistant booms are typically towed in a U-configuration by two boats or small ships. Oil is collected in the apex and ignited and the boom is towed so that oil continues to enter the boom. Tow speeds must be maintained below about 0.4 m/s (0.75 knots) to avoid oil loss. A 200-m boom will provide a maximum burn area of about 1,500 m^2. This burn area would remove oil at a maximum rate of 300 m^3/h. The rate for a typical crude would be about half of this and, for a heavier oil, could be as low as 1/4 of this.

As the U-configuration is difficult to maintain with two tow vessels, a tether line or cross bridle is often extended across the open end of the U to assist in maintaining the configuration. Concepts for deploying booms in other configurations as well as in diversionary mode are described. Possible techniques for using available materials and conventional booms are also discussed.

The types of ignition devices available for starting in-situ fires are outlined. The helitorch uses gelled fuel to ignite spills from a helicopter. Detailed procedures are given for fueling and deploying these devices. Several hand-deployable ignition devices have been built over the years, some of which can be made from readily available materials. Slicks have often been ignited with fuel-soaked rags or sorbent, indicating that ignition is not usually difficult.

All burn operations must be conducted with safety in mind. Provisions must be made for good communications and backup measures. Burns should be monitored by aircraft whenever possible to provide early warning of heavy oil concentrations and other vital information such as movement of the smoke plume and problems with boom tows and other equipment. A backup method of monitoring burns is to use a larger ship, which provides a better view of the operations than from smaller vessels. The boom tow vessels should be equipped with fire hoses or monitors to drive back oil or burning oil if it approaches too close to the vessel. Burn crews must be trained in methods of escape, how to control unwanted fires, and how to extinguish fires.

The emissions of burning are discussed extensively in this Report. These emissions include those from the smoke plume, particulate matter precipitating from the smoke plume, combustion gases, unburned hydrocarbons, organic compounds produced during the burning process, and the residue left at the burning pool site. Soot particles, although consisting largely of carbon particles, contain a variety of absorbed and adsorbed chemicals. The following is a brief summary of each type of emission.
Particulate Matter/Soot - All burns, especially those of diesel fuel, produce an abundance of particulate matter. Particulate matter at ground level close to the fire and under the plume is a health concern. Concentrations of particulate in emissions from burning diesel are approximately four times that from a similar-sized crude oil burn 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 health concern levels (150 $\mu g/m^3$) as far downwind as 500 m from a small crude oil fire (<500 m^2 burn area).

The greatest concern is the smaller or respirable particulates. The PM-10 fraction, or particulates less than 10 µm, are generally about 0.7 of the total particulate concentration (TSP) of all particulates measured. The PM-2.5 fraction is not easily measured, nor are all facets of particulate understood at this time.

Polyaromatic Hydrocarbons (PAHs) - Oils contain significant amounts of polyaromatic hydrocarbons that 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. This includes the concentration of multi-ringed PAHs, which are often created during other combustion processes such as in 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. When diesel fuel is burned, the emissions show an increase in the concentration of multi-ringed PAHs in the smoke plume and residue, but a net destruction of PAHs is still found.

VOCs - Many volatile organic compounds are emitted by fires, but in lesser amounts than when the oil is not burning. While VOCs are not generally a concern, they can rise almost to health levels of concern very close to the fire [<100 m].

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

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

Gases - Combustion gases such as carbon dioxide, carbon monoxide, and sulfur 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 calculated for fires of various sizes and types. Equations for predicting concentrations of emissions for the various groups and for more than 150 specific compounds are provided, as well as tables of results. A standard crude oil fire would not exceed health levels of concern for emissions beyond about 500 m from the fire.

In some circumstances, the particulate concentrations from in-situ oil fires should be monitored. Procedures and instrumentation to do this are described. On-site measurements are not accurate enough to regulate the use of burning, but rather serve to document what concentrations were reached at a given location. Direct-reading instruments currently do not provide good readings because data require correction for background values and other manipulations such as averaging. The concentration of VOCs can also be measured to provide documentation. A sampling technique for VOCs is described.

1. Introduction

1.1. Purpose

This report outlines the operational steps involved in using in-situ burning to clean up an oil spill focusing on open waters and near shore spill scenarios. In situ burning applied to spills in wetlands, or in other land situations are also –but tangentially- addressed. Information is provided to assist those responding to oil spills to determine whether in-situ burning is a feasible cleanup method for a particular spill. As few in-situ burns have been carried out during actual oil spills, the expertise in this area has been confined to a small group of researchers and responders. This report gathers this expertise into one publication where it will be accessible to all who are interested in this oil spill cleanup technique.

1.2. Scope

This report deals with in-situ burning of oil spills on open water, in marshlands, near shore, and in inter-tidal zones.

1.3. Organization

An overview of in-situ burning is provided in Section 2, which includes the scientific aspects of burning oil and a summary of past research and trials. The steps followed in a typical burn are outlined and the technique is compared to other spill cleanup techniques.

In Section 3, information is provided to assist those responding to oil spills on water to determine whether in-situ burning is a feasible cleanup method for a particular spill. Regulatory approvals are outlined as well as environmental and health concerns associated with burning oil, including the safety of response personnel and the general public, the types of air emissions produced by an in-situ oil burn and how these emissions and a corresponding safe distance downwind from such a fire are calculated, and effects on water quality. The effect on in-situ burning of both the properties and conditions of the oil and weather and ambient conditions are also discussed. Burning oil spills in environmentally sensitive locations such as marshes or near shore areas is also discussed.

In Section 4, the types of equipment required for an in-situ burn are described. This includes containment booms, ignition devices, treating agents, support vessels and aircraft, monitoring, sampling, and analytical equipment, and equipment for recovering residue. How this equipment is deployed and the operating procedures for the equipment are included in this section.

In Section 5, information is provided on how to develop a Net Environmental Benefit Analysis and on specific oil spills that could be dealt with by in-situ burning and some strategies are outlined for actual burning techniques.

In Section 6, actions to be taken after a burn are discussed, including follow-up monitoring and estimating burn efficiency, burn rate, and the amount of oil burned.

Health and safety precautions to be taken by personnel operating equipment during an in-situ burn are discussed in Section 7. This includes ways of preventing unwanted ignition and secondary fires, when to reassess or terminate burning, a review of potential problems while burning, ways to control or extinguish a fire, safe handling of booms, safe operation of ignition systems, particularly helitorches, exposure of personnel to burning operations, personal protective equipment, training for response personnel, vessel and aircraft safety, and public health and safety precautions.

A glossary of technical terms related to in-situ burning is included in Section 9.

To supplement topics discussed in the text, more detailed information is supplied in the Appendices.

2. An Overview of In-Situ Burning

2.1. 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 (Evans *et al.*, 1991). 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. For in-situ fires, the rule-of-thumb is that the slick must be at least 2 to 3 mm thick for ignition to start. Actually a sufficient abundance of vapors is what is necessary to start an oil layer burning. Once a crude oil slick is burning, it burns at a rate of about 3.75 mm per minute. A heavier oil may burn at rates as low as 1 mm/min (Fingas *et al.*, 2004). 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 area covered by the oil because of the physics of a burn, that is, the volume does not affect the amount burned in a given time, only the area burned.

- Oils on water must have a minimum of vapors above an oil layer in order to burn. The rule of thumb is that light oils must be 2 to 3 mm thick to be ignited and sustain burning because of heat loss to water.
- Burn rate for crude oil is usually 3.75 mm/min, which yields a rule-of-thumb of about 5000 L/m^2day. Burn rate for heavy oils may be as low as 1 mm/min which yields a daily rate of about 1300 L/m^2day.
- Oil completely emulsified with water may not ignite but less stable emulsions may burn if a sufficient area is ignited.

The 'steady-state' burning implies that the conditions noted above are met (Thompson *et al*., 1979). 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. This has been estimated to be about 2 to 3% of the heat from a fire (Buist *et al.*, 1994). 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 2 to 3 mm thick, as noted above, to be ignited and yield a steady-state burn. Once burning, the heat radiated back to the slick and the insulation are usually sufficient to allow combustion down to about 1 mm of oil.

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 diesel fuel 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 (Fingas *et al.*, 1996a).

The amount of oil that can be removed in a given time depends on the area covered by the oil. As mentioned above, most oil pools burn at a rate of about 3.75 mm per minute, which means that the depth of oil is reduced by 3.75 mm per minute. As a rule of thumb, oil burn rate is about 5,000 L/m^2.day. Several tests have shown that this does not vary significantly with oil type and weathering (Evans *et al*., 1990). Emulsified oil may burn slower as its water content reduces the spreading rate and increases the heat requirement.

Historically, it was thought that the burn rates depended on scale size. The early work proposed a cyclic relationship between burn rate and pan diameter (Buist *et al*., 1994). This theory was based on propositions about flame characteristics in the laminar flow region (0 to 10 cm), to the transition zone (10 to 100 cm), through to the turbulent flow regime (>100 cm). Since most tests and actual burns are more than 100 cm in diameter, this theory may not be relevant to in-situ burning. Some authors reported an increase in burn rate with wind speed (Buist *et al*., 1994). This work reported an increase equal to 0.15 times the wind speed multiplied by the quiescent burn rate. This translates into about a two-fold increase in burn rate for a ten-fold increase in wind speed.

Studies conducted in the last ten years have shown that the type of oil is relatively unimportant in determining how an oil ignites and burns. However, heavy oils require longer heating times and a hotter flame to ignite than lighter oils. Heavier oils burn more slowly than light oils (Fingas *et al*., 2004a). Earlier studies appeared to indicate that heavier oils and oils with water content required greater thickness to ignite; however, recent testing has shown this to be incorrect (Buist *et al*., 1994).

Burn efficiency is the initial volume of oil before burning, less the volume remaining as residue, divided by the initial volume of the oil. The amount of soot produced is usually ignored in calculating burn efficiency. 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%. Current research has shown that other factors such as oil type and low water content only marginally affect efficiency.

Most, if not all, oils will burn on water if slicks are thick enough. Except for light refined products, different types of oils have not shown significant differences in burning behavior. Weathered oil requires a longer ignition time and somewhat higher ignition temperature (Twardus, 1980). At the time of the *Torrey Canyon* spill, it was not known that the thickness of the oil would be a limitation. Glassman and Hansel (1968) conducted studies shortly after this incident and concluded that the slicks that did not ignite were below minimum thickness. Maybourn (1971) studied oil ignition thicknesses and found that slicks that were 3 and 6 mm thick burned. Twardus (1980) conducted preliminary tests of minimum burning thicknesses and proposed that all fuels burned at the 5 mm initial thickness tried. Bunker C required longer heating times and the addition of crude.

Further testing on light crudes showed that the minimum thickness for ignition was 0.58 to 0.62 mm and the residues varied between 0.35 and 0.58 mm (Twardus and Bruzustowski, 1981). This was compared to unconfined fresh oil thicknesses of 0.5 to 0.6 mm at 0 °C, 0.2 to 0.25 mm at 5 °C, and 0.5 mm at 10 °C. Aged oil showed limited spreading thicknesses of 1.90 to 3.0 mm at 0 °C, 1.2 to 2 mm at 5 °C, and 1.2 to 1.3 mm at 10 °C.

Arai *et al.* (1993) studied burn rates of various crudes and found that rates decreased at thicknesses from 18 to 1 mm, but most oils could be ignited at 1 to 2 mm. It was thought that the initial burn thickness depended on variances in the thermal conductivity of the starting oil. Elam *et al.* (1989) measured the thermal conductivity of three crude oils as being 130 mW/m K over a 50 K temperature range. Little difference was found for oil type or temperature. Overall, most workers have concluded that the rule-of-thumb is that the minimum ignitable thickness of oil is 2 to 3 mm as this thickness will always burn.

Some studies have been conducted of the final thickness of burning oil on water before it is extinguished. Buist *et al.* (1994) reviewed a large number of cases in which oil burn residue, or the thickness of the oil at the end of the burn, was measured. They found that the average final thickness was 1 mm and the residue ranged in thickness from about 0.5 to 2 mm. Thus, it was proposed that 1 mm be adopted as the rule-of-thumb for final burn thickness.

It is uncertain whether oil that is completely emulsified with water can be ignited. Oil containing some emulsion can be ignited and burned (Smith and Diaz, 1987). During the successful test burn of the *Exxon Valdez* oil, some patches of emulsion were present (probably less than 20% by areal coverage). While it did take longer to ignite the burn (>5 minutes), it did not affect the efficiency of the burn (Allen, 1990). It is suspected that fire breaks down the water-in-oil emulsion and thus water content may not be a problem if the fire can be started. Evidence is inconclusive at this time on the water content at which emulsions can still be ignited. One test suggested that a heavier crude would not burn with about 10% water (Smith and Diaz, 1987), another oil burned with as much as 50% water, and still another burned with about 70% water (Twardus, 1980).

Twardus (1980) noted that mixtures containing less than 20% water ignited readily but required pre-heating. Mixtures of oil with 30 to 50% water required a powerful igniter and a still longer pre-heating time. Three mixtures containing about 70% water burned with a long pre-heating time and a powerful igniter. One study indicated that emulsions may burn if a sufficient area is ignited (Bech *et al*., 1992). Further studies indicated that stable emulsions will not burn but oil containing less than 25% water can be ignited. The burning of emulsions may be related to their stability class (Fingas *et al*., 1998a). It should be noted that the emulsion stability was not measured in any of the previous studies. Emulsions may not be a problem because chemical de-emulsifiers could be used to break enough of the emulsion to allow the fire to start.

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.

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 1 to 3% for crude oil fires and about 8% for diesel fires (Fingas *et al*., 1996b). 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.

Soot consists of agglomerates of spherical particles. Nelson (1989) measured several soot agglomerates and found that the individual spheres had radii of 5 to 25 nm (1 nm = 1000 µm). Soot particles were aggregates of 50 to 250 spheres and the aggregation could be described as a fractal dimension of 1.7 to 1.9. Sorensen and Feke (1996) studied soot particles and found that the aggregates ranged from 50 nm to 400 µm with a fractal dimension of 1.8. The primary particle size was found to be 5 nm with the smallest typical aggregation being 10 to yield the smallest typical diameter of 50 nm.

The total heat radiated by a given burn has been measured as 1.1 MW/m^2 (Evans *et al.*, 1988). Evans calculated that the heat required to vaporize the oil was 6.7 KW/m^2 and the heat lost from conduction through the slick to the underlying water was 2.5 KW/m^2. The fraction of heat released that was radiated back to the pool was about 0.02 at the rim of the pool and 0.045 at the centre. Other researchers report a re-radiated heat fraction between 0.01 and 0.02 (1 to 2%) (Buist *et al.*, 1994).

McCourt *et al.* (1998) reported on the total heat radiated by various fires. Alaska North Slope oil showed a heat release rate of 176 KW/m^2, diesel fuel 230 KW/m^2, and propane, 70 KW/m^2. The heat radiated by a liquid propane fire enhanced by air flow and increased pressures was 180 KW/m^2. The heat flux on booms as a result of these fires was reported as 140 to 250 KW/m^2 for crude oils, 120 to 160 KW/m^2 for diesel fuel, 60 to 100 KW/m^2 for propane, and 100 to 160 KW/m^2 for enhanced propane burning.

Flame spreading rates have been measured at several fires (Buist *et al*., 1994). Flame spreading rates do not vary much with fuel type, but vary significantly with wind, especially as this relates to up and down wind. 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. Fingas *et al*. (2004a) measured the flame spread of a variety of heavy oils including Orimulsion and Bunker C as an average 0.05 m/s. Wu *et al.* (1997) measured flame velocities as a function of external heat fluxes and found these to vary from 0.01 to 0.16 m/s (0.02 to 0.3 knots), depending on the heat flux.

Higher heat fluxes yielded high flame spread rates. Flame velocities did not change when oil was thicker than 8 mm. Flame heights have been measured by several authors (Buist *et al*., 1994).While data vary significantly, a rule-of-thumb could be that the flame height of a small fire less than 10 m (33 ft) 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 (Buist *et al.*, 1994). This is caused by increasing heat transfer back to the water surface with decreasing slick thickness. Significant amounts of heat are transferred to water near the end of a burn when slick thickness approaches 1 mm (0.04 in) 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 the NOBE burn, no vigorous burning was observed and thermocouple measurements in the water showed no increase in the water temperature (Fingas *et al.*, 1994b). This is due to two factors, first the movement of the slick over the water and secondly, the vast amount of water under the burn. Thus, the phenomenon of the rapid or vigorous burn phase is not relevant to the at-sea situation.

Pilewskie and Valero (1992) measured the radiative effect of the Kuwait oil fires at a point about 100 km downwind of the fires. They found that the smoke plume absorbed about 78% of the solar radiation and about 8% was transmitted to the land surface. The smoke reached a maximum height of 4.5 km with little penetrating the stratosphere, which indicates that self-lofting did not occur. This is a phenomenon that may occur if a plume maintains or increases its buoyancy as a result of heat absorption from the sun.

The history of the science of in-situ burning is filled with interesting theories and suppositions. There are several reviews on older theories (Buist *et al*., 1994; Evans, 1994). In summary, much of the older data may be irrelevant to burning per se, simply because newer studies have shown many of the factors or possible burn parameters to be less important than once thought.

2.2. Summary of In-situ Burning Research and Trials

The first reference in the literature to the burning of oil on water was the use of a log boom to burn oil on the Mackenzie River in 1958 (McLeod and McLeod, 1972). This same reference notes that burning of spilled oil on land had gone on for many years. Failed attempts to ignite the oil spilled from the *Torrey Canyon* in 1968 were widely known (Swift *et al.*, 1968). Extensive research on in-situ burning of oil spills began in the late 1970s and was carried out in North America by Environment Canada, the U.S. Coast Guard (USCG), the U.S. Minerals Management Service (USMMS), and the U.S. National Institute of Standards and Technology (NIST).

Over the years, research into in-situ burning has included laboratory-, tank-, and full-scale test burns. The initial tests in the early 1980s were performed by ABSORB (now Alaska Clean Seas) and USMMS to evaluate the burning of oil in ice-covered areas. This research covered environmental and oil conditions such as sea state, wind velocities, air and water temperatures, ice coverage, oil type, slick thickness, and degree of oil weathering and emulsification (Tennyson, 1994). Several tests have also been performed in an oil spill test tank at the USMMS OHMSETT Facility in New Jersey. Since the early 1990s, several meso-scale burns have been performed at the USCG Fire and Safety Detachment in Mobile, Alabama.

The largest and most extensive offshore test burn took place off the coast of Newfoundland, Canada in August 1993 (Environment Canada, 1997; Fingas *et al.*, 1994a, 1994b, and 1995a). The Newfoundland Offshore Burn Experiment (NOBE) involved 25 agencies from Canada and the United States. Two 50,000 L lots of oil were released and burned within a fire-resistant boom. During this test, more than 2,000 parameters were evaluated using various sampling and sensory methods.

The major findings were that all emission and pollutant levels measured 150 m away from the burn were below health concern levels and that at 500 m from the burn, these levels were difficult to detect. In many cases, pollutants in the smoke plume were less than detected in the original unburned oil. The results also showed that the emission levels from this large burn were lower than found during the meso-scale burns.

Tests of various aspects of burning were conducted at the USCG facility in Mobile Bay, Alabama in 1991, 1992, and 1994 (Fingas et al., 1993, 1996a). More than 35 burns were conducted using crude oil and diesel fuel. Physical parameters were measured as well as emission data.

Fire boom test evaluations using diesel fuel were conducted in 1997 and 1998 by the National Institute of Standards and Technology (NIST) and sponsored by the U.S. Coast Guard Research and Development Center and the U.S. Minerals Management Service (Walton et al., 1998, 1999). Five booms were evaluated in 1997 and six in 1998. The test evaluations were conducted in a wave tank designed specifically for evaluating fire-resistant containment booms located at the U.S. Coast Guard Fire and Safety Test Detachment facility in Mobile Bay, Alabama. The wave tank was designed to accommodate a nominal 15-m boom section, forming a circle approximately 5 m in diameter. The test cycle consisted of three one-hour burning periods with two one-hour cool-down periods between the burning periods, in accordance with the draft American Society of Testing and Materials (ASTM) F-20 Committee standard (ASTM, 1999b). Four of the six booms evaluated in 1998 were shipped to the OHMSETT facility for post-burn oil containment and tow tests based on ASTM suggestions. In general, there was some degradation of materials in all of the booms.

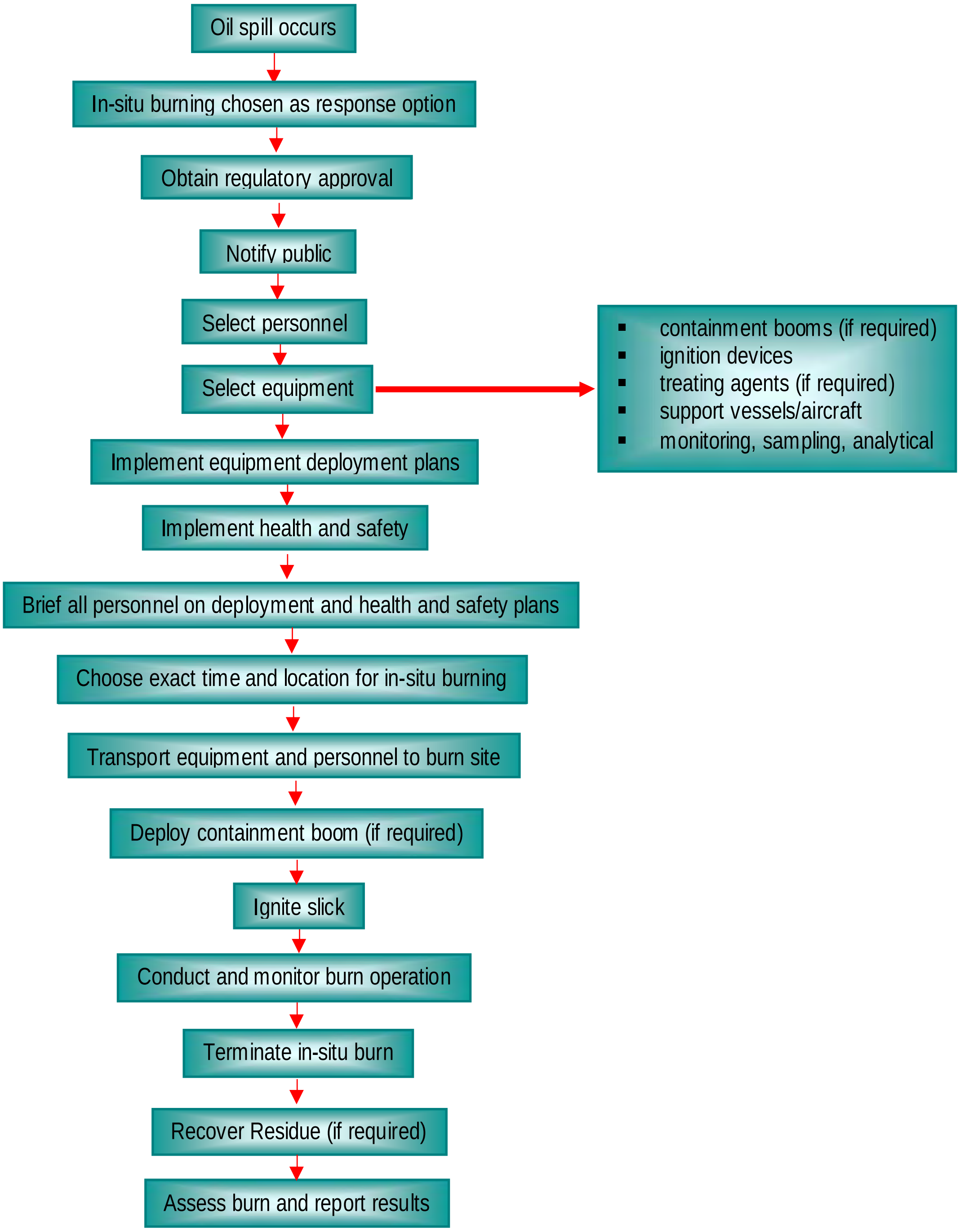
More tests were conducted in 1996 and 1997 by S.L. Ross Environmental Research Ltd., sponsored by the U.S. Minerals Management Service and the Canadian Coast Guard (McCourt *et al.*, 1998). These tests evaluated fire booms using propane rather than the smoke-producing fuels such as diesel or crude oil. The propane test evaluations were conducted in a wave tank located at the Canadian Hydraulic Centre, National Research Council of Canada in Ottawa. The heat flux measured in the 1997 tests with air-enhanced propane was compared to those measured in the diesel fuel fires.

Two separate fire boom test evaluations using air-enhanced propane were conducted in the fall of 1998 by MAR, Inc. and S.L. Ross Environmental Research Ltd (McCourt *et al.*, 1998, 1999). Both tests were conducted at the OHMSETT facility in Leonardo, New Jersey. The first test was sponsored by the U.S. Minerals Management Service and the U.S. Navy Supervisor of Salvage (SUPSALV). Three candidate fire protection systems were tested and evaluated. Each consisted of a water-cooled blanket designed to be draped over existing oil boom to protect its exposure to an in-situ oil fire. In the second fire boom evaluation, a prototype stainless steel Pocket Boom was tested and evaluated using the air-enhanced propane system. The Pocket Boom was a redesign of the Dome boom originally developed for use in Arctic seas. Liquid propane from a storage tank was heated to create gaseous propane and piped to an underwater bubbling system. The test protocol was similar to the ASTM draft method noted above. The booms generally survived the tests and showed less degradation than previous models of the same booms.

2.3. How Burns are Conducted

There are several basic steps involved in burning oil spills at sea which are summarized in Figure 1. 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 are reviewed. The “prime rule” of in-situ burning is that oils will ignite if they are at least 2 to 3 mm thick. Although oils may burn at lesser thicknesses, they will almost always burn at these thicknesses.

Figure 1 - Steps on In-situ Burning



The questions to be asked before deciding to use in-situ burning at a particular spill situation are outlined in Figure 2. If burning is possible and the response organization is prepared for burning, planning will then begin. A plan is formulated 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 within hours.

Personnel and equipment are then transported to the site. In most cases, fire-resistant boom is deployed downwind of the spill and a tow begun. When the oil collected in the boom is thick enough, it is ignited using a helitorch or a hand-deployed igniter. 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 or 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.

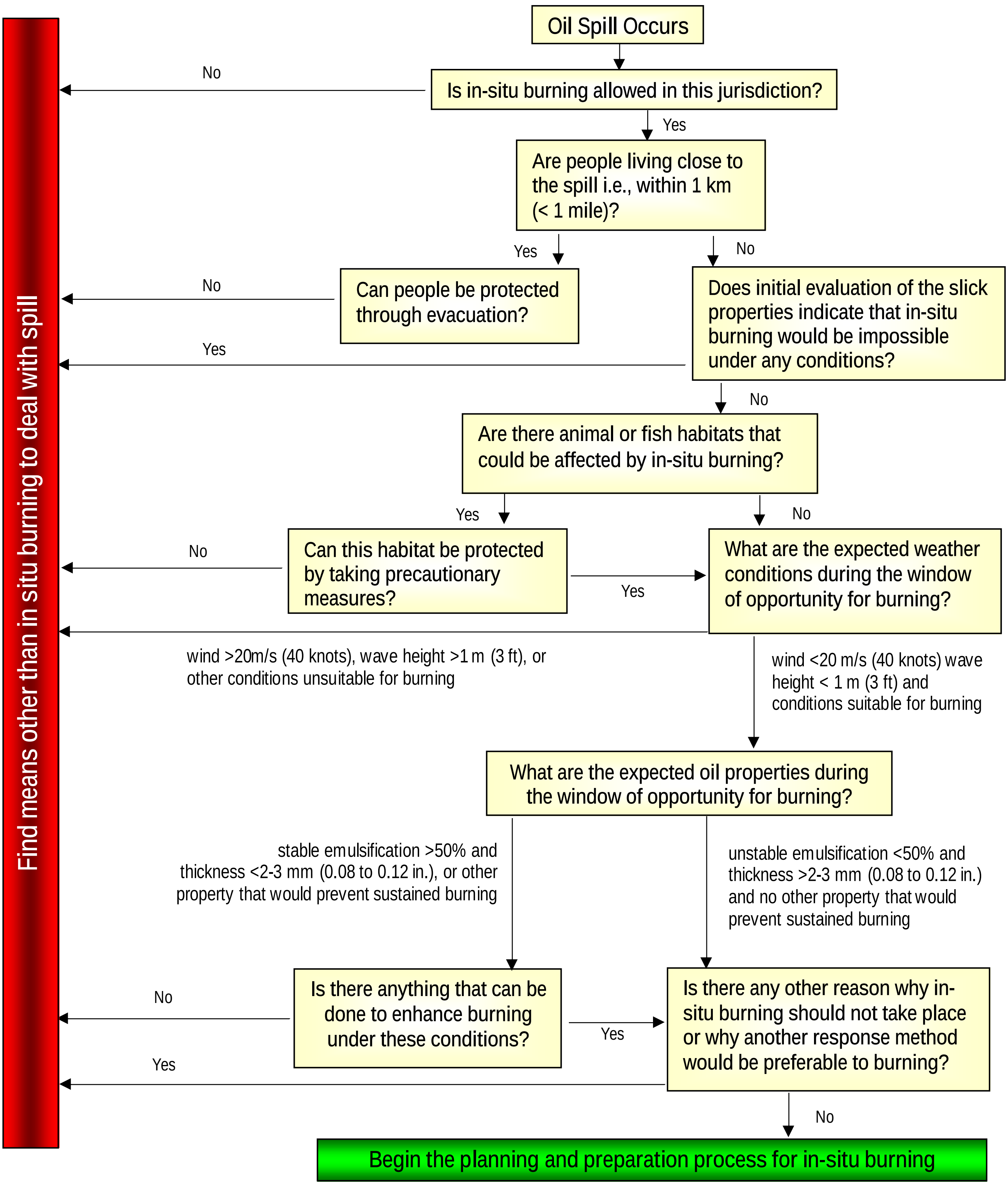
If the burning stops because there is not enough oil in the boom, the tow can be resumed going downwind and then turning around into the wind before re-igniting. After the burn operation is finished, for the day or for the single burn, the burn residue must be removed from the boom. As the burn residue 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.

During the cleanup of the *Exxon Valdez* spill in 1989, 137 m of boom and 152 m long tow lines were used in a U configuration to concentrate several patches of slightly emulsified oil. An estimated 57,000 to 114,000 L of oil were collected. The collected oil was then towed to an area away from the surrounding slick and set on fire by igniting a small plastic bag of gelled gasoline and throwing it towards the slick from one of the tow boats.

During the burn, the fire's intensity was controlled by adjusting the speed of the tow vessels. Slowing down the tow speed increased the size of the burn area and moved it towards the opening of the U. Increasing the tow speed increased the concentration of the oil in the apex of the boom. The burn lasted 1 hour and 15 minutes, with the most intense part of the burn lasting about 45 minutes. The residue from the burn was a thick tar-like material that was easily recovered. The total volume of residue was approximately 1,100 L, resulting in an estimated burn efficiency of greater than 98% (Allen, 1990).

Oil can also sometimes be burned without containment and by using natural containment features such as oceanic fronts, ice, or shorelines to contain oil. Details on the use of booms and other techniques are provided in Table 8 in Section 5.

Figure 2 - Decision Flow Chart for In-situ Burning



2.4. 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 the only cleanup option in some situations, e.g., oil-in-ice conditions (ASTM, 2002).

The most significant of these advantages is the ability 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 highly 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 stored, transferred, and disposed of, burning generates a small amount of burn residue. This residue is relatively easy to recover and 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. During the Newfoundland Offshore Burn Experiment (NOBE) conducted off the coast of Newfoundland in 1993, efficiency rates of at least 98 and 99% were achieved.

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 is available when large spills occur. Burning is relatively inexpensive in terms of equipment needed and actually conducting the burn operations. And finally, burning may be the only available option in some circumstances, such as in remote areas or when oil is mixed with or on ice.

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

- large black smoke plume created and public concern about toxic emissions to the air and water;
- limited time frame in which the oil can be ignited;
- oil must be a minimum thickness in order to ignite and burn and must usually be contained to achieve this thickness;
- risk of fire spreading to other combustible materials; and
- burnt residue must be disposed of (ASTM, 1997).

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 results of these studies are discussed in Section 3.4. The second disadvantage is that the oil will not ignite and burn unless it is a certain thickness. Most oils spread rapidly on water and the slick quickly becomes too thin for burning to be feasible. Fire-resistant booms are 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. Furthermore, reprocessing facilities are not readily accessible in most parts of the world.

2.5. 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. This can be desirable when an oil slick is threatening a bird colony or a particularly sensitive shoreline.

Two major issues associated with the use of dispersants - the toxicity of the resulting oil dispersion in the water column and their effectiveness - have generated controversy in the last 30 years. The toxicity associated with dispersant use relates to the toxicity of the dispersed oil. In shallow or confined waters, dispersed oil could be toxic to aquatic life. For this reason, dispersants are not often used close to shore. Special permission is necessary in most countries to use dispersants.

Effectiveness is influenced by many factors, including the composition and degree of weathering of the oil, the amount and type of dispersant applied, sea energy, salinity of the water, and water temperature. The composition of the oil is the most important of these factors, followed closely by sea energy and the amount of dispersant applied. Dispersion is not likely to occur when oil has spread to thin sheens so that the oil in thinner portions of the spill will not disperse when dispersants are applied.

A significant disadvantage of dispersants is that either they do not work at all or they do not work well on weathered oil, emulsified oils, heavy oils, and thin sheens. Dispersants work best on light crude oils and not at all on residue oils. Burning could also be used in place of dispersants if there are questions about the effectiveness of a dispersant. There is a narrow window of opportunity after a spill during which dispersants can be applied, which can be as short as a few hours or a day. After a period of time, the oil becomes too weathered or emulsified with water.

An advantage of dispersants is that they can be applied without any activity on the water surface, and thus can be applied in remote locations. Another advantage is that dispersants can be applied very rapidly and large amounts of oil can be treated in a short time.

In-situ burning is also compared to mechanical recovery of oil spills. In open waters, burning has advantages over mechanical recovery. 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 (0.7 knots) 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. Historically, the record for physical recovery is poor and is often as low as only 10% of the volume of oil spilled (Fingas, 2000). 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.

In some spill situations, the best cleanup strategy involves a combination of mechanical recovery techniques, burning, and chemical dispersants 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, which results in the least environmental impact of the spill.

3. Assessment of Feasibility of Burning

3.1. Deciding Whether To Burn

When an oil spill occurs, information must be obtained on the spill location, weather conditions, and any other relevant conditions at the site. A detailed Burn Evaluation Sheet, which also includes information on response equipment, is provided in Appendix A.

3.2. 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.

3.3. 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 aggravated by the fact that the public is reluctant to accept regulations that allow any kind of burning. People must be provided with information about the issues associated with in-situ burning in order to accept regulations 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 (Snider, 1994).

In general, regulatory agencies are most concerned with how the burn will affect air quality (Snider, 1994). 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.

When using in-situ burning on the open ocean, international laws governing activities at sea must be observed, particularly the *1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972*, referred to as the 1996 Protocol to the London Convention. Several countries have signed this Convention, including Canada and the United States, which means that they must incorporate the terms of the 1996 Protocol into their domestic law. In Canada, these laws are being incorporated into the revised *Canadian Environmental Protection Act (CEPA)*. In the United States, they are being incorporated into new acts promulgated by the Environmental Protection Agency.

It is recommended that anyone involved in the decision-making process associated with in-situ burning should obtain legal advice on how the terms of the Protocol should be applied and how these terms affect in-situ burning in their particular situation(s) and jurisdiction. General observations on how the Protocol relates to in-situ burning are outlined here.

Article 5 of the 1996 Protocol prohibits "incineration at sea". In Article 1, Section 5 "incineration at sea" is defined as:

"..... the combustion on board vessels, aircraft, platforms or other man-made structures of wastes or other matter for the purpose of their deliberate disposal by thermal destruction. 'Incineration at sea' does not include the incineration of wastes or other matter on board vessel, aircraft, platform or other man-made structure at sea if such wastes or other matter were generated during the normal operation of that vessel, platform or other man-made structure at sea."

Based on this definition, in-situ burning of an oil slick on water would not be considered incineration because the oil is not "on board a vessel, aircraft, platform or other man-made structure". However, other methods related to in-situ burning as discussed in Section 4.2.6 of this report would be considered incineration at sea under the first part of this definition. An example of this would be lifting oil from the water using a partially submersed barge and then burning the oil. On the other hand, it could be argued that if a vessel was designed specifically to lift the oil from the water and burn it on board the vessel, it could be interpreted as the "normal operation of that vessel" as defined in the second part of the definition and therefore not considered to be incineration.

Regardless of whether burning spilled oil is considered incineration at sea, in Article 8, Section 1 of the Protocol, the prohibition on incineration is lifted:

"......when it is necessary to secure the safety of human life or of vessels, aircraft, platforms or other man-made structures at sea..... if dumping (incineration) appears to be the only way of averting the threat and if there is every probability that damage consequent upon such dumping will be less than would otherwise occur. Such dumping (incineration) shall be conducted so as to minimize the likelihood of damage to human or marine life and shall be reported forthwith to the Organization (International Maritime Organization)."

It could be argued that these conditions apply in many spill situations. As well, under Article 8.2 of the Protocol, an emergency permit can be issued for incineration at sea "in emergencies posing an unacceptable threat to human health, safety or the marine environment and admitting of no other feasible solution".

Public Protection

- Methods are now available for calculating safe distances downwind from in-situ oil fires.
- A 500 m^2 burn of crude oil, which is a typical area for a boom tow, is considered to be safe about 500 m downwind from the fire.

3.4. Environmental and Health Concerns

The primary environmental and health concern related to in-situ burning is the emissions produced by the fire. The measurement of emissions and calculations using equations developed from emission data 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 m^2) would not exceed health limits for emissions beyond about 500 m from the fire.

The emissions produced by in-situ burns are discussed in Section 3.4.3. People and the environment can be protected by ensuring that the burn is kept the minimum distances away from populated and sensitive areas. Procedures for calculating these safe distances are given in Section 3.4.4.

3.4.1. 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 in Section 7. These guidelines should be used to develop site-specific plans once it has been decided that in-situ burning will take place.

3.4.2. Public Health

In general, depending on weather conditions, in-situ burning should not be carried out within 1 km of heavily populated areas. Weather conditions to be considered include the presence or absence of an inversion and the wind direction. According to monitoring of oil fires done up until 1994, ground-level emissions from crude oil fires have never exceeded 25% of established human health concern levels more than 1 km away from the fire (ASTM, 1997). Therefore, if no significant air turbulence or ground-level atmospheric inversions occur, burning can be conducted close 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. These are given in Section 3.4.4.

3.4.3. 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 principles governing the combustibility of oil-on-water. Extensive research is currently under way into the many facets of burning oil. Several agencies in the United States and Canada have joined forces to study burning and to conduct large-scale experimental burns. This effort is producing data that should increase acceptance of in-situ burning as an alternative method for cleaning up oil spills. 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. Complete analysis of the emissions from a burn has involved measuring all these components.

Emissions

- Respirable particulates (PM-10) are emissions of primary concern from in-situ oil fires.
- PAHs on particulates are the secondary concern and volatile organic compounds (VOCs) are third.
- VOCs are greater from evaporating oil slicks than from burning oil slicks.
- Highly toxic dioxins/dibenzofurans are not generated by oil fires.

The emphasis in sampling has been on air emissions at ground level as these are the primary human health concern and the regulated value. This section will focus on these emissions. It should be noted that the monitoring of emissions conducted at past burns was as comprehensive as possible and the best field samplers and instrumentation available at the time were used. Measurement techniques have progressed over the years, however, and continue to improve. In addition, the data from these burns are so extensive that not even encapsulating summaries can be provided here. The summarized data appears in the references cited in this section and qualitative statements about that data will be made here.

Extensive measurement of burn emissions began in 1991 with several burns conducted in Mobile, Alabama to measure various physical facets of oil burning (Fingas *et al.*, 1993). Analysis of the data from these burns showed several interesting facts as well as some gaps in the data. In 1992, two further series of burns were monitored for emissions (Fingas *et al.*, 1993; Booher and Janke, 1997). In 1993, two major burns were conducted at sea specifically to measure emissions, although many other measurements were also taken (Fingas *et al.*, 1994a; 1994b; 1995a; 1995b). Further tests were conducted in 1994 and 1997 (Fingas *et al.*, 1996a; 1996b; 1996d; 1998b; Lambert *et al.*, 1998). These tests and the number of burns monitored are summarized in Table 1.

Table 1 – Summary of Studies Used to Measure In-Situ Burn Emissions
(Fingas, M. and M. Punt, 2000)

Location	*Year*	*Number of Burns*	*Number Monitored*	*Oil Type*	*Prime Purpose*	*Burn Area Range (m^2)*	*Time of Burns (min.)*	*Number of Instruments*	*Number of Target Compounds*
Mobile	1991	14	14	Louisiana crude	physics	37 to 231	20 to 60	30	70
Mobile	1992	6	6	Louisiana crude	physics	36 to 231	20 to 60	30	70
Calgary	1992	20	3	Crude, diesel	emissions	37	20 to 70	25	40
Newfoundland	1993	2	2	Crude (ASMB)	emissions	467 to 600	60 to 90	200	400
Mobile	1994	3	3	diesel	physics	199 to 231	60 to 80	95	400
Mobile	1997	9	8	diesel	boom tests	25	60	95	400
Mobile	1998	12	9	diesel	boom tests	25	60	76	400

Particulate Matter/Soot - All burns, especially those of diesel fuel, produce an abundance of particulate matter which is the first emission from an oil fire that exceeds 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 (150 $\mu g/m^3$) as far downwind as 500 m from a small crude oil fire. The greatest concern is the smaller or respirable particulates. The PM-10 fraction, or particulates less than 10 µm, are generally about 0.7 of the total particulate concentration (TSP) of all particulates measured. The PM-2.5 fraction is not easily measured, nor are all facets of particulates understood at this time.

Polyaromatic Hydrocarbons (PAHs) - Crude oil burns result in polyaromatic hydrocarbons (PAHs) downwind of the fire, 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 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. When diesel fuel is burned, the emissions show an increase in the concentration of multi-ringed PAHs in the smoke plume and residue, but a net destruction of PAHs is still found.

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 released. The emission of volatile compounds was measured at several test burns (Fingas *et al.*, 1993, 1994a, 1994b, 1995a, 1995b, 1996a, 1996c, Li *et al.*, 1992). One-hundred and forty-eight volatile organic compounds have been measured from fires and evaporating slicks. The concentrations of VOCs are relatively low in burns compared to an evaporating slick. Concentrations appear to be below human health levels of concern even very close to the fire. Concentrations appear to be highest at the ground (1 m) and are distributed exponentially downwind from the fire source. 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 has been analyzed for dioxins and dibenzofurans. These toxic compounds were at background levels at many test fires, indicating no production by either crude or diesel 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. Carbonyls from diesel fires are somewhat higher but also below concern levels.

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. The three-dimensional distributions of carbon dioxide around a burn have been measured. Concentrations of carbon dioxide are highest at the 1 m level and fall to background levels at the 4 m level. 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. Carbon monoxide appears to be distributed in the same way as carbon dioxide.

Sulfur Dioxide - Sulfur 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. Sulfuric acid, or sulfur dioxide that has reacted with water, is detected at fires and levels, although not of concern, appear to correspond to the sulfur content of the oil.

Other Gases - Attempts were made to measure oxides of nitrogen and other fixed gases. None was measured in about 10 experiments.

Other Compounds - There is a concern when burning crude oil about any "hidden" compounds that might be produced. In one study conducted several years ago, soot and residue samples were extracted and “totally” analyzed in various ways. While the study was not conclusive, no compounds of the several hundred identified were of serious environmental concern. The soot analysis revealed that the bulk of the material was carbon and that all other detectable compounds were present on this carbon matrix in abundances of parts-per-million or less. The most frequent compounds identified were aldehydes, ketones, esters, acetates, and acids, which are formed by incomplete oxygenation of the oil. Similar analysis of the residue shows that the same minority compounds are present at about the same levels. The bulk of the residue is unburned oil without some of the volatile components.

3.4.4. Calculation of Emission Concentrations Downwind

Sufficient data are now available to assemble emission data and correlate the results with spatial and burn parameters. The correlations are summarized in Appendix A. Although many correlations were tried, 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 the 30 test burns conducted to date. Sufficient data were available to calculate equations for over 150 individual compounds and for all the major groups.

In some cases, however, the data are insufficient to yield high correlation coefficients and low errors. This will improve as more data are collected.

These correlations will significantly increase understanding of in-situ burning in the areas of assessing the importance of specific emissions and classes, predicting a ‘safe’ distance for burning, and predicting concentrations at a given point from the fire. These predictions are based solely on actual data and therefore may be more accurate than theoretical-based predictions. This increased accuracy applies to situations where the conditions are the same as those under which the emissions data were collected. 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 are given in Table 2.

Table 2 – Prediction Equation Parameters
Y=a + b (size of fire, m) – c* (distance from fire, m)*
[Constants and units of Y for this equation are listed in the table]
(Fingas, M. and M. Punt, 2000)

	Crude Oil					*Diesel*					
Substance	a	b	c	r^2	Error	a	b	c	r^2	Error	Units
Total particulates	12.7	0.0347	4.79	0.69	2.6	2.65	0.00886	0.854	0.55	0.58	mg/m³
PM-10	12.7	0.347	4.79	0.69	1.8	1.49	0.00558	0.467	0.56	0.33	mg/m³
PM-2.5	12.7	0.347	4.79	0.69	1.5	1.34	0.00523	0.412	0.52	0.33	mg/m³
Total VOCs	13450	24.02	4426	0.35	4700	203	2.1	4.77	0.36	99	µg/m³
PAHs	16.2	0.0048	3.03	0.19	4.8	51.7	0.124	16.9	0.57	8.2	µg/m³
Fixed gases											
Sulphur Dioxide	19.4	0.0266	5.29	0.69	2.8	0.557	0.00114	0.183	0.54	0.06	ppm
Carbon Dioxide	520	0.523	81.5	0.18	130	77	0.246	19.6	0.49	25	ppm
Carbon Monoxide	7.72	0.0012	1.56	0.18	1.8	3.06	0.0237	1.935	0.63	067	ppm

These data were then used to calculate the difference between the regulated level (typically the time-weighted average recommended exposure to a substance) and the calculated amount of the substance for several burns. Results of a simple exercise of this type are shown in Table 3. This table shows that emissions, especially of particulate matter, are significantly higher from a diesel fire than from a crude oil fire, as had been noted in several studies of particulate emissions (Fingas *et al.*, 1996a; 1996b). Other emissions of concern are similar for diesel and crude oil, although the PAHs are somewhat higher when diesel burns. This calculation confirms that particulate matter is the greatest concern, followed by the PAHs on the particulate matter, and the total VOCs.

Table 3 – Calculation of Concern Levels for Emissions Groups
(Fingas, M. and M. Punt, 2000)

	Crude Oil			*Diesel*		
	500 square meter burn / continuous burn			*500 square meter burn / continuous burn*		
Substance	Percent of Concern Level at 500 m	Percent of Concern Level at 1500 m	Distance to the Safe Health Level (m)	Percent of Concern Level at 500 m	Percent of Concern Level at 1500 m	Distance to the Safe Health Level (m)
Total particulate	130	0	510	1180	560	3340
PM-10	130	0	520	920	580	6930
PM-2.5	0	0	530	1910	1170	7340
Total VOCs	0	0	-	0	0	-
PAHS	0	0	-	4	0	-
Fixed gases	0	0	-	0	0	-
Carbonyls	0	0	-	0	0	-

Analysis of the VOC data shows these to be close to being a matter of concern, however, it should be noted that the level of VOCs is much higher (as much as three times higher as measured in some tests) when oil is evaporating in the absence of burning than when burning. Carbonyls are another emission of concern, although they are significantly below health concern levels for the scenarios in Table 3. The level of concern is the percentage of the regulated level attained by the emission. For example, if a regulated level is 75 µg/m³ and the calculated value is 150, then the level of concern is given as 200%. There is no health concern for fixed gases such as carbon dioxide or carbon monoxide.

Safe distances downwind from a crude oil burn (based on PM-10 concentrations) can be calculated as:

$$\text{Safe Distance (m)} = \frac{\exp\left[12.2 + 0.0347 \times \text{fire zize } (m^2)\right]}{4.79}$$

Safe distances downwind from a diesel fire can be calculated as:

$$\text{Safe Distance (m)} = \frac{\exp\left[1.19 + 0.0052 \times \text{fire zize } (m^2)\right]}{0.437}$$

Note: To convert feet to meters, multiply by 0.3.
To convert meters to feet, multiply by 3.3.

A final point should be made that the level of PM-2.5 measured for diesel emissions is the same as the PM-10 level or exceeds it. This indicates that either most of the matter consists of PM-2.5 or the devices for measuring PM-2.5 fracture the particles during collection. Further work is needed on PM-2.5 measurements and emissions.

Based on these data, safe distances have been calculated for a variety of fire sizes. These are given in Table 4.

Table 4 - Safe Distance Calculations
(based on PM-10 concentrations)
(Fingas, M. and M. Punt, 2000)

	Safe distance in kilometers
Crude Oil Burns	
small area 250 m^2	0.08
full boom pull 500 m^2	0.5
large boom pull 750 m^2	3.2
Diesel Burns	
small area 250 m^2	0.35
full boom pull 500 m^2	6.9

3.4.5. Water Quality

> **Water Quality Concerns**
> - Tests show burns do not release material toxic to aquatic life.
> - The sinking of burn residue could be a concern, although it rarely happens.

Research has shown that 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 (ASTM, 1997). Water samples from under burning oil have been analyzed and no organic compounds were detected (Daykin *et al.*, 1995; Fingas *et al.*, 1995b). Only low levels of hydrocarbons have been found, at concentrations that would not result in fish mortality, even in a confined body of water. 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 noted.

The burning process leaves a residue, however, that is primarily composed of oil with little removed other than some of the more volatile materials (Fingas *et al.*, 1994a and 1995a). 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.

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 no more toxic than other weathered oils and, in fact, is much less toxic than fresh oils of the same type. 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 (ASTM, 1997).

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 hydrocarbon found in the original oil. A very efficient burn of a heavier crude oil will produce a dense residue that may sink and pose a threat to benthic species. Sinking is very rare, however, and has been recorded in only 2 of about 200 burns worldwide. Toxicity tests performed on samples of residue have shown very low toxicity (Fingas, 1997). Residues can be collected in a backup boom using sorbents or a skimmer can be used to collect lighter residues.

Another concern is that burning will raise the water temperature below the oil, as extreme temperature changes can affect marine species (Fingas *et al.*, 1993 and 1994b). Measurements during burn trials, however, show no significant increase in water temperature, even 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.

3.4.6. Effects on Land

Where possible, every effort should be made to prevent spilled oil from reaching a shoreline, as removing oil from sand, rocks, and vegetation is difficult and costly. In-situ burning is a rapid response method that can be used effectively to protect shorelines from spilled oil.

To prevent the deposit of soot on shorelines, however, burning should be conducted at least 1 km away from the shoreline, if this is possible.

3.4.7. Effects on Birds and Other Species

Wildlife on land is generally not affected if burning is conducted more than 1 km away from shore. It has also been observed that birds will avoid the burning site and therefore will not 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.

3.4.8. Infrastructure Concerns

Oil slicks should not be burned close to infrastructures such as docks, lighthouses, oil platforms, and vessels that originally contained the oil.

3.5. 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, dissolution, and biodegradation. 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.

3.5.1. Slick Thickness

Over the years, a wide variety of oils has been burned in tests and at actual spills. Research has shown that virtually all oils will burn on water if the slick is thick enough. In general, slicks over 2 to 3 mm thick can be ignited and will sustain burning and a burn will be extinguished once the slick becomes less than approximately 1 mm thick (Tennyson, 1994). This thickness is required for heat transfer to take place. As the slick becomes very thin, the heat generated by burning is lost to the water below the slick, resulting in insufficient heat available to vaporize the constituents of the oil required to sustain combustion (ASTM, 2002). An oil spill containment boom or other containment method is often used to increase a slick's thickness or to maintain it at the thickness required for burning. In some circumstances, e.g., on dry sand, oil can sometimes be ignited at lower thicknesses.

3.5.2. 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 and/or longer ignition exposure times may be required (ASTM, 1997; McKenzie, 1994). During one burn test, it was found that weathered oils actually burned with an average 7% greater efficiency than fresh oils (Tennyson, 1994). A computer model known as ADIOS can be used to calculate weathering, but weathering does not change burn conditions significantly (ADIOS, 2004).

3.5.3. 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 (Fingas *et al*., 1997). 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 sometimes breaks down the emulsion and allows the slick to continue to burn (Bech *et al*., 1992).

Strictly speaking, all emulsions can be broken down either by mechanical means or will break down on their own over time. Based on the commonly accepted definition of stable emulsions - an emulsion that persists for at least five days at 15 °C (Fingas *et al*., 1995c and 1997) - studies have shown that stable and unstable emulsions have different characteristics. The two most obvious characteristics relate to color and viscosity.

Stable emulsions are reddish brown whereas unstable emulsions are black. The viscosity of stable emulsions is usually more than three orders of magnitude greater than the oil from which the emulsion was made, whereas the viscosity of an unstable emulsion is less than one order of magnitude greater than the original oil. There is also a middle form or meso-stable emulsion which usually is brownish in color and has a viscosity of about 50 times that of the starting oil. Some typical properties of water-in-oil states are given in Table 5. Fingas and Fieldhouse (2004) describe a new model available to calculate emulsification.

Oil Limitations

- Amount of vapor is the primary limitation when attempting to ignite oil. As a rule-of-thumb, oil must be a minimum of 2 to 3 mm thick in order to be ignited.
- It may take longer to ignite weathered oil.
- It may be difficult to ignite emulsified oil without breaking the emulsion first.

Table 5 – Typical Properties for the Water-in-Oil States
(Fingas, M. and M. Punt, 2000)

		Stable Emulsion	Meso Emulsion	Entrained Water	Unstable Water-in-Oil
Day of Formation Appearance		brown solid	brown viscous liquid	black with large droplets	like oil
Water Content on first day	%	80	62	42	5
Appearance after one week		brown solid	broken, 2 or 3 phases	separated oil and water	like oil
Water Content after week	%	79	38	15	2
Stable Time	days	>30	<3	<0.5	not
Starting Oil					
Density	g/mL	0.85-0.97	0.84-0.98	0.97-0.99	0.8-1.03
Viscosity	mPa.s)	15-10000	6-23000	2000-60000	2 – 5.1 x 10^6
Saturates	%	25-65	25-65	19-32	23-80
Aromatics	%	20-55	25-40	30-55	5-12
Resins	%	5-30	6-30	15-30	0-32
Asphaltenes	%	3-20	3-17	3-22	032
Asphaltenes/Resins		0.74	047	0.62	0.45
Properties on day of formation					
Average Ratio of Viscosity Increase		1100	45	13	1
Properties after one Week					
Average Ratio of Viscosity Increase		1500	30	2	1

The literature has shown that the stability of an emulsion depends on the concentration of ashphaltenes and, to a lesser extent, resins in the oil. These compounds form a viscoelastic film at the oil water interface (Fingas *et al.*, 1995c and 1997). As well, oil will not create a stable emulsion with a very low (<30%) or very high (>90%) water content. In general, the water content of stable emulsions ranges from 60 to 75%, although there is no correlation between water content and stability of an emulsion within this range (Fingas *et al.*, 1995c and 1997).

3.6. Weather and Ambient Conditions

Weather conditions such as wind speed, gusts, shifts in wind direction, 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) (ASTM, 2002, 1999a). Tank tests have shown that at wind speeds greater than 15 m/s (30 knots), the flames would not propagate upwind (ASTM, 2002). During a test in England, however, oil burned in winds up to 25 m/s (50 knots) (Guénette and Thornborough, 1997). Fingas and Ka'aihue (2004) developed a model for wind effects on burning and noted that burning may have the highest wind limits of all countermeasures. This report also includes the estimations for the limits of many types of countermeasures.

Sea State and Winds

- The primary limitations on oil spill containment at sea are the sea state or wave height. The containment limitation is the critical factor - usually splashover occurs when waves are higher than 1 m.
- Winds greater than 20 m/s (40 knots) may make it difficult to ignite the oil.

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 (Tennyson, 1994). While no 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.

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 (ASTM, 1997). 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 (Tennyson, 1994). In fact, ice is typically used as a natural method to contain oil for burning.

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, uncontained spill at sea, especially if the spill is offshore and its extent is well known. Some near shore 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.

3.7. Burning in Special Locations

There is only limited experience in the application of burning in a variety of special locations. Summary information on the use of burning at locations other than on open waters using fire-resistant boom is provided in this section.

3.7.1. Marshes

Several marsh burns have been conducted around the world, including recent well documented burns in Louisiana and Texas (Zengel et al., 2003). 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 will 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.

Several studies have been conducted on the depth of water that is best for minimizing damage (Bryner et al., 2000, 2001; Lin et al., 2004a, 2004b: Lindau et al., 1999, 2003).

These studies have shown that the damage to Spartina and other marsh plants is negligible when the water depth is 10 cm over the roots and soil surface. The damage to the plants is measurable with a 2 cm water depth and is more severe when the water depth is 2 cm below the soil surface.

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. When burning in marshes, care must be taken to prevent damage to shrubs and trees that grow in the back and higher areas of the marsh. A fire-break must be available to prevent the fire from spreading outside the marsh and to ensure that wind will not drive the fire into nearby forested areas.

3.7.2. Near Shore

Burning can be conducted near shore 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, near shore burning is not often conducted. The exception to this is in the Arctic where these conditions often exist and where near shore 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.

3.7.3. Inter-tidal 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 extreme 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 the extensive inter-tidal flats in the Bay of Fundy in Eastern Canada.

4. Equipment - Selection, Deployment, and Operation

This section outlines the types of equipment that are used in responding to a spill with in-situ burning and the steps involved in deploying and operating this equipment. This equipment includes containment booms; other containment and burning equipment; igniters; aircraft and response vessels; treating agents; monitoring, sampling, and analytical equipment; and residue recovery equipment. This section is intended to assist response personnel in the proper selection and deployment of equipment for particular response situations. Details on specific equipment available for use during in-situ burn operations can be found in the links provided in Appendix B.

Uncontained Burning

- This may be possible if the slick is thick enough.
- For safety reasons, response workers must ensure that there is no direct link between the oil and its source, e.g., the tanker or platform.
- 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.

4.1. Burning Without Containment

Controlled burning of uncontained slicks is sometimes possible if the slick is thick enough and all other safety factors are considered. Because it takes time to get containment booms to a site, 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 containment booms to thicken the remaining parts of the slick for a second burn. Uncontained oil can be ignited with a helitorch at the location where the oil is thickest. See Section 4.3.1 for information on helitorches.

When burning an uncontained 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, to prevent the fire from spreading to the source. The safest and quickest option is to move the source away from the slick. In the case of a tanker spill, this can be done using a tug boat. When the spill originates from a platform or other fixed source, the portion of the slick that is to be burned should be moved away from the source and the slick around the source should be isolated using containment booms.

Several oil spills or blowouts have accidentally caught fire while uncontained and have burned well (McKenzie, 1994). While it is not known what conditions are best for burning uncontained oil, emulsified oil may stop or retard the spreading of uncontained oil while it burns (McKenzie, 1994). 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. In populated areas, the weather conditions must be such that the smoke plume will drift offshore. Zones of convergence can also be used to contain oil. Local oceanographers must be consulted to determine the location of these zones. The Coast Guard and local fishermen are also familiar with currents in an area.

4.2. Oil Containment and Diversion Methods

As discussed in Sections 2.1 and 3.5.1, an oil slick must be at least 2 to 3 mm thick in order to be ignited and continue to burn. Several methods for increasing the thickness of a slick to this level or to maintain a thickness at or above this level are discussed in this section.

> **Fire-resistant Booms**
> - Several commercial fire booms now exist which have passed ASTM specified tests.
> - The types of commercial fire booms are water-cooled, stainless steel, thermally resistant, and ceramic booms.

4.2.1. 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. Very few fire-resistant booms are commercially available because the market is small and the cost of production is high. Fire-resistant booms can sometimes cost considerably more than conventional booms. These booms are constantly being tested for fire resistance and for containment capability and designs are modified in response to test results.

The fire resistance of these booms has been extensively tested at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. These booms have also been tested for strength, integrity, and oil containment capabilities during tow tests at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility in Leonardo, New Jersey.

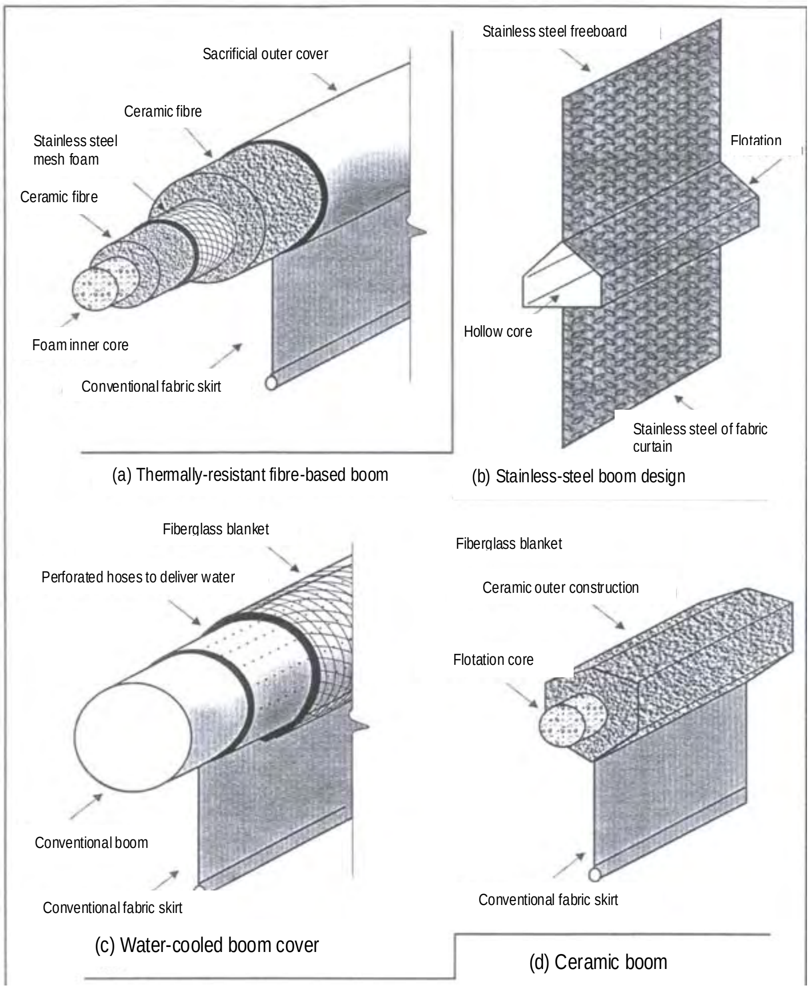
The different types of fire-resistant boom are water-cooled booms, stainless steel booms, thermally resistant booms, and ceramic booms. Fire-resistant booms require special handling, especially stainless steel booms, because of their size and weight. Thermally resistant booms are similar in appearance and handle like conventional booms, but are built of many layers of fire-resistant materials. The various types of fire-resistant boom are shown in Figure 3.

Fire-resistant booms developed by Environment Canada in the late 1970s consisted of a series of ceramic, stainless steel designs or those that used air or water sprays to contain oil during burning (Meikle, 1983; Buist *et al.*, 1983). Environment Canada also worked with conventional booms using water cooling systems and with log booms.

In the early 1980s, Dome Petroleum Ltd. further modified the stainless steel boom developed by Environment Canada. The Dome boom consists of 1.5 m vented stainless steel flotation units with a pentagonal cross section. A stainless steel panel attached to the top of each unit creates the freeboard and a PVC-coated nylon skirt attached to the bottom of the float provides the draft. The flotation sections are attached using 0.75-m flexible panels constructed of stainless steel mesh encased in a Fibrefax blanket with a PVC-coated nylon skirt. The Dome boom was designed to be used for more than one in-situ burn incident. Fire-resistant booms manufactured today are generally designed to survive several burns at one site, but are then disposed of or refurbished. Sections of the Dome boom previously used for testing are still in storage at the Canadian Coast Guard's spill response depot in Tuktoyaktuk, Northwest Territories. A new version of this has recently been designed. Spill-Tain also manufactures a stainless steel boom which is described in this section and in Appendix B.

The only documented use of a fire-resistant boom for burning at a major oil spill is the use of the 3M Fire Boom at the *Exxon Valdez* spill (Allen, 1990). A variation of the 3M Boom is now constructed and marketed by American Marine, Inc. under license from 3M. This 3M/American Marine boom with some experimental prototype sections was used during the Newfoundland Offshore Burn Experiment (NOBE) in 1993 at which two burns of 50,000 L of oil were conducted. After the first burn, small gaps were found in the Nextel ceramic fabric above the waterline between the flotation logs, caused by abrasion. The damage was minor enough to allow the boom to undergo a second burn. After the second burn, the stainless steel wire mesh in one of the prototype sections had parted resulting in the loss of two meter-long flotation logs. 3M and American Marine have since corrected this problem by using higher-temperature-resistant stainless steel mesh and an external tension member rather than an internal one.

Figure 3 - Fire-resistant Boom Designs



A standard has been devised by ASTM to test the durability of fire-resistant booms for in-situ burning (ASTM, 1999b; Walton 2003). 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 centre 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.

In 1994, the Marine Spill Response Corporation (MSRC) conducted at-sea towing tests of four fire-resistant booms: the American Marine (3M) Fire Boom, the Applied Fabrics PyroBoom, the Kepner Plastics SeaCurtain FireGard and the Oil Stop Auto Boom Fire Model (Nordvik *et al*., 1995). The purpose of these tests was to evaluate the relationship between boom performance and buoyancy-to-weight ratio, tow speed, and sea state. The booms were towed in a U configuration at tow speeds of between 0.25 and 1.25 m/s (0.5 and 2.5 knots). The results of these tests showed that the higher the buoyancy-to-weight ratio of the boom the faster the boom can be towed before it will submerge. In general, fire-resistant booms have a lower buoyancy-to-weight ratio than conventional booms. It was also found that three of the four booms tested exhibited mechanical failure at high tow speeds. The report further concluded that the mechanical integrity, sea-keeping performance, and ease of deployment and recovery of commercially available fire-resistant boom must be improved.

The United States Coast Guard and the US Minerals Management Service evaluated the containment behavior of several fire-resistant booms in a test tank and compared these results with previous at-sea performance results (Bitting and Coyne, 1997). This study 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 submersed or suffered structural damage. The results of these tests are summarized in Table 6.

The following are the conclusions of these tests.

- In terms of oil containment, the performance of the fire-resistant booms was similar to conventional, non-fire resistant 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), with the exception of the Spill-Tain boom for which the critical tow speed exceeded 3 m/s (6 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 following is a brief description of the fire-resistant booms currently on the market. Detailed specifications for these booms can be found through the links provided in Appendix B.

American Marine (3M) Fire Boom has flotation sections made of rigid ceramic foam surrounded by two layers of stainless steel knitted mesh, a high temperature-resistant ceramic textile fabric and a PVC outer cover that also forms the skirt. This boom is normally deployed from a container or tray.

Auto Boom Fire Model (Oil Stop) is an inflatable boom with an internal water-cooling system. The flotation chamber is insulated with a ceramic blanket covered with a stainless steel mesh. The skirt is made of a polyurethane fabric. This boom can be stored and deployed from a reel. Before the boom is placed in the water, however, the water-cooling system must be connected on a large, flat area.

The **Automatic Inflatable and Water-cooled Fire Oil Boom** (No. 450 S-F) (Environmental Marine Technology and Associates) has a flotation chamber consisting of a continuous flexible pipe covered with a water-cooled flexible shield. The skirt is made up of two sheets of fabric each attached to either side of the flotation chamber allowing seawater to rise up into the flotation chamber. This boom is self-inflating and can be stored and deployed from a reel.

Table 6 - Performance of Fire-resistant Containment Booms
(Bitting and Coyne, 1997)

Boom Type	Loss	First and Gross Loss Tow Speeds, m/s (knots)				Loss Rate Test, L/min @ Tow Speed m/s (knots)		Critical Tow Speed m/s (knots)
		Wave Conditions*						
		C	1	2	3	1st loss + 0.05 m/s (0.1 knots)	1st loss + 0.15 m/s (0.3 knots)	
PyroBoom	First Gross	0.51 (1.00) 0.62 (1.20)	0.37 (0.72) 0.48 (0.93)	0.55 (1.07) 0.67 (1.30)	0.49 (0.95) 0.57 (1.10)	246 @ 0.57 (1.10)	534 @ 0.67 (1.30)	1.03 (2.75)
Spill-Tain	First Gross	0.44 (0.85) 0.54 (1.05)	0.21 (0.40) 0.31 (0.60)	0.44 (0.85) 0.54 (1.05)	0.45 (0.88) 0.55 (1.07)	27 @ 0.49 (0.95)	178 @ 0.59 (1.15)	3.08 (>6.00)
American Marine/3M	First Gross	0.44 (0.85) 0.57 (1.10)	0.37 (0.72) 0.46 (0.90)	0.45 (0.87) 0.59 (1.15)	0.46 (0.90) 0.59 (1.15)	64 @ 0.49 (0.95)	303 @ 0.59 (1.15)	1.16 (2.25)
Dome Boom	First Gross	0.49 (0.95) 0.68 (1.32)	0.38 (0.75) 0.54 (1.05)	0.49 (0.95) 0.62 (1.20)	0.52 (1.00) 0.64 (1.25)	32 @ 0.54 (1.05)	151 @ 0.64 (1.25)	1.03 (2.00)
Oil Stop	First Gross	0.46 (0.90) 0.63 (1.22)	0.41 (0.80)	0.55 (1.07)	0.52 (1.00)	74 @ 0.51 (1.00)	286 @ 0.61 (1.20)	1.80 (3.50)

* Wave Conditions

C = calm water, no waves generated
1 = wave #1, regular sinusoidal wave, $H^{1/3}$ = 25 cm, L = 4.9 m
2 = wave #2, regular sinusoidal wave, $H^{1/3}$ = 33.8 cm, L = 12.8 m
3 = wave #3, regular sinusoidal wave, $H^{1/3}$ = 22.6 cm, L not calculated.

FESTOP Fire Boom is a new stainless steel fire boom available in two sizes that can withstand temperatures up to 1,260 C.

The **Hydro-Fire Boom** (Elastec/American Marine) is a water-cooled, inflatable boom that is sometimes stored on and deployed from a reel. A 150-m length of boom can be stored on a reel with sections (30 m) pre-connected.

PyroBoom (Globe Boom) is a fence boom with a freeboard constructed of a patented refractory material and a skirt made of a urethane-coated material. Hemispherical stainless steel floats are attached to either side of the fence portion. This boom must be stored in a container and deployed from a large flat area in order to properly connect the sections.

SeaCurtain FireGard (Kepner Plastics) uses a heavy-gauge stainless steel coil covered with a high temperature refractory material to make up the flotation sections of the boom. The skirt is made of a polyurethane-coated polyester or nylon fabric. The stainless-steel coil causes the boom to self-inflate during deployment, but the boom must be manually compacted during recovery.

Spill-Tain Fire Proof Boom is a stainless steel boom constructed in sections connected by hinges. Floats, made of stainless steel filled with closed cell glass foam, are located at the midway point of the stainless steel panels so that the lower half of the panel forms the skirt and the upper half forms the freeboard. This boom is stored and deployed from a folded position. Larger sizes of the boom would require a boat hoist or crane for deployment.

4.2.2. 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. It is often much quicker to get a conventional boom to a spill site, however, as they are much less expensive and very few fire-resistant booms are stockpiled at spill response depots.

Conventional booms can be used to corral a slick and contain it until a fire-resistant boom can be obtained. These booms can also be used to contain and thicken a slick to an acceptable burning thickness and then burn it, thus sacrificing the boom. The overall burn efficiency of this method is questionable, however, as the boom will not remain intact for very long once the oil is burning. When the boom fails, the slick could spread and quickly become too thin to sustain burning.

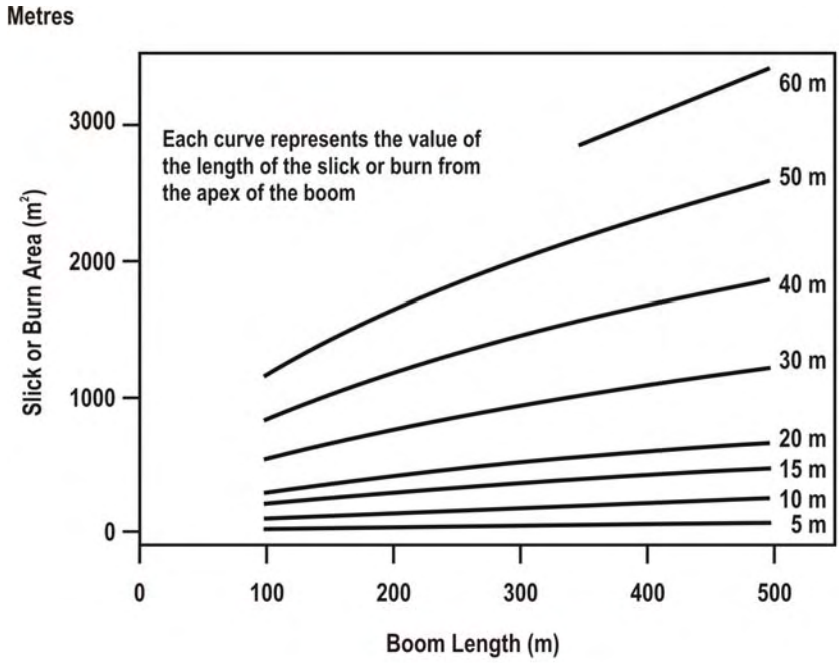
Logs or other floating material can sometimes be used as temporary booms. In narrow rivers, dams can be constructed across the upper layer of water to contain or divert the oil for burning.

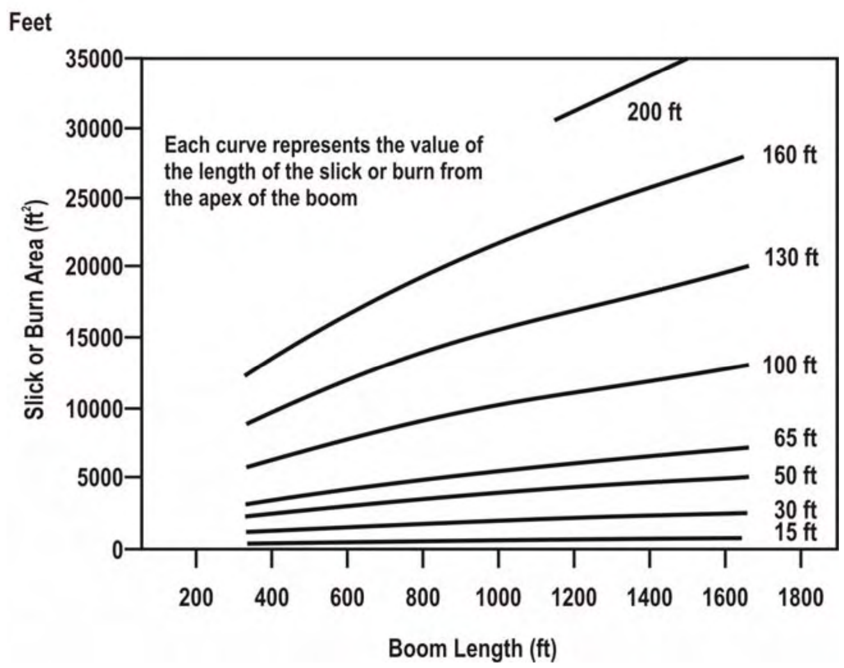
4.2.3. Boom Configurations and Towing

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. 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 (Environment Canada, 1993). Most commercial booms come in standard lengths of 15 or 30 m.

The relationship between the length of the boom and the area of oil that can be contained is shown in Figure 4. The overall height of the boom should be equal to the maximum expected wave height (short period waves, not swell) from peak to trough.

Figure 4 - Nomogram to Calculate Burn or Slick Area
(Fingas, M. and M. Punt, 2000)





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 NOBE trials showed that the air and water temperature ahead of the burn levels off very quickly (Environment Canada, 1997). 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 long. 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.

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 (ASTM, 2002). 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.

Fire-resistant Containment Booms

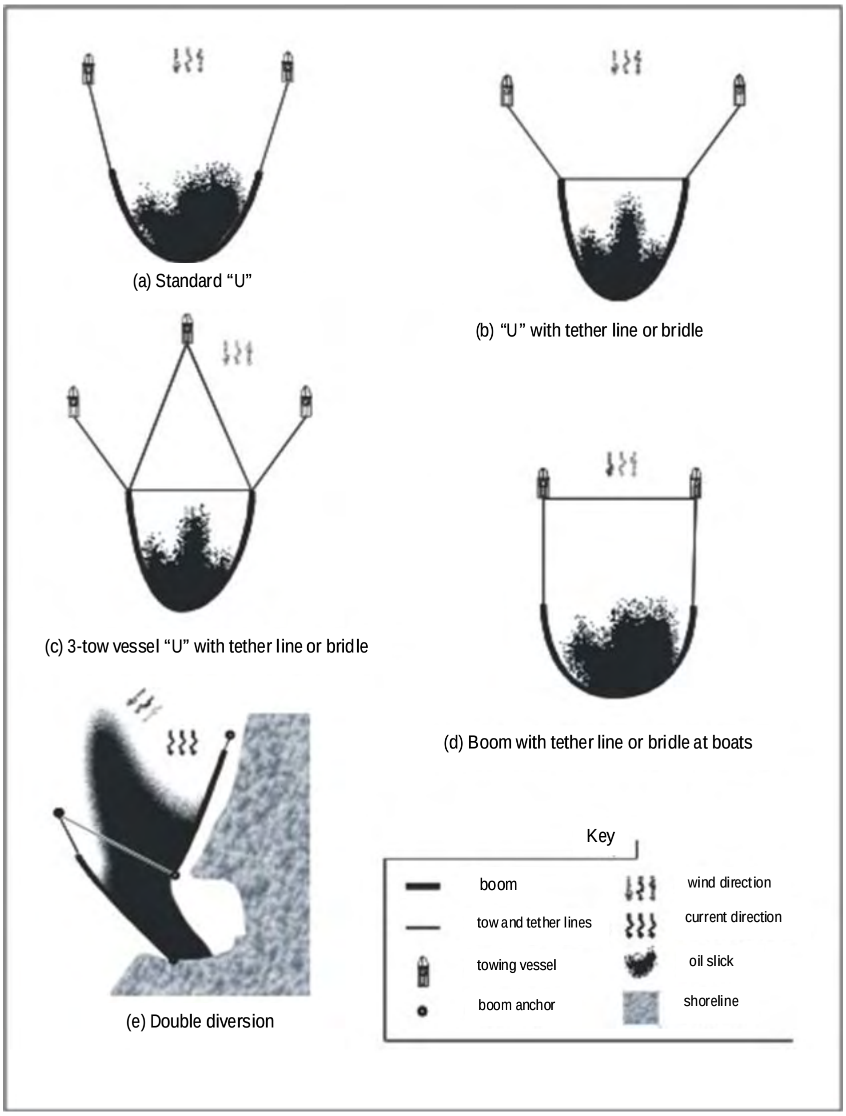
- These booms can be towed in several configurations, U-shaped being the most common.
- Booms must generally be towed at less than 0.4 m/s (0.7 knots) relative to the current to prevent oil from splashing over or becoming entrained beneath the boom.
- A length of 150 to 275 m boom yields convenient collection and burn sizes.

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 oil spill booms are shown in Figure 5.

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 5 (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 5 (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 5 (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 5 (d). One vessel tows the boom by pulling from the centre 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. This configuration was used during the NOBE tests in 1993. During these tests, 210 m of boom was towed in a modified U configuration. A 45-m tether line or cross bridle was attached across the ends of the U. One vessel towed the boom using two 120-m lines attached to the ends of the U. The U was kept open by lines towed from two other vessels in an outward direction at an approximately 45° angle. The towing speed was maintained at 0.25 m/s (0.5 knots) throughout the burn.

Figure 5 - Boom Configurations for In-Situ Burning
(Fingas, M. and M. Punt, 2000)



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 5 (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 near shore 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.

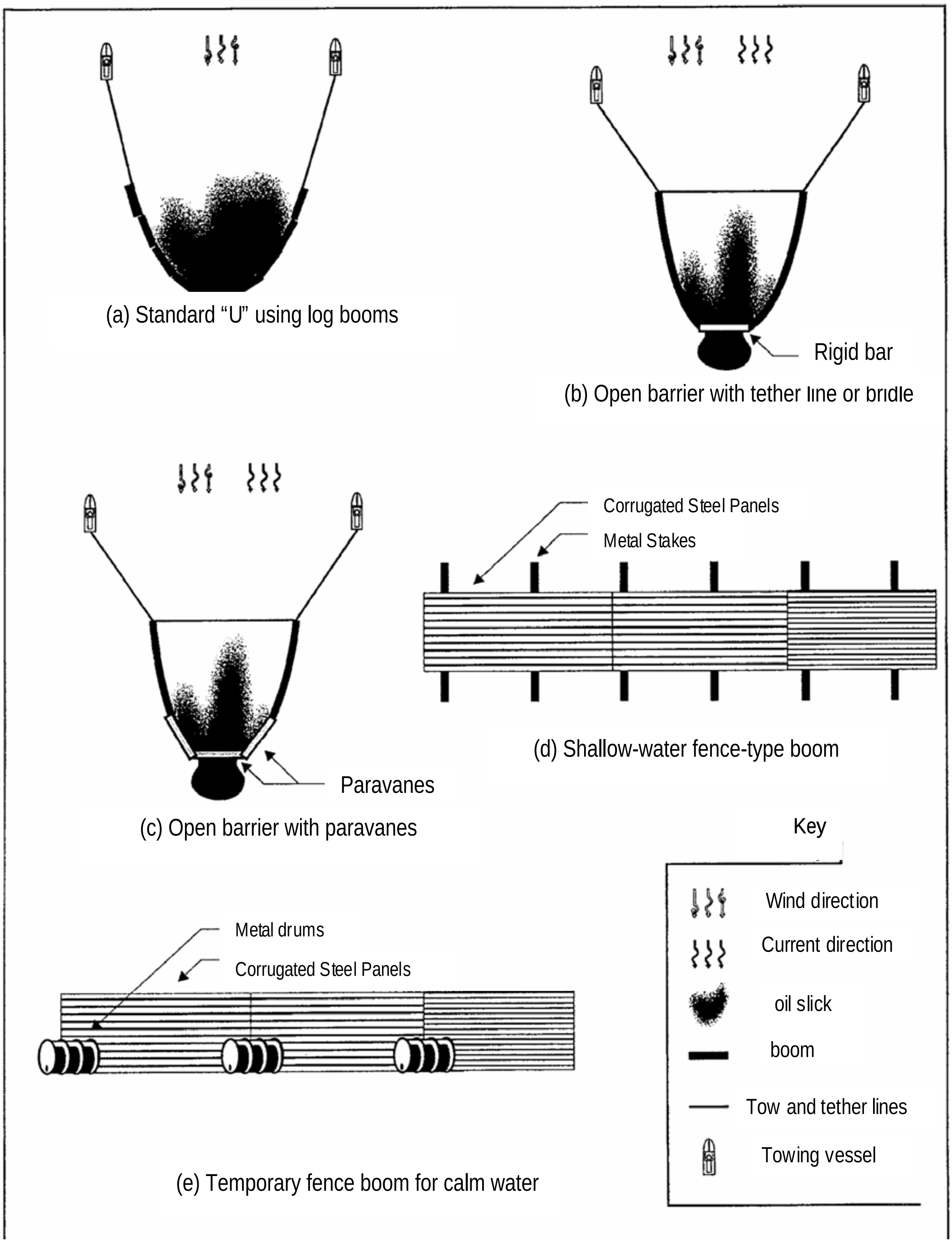
4.2.4. Untested Containment Configurations

A number of boom configurations or containment methods have been proposed in the literature or at workshops. Most of these have not been tested or have not been tested quantitatively. Log booms, which are illustrated in Figure 6 (a), have been used several times in Northern Canada. In fact, the first documented in-situ burn was conducted successfully using a log boom on the Mackenzie River in 1958 (McLeod and McLeod, 1972). Although log booms burn, if the boom maintains its buoyancy ratio, there is sufficient time to conduct a burn lasting several hours. The major problem with log booms is the leakage between sections. The gaps between sections are usually sealed with fire-resistant material such as fiberglass cloth.

Booms can also be used to divert oil slicks rather than to contain them. Diversion modes are usually used when the current is too fast for the oil to be contained in a U configuration, i.e., greater than 0.4 m/s (0.75 knots). Conventional booms can be used to divert oil so that the oil is actually burned beyond the boom or contained by a natural barrier, such as the shoreline. One such method involves concentrating and “funneling” the oil through an opening created by two booms as shown in Figure 6 (b), so that the burning takes place mostly behind the boom. As far as is known, this type of configuration has never been tested even in model form. Boom with solid flotation sections would have to be used because any flame impingement on inflatable boom causes rapid failure. Despite the apparent weaknesses, the proposal has merit in that it would only be used in a situation where complete containment is not necessary and losses, even failures, would not cause major problems. The rear opening would have to be wide enough to avoid buildup of oil in front of the boom and narrow enough to ensure that the oil slick is thick enough to sustain burning even with the re-spreading that would occur behind the boom.

A modification of this configuration is the use of paravanes, rigid metal boom-towing sections that attach at the rear mouth of the conventional boom. This is illustrated in Figure 6 (c). This is also an untested concept, but with the advantage of having relatively fire-resistant paravanes at the mouth of the boom. Thus, if fire does propagate inside the boom, there would be no catastrophic boom failure.

Figure 6 – Untested Containment /Diversion Configurations for In-situ Burning
(Fingas, M. and M. Punt, 2000)



The use of corrugated steel sheets as temporary fire boom has also been proposed (Marine Research Associates, 1998). The corrugated sheets could be fastened to metal stakes in shallow water as shown in Figure 6 (d) or coupled to drums for application in deeper waters, as shown in Figure 6 (e). As this has never been tested, it is not known how long the corrugated steel would withstand the heat flux of the fire, although it would probably withstand at least a few hours.

4.2.5. Deployment of Boom

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.

> **Boom Deployment**
> - The number and type of vessels needed is based on the type of boom and the configuration selected.
> - Boom deployment vessels must have:
>   - ✓ space to store and deploy boom;
>   - ✓ crane, winch, etc. for deploying and recovering boom; and
>   - ✓ stability to handle recovery of waterlogged boom.
> - For river deployment, boom must be secured either to the shoreline or with anchors.

After floating in the water for some time, containment boom becomes 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. See Section 4.5 for more information on vessels used for deploying booms.

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.

Containment boom normally comes in sections that are joined by a connector. Many of the commercially available fire-resistant booms are being designed with standard connectors as prescribed by ASTM or to accommodate adapters that fit such standard connectors (Schulze, 1997). 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 near shore, 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 (ASTM, 1999b) indicates that a fire-resistant boom section that is at least 150 m long must be able to withstand towing in a straight line at 2.5 m/s (5 knots) for a period of 2 hours.

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 now becomes one of the towing vessels.
- 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 5 (b), (c), 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 5 (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.

The method for deploying diversion barrier in a river [see example in Figure 5 (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 normally more secure to use anchors.

In fact, the Canadian Petroleum Association (CPA) has found that two anchors placed in series are usually required to prevent the boom from moving in high current situations (PROSCARAC, 1992). The proper deployment of anchors in order to hold boom can be difficult, as they must be deployed slowly and systematically in order to properly set in the river bottom. The anchors should be securely in place before the boom is deployed. The Canadian Petroleum Association has developed a detailed guideline for the deployment of anchors and diversion boom in fast flowing rivers. This guideline is presented in Figures 7 and 8.

Figure 7- River Boom Deployment Schematic
(Adapted from PROSCARAC, 1992)

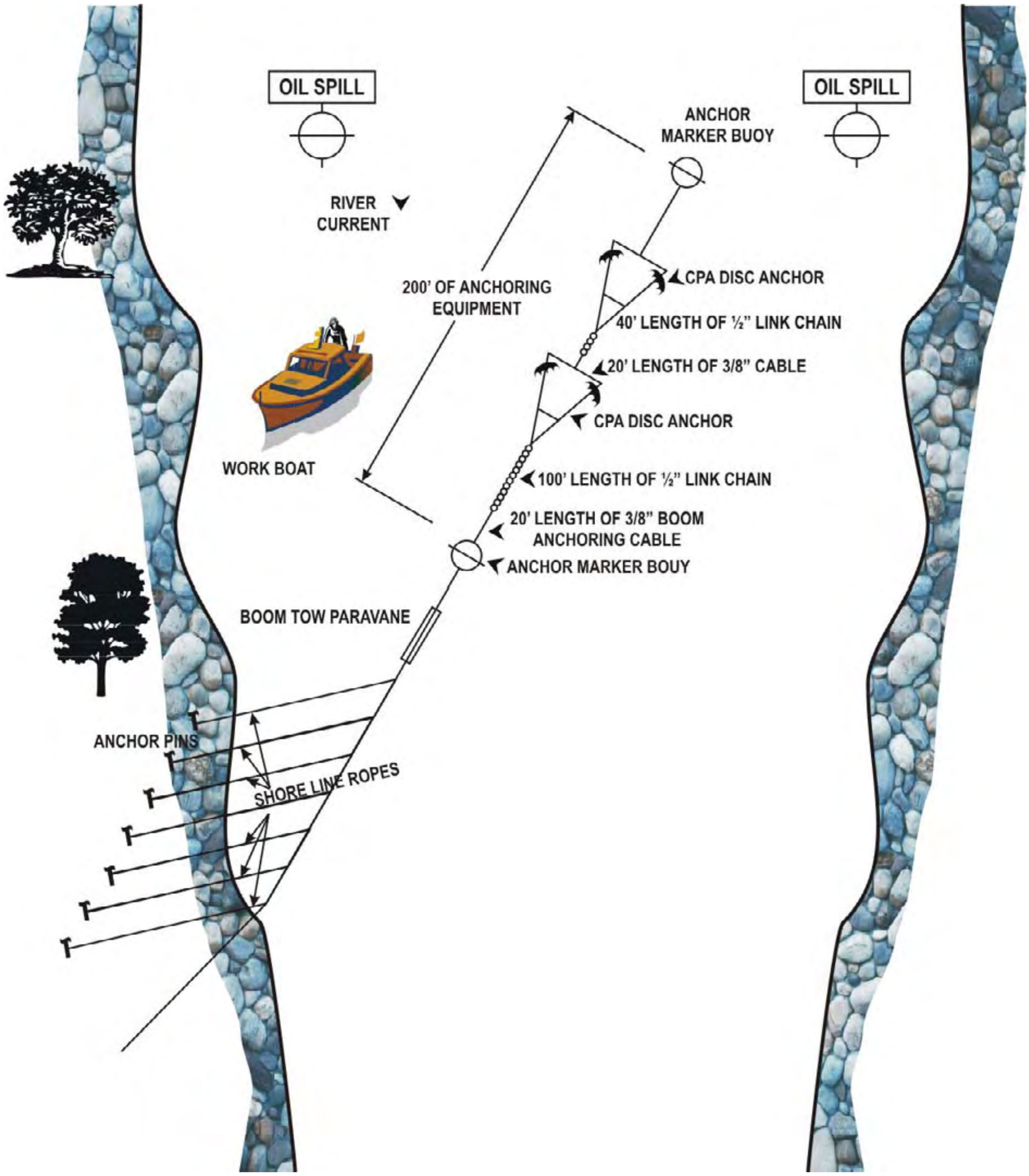
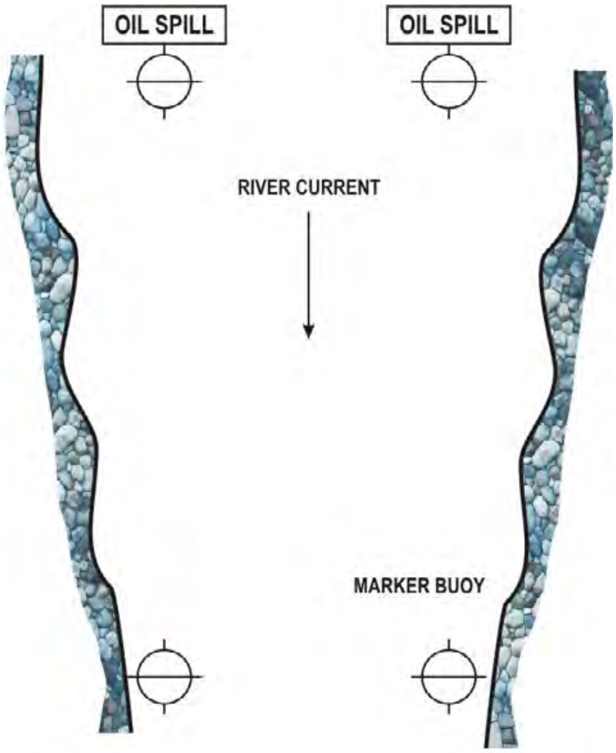


Figure 8 – River Boom Deployment Procedures
(Adapted from PROSCARAC, 1992)

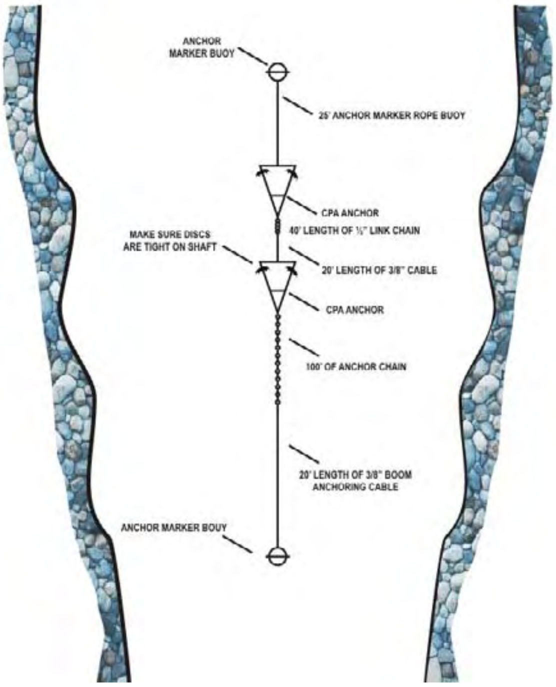
Step 1

Install anchor buoys at upstream and downstream ends of control points



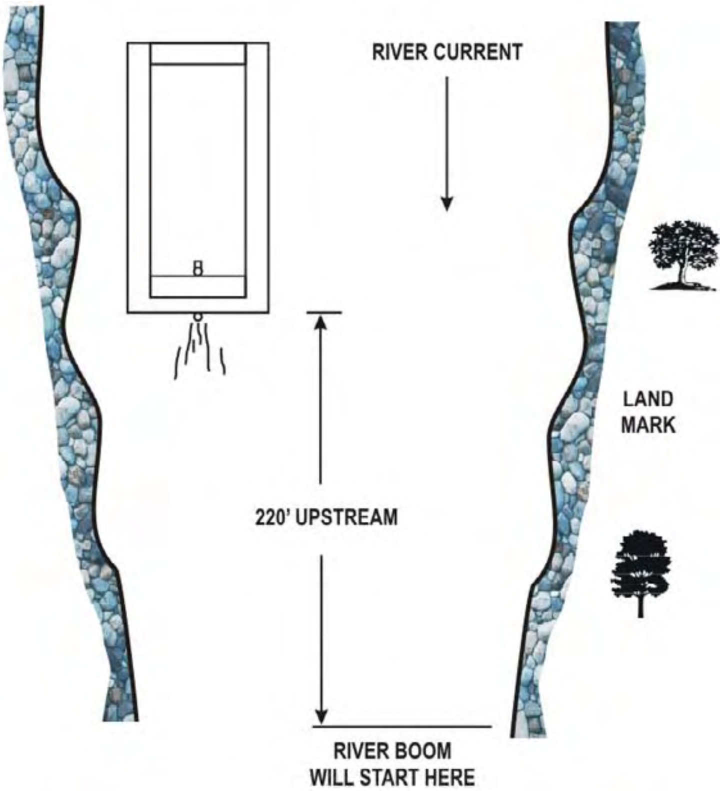
Step 2

Connect two CPA anchors together on work barge deck with appropriate cable, Anchor chains and anchor marker buoys



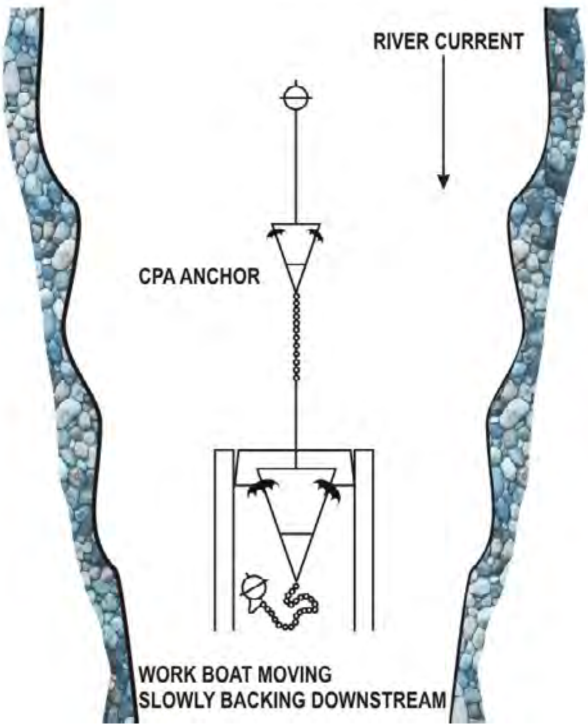
Step 3

Mark approximate locator where river boom will be deployed using a fixed landmark. Move upstream approximately 200 feet.
<u>Important</u> - Never set anchors out farther than the maximum deflection angle and boom length allowed by the current conditions



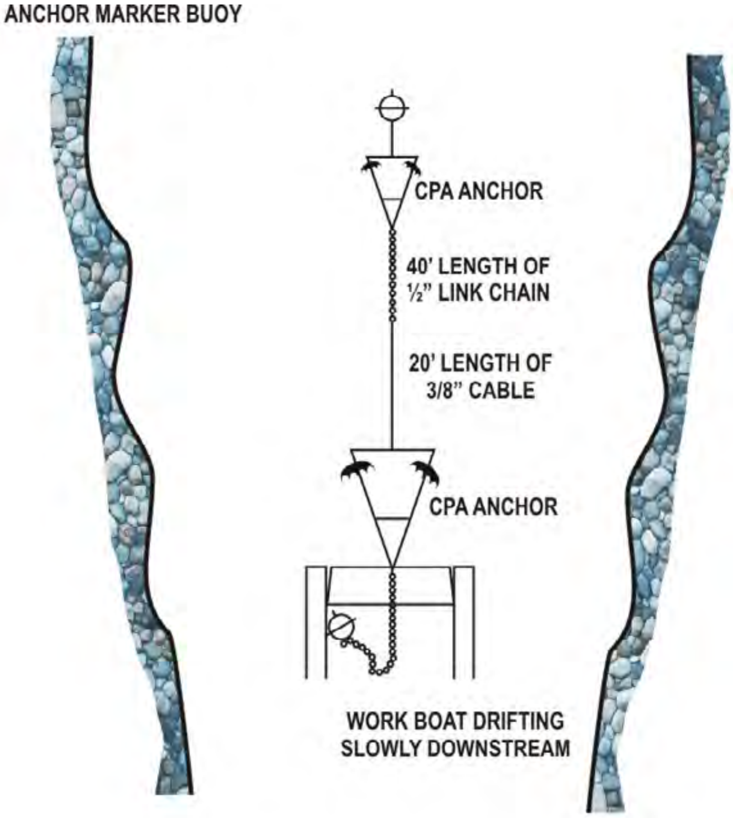
Step 4

Put out anchor marker buoy, deploy front CPA anchor, once anchor is on bottom work boat slowly drifts down stream - do not get chain or rope into the teeth of anchor



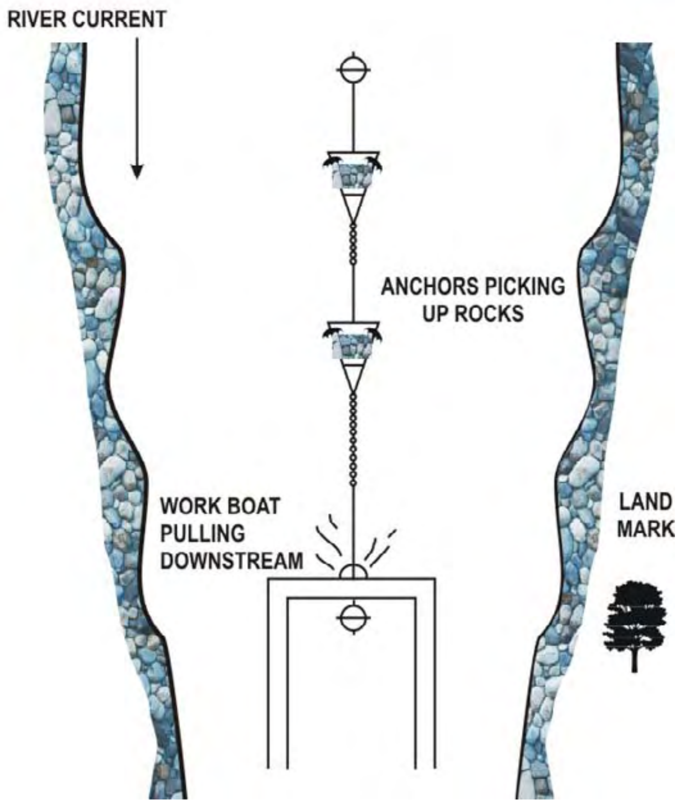
Step 5

As chain from front CPA anchor tightens, start deploying rear CPA anchor. Be careful not to tangle rope or chain into anchor.



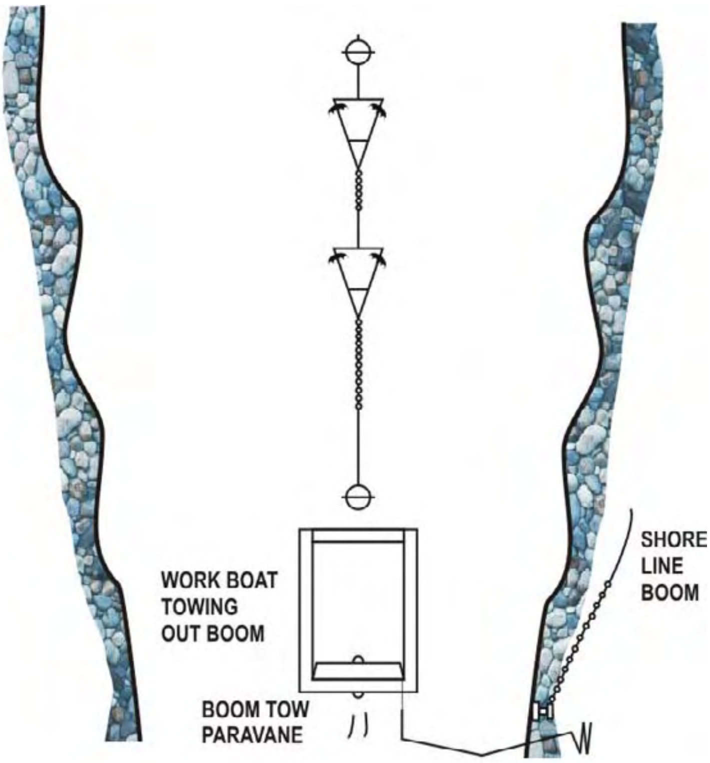
Step 6

After both anchors are in river, hook work boat onto anchor cable marker buoy and start pulling anchors downstream to set them



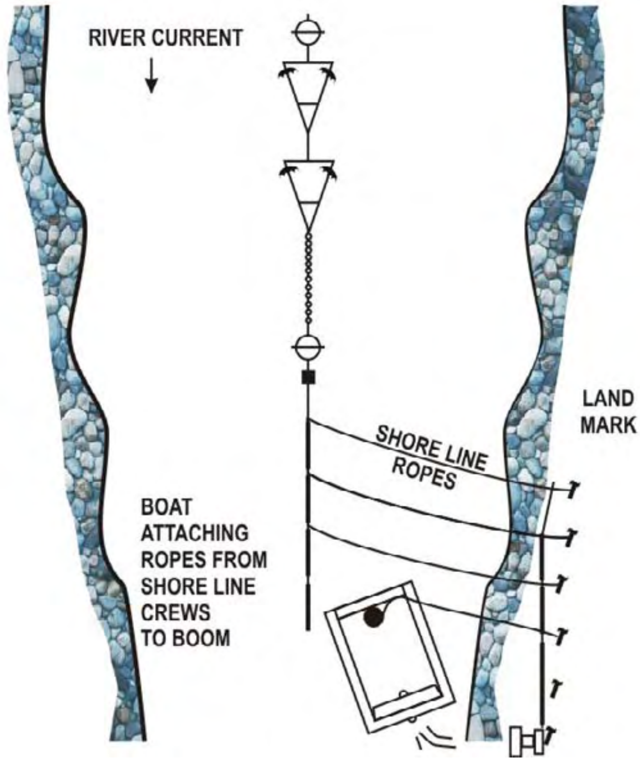
Step 7

After the CPA anchors are set, tow the river boom to the anchoring cable for attachment



Step 8

After the river boom is attached to the anchor, attach shoreline ropes or cables to the boom

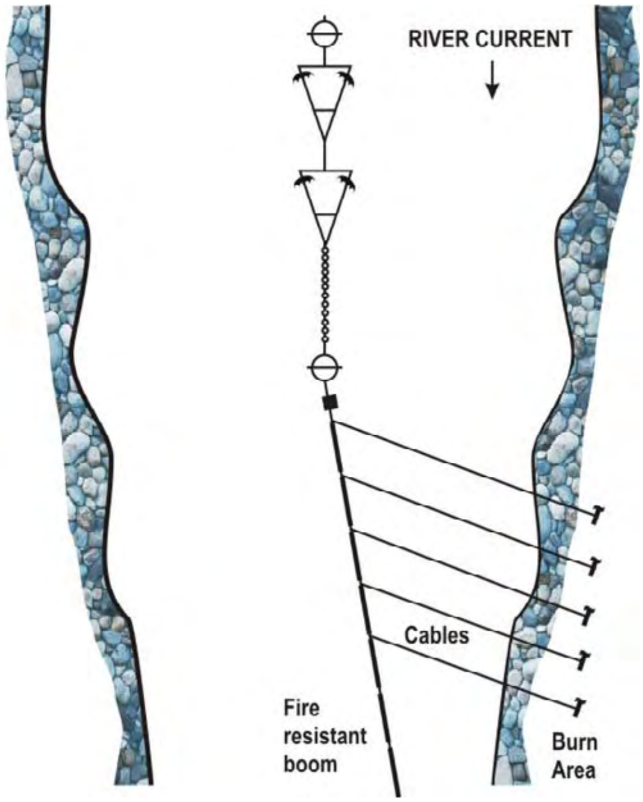


Step 9

After the shoreline ropes or cables are attached, pull the boom toward the shore. Ensure that the angle of the boom doesn't exceed the critical angle

Step 10

Burn is conducted once boom is in place. After the burn is complete boom and anchors are removed and all equipmer cleaned and returned



4.2.6. Backup Booms

A backup boom can be placed 200 to 300 m behind the burn to contain any oil that has been entrained or has splashed over a fire-resistant boom during the burn. A conventional boom that is not fire-resistant can be used as any burning stray oil would be extinguished on its own or by the fire-extinguishing vessel before it reaches this boom.

It has also been found that oil escaping from the fire-resistant boom will usually pool directly behind the boom because of eddies formed in this area. This oil usually remains in this area for some time and therefore can become re-lighted or remain lighted. If this oil escapes from this area, it will spread and become too thin to sustain burning and can therefore be safely collected in the backup boom.

4.2.7. Alternatives to Booms

A number of ideas have been proposed to replace fire-resistant booms when burning oil on water. Marine Research Associates have proposed the use of modified barges to contain the oil for burning. Some of these are shown in Figure 9 (Marine Research Associates, 1998). One concept involves cutting the centre tanks from a barge or extensively modifying a barge without centre tanks, so that only wing tanks remain. The barge would be towed at the apex of a boom and oil contained within the centre of the barge as illustrated in Figure 9 (a). A design for a barge with inflatable sides is illustrated in Figure 9 (b) and another design which uses forced air to enhance burning is also illustrated in the figure. These concepts and several variations of these are analyzed in detail in the Marine Research Associates report to US MSS, which shows that the barge concepts should provide a stable burn platform and a far extended life over fire-resistant boom (Marine Research Associates, 1998). These concepts are very costly to implement, however, and result in large, heavy devices.

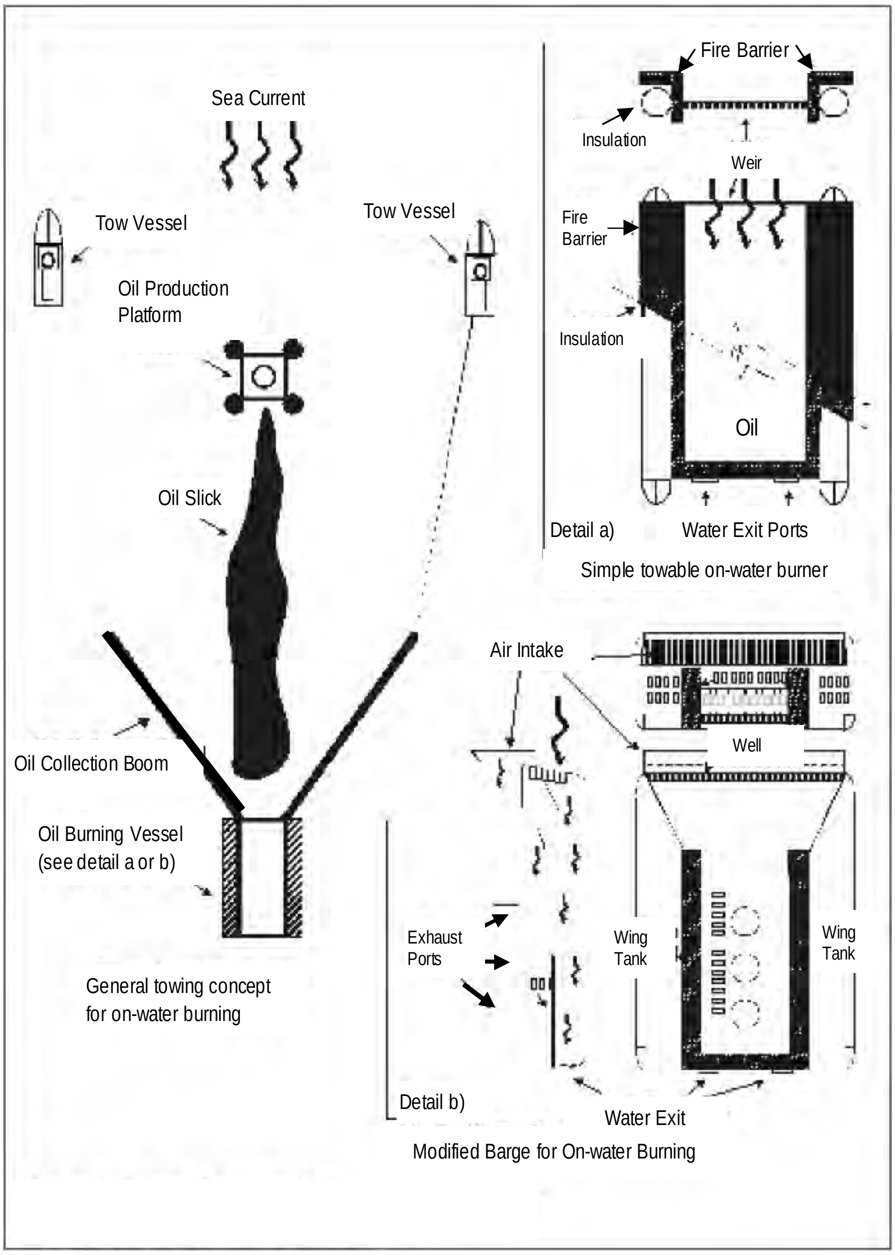
Bubble barriers are another concept that has been relatively effective at containing oil when tested in calm waters under actual operation situations, although it has never been used in conjunction with burning. A bubble barrier consists of an underwater air delivery system which creates a curtain of rising bubbles that deflects the oil. This concept is illustrated in Figure 10. Work on bubble barriers has shown that the horsepower requirement is high (Marine Research Associates, 1998), with a very large compressor needed for barriers longer than about 100 m. Testing has also shown that a large blower can power a bubble barrier using a fire-hose as outlet. The maximum length of the barrier in this case varies from 50 to 150 m (Alyeska, 1998).

Environment Canada has also worked on the development of a water jet barrier which could potentially be used for in-situ burning (Punt, 1990). The design developed consists of high-pressure hoses connected to a water pump. Each arm of the barrier is formed by two hoses, each with four evenly spaced sets of opposing jets. The force from the water jets holds the oil in the V formed by the barrier arms. This containment would allow oil to be safely burned. It was also felt that air entrained by the water jets would increase the efficiency and cleanliness of the burn. Unfortunately, these claims have not been fully tested due to mechanical problems and difficulties in maneuvering the barrier using its current configuration.

4.3. Ignition Devices

A variety of ignition devices or methods, both commercial and noncommercial, have been used to ignite oil slicks, although the methods of igniting oil on water have not been well documented (McKenzie, 1994). Many of the methods used are modifications of ignition devices used for other purposes.

Figure 9 – Novel Concepts for Burning Oil on Water
(Adapted from Maritime Research Associates, 1998)



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 then keep it burning and it must be safe to use. Safety issues to be considered when operating ignition devices are outlined in Section 7.1.3.

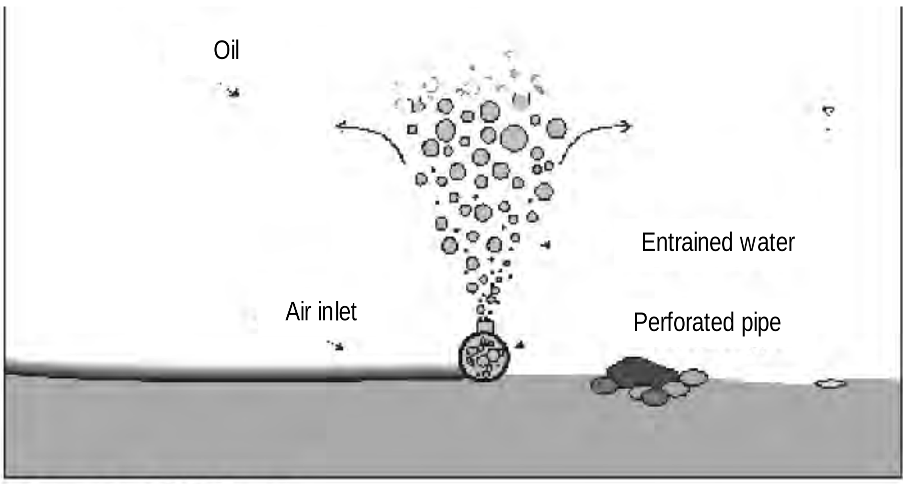
Research has shown that an oil slick must be at least 2 to 3 mm thick in order to ignite. The thicker the slick, the more easily and quickly it will ignite. As well, the lighter, i.e., more volatile or less weathered the oil, the more easily it will ignite. For heavy oils, more heating time is required to produce enough ignitable vapors.

Ignition Devices

- A convenient ignition system is the helitorch - a helicopter-borne ignition system.
- Hand-held igniters can be made or purchased.
- Ignition is relatively easy for most spills.

As discussed in Section 3.5.3, unstable emulsions can be ignited, but may require additional energy before burning is sustained. On the other hand, 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.

Figure 10 – Bubble Barrier



Commercially available ignition 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 or torches have also been suggested as an ignition device for in-situ burning.

In the late 1970s, research began into the development of aerial ignition devices for in-situ burning. The various commercial and noncommercial devices or methods available for igniting oil slicks and the operational procedures for their use are discussed in this section.

4.3.1. Helitorches

The most sophisticated commercial devices used today for igniting oil slicks are the helitorch igniters. 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 (ASTM, 2002, 1999a). This type of igniter was designed for the forestry industry and is used extensively for forest fire management.

Two helitorch systems suitable for igniting in-situ burns are the Simplex Heli-torch manufactured by Simplex Manufacturing of Portland, Oregon and the Universal Drip Torch available from Universal Helicopters of Deer Lake, Newfoundland or Canadian Helicopters of Prince George, British Columbia. These helitorches are shown in Figures 11 and 12. The Simplex helitorch was used effectively during the NOBE in-situ burn exercise off the coast of Newfoundland in 1993 (Lavers, 1997).

While the two units are assembled differently, they operate in a similar way. Both have a 205-L fuel barrel connected to a fuel pumping and ignition system. On the Simplex torch, all parts are mounted on an aluminum frame to which the slinging cables are attached. The pumping and ignition system of the Drip Torch are attached to the fuel transport pipe which is connected with a hose to the opening of the barrel. The pipe with all the attachments is mounted on top of the barrel with clips and the whole system is slung by cables running from the pipe. The components of a helitorch are illustrated in Figure 13.

The fuel used in the helitorch system is a mixture of a powdered gelling agent with either gasoline, jet fuel, 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. The manufacturer claims that this new product mixes easier, gels faster and at a lower temperature, and remains in suspension longer than the original product. 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. The general setup of these areas is shown in Figures 14 and 15. 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 organizational structure for all those involved in operating the helitorch system during an in-situ oil spill burn is shown in Figure 16. This is a simplified version of the structure described in helitorch operation manuals, which are written mainly for controlled burning on land, i.e., forestry operations that require additional team members. For small spills, where very few drums of gelled fuel are needed, this team could be further simplified to the following three persons: the Helitorch Supervisor, who would also perform the duties of the Safety Officer and the Hookup Operator, one Fuel Mixer, and the Pilot. The duties of each person listed in Figure 16 are outlined in Appendix C.

Figure 11 – Simplex Helitorch
(Fingas, M. and M. Punt, 2000)

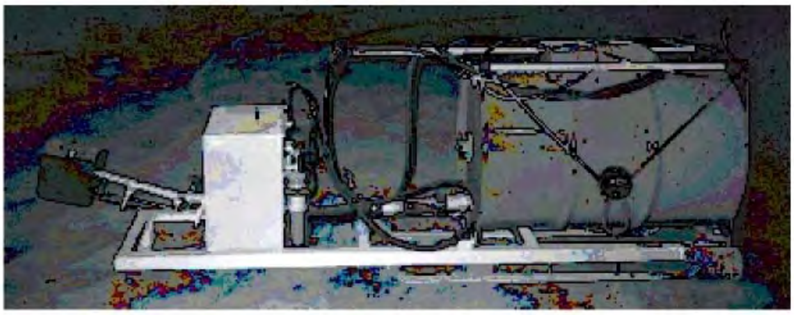


Figure 12 – Universal Drip Torch
(Fingas, M. and M. Punt, 2000)

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 gelled agent is required. The gelling times of various types of fuel when mixed with the SureFire brand of gelling agent are shown in Table 7. In most cases, unleaded gasoline is recommended as it is often the most readily available fuel. The mixing ratios should be determined using the tables provided in Appendix D. Mixing times at various temperatures are also given in these tables.

Figure 13 – Helitorch Components

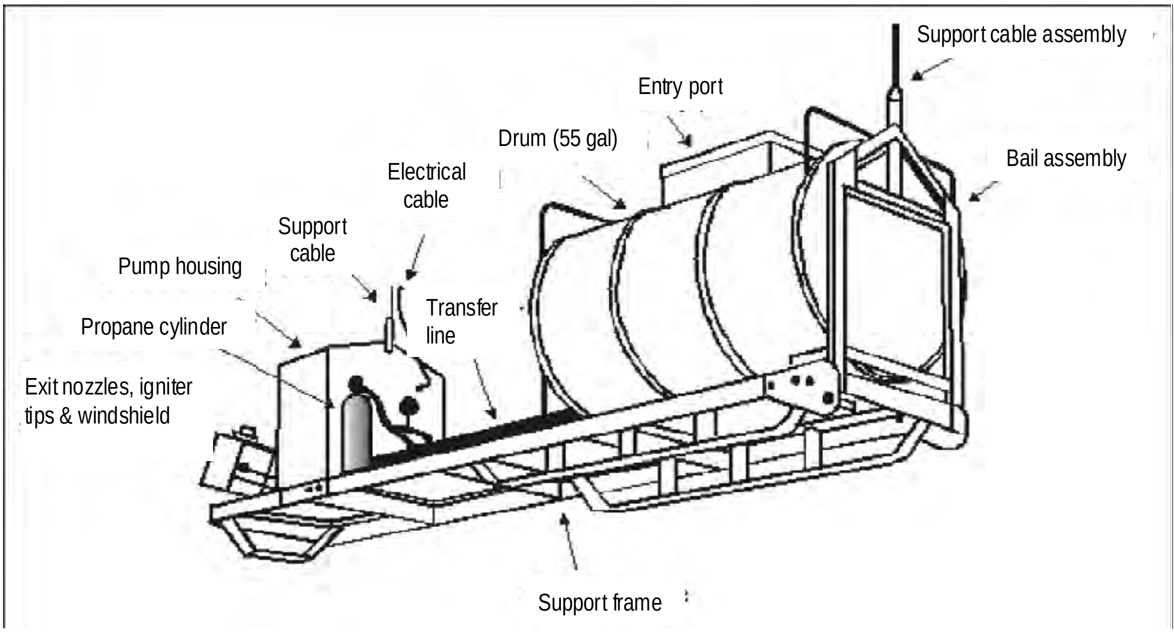


Figure 14 – Location of Fuel Mixing and Helitorch Loading Areas
(Adapted from OMNR, 1990)

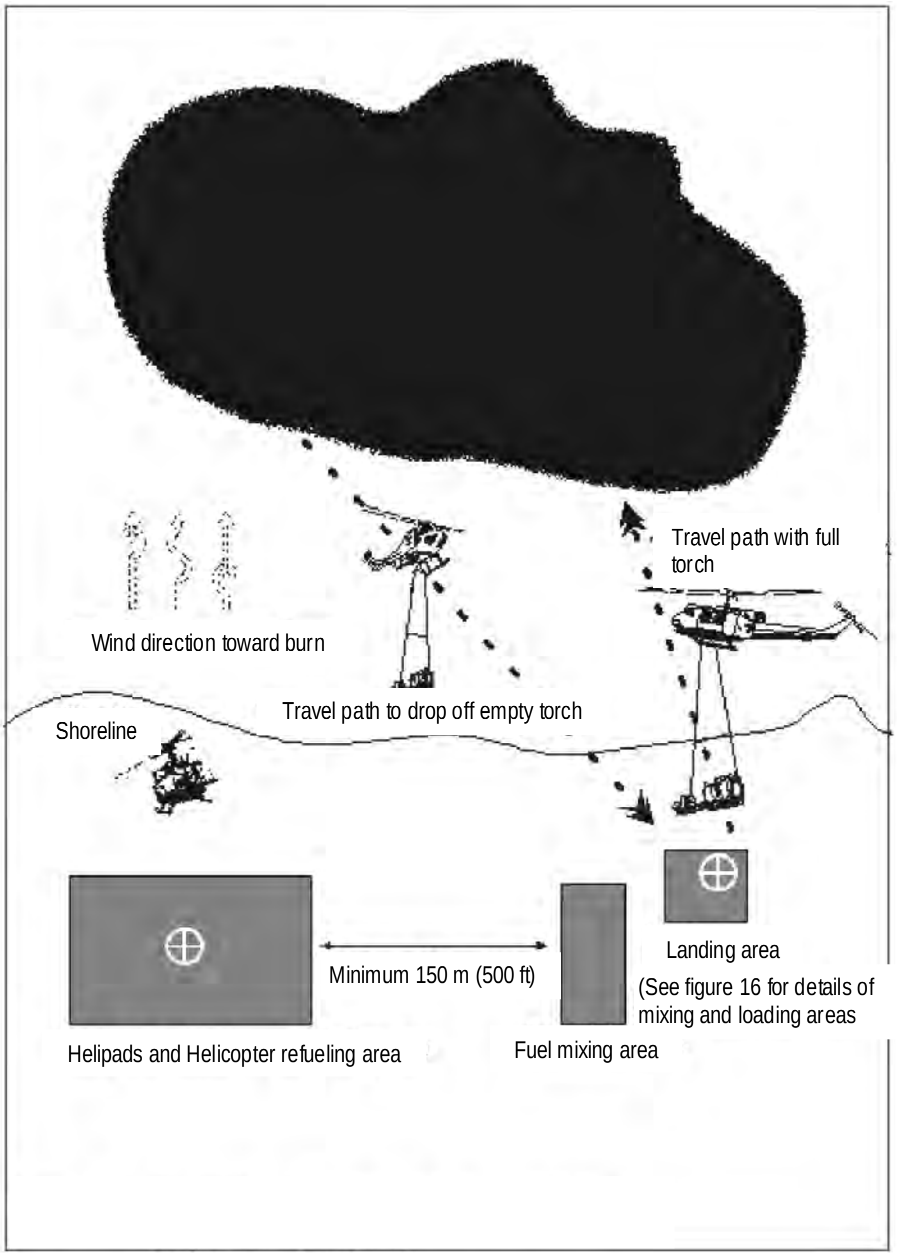
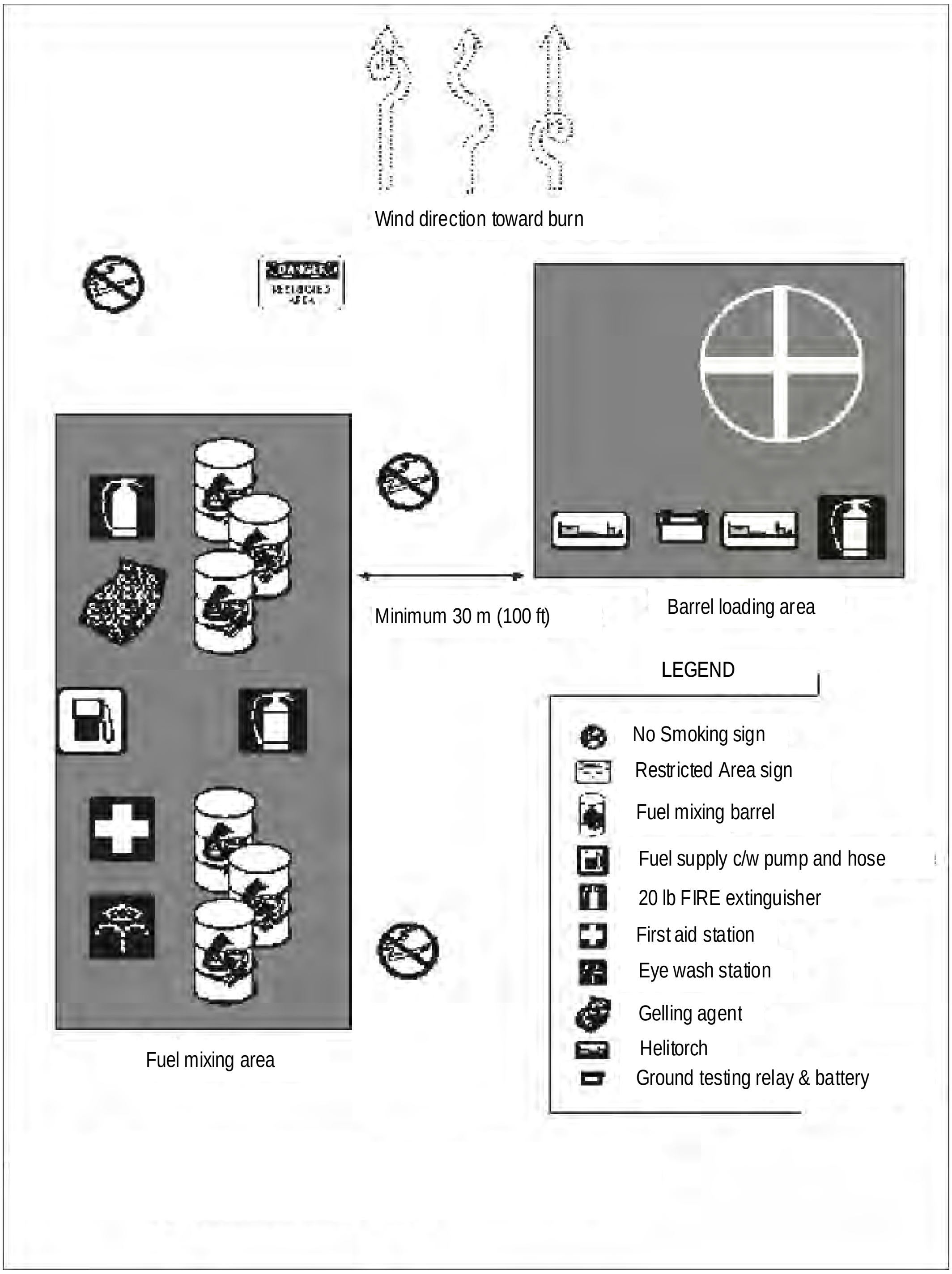


Figure 15 – Setup of fuel Mixing and Helitorch Loading Areas
(Adapted from OMNR, 1990)



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 fuel should not normally be related to the amount of oil to be burned. During the NOBE burn test in 1993, 20 L of gelled fuel were used to ignite a slick of 50,000 L. One barrel of gelled fuel containing 180 L could ignite approximately 450,000 L of oil covering the same area as during this trial. The volatility of the type of 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.

Figure 16 – Helitorch Operating Team

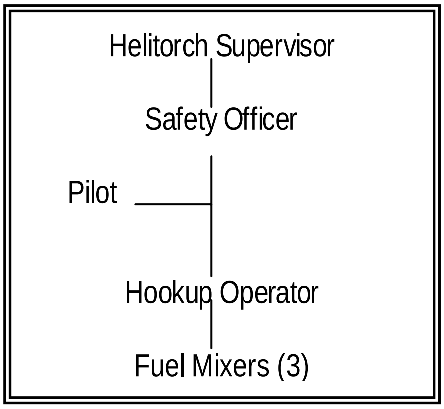


Table 7 - Gelling Times of Some Oils (Using Sure Fire)
(Fingas, M. and M. Punt, 2000)

Fuel Type	Mixing Time Required to Attain Desired Viscosity *(depends on temperature and mixing ratio)*	Effect of Air Temperature	Stability of Gelled Fuel	Comments
Jet Fuel A	Mixes very slowly (20 to 120 minutes)	Recommended when air temperatures are high, because of stability, but longer mixing time is required.	Most stable - lasts 4 to 5 weeks, 2 to 3 days at higher than 20°C	
Jet Fuel B	Mixes quickly (8 to 18 minutes)	Increase in air temperature has little effect on mixing time.	Stable for 2 to 3 weeks or 2 to 3 days at higher than 20°C	
Regular or Unleaded Gasoline	Mixes fairly quickly (10 to 45 minutes)	Recommended for air temperatures below 10°C to ensure continuous ignition.	Stable for 2 to 3 weeks or 2 to 3 days at higher than 20°C	
70% Diesel/30% Gasoline	Mixes slowly (10 to 110 minutes)	Increase in air temperature affects mixing time.	Stable for 2 to 3 weeks or 2 to 3 days at higher than 20°C	Percentage of gasoline should be increased below 10°C

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 attachment of the helitorch to the helicopter is illustrated in Figure 17. 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 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.

The safety aspects of helitorch operation are outlined in Section 7.1.3.1.

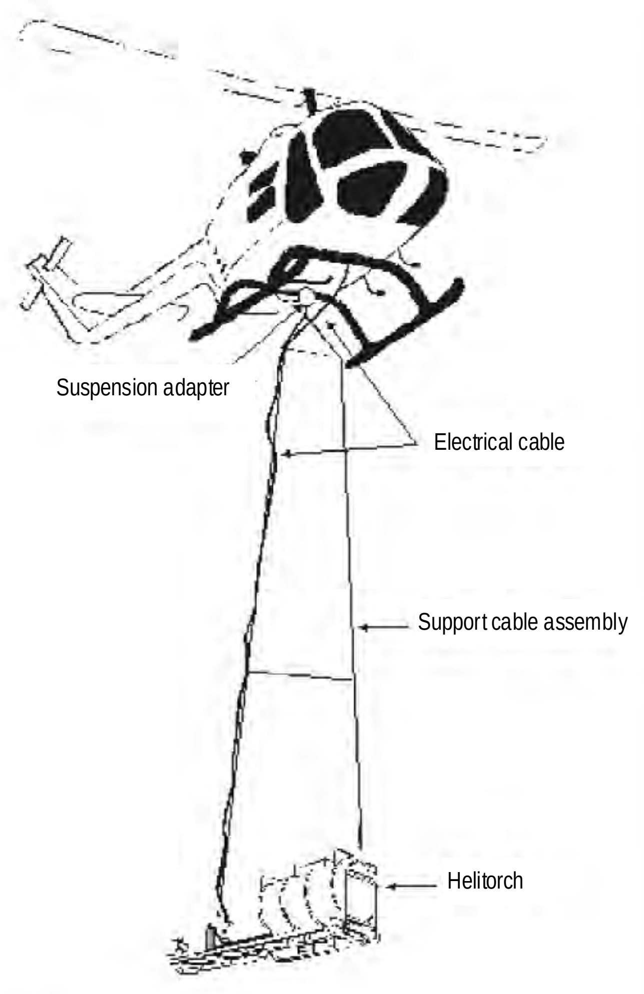
4.3.2. Noncommercial Ignition Devices

Simple ignition methods such as oil-soaked paper, rags, or sorbent have been used to ignite oil at actual and test spills (ASTM, 2002, 1999a). For example, gelled fuel in a plastic bag was used to ignite some of the oil from the *Exxon Valdez* spill. The bag was ignited, thrown towards the slick from a boat, and floated into the slick. It should be noted that diesel oil is preferable to 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.

A variety of hand-held igniters have been devised for igniting oil slicks (ASTM, 2002; ASTM, 1999a). 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 (ASTM, 1999a).

Some igniting devices use reactive metals and therefore do not have to be lit before being deployed. The Kontax igniter is an example of such a self-igniting device which was tested and marketed in the 1970s (ASTM, 1999a). This device consisted of a metal cylinder filled with calcium carbide with a metal bar coated with sodium metal running through the middle. When the device was thrown into the spill, the sodium metal reacted with the water to produce heat and hydrogen. The calcium carbide reacted with the water to produce acetylene. The hydrogen ignited and in turn ignited the acetylene. The flame from the burning acetylene was sustained long enough to heat the oil and produce vapors that were subsequently ignited. The main concern with this type of device is safety. The chemicals must be stored in a very dry place as accidental exposure to water would cause them to ignite.

Figure 17 – Mounting configuration of Helitorch to Helicopter
(Adapted from OMNR 1998)



In the late 1970s, during offshore oil exploration activities in the Beaufort Sea, researchers began investigating the use of aerial ignition devices for in-situ burning of oil spills. This work led to the development of two Canadian igniters - the DREV Igniter and the Dome Igniter. The DREV igniter was initially designed in the early 1980s by the Canadian Defence Research Establishment in Valcartier, Quebec (DREV) in conjunction with the Environmental Protection Service of Environment Canada (Allen, 1986; Energetex Engineering, 1981; and Twardawa and Couture, 1983). Several configurations of the igniter were built, some intended for deployment on pools of shallow water on ice. This igniter has also been referred to as the EPS Igniter, the AMOP Igniter, the DREV/ABA Igniter, and the Pyroid.

It was manufactured by Astra Pyrotechnics, Ltd. (formerly ABA Chemical Ltd.) of Guelph, Ontario, but is no longer in production. As recently as 1993, however, these devices could be obtained by special order from Hand Chemical. The advantage of this type of igniter is that it is built by a licensed pyrotechnic company using approved components and is licensed to be transported by truck or air freight.

Hand-held Igniters

- A simple igniter can be made from a flare, a jar of gelled fuel, and a piece of foam.
- The DREV igniter can be made by special order.

As shown in Figure 18, the DREV igniter is an air-deployable igniter with a pyrotechnic device sandwiched between two square flotation pads. Before tossing the device from the aircraft into the slick, the operator pulls the firing switch which strikes a primer cap. The system has a 25-second delay mechanism that allows time for the device to be thrown and to settle into the slick. After the delay, an initial fast-burning ignition composition is ignited that in turn ignites a rocket motor propellant consisting mainly of 40 to 70% ammonium perchlorate, 10 to 30% magnesium or aluminum metal, and 14 to 22% binder. This produces a ring of fire with temperatures close to 2,300°C that burns for 2 minutes - long enough for the surrounding oil to vaporize and ignite.

The Dome igniter was developed by Dome Petroleum Ltd. in Calgary, Alberta in conjunction with Energetex Engineering of Waterloo, Ontario (Allen, 1986 and Energetex Engineering, 1982). It has also been known as the Energetex Igniter or the Tin Can Igniter and was intended to be manufactured on site. This unit is no longer in production. As shown in Figure 19, the wire-mesh fuel basket, which contains a solid propellant and gelled kerosene, is surrounded by two metal floats. An electric ignition system activates a fuse wire allowing about a 45-second delay. The fuse then ignites a thermal igniter wire, which ignites the solid propellant, and finally ignites the gelled kerosene. The gelled kerosene burns at temperatures of 1,200 to 1,300°C for about 10 minutes allowing the oil to vaporize and burn.

The drawback of both the DREV and the Dome igniters is that one igniter is required for each slick or part of a slick to be burned. For large oil slicks and oil in melt pools, several igniters may be required, which is costly and time-consuming.

Another technique for igniting in-situ oil fires is the use of lasers. In the 1980s, Environment Canada sponsored research by the Canadian company Fleet Technology Ltd. (formerly Arctec Canada, Ltd.) and Physical Sciences Inc. of Andover, MA (Frish *et al.*, 1986 and 1989). This involved testing various laser techniques for igniting a variety of types of oil at different temperatures. The most successful technique in laboratory tests was to use a continuous-wave CO_2 laser to heat a localized area of the oil slick. The laser heats the oil to a temperature above its fire point. The heating time varies from a few seconds to more than 30 seconds depending on the type of oil, degree of weathering, and the oil temperature. The oil vapors are then ignited by a spark produced just above the oil surface by a focused high-power pulse beam from a second laser. A laser-focusing telescope with focusing mirrors is used to aim this second laser. Despite the success of this research, this device was not fully developed due to lack of funding.

Figure 18 – DREVIgniter
(Adapted from Twardawa & Couture, 1983)

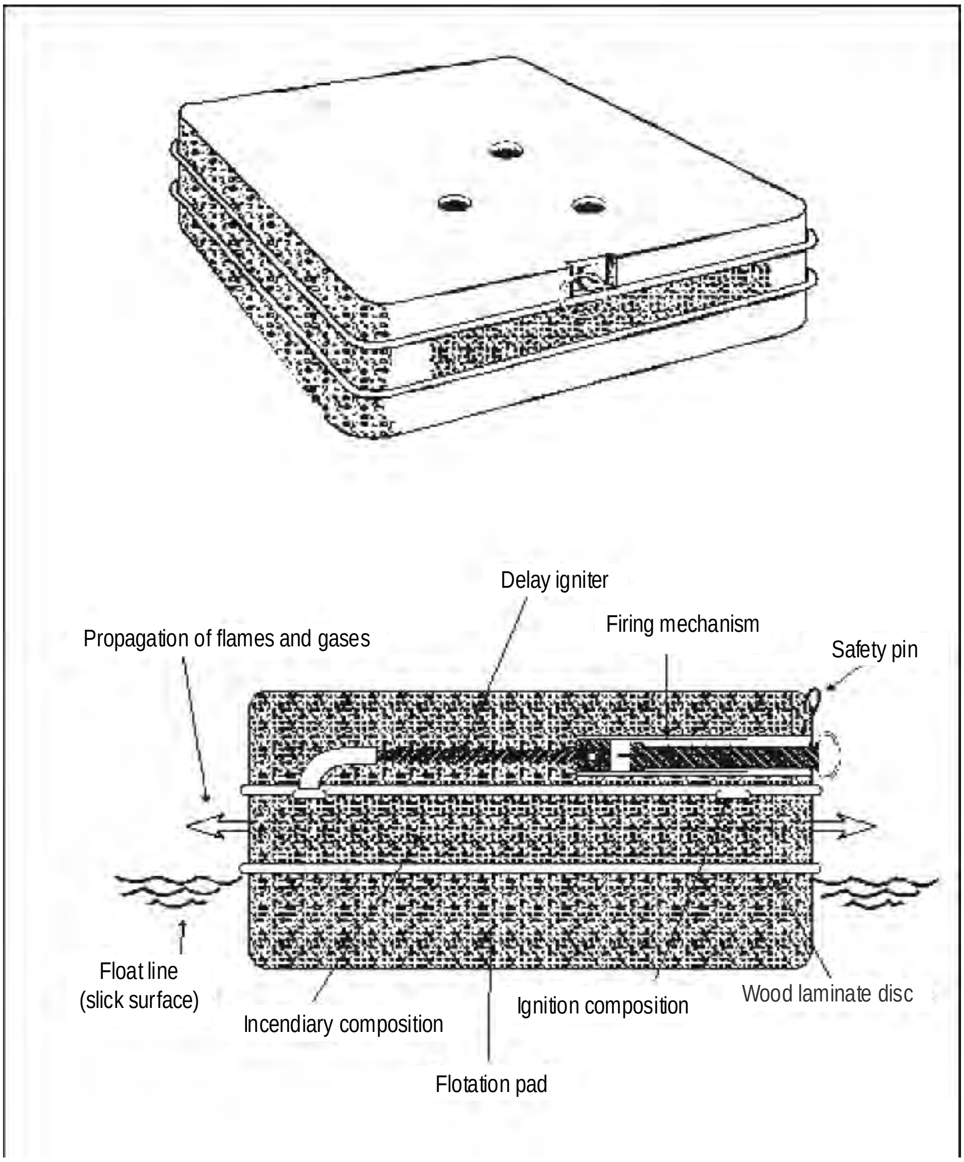


Figure 19 – Dome Igniter
(Adapted from Buist et al. 1994)

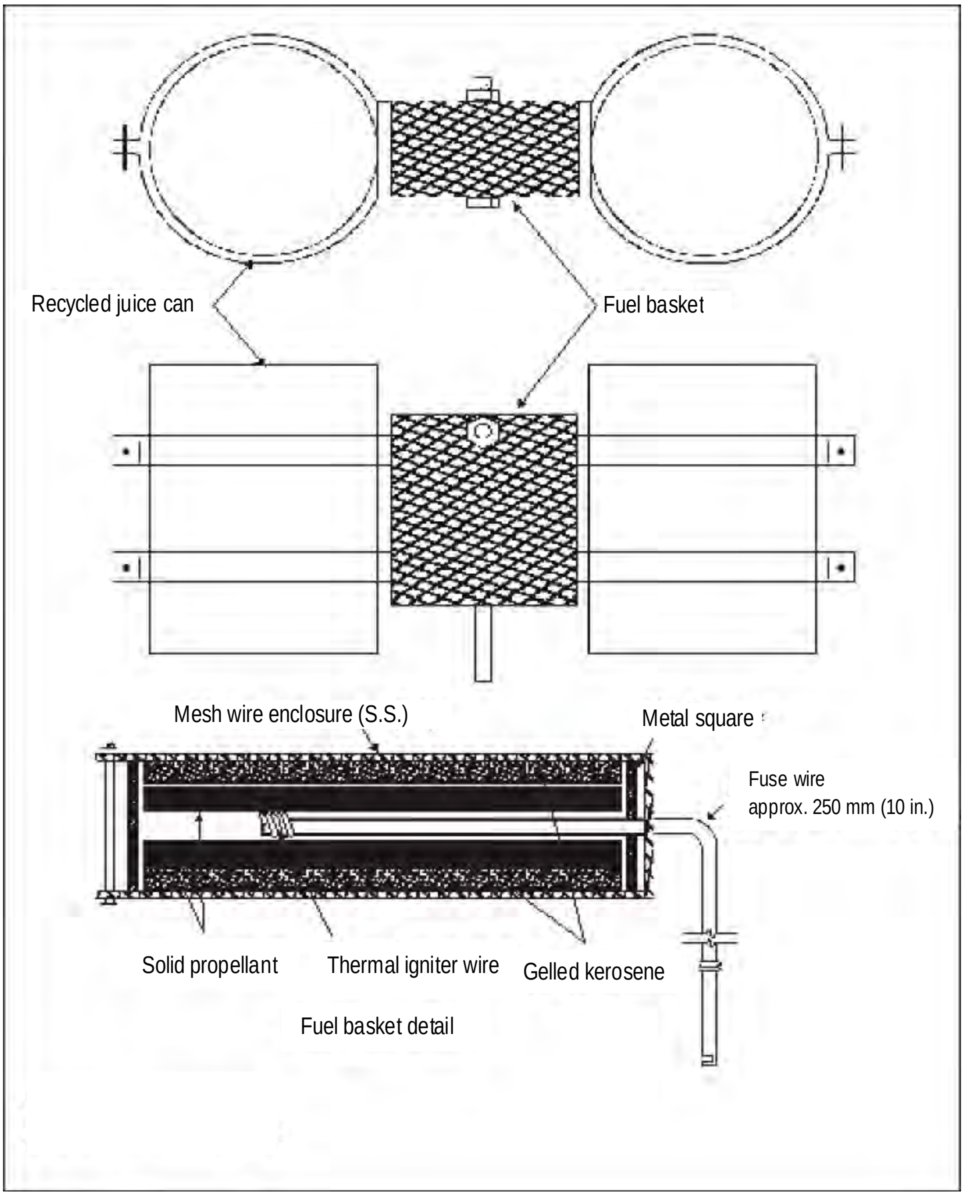
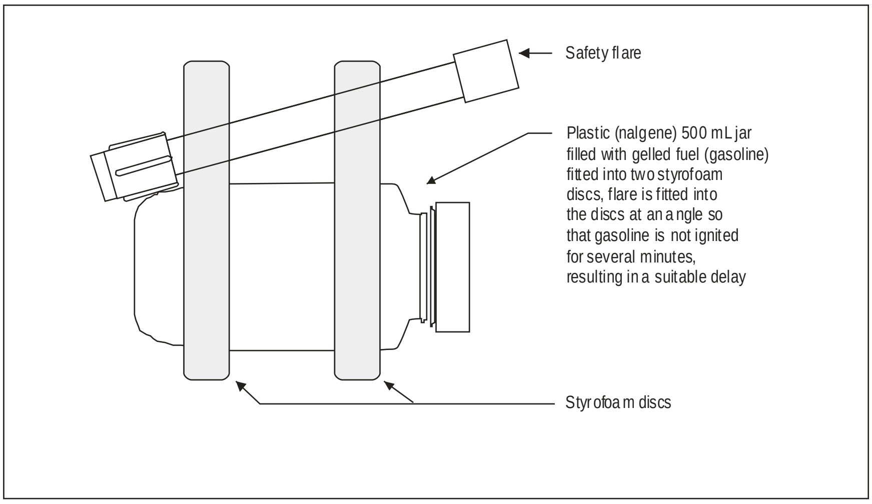


Figure 20 – Hand-held Igniter



A hand-held igniter, designed by Simplex and Spiltec, was used during in-situ burning tests in 1996 off the shores of Great Britain (Guénette and Thornborough, 1997). This igniter consists of a 1-L polyethylene “Nalgene” bottle filled with gasoline gell. The gel was made by mixing 1 L of gasoline with 0.01 kg of SureFire fuel gelling agent, which is the agent used in the helitorch. This 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. Such a device, which is relatively easy to make and to deploy, is shown in Figure 20.

Safety issues when operating ignition devices are outlined in Section 7.1.3.

4.4. Treating Agents

In general, as a burn becomes hotter and thus more efficient, the emissions from the burn are reduced. 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. Recent Norwegian work showed that combining chemicals that suppress smoke emissions with those that break emulsions and promote combustion is ineffective (McKenzie, 1994). However, the agents worked well separately. Chemicals could also be added to oil before transport so that it will burn more efficiently if spilled. Oxidizers, such as the chemical ferrocene that is used to solidify rocket fuel, can also be added to oil after spillage.

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 trails and rarely in actual spills. Some information is available on specific formulations of these agents, but the formulations vary extensively and many are not specifically patented.

Only three products, Gamelin EB439, Vytac DM, and Breaxit OEB-9, are specifically marketed for oil spills at this time (Walker *et al.*, 1993). Another product, Alcopol 60, has also been used extensively in field trials. Many products of this type are marketed for use in breaking emulsions that occur in petroleum production, but most have never been applied to oil spills (Ross *et al.*, 1992).

Several tests of emulsion breakers or inhibitors have been conducted. The results of some of these tests may not be useful; however, as they did not focus on the fact that there are several stability classes or water-in-oil states, i.e., stable emulsions, meso-stable emulsions, unstable emulsions, and entrained water. Furthermore, some testing may not have used proper analytical methods to evaluate the effectiveness.

The action required of the product must also be considered when developing effectiveness tests. It has been shown that some products will inhibit emulsification better than they will break an emulsion that is already formed (Fingas and Fieldhouse, 1994). It is therefore appropriate to have two types of tests for each of these functions. In addition, some emulsion breakers are used on the open sea, which is called an open system, and others are used in conjunction with skimmers, tanks, and pumps, with little water present, which is called a closed system. Thus, a total of four different tests are required to test all facets of emulsion treating agents.

Environment Canada has evaluated two treating agents in tests that are designed to measure each of the four testing regimes (Fingas and Fieldhouse, 1994). Different results were obtained with the same agents in the four different tests. In breaking stable emulsions in open systems, as would be the case in the open sea, the minimum ratio of 1:300 (wt:wt) was needed for Vytac DM and 1:200 for Alcopol 60. In breaking stable emulsions in a closed system such as would be the case with a skimmer or a closed vessel, Vytac required a minimum ratio of 1:250 and Alcopol, 1:280. Much less agent is required to inhibit the formation of a water-in-oil emulsion than to break such an emulsion. Furthermore, it was found that meso-stable emulsions required much less agent, although this amount was too variable to measure. Tests were also conducted to determine the amount necessary to prevent the formation of emulsions.

Buist and coworkers tested several combinations of the oilfield emulsion breaker, EXO 0894, to break emulsions of Alaska North Slope oil before burning (Buist *et al.*, 1995). It was found that 500 to 5000 ppm of EXO 0894 was sufficient to break emulsions that contained up to 65% water, so that these would burn. Emulsions containing more water would not burn. These laboratory-scale tests also found that at least one hour of mixing time was often required after spraying with the emulsion breaker before the emulsion would break. When used in tests, emulsion breakers have been applied using hand sprayers. In actual situations, it has been proposed that dispersant application equipment would be used.

Ferrocene is a chemical that can reduce or eliminate soot production from burns (Mitchell, 1990, 1991, 1992, 1993). Tests have shown that ferrocene, if it can be mixed, is highly effective at percentages from 1 to 2%. The problem with ferrocene is that it is denser than oil and water so it must be pre-mixed just before burning, which is very difficult to do outside a pan test burn.

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 (Thompson *et al.*, 1979). None of these agents is currently available. Some have suggested that such agents may be useful in burning uncontained 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 (Coupal, 1972). It was shown that such agents could reduce the minimum burning thickness and increase the efficiency of a burn. Sorbents may allow uncontained burning to be conducted in marginal conditions, but again more research is needed.

4.5. Support Vessels/Aircraft

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. 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. Separate, smaller tow vessels can be used to tow the boom.

Surveillance

- Any offshore burn should be monitored using helicopters or fixed wing aircraft.
- A separate vessel should also be dedicated to monitoring the burn and ensuring the safety of the boom tow team.
- Good communications must be in place to ensure a safe and well coordinated operation.

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. 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. When using more powerful twin engine helicopters in ignition operations, however, the oil must be ignited high enough above the slick to ensure that the down draft from the helicopter does not extinguish the burn.

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 refuelling operations.

When burning against a shoreline without the use of deflection or containment booms, only one helicopter (preferably a twin engine) 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 sea-truck 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 considering vessel stability. Depending on sea conditions and the dimensions and displacement of the sea-truck, such a vessel could carry an estimated 1 to 5 tons of residue. See Section 4.7 for more information on recovering oil residue.

4.6. Monitoring, Sampling, and Analysis

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-10 particulate matter in the smoke
- real-time monitoring of volatile organic compound (VOCs) in the smoke
- soot sampling for analysis for organic compounds and polyaromatic hydrocarbons (PAHs); 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 activities.

4.6.1. 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 a diameter of 10 m or less (PM-10) should be less than 150 μg/m3 for a 24-hour period. This is the standard set out by the National Institute of Occupational Health and Safety (NIOSH) and described in the U.S. Code of Federal Regulations (Office of the Federal Register, 1991).

A new PM-2.5 standard of 65 μg/m3 for a 24-hour period has been proposed. The second emission of concern is polyaromatic hydrocarbons or PAHs on the particulate matter. Volatile organic carbons or VOCs are a tertiary concern.

The devices currently used to carry out real-time monitoring of particulates are the RAM and DataRAM aerosol monitors, which are capable of detecting the PM-10 particulates emitted by a burn. 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 RAM 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 DataRAM has an internal recorder.

Emissions Monitoring

- Burn emissions should be monitored to ensure that they do not exceed human health concern levels and the levels should be documented.
- Real-time particulate monitors should be used to monitor PM-10 particulate matter under the plume.
- VOCs can be sampled using Summa canisters.
- Personal sampling pumps with filters can be used to collect material for PAH analysis.

A protocol developed by the U.S. Coast Guard, U.S. National Oceanic and Atmospheric Administration, U.S. Environmental Protection Agency, the Centers for Disease Control and Prevention, and the U.S. Minerals Management Service for real-time monitoring during in-situ burning or dispersant operations is available at http://response.restoration.noaa.gov/oilaids/SMART/SMART.html.

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 it 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 as discussed in Section 4.6.3.

4.6.2. 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 centres, 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.

4.6.3. 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.

The secondary emissions of concern from an in-situ burn are the PAHs associated with the particulate matter. There are several simple methods for collecting these particles for subsequent laboratory analysis. Simple sampling pumps can also be used to confirm particulate counts as well as to trap particles. Analysis of the trapped particles is complex and must be done by a laboratory with the required equipment and experience in PAH analysis.

Volatile organic compounds or VOCs are a third emission of concern. These can be sampled using evacuated metal canisters known as Summa canisters, which are opened for a specified time to collect a representative sample of the gas. The compounds must be analyzed by a specialized laboratory with the required equipment and experience in analyzing VOCs from Summa canisters.

4.6.4. Data Analysis

Analysis should be performed on the electronically recorded real-time particulate data. First, a base-line of background values should be established, which can be done graphically. This background should then be subtracted from the entire data set. This baseline may change throughout the burn as is evidenced by the data trend moving up or down throughout the monitoring period.

If the background does change, which happens frequently, it is more complex to subtract because it changes at each point in time. The background data can be subtracted by using a spreadsheet program that uses the slope of the line to subtract the background at each point in time. Secondly, the data should be averaged over the time period that the data was taken. Thirdly, the data needs to be corrected to reflect a 24-hour period, which is the time period over which the maximum exposure is usually specified. For example, if the average particulate concentration was 100 $\mu g/m^3$ over a 6-hour period, the 24-hour value is 25 $\mu g/m^3$, assuming there is no other source of particulates.

Because of these necessary data manipulations, data from real-time monitoring of burn emissions must be regarded with caution and cannot be used to establish that a burn is either safe or unsafe.

4.7. Final Recovery 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 area of concern.

The decision to recover the residue mechanically or leave it to break down biologically 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.

Residue is best recovered using a vessel with low freeboard which provides easy access to the water surface. A sea truck 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. Depending on sea conditions and the dimensions and displacement of the sea truck, 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.

Residue Cleanup

- Residue is viscous, adhesive, and dense.
- Small amounts of residue can be cleaned up with hand bailers and sorbents.
- Heavy oil skimmers are needed for large amounts of 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 such as the Desmi DOP-250 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 Desmi DOP-250, 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. Because of the small areas involved, hand-held igniters are more suitable than helitorches for re-igniting residue.

4.8. Equipment Availability

Depending on the jurisdiction responsible for the spill equipment, equipment for an in-situ burn response operation can be obtained by prior agreement from various organizations including the Marine Spill Response Corporation (MSRC), Clean Harbors Environmental Services, Inc., Clean Caribbean & Americas, Clean Bay Incorporated, National Response Corporation, Marine Pollution Control, and FOSS Environmental & Infrastructure. Some of these organizations are able to assist for a fee or can lease equipment and operators.

4.9. Equipment 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 Appendix E.

In the U.S., the National Oceanic and Atmospheric Administration (NOAA) has developed a service called SpillTools which consists of computer-based tools and learning aids designed to help both government and private organizations gain access to information for developing plans for possible spills. Specifically, the in-situ burn calculator provides oil spill planners and responders with calculations for estimating time and fire boom lengths required for burning oil in either a single release (batch) or a continuous release of oil. This calculator depends on the knowledge of oil slick thicknesses or source release rates. The calculator permits rapid computation for a range of conditions for a burn scenario which should provide some realistic solutions. The model can assist in selecting and staging appropriate equipment.

The in-situ burn calculator is available through the “Aids for Oil Spill Responders” link from the web site: http://response.restoration.noaa.gov/index.html

5. Net Environmental Benefit Analysis and Possible Spill Situations

All decisions associated with spill response have inherent trade-offs. Net Environmental Benefit Analysis (NEBA) is a tool to assist decision makers in selecting the oil spill response option(s) or strategy that will result in the lowest overall negative impact on the environment. NEBA is best described as a "process" to gain consensus among stakeholders that considers and weighs the advantages and disadvantages of the different response options compared with the advantages and disadvantages of natural clean-up (no response) to arrive at a spill response decision that can result in the lowest overall environmental and socioeconomic impacts. An excellent reference on NEBA is the IPIECA Report Series Volume Ten – "Choosing Spill Response Options to Minimize Damage *Net environmental Benefit Analysis"* which can be downloaded from the IPIECA website (www.ipieca.org).

Post spill decisions can be best made in a timely manner if based on pre-spill analysis, scientific work, consultations and agreements by the appropriate stakeholders long before the occurrence of an actual oil spill. For this reason, NEBA should be conducted as part of oil spill contingency planning. The response countermeasures that are generally evaluated in the NEBA process are:

- Mechanical (containment and recovery with booms & skimmers)
- Recovery by hand (rakes and shovels)
- Chemical Countermeasures (dispersant)
- In-situ Burning
- No response (natural clean-up)

There are a number of steps to take in order to develop an effective NEBA. These include:

- Gather detailed information on the local environment. The term "environment" includes both natural – such as mangroves, coral reefs, bird nesting areas, various types of beaches, etc. - and man-made – such as water intakes, wharfs, tourist facilities, etc. In fact, if one has not already been produced for the area, this is a great opportunity to develop a complete sensitivity map showing ALL environmentally (natural and man-made) sensitive sites. NOTE: Keep in mind that sensitivity's may change depending on the season. For example, migratory birds are obviously not a high priority when they are not present (although their nesting areas may be).
- Identify the products that could possibly be spilled that would threaten these sites. Included in this evaluation would be the predicted spread, thickness and oil movement and deposition, including weathering and chemical composition
- Once the above information is gathered each site needs to be prioritized as to its sensitivity and given a rating as to its recoverability. For example, mangroves may have a high sensitivity rating and a "slow" recovery rate if it is oiled while a sandy tourist beach may be relatively less sensitive and have a high recovery rate. The key here is to work very closely with all stakeholders, especially government officials.
- Consider all response strategies that could be used to respond to a spill of the various identified products.
- Again, working with stakeholders, develop predictions of how each of the identified response strategies will affect each of the identified sensitive areas. Using a mangrove swamp as an example, one could predict the mangroves will be significantly affected should no action take place or recovery is done by hand while there may be no to little affect if the oil is dispersed before it can interact with the mangroves.

- Once all this work is completed an evaluation of each of the response strategies and their predicted effects on each of the sensitive sites is done by comparing the advantages and disadvantages to the environment.
- Finally, using all of the information gathered the most optimum response method can be identified.

As is apparent, it is difficult to conduct this process on the spur of the moment. It needs to be completed as part of the contingency planning process with the input from all of the key stakeholders including applicable government agencies. By working together all parties will have a much better understanding of what is at stake should a spill incident occur and how best to respond to that spill.

The strategies listed in Table 8 can best be implemented using specific tactics. These tactics are listed in Table 9 and each one is illustrated separately in Figures 21 to 29. Each of these tactics has specific advantages and limitations.

The well-known tactic of using towed fire boom to collect and burn oil directly in the boom is shown in Figure 21. 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 shown in Figures 22 and 23. 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. The use of towed boom to protect amenities from a burning source of oil is shown in Figure 24.

Using anchored boom to burn oil is shown in Figure 25. This tactic poses no risk to tow boats and their crew. The boom may not maintain correct alignment with the wind and current, however, and the relative velocity of the surface current and the boom are also considerations.

The use of anchored deflection boom to direct oil away from amenities or toward burn areas is shown in Figure 26. The burning of oil against shoreline is shown in Figure 27. This can only be done if there is no combustible material such as trees and buildings on the shoreline. In addition, highly adhesive oil residue may be left on the shoreline, which may be difficult to remove.

Oil can be contained in shallow water using a temporary steel boom as shown in Figure 28 and as described in Section 4.2.4 and shown in Figure 6 (d) and (e). The boom is constructed of corrugated steel sheets and metal stakes. As a portion of the corrugated steel is in the water, heat is dissipated and the sheet metal should remain intact long enough for the oil to be burned. It is important to stress that this method has not been extensively tested and backups should be in place in case of failure.

Finally, burning uncontained oil is shown in Figure 29. While this method is simple and economical, the oil must be thick enough to support ignition and burning, which is rare for most uncontained spills of crude oil.

Table 8 - Specific Spill Scenarios and Burning Strategies

Scenario 1 Burning at sea	Strategy
Location: At sea **Position:** Offshore **Proximity of Oil to Source:** A large slick of oil well away from the source without any trail leading back to the source **Condition of Oil:** The oil in the centre of the slick is more than 3 mm thick and is not emulsified **Weather and Sea State:** Calm conditions	**General** Verify wind and current direction to ensure that burning the slick will not affect people, property, or environmentally sensitive areas. As a first response, as much of the slick as possible can be burned without using containment. This will require a helicopter with a helitorch. Several ignition points may be required to burn all parts of the slick that are burnable. Depending on the size of the slick and distance from land, a ship stationed near the slick may be required to refuel the helicopter and helitorch. Once the slick will no longer burn, containment can be used to further thicken the remaining oil and attempt to burn it again. **Containment Configuration** For the second stage of burning, ideally a fire-resistant boom should be used in the U configuration towed by two vessels. If a fire-resistant boom is not available, a conventional boom can be used with the understanding that the boom would be sacrificed and that its containment ability will be severely limited as the burn proceeds. Depending on the amount of oil to be burned, manageable sections of the slick (about 1/3 of the boom's U area) should be carved off from the main slick using the boom and transported away from the slick for burning. The slick should be approached from downwind and the boom should be towed into the wind during burning. **Protection** Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected. A standby boat should be nearby for helicopter rescue. Aircraft with extinguishing foam or water-bombing capability should be available. During containment operation, towing vessels should have water spray guns ready to protect them from flames. **Accident Response** During containment operation, tow vessels disconnect boom towing lines and sail away upwind from the burning oil or they should speed up to entrain oil, thus reducing slick thickness and extinguishing the burn. Notice of a floating hazard is filed to ships in the area. Aircraft with extinguishing foam or water-bombing capability fly over burn

Scenario 2 Burning at sea	Strategy
Location: At sea Position: Offshore Proximity of Oil to Source: A large slick of oil with a trail leading back to the tanker from which it was spilled. Condition of Oil: The oil in the centre of the slick is more than 3 mm thick and is not emulsified Weather and Sea State: Calm conditions	General As a first response, send tugs out to the site to move the tanker away from the main part of the slick. Surround the tanker with containment boom to prevent further seepage from the area and fully separate the vessel from the main slick. Water cannons can be used to separate any sheen connecting the tanker to the main part of the slick. Verify wind and current direction to ensure that burning the slick will not affect people, property, or environmentally sensitive areas. As much of the slick as possible can be burned without using containment. A helitorch should be used for ignition. Several ignition points may be required to burn all parts of the slick that are burnable. Depending on size of slick and distance from land, a ship stationed near the slick may be required to refuel the helicopter and helitorch. Once the slick will no longer burn, containment can be use to further thicken the remaining oil and attempt to burn the slick again. Containment Configuration For the second stage of burning, ideally a fire-resistant boom should be used in the U configuration towed by two vessels. If a fire-resistant boom is not available, a conventional boom can be used, with the understanding that the boom will be sacrificed and that its containment ability will be severely limited as the burn proceeds. Depending on the amount of oil to be burned, manageable sections of the slick (about a third of the U area) should be carved off from the main slick using the boom and transported away from the slick for burning. The slick should be approached from downwind and during burning, the boom should be towed into the wind. Protection Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected. Vessels with water sprayers can be situated around the tanker to prevent any flames from reaching it. A standby boat should be situated nearby for helicopter rescue. Aircraft with extinguishing foam or water-bombing capability should be available. During containment operation, towing vessels should be equipped with water spray guns to protect vessels from flames. Accident Response During containment operation, tow vessels should disconnect boom towing lines and sail upwind from the burning oil or they should speed up to entrain oil, thus reducing slick thickness and extinguishing the burn. Notice of a floating hazard is filed to ships in the area. Aircraft with extinguishing foam and/or water-bombing capability fly over burn.

<table>
<tr><th>Scenario 3
Burning at sea</th><th>Strategy</th></tr>
<tr><td>Location: At sea

Position: Offshore

Proximity of Oil to Source: A large slick of oil well away from the source without any trail leading back to the source

Condition of Oil: The oil in the slick is less than 2 mm thick and some parts of the slick are emulsified

Weather and Sea State: Winds approximately 15 m/s (30 knots) and waves occasionally greater than 1 m</td><td>General
An emulsion breaking treating agent should be applied to the parts of the slick that have stable emulsions.

Verify wind and current direction to ensure that burning the slick will not affect people, property, or environmentally sensitive areas.

Using containment boom with an overall height of at least 1 m, small sections of the slick should be pulled away from the main slick and burned.

Monitor wave heights and try to burn during times when waves are less than 1 m or, if possible, tow contained portion to an area where waves are less than 1 m high.

Ideally, a helicopter with a helitorch would be required to burn the contained oil.

Depending on the size of the slick and distance from land, a ship stationed near the slick may be required to refuel the helicopter and helitorch.

Containment Configuration
Because several burns will have to take place, a fire-resistant boom in the U configuration towed by two vessels should be used.

Manageable sections of the slick (about a third of the U area) should be carved off from the main slick using the boom and transported away from the slick for burning.

The slick should be approached from the downwind side and boom should be towed into the wind during burning.

Protection
Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected.

A standby boat should be nearby for helicopter rescue.

Aircraft with extinguishing foam or water-bombing capability should be available.

Towing vessels should have water spray guns to protect vessels from flames.

Accident Response
During containment operation, tow vessels disconnect boom towing lines and sail away upwind from the burning oil or they should speed up to entrain oil, thus reducing slick thickness and extinguishing the burn.

Notice of a floating hazard is filed to ships in the area.

Aircraft with extinguishing foam and/or water-bombing capability fly over burn.</td></tr>
</table>

Scenario 4 Burning in protected bay	Strategy
Location: Protected bay Position: Near shore, close to a small populated area Proximity of Oil to Source: Well away from the source without any trail leading back to the source Condition of Oil: Slick less than 2 mm thick Weather and Sea State: Calm conditions	General If the shoreline around the bay is too sensitive to allow for burning, the oil should be pulled out of the bay using containment boom and burned away from the shoreline. A helitorch can be used for igniting the burn. If combustible materials are well away from the edge of the shoreline or the shoreline can be protected, the oil can be burned within the bay using the shoreline and/or containment booms to concentrate and contain the oil for burning. A helitorch can be used for ignition, but if accuracy is a concern, hand-held igniters should be used, thrown from a boat and allowed to float into the slick. Verify wind and current direction to ensure that burning the slick would not affect people, property, or environmentally sensitive areas. Containment Configuration If oil is to be burned outside the bay, booms should be used in a U configuration to bring the oil out of the bay and away from the shoreline for burning. If possible, the burning should take place within a fire-resistant boom and the slick should be lighted with a helitorch. Boom should be towed into the wind during burning. If burning is to take place in the bay, boom should be used in a diversion mode to direct the oil towards a calm part of the bay to concentrate it for burning. The slick can be lighted with either a helitorch or an igniter thrown into the slick from a vessel. Protection Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected. A standby boat should be nearby for helicopter rescue, if a helitorch is being used. Aircraft with extinguishing foam or water-bombing capability should be available. For offshore burning, towing vessels should be equipped with water spray guns to protect vessels from flames. Within the bay, burning should take place at low tide if possible and the shoreline should be soaked with water before and during the burn. Water sprayers can be located on shore to divert flames from shoreline. If possible, fire trucks should be placed on the shoreline in case flames reach combustible material on the shoreline. Accident Response For offshore burning, tow vessels disconnect boom towing lines and sail upwind from the burning oil or they should speed up to entrain oil, thus reducing slick thickness and extinguishing the burn. Notice of a floating hazard is filed to ships in the area. Aircraft with extinguishing foam and/or water-bombing capability fly over burn and fire trucks are available on the shoreline.

<table>
<tr><th>Scenario 5
Burning on river</th><th>Strategy</th></tr>
<tr><td>Location: River

Position: Near shore, away from amenities and populated areas

Proximity of Oil to Source: Distant - no trail back to the source

Condition of Oil: Slick less than 2 mm thick

Weather and Sea State: Calm conditions, current more than 0.5 m/s (knots)</td><td>General
Before burning can take place, the oil should be diverted to a calm part of the river (slow current area, a point or bay area) where the shoreline is free of combustible materials or can be protected from the flame.

Both the shoreline and containment booms should be used to concentrate and contain the oil for burning.

A helitorch can be used for ignition, but if accuracy is a concern, hand-held igniters should be used, thrown from a boat and allowed to float into the slick.

Verify wind and current direction to ensure that burning the slick will not affect people, property, or environmentally sensitive areas.
Containment Configuration
Boom should be used in a diversion mode to direct the oil towards a calm part of the river to concentrate it for burning.

If containment boom is required during the burning phase, a fire-resistant boom should be used when possible.

Protection
Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected.

Aircraft with extinguishing foam or water bombs should be available.

The shoreline should be soaked with water before and during the burn. Water sprayers can be located on shore to divert flames from shoreline.

If possible, fire trucks should be available on the shoreline in case flames reach combustible material on shore.

Accident Response
Aircraft with extinguishing foam and/or water-bombing capability should fly over burn and fire trucks should be available on shore.</td></tr>
</table>

Scenario 6 Burning in Salt Marshes	Strategy
Location: Salt marshes Position: Near shore, away from amenities and populated areas Proximity of Oil to Source: Distant - no trail back to the source Condition of Oil: More than 3 mm thick and emulsification that has remained stable over several days Weather and Sea State: Calm conditions, wind speeds approximately 20 m/s (40 knots)	General An emulsion breaking treating agent should be applied to the parts of the slick that have stable emulsions. Verify wind and current direction to ensure that burning the slick will not affect people, property, or environmentally sensitive areas. A helitorch should be used to ignite the oil in area of concern. Depending on the size of slick and the distance from land, a ship may have to be stationed near the slick to refuel the helicopter and helitorch. Containment Configuration Containment boom should not be required as the melt pools should act as natural containment. Water spray can be used to push oil to one side of the pool during the burn to keep the thickness at a burnable level. Protection Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected. Standby boat should be nearby for helicopter rescue. Aircraft with extinguishing foam or water-bombing capability should be available. Accident Response Aircraft with extinguishing foam and/or water-bombing capability fly over burn.

Scenario 7 Burning in inter-tidal zone	Strategy
Location: Inter-tidal zone **Position**: Near shore **Proximity of Oil to Source**: Well away from the source without any trail leading back to the source **Condition of Oil**: The oil in the slick is less than 2 mm thick **Weather and Sea State**: Calm conditions	**General** If possible, install temporary sheet metal boom or fire-resistant boom in shallow waters and initiate burn. If the shoreline is too sensitive to allow for burning or the containment boom is too close to populated or sensitive areas, the oil should be pulled away from the area using containment boom and burned away from the shoreline. A helitorch can be used for igniting the burn. If combustible materials are well away from the edge of the shoreline or the shoreline can be protected, the oil can be burned against the shore using the shoreline and/or containment booms to concentrate and contain the oil for burning. A helitorch can be used for ignition, but if accuracy is a concern, hand-held igniters should be used, thrown from a boat and allowed to float into the slick. Verify wind and current direction to ensure that burning the slick would not affect people, property, or environmentally sensitive areas. **Containment Configuration** If oil is to be burned away from the area, booms should be used in a U configuration to bring the oil away from the shoreline for burning. If possible, the burning should take place within a fire-resistant boom and the slick should be lighted with a helitorch. Boom should be towed into the wind during burning. If burning is to take place in the area, boom should be used in a diversion mode to direct the oil towards a calm area to concentrate it for burning. The slick can be lighted with either a helitorch or an igniter thrown into the slick from a vessel. **Protection** Aircraft overflights should be carried out to ensure that burning is under control and that sensitive areas are not being affected. A standby boat should be nearby for helicopter rescue, if a helitorch is being used. Aircraft with extinguishing foam or water-bombing capability should be available. For offshore burning, towing vessels should be equipped with water spray guns to protect vessels from flames. Burning should take place at low tide if possible and the shoreline should be soaked with water before and during the burn. Water sprayers can be located on shore to divert flames from shoreline. If possible, fire trucks should be placed on the shoreline in case of flames reaching combustible material on the shoreline. **Accident Response** For offshore burning, tow vessels disconnect boom towing lines and sail upwind from the burning oil or they should speed up to entrain oil, thus reducing slick thickness and extinguishing the burn. Notice of a floating hazard is filed to ships in the area. Aircraft with extinguishing foam and/or water-bombing capability fly over burn and fire trucks are available on the shoreline

Table 9 – Tactics Used to Deal with Oil in Various Situations
(Fingas, M. and M. Punt, 2000)

Figure Number	*Tactic*	*Application*
20	Towed boom – burn in tow	Burning source
		Separation between source and oil
		Source separated
21	Towed boom – collect and burn	Non-burning source
		Oil near habitation or sensitive areas
22	Towed boom – source separated	Non-burning source
23	Boom used to separate source or protect amenities	General
24	Anchored boom	River, estuaries or shallow water
		Oil over subsurface sources or blowouts
25	Deflection boom	Oil deflected away from amenities
		Oil deflected to burn area
26	Burning against shoreline	Remote shoreline with no hazards
27	Temporary steel boom	Oil can be contained in shallows
28	Uncontained burning	Oil is thick enough to burn

Figure 21 – Use of Towed Boom to Burn Oil Directly

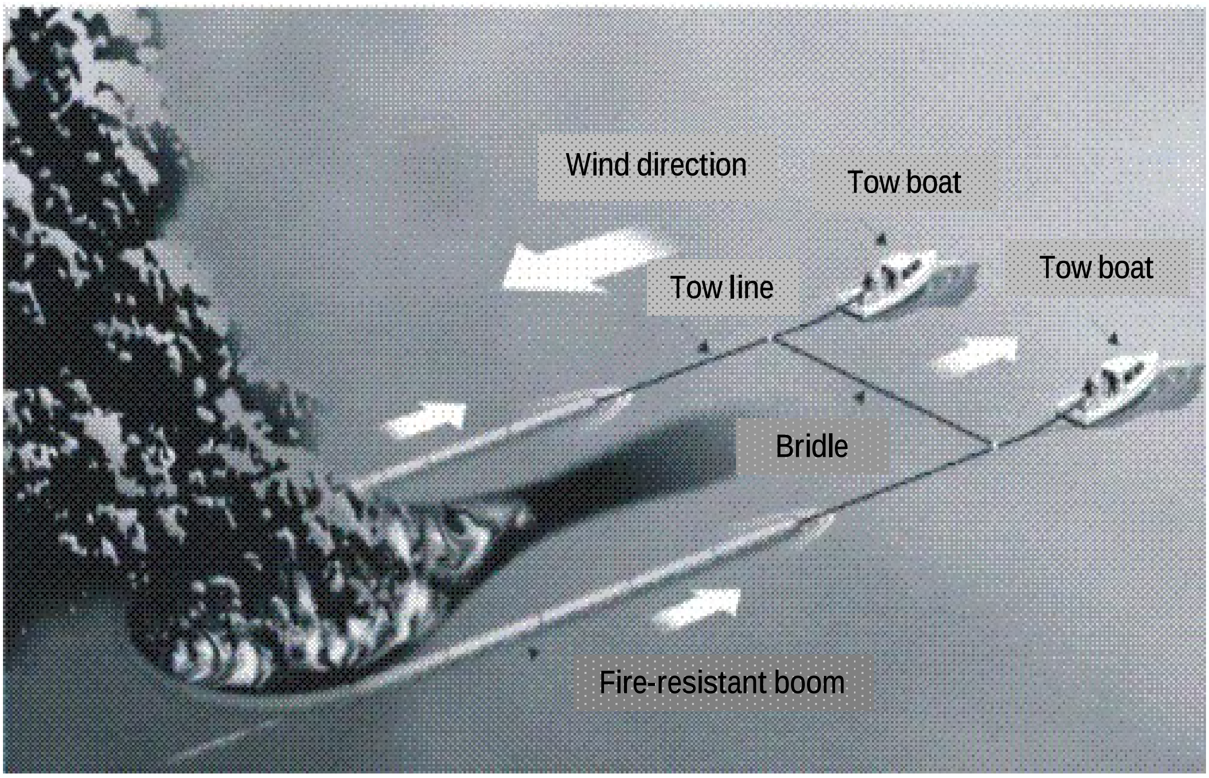


Figure 22 - Use of Towed Boom to Collect and Burn Oil

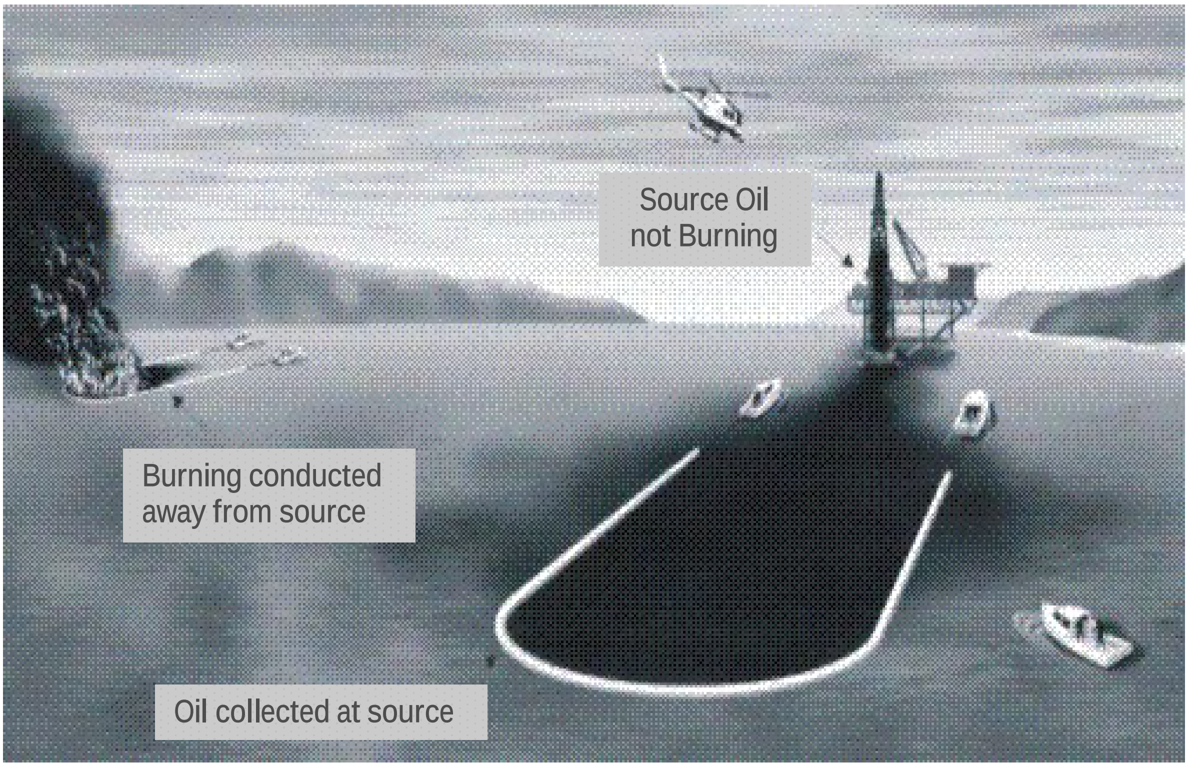


Figure 23 - Use of Towed Boom to Burn and to Separate Source from Fire

Figure 24 - Use of Fire-resistant Boom to Protect Amenities

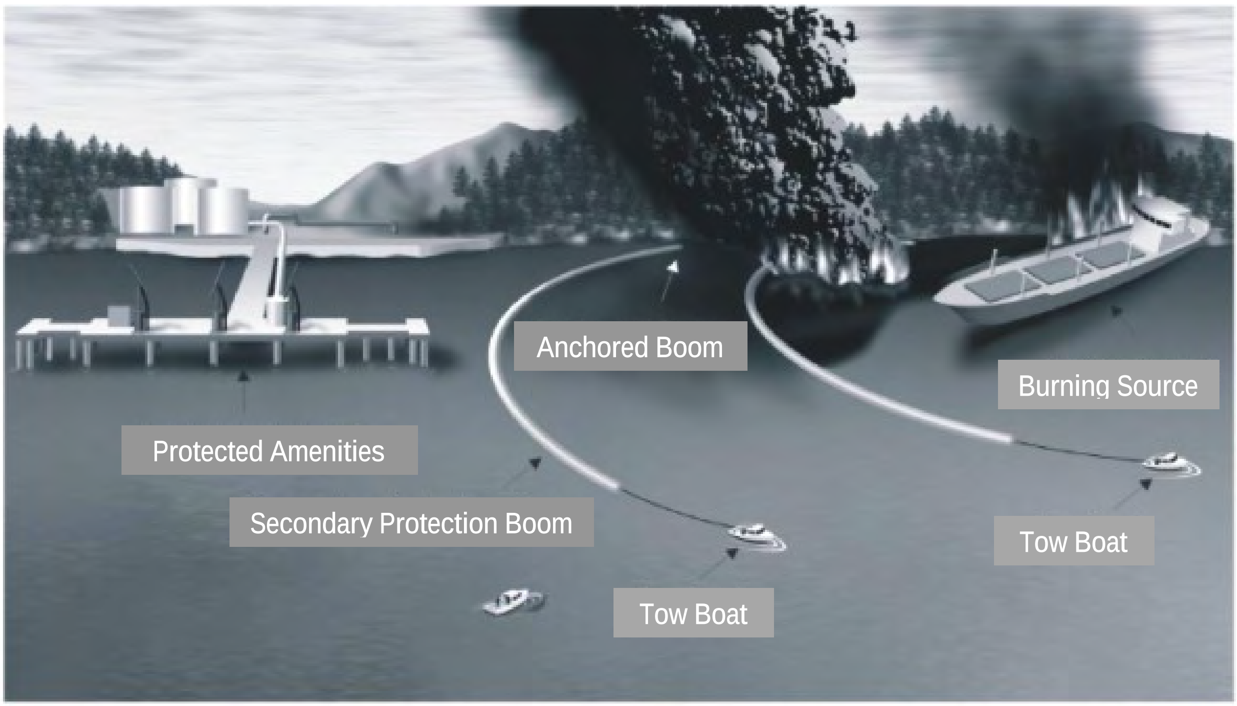


Figure 25 - Anchored Boom

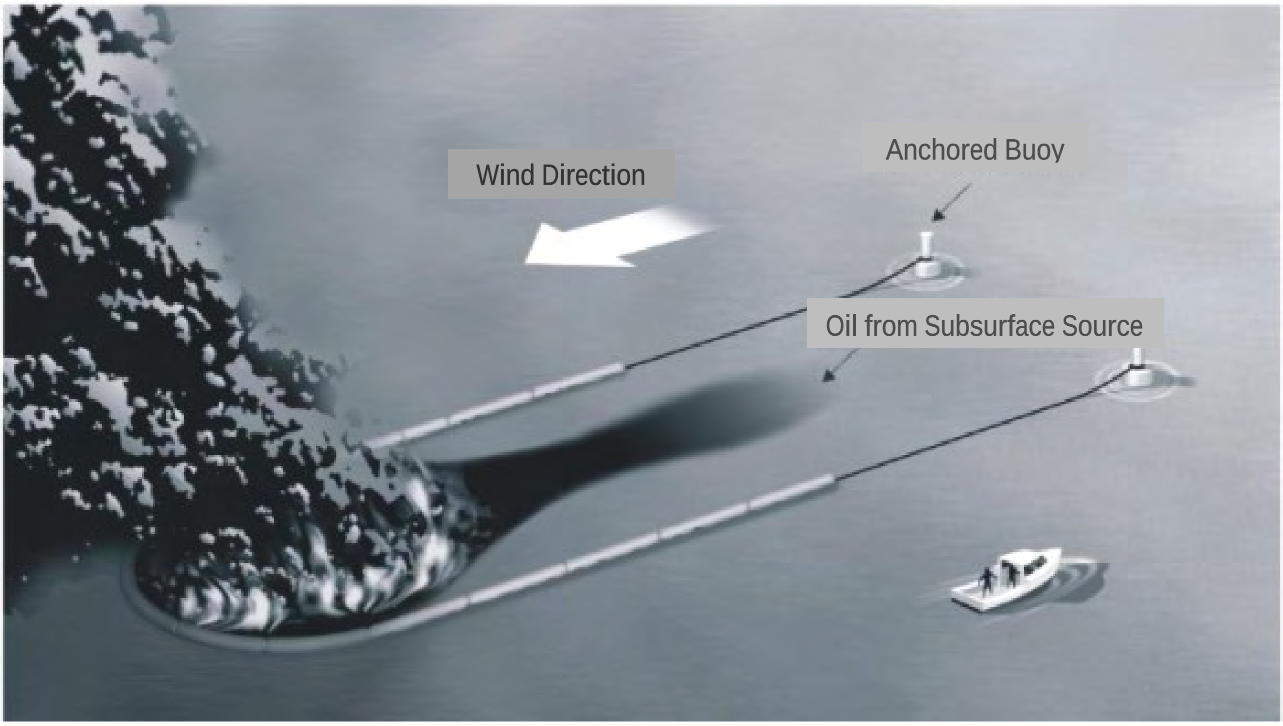


Figure 26 - Deflection Boom

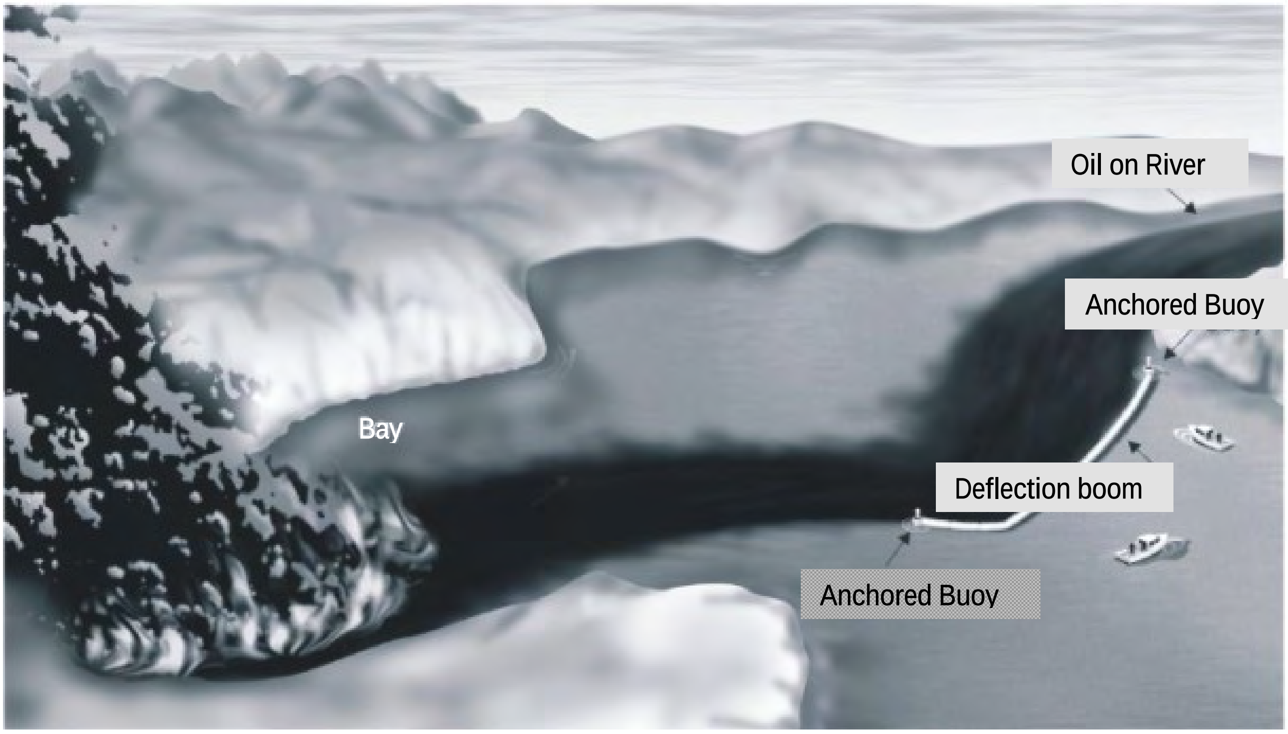


Figure 27 - Use of Temporary Steel Boom

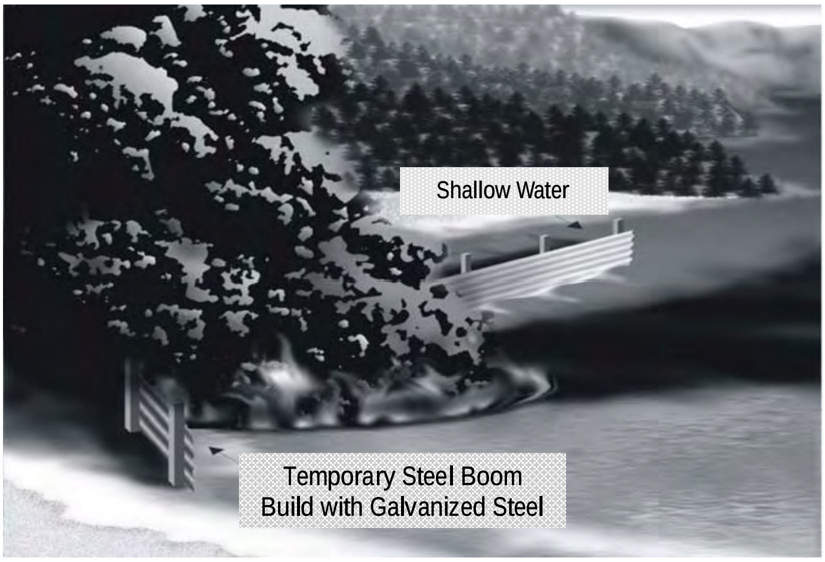
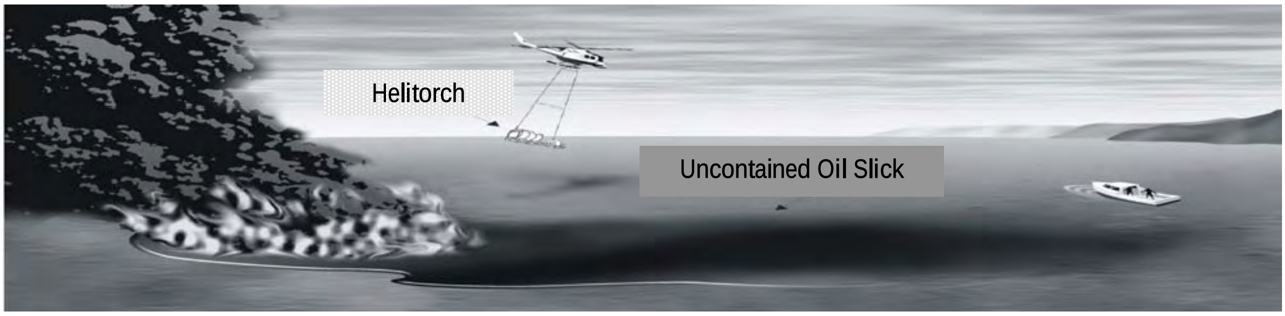


Figure 28 - Uncontained Burning



6. Post-burn Actions

6.1. Follow-up Monitoring

The site must be surveyed immediately after the burn to ensure that no burning materials remain in the area. 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 value and the amount of residue are important in estimating the overall mass balance.

Analysis of particulate matter, PAHs, and VOCs at the downwind locations should be completed if these are 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 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 remains if there are any questions on efficiency or other issues.

6.2. Estimation of Burn Efficiency

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 (ASTM, 1997):

$$E = \frac{V_{oi} - V_{of}}{V_{oi}}$$

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 coastal 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 off-shore 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 over flights, aerial photographs, or remote sensing devices. This area, together with an estimate of the average thickness of the oil, performed either visually by taking samples or by remote sensing, can then be used to estimate the volume of the slick.

It should be noted that this equation does not take into account the volume of oil lost through soot produced from the burn, which is a small amount and difficult to measure, or any residue that has sunk or cannot be collected.

If the residue remains afloat, it can be recovered either by skimmers or sorbents. The volume of residual oil remaining after burning, v_{of}, can be estimated by measuring the volume or weight recovered. If the residue cannot be recovered, the volume of the residue slick can be measured by estimating its area and thickness, in the same way described for estimating the initial volume of oil. The volume of any tar balls in the residue should also be taken into account.

If some or all of the residue sinks, which is rare, the amount of oil that burned (v_{oi} - v_{of}) can be estimated using the fact that, for most oils and conditions, an oil slick burns at a rate of 3 to 4 mm/min, generally taken at 3.75 mm/min. The amount burned can be estimated using this range, the area of the slick on fire, and the total time of the burn.

Research has shown that burn efficiency depends primarily on the thickness of the slick. Regardless of the initial thickness of the oil, the final thickness will be in the order of 1 to 2 mm. As such, much greater burn efficiency is achieved when burning a 20-mm thick slick than a 2-mm thick slick. The burn efficiency also depends on the flame-contact probability. This is a random parameter that can be controlled by proper containment, but is also affected by wind speed and direction. The burn efficiency can be reduced if the thickness of the slick is inconsistent, i.e., the flame reaches patches that are too thin to sustain burning or if the slick is not continuous. As noted in earlier sections, heavier oils will typically only burn to about 70% efficiency as there are fractions of oil present that do not vaporize from the slick at the temperatures typical pool burns attain.

6.3. Burn Rate

It is generally accepted that a crude oil slick burns at a slick thickness reduction rate of 3 to 4 mm/min, generally taken at 3.75 mm/min (ASTM, 2002 and Environment Canada, 1993). This range translates to about 5000 L/m^2.day. During the final stages of burning when the slick becomes very thin, or for heavy oils such as Bunker C, the rate decreases to about 1 mm/min. (Twardus, 1980).

Like the burn efficiency, the burn rate is virtually independent of the physical conditions and properties of the oil except for the heavy oil conditions noted. Oil emulsification can reduce the burn rate, however, because the water in the oil increases the amount of heat required for burning and thus reduces the rate at which the burn spreads.

The U.S. National Oceanic and Atmospheric Administration (NOAA) has developed an “in situ burn calculator” that calculates the burn rate and soot production based on inputted spill information. This is available through a link from the web site: http://response.restoration.noaa.gov/index.html.

7. Health and Safety Precautions during Burning

7.1. 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.

7.1.1. 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. Surveillance of the burn area should be arranged to provide such essential information to the tow operators as the 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.

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.

Safety Measures

- Surveillance of the burn from a larger vessel and from aircraft is suggested to spot precise wind direction, relative slick thickness, area of oil burning, and potential dangerous situations.
- Flames spread in two ways - on the surface and through the vapor cloud in the case of a volatile liquid, which is referred to as **vapor flashback**. Flames spread much faster through vapors than on the surface.
- Flames spread on the surface at a speed of about 0.2 m/s (0.4 knots), which is less than the usual boom tow speed of 0.2 to 0.4 m/s (0.4 to 0.8 knots). If a boom is towed at this speed and into the wind, flames are not likely to spread to the tow boats. Caution must be taken, however, because of possible changes in wind direction.
- Burning should **not** be conducted if tow boats are in or about to go through thick oil.
- Volatile fuels such as gasoline produce enough vapors to allow flames to spread as fast as 100 m/s (200 knots). Such fuels should not be burned if vapor flashback poses a threat to people, wildlife, the environment, or human infrastructures.
- Burning slicks can be extinguished by releasing one end of the boom tow, increasing the boom tow speed to greater than containment velocities (0.4 m/s or 0.8 knots), or by using firefighting foams.

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 them.

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 cover, 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. In theory, it has been proposed that a towed boom burn at sea can be stopped by releasing one end of the boom tow or by speeding up the tow so that oil is submerged under the water. Questions exist as to whether these two methods will extinguish a fully developed burn. Another suggested method is to slow down the towing rate thereby reducing the encounter rate (ASTM, 1997).

It is recommended that fire extinguishing equipment be available during the burn. One dedicated fire extinguishing equipment 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 and, if available, aircraft with water-bombing capabilities. To ensure safety, at least two of these extinguishing methods should be ready at a burn site. When burning is done close to shore, fire trucks and crews can be stationed at strategic points on land to fight unwanted secondary fires.

7.1.2. Boom Handling

When booms are being moved and recovered, personnel should avoid cables under tension such as the boom towing lines or tugger winch cables when in use. Personnel should also avoid standing in the coil or bight of a rope or cable lying on deck, which could tighten around a leg or foot and drag a person overboard.

Crane operations –onboard ship- are particularly dangerous as the roll of the ship may cause the load to swing like a pendulum on the crane wire. Anything being lifted by crane should have two handling lines attached to control the load. Only the crane operator, the signal person, and the two persons holding the load control lines should be involved in the operation. All other personnel should stay well away from the load while it is being lifted. The signal person is in charge of the operation. All personnel must maintain visual contact during the work. Hand signals should be reviewed and understood before operations begin.

Communications between the vessel bridge and the deck supervisor should be clear. Hand signals should be understood by all participants. It is recommended that a trained spill response team leader should supervise the entire operation from a safety point of view to detect any unsafe situations as they arise.

Recovering the boom after the burn has been completed is difficult and extremely messy work as the boom is usually waterlogged and covered with a tar-like residue. Workers should wear rain gear with neoprene gloves, rubber boots, and eye goggles.

Cuffs should be taped with duct tape. Appropriate decontamination materials are also required for cleaning personnel after the work is completed. Sorbent materials, rags, paper and fabric towels, citrus cleaners, soap and warm water, hand cream, garbage bags, and containers should all be available onboard the vessel. Any cleaning materials used should be collected after the burn for proper disposal.

7.1.3. Ignition Operation Safety

The following are some general safety issues that relate to ignition devices (ASTM, 1999a).

- 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 outlined in Section 7.1.3.1.
- Any device deployed from a helicopter should not require the use of open flames or sparks within the aircraft.

7.1.3.1. Helitorch Safety

Because the safety aspects associated with helitorch setup and deployment are multifaceted, strict coordination among the various persons involved in the operation is extremely important. The duties of each person in the helitorch operating team are outlined in Appendix C. There are safety issues associated with helicopter operations, shipboard operations (if the fuel is being stored onboard and/or the helitorch is being deployed from a ship), and the storage, mixing, transporting and loading of flammable liquids.

Under no circumstances should any untrained persons be involved in the helitorch operation. In particular, those responsible for preparing, deploying, and igniting the helitorch must be fully trained in helicopter safety, and the grounding procedures when transferring fuel.

Helitorch Safety

- Only trained operators should use the helitorch.
- Equipment and supplies should be laid out on the helipad in a given order.
- A three-person fire safety crew is needed to extinguish unwanted torch fires.
- When in transit to a burn site, the helitorch should be carried at a forward speed no greater than 25 m/s (50 knots).
- The pilot should approach the burn site and ignite from an upwind or side-wind direction.
- The helitorch is best deployed at about 15m altitude and at a very slow forward speed.

They must also be aware of the volatility of the fuel mixtures used and understand that static charges can occur when fuelling and moving equipment (OMNR, 1990).

The helitorch is ignited by the helicopter pilot. The door on the pilot's side of the helicopter can be removed to give the pilot a clear view of the helitorch. The helitorch control switch (toggle switch) should be mounted directly on the cyclic stick at a point where the pilot can comfortably operate it.

The attachment of the helitorch frame to the helicopter is crucial from a safety point of view. The device must remain stable when carried from the helicopter's cargo-hook, but it must also detach quickly if it needs to be jettisoned in the event of an emergency.

If the helitorch is deployed from a ship where space for maneuvering a helicopter is limited, the following precautions should be taken.

1. When the helitorch is ready for pickup and the helipad is clear of equipment, the helitorch supervisor radios the pilot with a request to move into position and pick up the torch.
2. When the helicopter returns for refueling, it hovers over the helipad so that the helitorch can be disconnected. The helicopter then moves away from the ship and assumes the hover position. The helicopter is not permitted to land until the helitorch and all other equipment and obstructions are removed from the helipad.

A three-person fire safety crew should be available on board the ship at all times, as well as a dedicated 68-kg fire extinguisher. Two 9-kg dry chemical fire extinguishers suitable for extinguishing fuel fires, a first-aid burn kit, and a spill cleanup kit for any fuel spills should be available both at the mixing and the loading areas. Personnel must wear fire protective clothing, goggles, a dust mask, and gloves when mixing and dispensing the gelled fuel and testing the system.

The helitorch must be maintained in good working order at all times. The valve that prevents the fuel from exiting the torch after the pilot has released the toggle switch can become clogged by dust or grit and remain partially open. The valve should therefore be checked and cleaned if necessary before each flight. As a further precaution, it is also recommended that the valve be thoroughly cleaned after every third or fourth refueling of the helitorch and that the O-ring in the valve be replaced as soon as it shows any sign of degradation. In general, all parts of the helitorch equipment must be cleaned regularly and any faulty parts replaced at the first sign of wear and tear or any other problem. Spare parts for the torch must always be available at the burn site.

All personnel involved in operating the helitorch must also be aware of the dangers of dealing with highly flammable gelled fuels. As such, proper grounding procedures must be used during the mixing of the fuels, when the fuel barrels are attached to the torch system, and when the torch is attached to the helicopter. It should also be noted that the helicopter picks up static as it flies through the air. The helicopter should therefore also be grounded as soon as it lands, before the torch is unhooked from the cargo hook.

The helitorch barrels must be filled using a non-sparking pump in a well ventilated area to dissipate fumes. If mixing is done by hand, a wooden or aluminum paddle should be used to prevent sparking. The proper grounding procedures to be followed in the mixing area are shown in Figure 29.

Before the helitorch is deployed, the water currents and wind conditions should be noted to determine the safest location for the ignition. A pre-flight test must also be carried out at this time to test the cargo hook, fuel pump, propane discharge, sparkers, and the toggle switch connected to the pilot's cyclic stick.

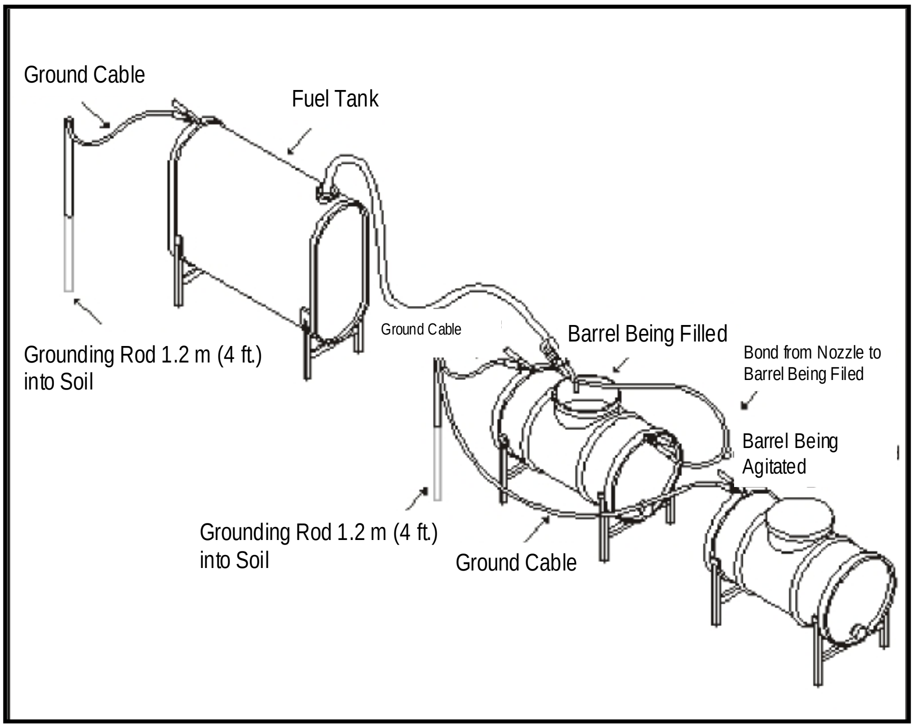
Before igniting the slick, a pre-determined location should be chosen to perform a test drop of a small amount of ignited gelled fuel. Wind and current direction should be checked again to ensure that the burning gelled fuel does not drift towards any of the operational vessels. If the test burn indicated 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 gelled fuel in order to concentrate the fire in one location.

When the ignition session is completed, the pilot disengages the helitorch circuit breaker to isolate the toggle switch so that no burning gelled fuel is accidentally dropped. The helicopter then returns to the land- or ship-based helitorch deployment site. When the helicopter lands, the recovery crew should stabilize and secure the helitorch before the helicopter pilot disconnects the cargo hook. This is especially important when the gelled fuel barrel is empty because the torch system can easily be blown off the helipad by the downdraft of the helicopter's rotors.

7.1.4. 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 (0.04 to 0.3 knots). 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.

Figure 29 – Grounding and Bonding Procedures for Mixing Helitorch Fuel
(Adapted from OMNR 1990)



Any crews working alongside the burn could be exposed to high concentrations of particulate matter, PAHs, and/or VOCs if the wind changes and blows towards them. For this reason, operational vessels should not operate behind the tow boat positions.

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.

7.1.5. Health and Safety Requirements

Extreme care must be taken when burning oil on water because of the heat, combustion gases, soot, and open flames. Burning must be conducted in a controlled, safe manner that complies with provincial, state, and federal laws and regulations to protect worker health and safety.

In the U.S., the Occupational Safety and Health Administration (OSHA) regulates operations to protect workers (29 CFR 1910.120), i.e., controlling exposure limits and requiring a hazard assessment for a specific emergency response. A 40-hour training course in hazardous waste operations and emergency response or its equivalent is required.

7.1.6. In-situ Burn Training

All personnel involved in a burn in the United States must complete the 40-hour Occupational Safety and Health Administration (OSHA) Haz-Mat course and the equivalent course should be completed by burn personnel in the relevant country. Personnel involved in a burn should be familiar with the technology and procedures in this report.

Training

- Operators near fire should have a 40-hour Haz-Mat training course and a special burn course.
- Helitorch operators require special training.
- Boom tow operators should have practice in towing, fire protection, and releasing of boom.

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.

7.1.7. Vessel Safety

The size, structure, and navigational equipment of any vessels used in an in-situ 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, a compass or gyrocompass, working radar, working depth sounder, HF radio, VHF radio, and telephone.

Under the relevant acts in the country, 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 in the relevant area should possess a valid Coast Guard inspection certificate. A survey by a qualified ship surveyor or naval architect is recommended before chartering a vessel.

7.1.8. Aircraft Safety

All flying operations must be carried out in accordance with federal flight regulations. All aircraft associated with an in-situ burn should be chosen carefully to suit the required tasks. Flight plans should be well thought out to take into consideration wind, visibility, cloud types and height, the presence or forecasted presence of fog, precipitation, sea state, and other relevant weather conditions.

For helitorch operations, the helicopter must have sufficient lift capacity to carry a pilot, co-pilot, and a helitorch full of fuel and be equipped with a cargo hook able to sling the helitorch as well as jettison it. The pilot must test the jettison mechanism before each helitorch operation. For safety reasons, a twin engine helicopter is preferred, particularly for offshore operations. These helicopters are more powerful than single engine machines and can therefore gain altitude more quickly. If a single engine helicopter is used, it must be equipped with floats to facilitate emergency landings. The helicopter must comply with the relevant regulations regarding helicopter maintenance and the operation being undertaken.

Only the pilot and co-pilot or one other person if required for the ignition activation should ride in the helicopter during the helitorch operation. All persons in the helicopter should wear a survival suit. During near shore operations, updraft and downdraft winds against cliffs must be considered. Emergency landing locations for the helicopter should be identified in advance through site surveillance in case of mechanical difficulty.

Helicopters capable of carrying a helitorch are required. It is recommended, however, that when helicopter services are being arranged, the performance capability of the aircraft and its suitability for its intended use be confirmed with the helicopter pilot and/or helicopter operator.

7.2. Public Health and Safety Precautions

The public should not be exposed to emissions exceeding the recommended human health concern levels. The most concern would be the exposure to particulates greater than 150 $\mu g/m^3$ over a 24-hour period. This can be determined by using the formulae provided in Section 3.4.3.1 to calculate minimum safe burn distances and by monitoring the particulate levels using the methods outlined in Section 4.6.

It is important to note that atmospheric inversions can occur that will increase ground-level concentrations to high levels, and that the smoke plume itself might drop to ground level at higher elevations further inland. Monitoring must be done to ensure that this situation does not occur. If there is the potential of this occurring, the burn should not be started. If a burn is already started and the plume drops to ground level, the situation should be immediately assessed to determine whether the burn should be stopped, people evacuated, and/or whether the plume could drop again. Any people who may be affected by the burning, even if only remotely, must be briefed so that they are aware of the activity and the possible need to evacuate the area on short notice.

If burning near land, sufficient personnel must be available on land, in good communications with the burn command vessel. The land-based personnel will monitor the smoke plume and stay in contact with local weather officials to be informed of any potential changes that could cause the plume to directly affect people on the ground.

If burning against or very near the shore, additional precautions must be taken to ensure that the fire does not spread from the oil to other combustible material. The fire should be monitored from shore by personnel with the ability to put out any potential fires. Trees and other combustibles near the shore might be wetted down as an extra precaution.

7.3. 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, calculated as shown in Section 3.4.3.1, and by the use of smoke plume modeling.

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.

The smoke model ALOFT (A Large Outdoor Fire Plume Trajectory model) was developed by the National Institute for Standards and Technology for the US Minerals Management Service (McGratten, 1999). It is designed to run on a PC and thus could be used as an immediate tool for predicting safety zones. The model has been used to prepare tables of safe distance predictions for typical fires. The model now also incorporates the effects of surface roughness.

The hazard zone distances for a fire consuming 0.044 m^3/s are shown in Table 10. The mixing layer depth shown in the table refers to the depth of atmospheric mixing or the atmospheric boundary layer. It might also be viewed as the height of the clouds.

Table 10 - Hazard Zone Distances Calculated Using ALOFT (distances in km)

Terrain Height (m)	Atmospheric Mixing Layer Depth (m)				
	0 to 100	100 to 250	250 to 500	500 to 1000	>1000
0 to 25 (flat terrain)	5	4	3	2	1
25 to 250	10	8	6	4	3
250 to 500	15	12	10	8	5
> 500	20	17	15	12	10

The U.S National Oceanic and Atmospheric Administration (NOAA) has a 'spill tool' available that provides a series of aids for calculating oil spill burning. In addition to calculating how much boom is needed and burn times, it also estimates plume heights, etc. The spill tool can be obtained on-line from http://response.restoration.noaa.gov/oilaids/spilltool/.

Procedures for using the historical emission data to calculate safe distances are described in Section 3.4.4. These procedures have been used to calculate safe distances as shown in Table 11. These distances are calculated on the basis of winds of about 5 m/s (10 knots) and atmospheric stability D, as was prevalent during the times that the experiments were conducted.

Table 11 - Safe Distances Calculated from Historical Emission Data
(Fingas, M. and M. Punt, 2000)

	Safe Distances	
Burn Area (m^2)	Crude Oil (kilometers)	Diesel Fuel (kilometers)
50	0.02	0.03
100	0.03	0.06
150	0.04	0.1
250	0.08	0.3
400	0.25	2.1
500	0.5	7
750	3.1	>50
1000	19	>100

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 many 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.

8. References

- ADIOS 2, Automated Data Inquiry for Oil Spills, National Oceanic and Atmospheric Administration, Seattle, WA, 2004. http://response.restoration.noaa.gov
- Allen, A.A., "Alaska Clean Seas Survey and Analysis of Air Deployable Igniters", *Proceedings of the Ninth Annual Arctic and Marine Oil Spill Program Technical Seminar*, pp. 353-373, 1986.
- Allen, A.A., "Contained Controlled Burning of Spilled Oil during the *Exxon Valdez* Oil Spill", *Spill Technology Newsletter*, Vol.15 (2), 1990.
- Allen, A.A., *In-situ Burning Manual, An Economical Solution for Oil Spill Control*, American Marine Inc., Cocoa Beach, FL, 1994.
- Alyeska Pipeline Service Company, "Supplemental Information Document #1, Section 8 - Burning", *Addendum to the Prince William Sound Contingency Plan*, Alyeska Pipeline Service Company, Anchorage, AK, 1998.
- Arai, M., K. Saito, and R.A. Altenkirch, "Flame Propagation Over a Layer of Crude Oil Floating on Water", *International Chemical Engineering*, Vol. 33, No.1, pp. 129-135, 1993.
- ASTM (American Society for Testing and Materials), *Standard Guide for In Situ Burning of Oil Spills on Water: Environmental and Operational Considerations*, Designation F 1788-97, ASTM, Philadelphia, PA, pp. 1007-1012, 2002.
- ASTM (American Society for Testing and Materials), *ASTM Standard Guide for In-Situ Burning of Oil Spills - Ignition Devices*, 5th Draft, ASTM, Philadelphia, PA, June, 1999a.
- ASTM (American Society for Testing and Materials) *Standard Guide for In Situ Burning of Oil Spills on Water: Fire-Resistant Containment Boom*", Revision #8, ASTM, Philadelphia, PA, June, 1999b.
- Bech, C., P. Sveum, and I. Buist, "In-situ Burning of Emulsions: The Effects of Varying Water Content and Degree of Evaporation", in *Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 547-559, 1992.
- Bitting, K.B. and Coyne, P.M., "Oil Containment Tests of Fire Booms", in *Proceedings of the Twentieth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 735-754, 1997.
- Booher, L.E. and B. Janke, "Air Emissions from Petroleum Hydrocarbon Fires during Controlled Burning", *American Industrial Hygiene Association Journal*, Vol. 58, pp. 359-365, 1997.
- Bryner, N.P., W.D. Walton, L.A. DeLaughter, W. Twilley, I. Mendelsson, Q. Lin, and J.V. Mullin, "In-situ Burning in the Marshland Environment - Soil Temperatures", *Proceedings of the Twenty-third Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 823-846, 2000.
- Bryner, N.P., W.D. Walton, W. Twilley, I. Mendelsson, Q. Lin, and J.V. Mullin, "In-situ Burning in the Marshland Environment - Soil Temperatures Resulting from Crude and Diesel Fuel Burns", *Proceedings of the Twenty-fourth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 729-754, 2001.
- Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy, and I.R. McAllister, "The Development and Testing of a Fireproof Boom", *Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, 1983.
- Buist, I.A., S.L. Ross, B.K. Trudel, E. Taylor, T.G. Campbell, P.A. Westphal, M.R. Meyers, G.S. Ronza, A.A. Allen, and A.B. Nordvik, "The Science, Technology and Effects of Controlled Burning of Oil Spills at Sea", MSRC Technical Report Number 94-013, 1994.
- Buist, I.A., N. Glover, B. McKenzie, and R. Ranger, "In-situ Burning of Alaska North Slope Emulsions", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 139-146, 1995.

- Coupal, B., "Use of Peat Moss in Controlled Combustion Techniques", Environment Canada, EPS Report 4-EE-72-1, Ottawa, ON, 39 p., 1972.
- Daykin, M.M., P.A. Kennedy, and A. Tang, "Aquatic Toxicity from In-situ Oil Burning - Newfoundland Offshore Burn Experiment (NOBE)", Emergencies Science Division, Environmental Technology Centre, Environment Canada, Ottawa, ON, 62 p., 1995.
- DeVitis, D., S. Cunneff, and J. Nash, "Test and Evaluation of Six Fire Resistant Booms at Ohmsett", U.S. Department of Transportation, U.S. Coast Guard Research and Development Center, Groton, CT, 1997.
- Elam, S.K., I. Tokura, K. Saito, and R.A. Altenkirck, "Thermal Conductivity of Crude Oils", *Experimental Thermal and Fluid Science*, Vol. 2, pp. 1-6, 1989.
- Energetex Engineering, "Arctic Field Trials of the DREV/AMOP Incendiary Devices", Environment Canada, Environmental Protection Service, Manuscript Report EE-17, Ottawa, ON, 25 p., 1981.
- Energetex Engineering, "Environmental Testing of Dome Air-Deployable Ignitor", Dome Petroleum Ltd., Calgary, AB, 18 p., 1982.
- Environment Canada, "NOBE - Newfoundland Offshore Burn Experiment", Ottawa, ON, June, 1993.
- Environment Canada, "Compilation of Physical and Emissions Data, Newfoundland Offshore Burn Experiment (NOBE) Report", Emergencies Science Division, Environmental Technology Centre, Ottawa, ON, 1997.
- Evans, D.D., G.W. Mulholland, D. Gross, H. Baum, and K. Saito, "Burning, Smoke Production and Smoke Dispersion from Oil Spill Combustion", in *Proceedings of the Eleventh Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 41-87, 1988.
- Evans, D.A., W. Walton, H. Baum, R. Lawson, R. Rehm, R. Harris, A. Ghoniem, and J. Holland, "Measurement of Large Scale Oil Spill Burns", in *Proceedings of the Thirteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1-38, 1990.
- Evans, D.D., G.W. Mulholland, J.R. Lawson, E.J. Tennyson, P.A. Tebeau, M.F. Fingas, and J.R. Gould, "Burning of Oil Spills", *Proceedings of the 1991 Oilspill Conference*, American Petroleum Institute, Washington, DC, 1991.
- Evans, D.D., "In Situ Burning of Oil Spills: Smoke Production and Plume Behavior", in *Proceedings of the In Situ Burning Oil Spill Workshop*, N.H. Jason (ed.), National Institute of Standards and Technology, NIST Special Publication 867, Gaithersburg, MD, pp. 29-37, 1994.
- Fingas, M.F., *The Basics of Oil Spill Cleanup*, Second Edition, Lewis Publishers, Boca Raton, FL, 2000.
- Fingas, M.F. and B. Fieldhouse, "Studies of Water-in-Oil Emulsions and Techniques to Measure Emulsion Treating Agents", in *Proceedings of the Seventeenth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp 213-244, 1994.
- Fingas, M.F. and B. Fieldhouse, "Modelling of Water-in-Oil Emulsions", in *Proceedings of the Twenty-seventh Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 335-350, 2004.
- Fingas, M.F. and L. Ka'aihue, "Weather Windows for Oil Spill Countermeasures", in *Proceedings of the Twenty-seventh Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 881-955, 2004.
- Fingas, M.F, K. Li, F. Ackerman, P.R. Campagna, R.D. Turpin, S.J. Getty, M.F. Soleki, M.J. Trespalacios, J. Paré, M.C. Bissonnette, and E.J. Tennyson, "Emissions from Mesoscale In-situ Oil Fires: The Mobile 1991 and 1992 Tests", in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 749-821, 1993.

- Fingas, M.F., F. Ackerman, K. Li, P. Lambert, Z. Wang, M.C. Bissonnette, P.R. Campagna, P. Boileau, N. Laroche, P. Jokuty, R. Nelson, R.D. Turpin, M.J. Trespalacios, G. Halley, J. Bélanger, J.R.J. Paré, N. Vanderkooy, E.J. Tennyson, D. Aurand, and R. Hiltabrand, "The Newfoundland Offshore Burn Experiment - NOBE - Preliminary Results of Emissions Measurement", in *Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1099-1164, 1994a.
- Fingas, M.F., G. Halley, F. Ackerman, N. Vanderkooy, R. Nelson, M.C. Bissonnette, N. Laroche, P. Lambert, P. Jokuty, K. Li, W. Halley, G. Warbanski, P.R. Campagna, R.D. Turpin, M.J. Trespalacios, D. Dickins, E.J. Tennyson, D. Aurand, and R. Hiltabrand, "The Newfoundland Offshore Burn Experiment - NOBE Experimental Design and Overview", in *Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1053-1061, 1994b.
- Fingas, M.F., G. Halley, F. Ackerman, R. Nelson, M.C. Bissonnette, N. Laroche, Z. Wang, P. Lambert, K. Li, P. Jokuty, G. Sergy, W. Halley, J. Latour, R. Galarneau, B. Ryan, P.R. Campagna, R.D. Turpin, E.J. Tennyson, J. Mullin, L. Hannon, D. Aurand, and R. Hiltabrand, "The Newfoundland Offshore Burn Experiment", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 123-132, 1995a.
- Fingas, M.F., F. Ackerman, P. Lambert, K. Li, Z. Wang, J. Mullin, L. Hannon, D. Wang, A. Steenkammer, R. Hiltabrand, R.D. Turpin, and P.R. Campagna, "The Newfoundland Offshore Burn Experiment: Further Results of Emissions Measurement", in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 915-995, 1995b.
- Fingas, M.F., B. Fieldhouse, L. Gamble, and J. Mullin, "Studies of Water-in-Oil Emulsions: Stability Classes and Measurement", in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON pp. 21-42, 1995c.
- Fingas, M.F., F. Ackerman, P. Lambert, K. Li, Z. Wang, R. Nelson, M. Goldthorp, J. Mullin, L. Hannon, D. Wang, A. Steenkammer, S. Schuetz, R.D. Turpin, P.R. Campagna, and R. Hiltabrand, "Emissions from Mesoscale In-Situ Oil (Diesel) Fires: The Mobile 1994 Experiments", in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 907-978, 1996a.
- Fingas, M.F., K. Li, F. Ackerman, Z. Wang, P. Lambert, L. Gamble, M.J. Trespalacios, S. Schuetz,, R.D. Turpin, and P.R. Campagna, "Soot Production from In-Situ Oil Fires: Review of the Literature, Measurement and Estimation Techniques and Calculation of Values from Experimental Spills", in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 999-1032, 1996b.
- Fingas, M.F., K. Li, F. Ackerman, P.R. Campagna, R.D. Turpin, S.J. Getty, M.F. Soleki, M.J. Trespalacios, Z. Wang, J. Paré, M.C. Bissonnette, and E.J. Tennyson, "Emissions from Mesoscale In-Situ Oil Fires: The Mobile 1991 Experiments", *Spill Science & Technology Bulletin*, Vol. 3, No. 3, pp. 123-137, 1996c.
- Fingas, M.F., K. Li, F. Ackerman, Z. Wang, P. Lambert, L. Gamble, M.J. Trespalacios, S. Schuetz,, R.D. Turpin, and P.R. Campagna, "Soot Production from In-Situ Oil Fires: Review of the Literature, Measurement and Estimation Techniques and Calculation of Values from Experimental Spills", in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 999-1032, 1996d.
- Fingas, M.F., B. Fieldhouse, and J. Mullin, "Studies of Water-in-Oil Emulsions: Stability Studies", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1-20, 1997.

- Fingas, M.F., B. Fieldhouse, and J.V. Mullin, "Studies of Water-in-Oil Emulsions: Stability and Oil Properties", in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1-25, 1998a.
- Fingas, M.F., P. Lambert, F. Ackerman, B. Fieldhouse, R. Nelson, M. Goldthorp, M. Punt, S. Whiticar, P.R. Campagna, D. Mickunas, R.D. Turpin, R. Nadeau, S. Schuetz, M. Morganti, and R.A. Hiltabrand, "Particulate and Carbon Dioxide Emissions from Diesel Fires: The Mobile 1997 Experiments", in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 569-598, 1998b.
- Fingas, M.F., B. Fieldhouse, C.E. Brown, and L. Gamble, "In-Situ Burning of Heavy Oils and Orimulsion: Mid-Scale Burns", in *Proceedings of the Twenty-seventh Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 207-233, 2004.
- Fingas, M. and M. Punt, *In-situ Burning: A Cleanup Technique for Oil Spills on Water*, Emergencies Science Division, Environment Canada, Ottawa, ON, 214 p., 2000
- French McCay, D., N. Whittier, S. Sankaranarayanan, and D. Schmidt Etkin, "Modeling Fates and Impacts for Bio-Economic Analysis", in *Proceedings of the Twenty-fifth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1051-1074, 2002.
- Frish, M., P. Nebolsine, M. DeFaccio, H. Scholaert, W. Kung, and J. Wong, "Laser Ignition of Arctic Oil Spills - Engineering Design", in *Proceedings of the Ninth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 203-221,1986.
- Frish, M., V. Gauthier, J. Frank, and P. Nebolsine, "Laser Ignition of Oil Spills: Telescope Assembly and Testing", Environment Canada, Environmental Protection Service, Manuscript Report EE-113, Ottawa, ON, 23 p., 1989.
- Glassman, I. and J.G. Hansel, "Some Thoughts and Experiments on Liquid Fuel Spreading, Steady Burning and Ignitability in Quiescent Atmospheres", *Fire Research Abstracts and Reviews*, *Vol. 6 (3)*, pp. 217-334, 1968.
- Goodier, J.L. and R.J. Siclari, "Combustion: An Oil Spill Mitigation Tool Phase II: The Burning of the M/T *Burmah Agate* (Ex-Danaland)", U.S. Department of Energy Report DOE/TIC-11471, Washington, DC, 1981.
- Guénette, C.C. and J. Thornborough, "An Assessment of Two Off-Shore Igniter Concepts", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 795-808, 1997.
- IPIECA, "Net Environmental Benefit Analysis", International Petroleum Industry Environmental Conservation Association, London, UK, 1993.
- ITOPF (International Tanker Owners Pollution Federation Ltd.), *Response to Marine Oil Spills*, Witherby & Co. Ltd., London, UK, 1987.
- Lambert, P., F. Ackerman, M. Fingas, M. Goldthorp, B. Fieldhouse, R. Nelson, M. Punt, S. Whiticar, S. Schuetz, A. Dubois, M. Morganti, K. Robbin, R. Magan, R. Pierson, R.D. Turpin, P.R. Campagna, D. Mickunas, R. Nadeau, and R.A. Hiltabrand, "Instrumentation and Techniques for Monitoring the Air Emissions during In-situ Oil/Fuel Burning Operations", in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 529-567, 1998.
- Lavers, L., Newfoundland Department of Forestry, personal communication, 1997.
- Li, K., T. Caron, M. Landriault, J.R.J. Paré, and M. Fingas, "Measurement of Volatiles, Semi-volatiles and Heavy Metals in an Oil Burn Test", in *Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 561-573, 1992.
- Marine Research Associates, *Technology Assessment and Concept Evaluation for Alternative Approaches to In-Situ Burning of Oil Spills in the Marine Environment*, Project Report for U.S. Minerals Management Service, Herndon, VA, 1998.

- Maybourn, R., “The Work of the IP Working Group on the Burning of Oil”, *Journal of the Institute of Petroleum*, Vol. 57, pp. 12-16, 1971.
- McCourt, J., I. Buist, J. Mullin, B. Pratte, and W. Jamieson, “Continued Development of a Test for Fire Booms in Waves and Flames”, in *Proceedings of the Twenty-first Arctic and Marine Oilspill Technical Seminar*, Environment Canada, Ottawa, ON, pp. 505-528, 1998.
- McCourt, J., I. Buist, W. Schmidt, D. Devitis, B. Urban, and J. Mullin, “OHMSETTs Propane-Fuelled Test System”, in *Proceedings of the Twenty-second Arctic and Marine Oilspill Technical Seminar*, Environment Canada, Ottawa, ON, pp. 505-528, 1999.
- McGrattan, K.B., “Smoke Plume Trajectory Modeling”, in *Proceedings of In-situ Burning of Oil Spills*, U.S. Minerals Management Service, Herndon, VA, pp. 75-83, 1999.
- McKenzie, B. “Report of the Operational Implications Working Panel”, *In Situ Burning Oil Spill Workshop Proceedings*, N.H. Jason (ed.), National Institute of Standards and Technology, Gaithersburg, MD, pp. 11-20, 1994.
- McLeod, W.R. and D.L. McLeod, “Measures to Combat Offshore Arctic Oil Spills”, in *Preprints of the 1972 Offshore Technology Conference*, pp. 141-162, 1972.
- Meikle, K.M., “An Effective Low-Cost Fireproof Boom”, in *Proceedings of the 1983 Oil Spill Conference*, 1983.
- Mitchell, J.B.A., “Smoke Reduction from Burning Crude Oil Using Ferrocene and its Derivatives”, *Spill Technology Newsletter*, Vol. 15, pp. 11-19, 1990.
- Mitchell, J.B.A., “Smoke Reduction from Burning Crude Oil Using Ferrocene and its Derivatives”, *Combustion and Flame*, Vol. 86, pp. 179-184, 1991.
- Mitchell, J.B.A., “Smoke Reduction from Pool Fires Using Ferrocene and Derivatives”, in *Proceedings of the Fifteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 681-687, 1992.
- Mitchell, J.B.A., “Hydrocarbon Fire Technology Program: Technical Report”, Esso Resources Canada Ltd., Calgary, AB, 87 p., August, 1993.
- Nelson, J., “Fractality of Soot Smoke: Implications for the Severity of Nuclear Winter”, *Nature*, Vol. 339, pp. 611-613, 1989.
- Nordvik, A.B., J.L. Simmons, and T.J. Hudon, “At-Sea Testing of Fire Resistant Oil Containment Boom Designs”, in *Proceedings of the Second International Oil Spill Research and Development Forum*, International Maritime Organization, London, UK, pp. 479-490, 1995.
- Office of the Federal Register, *Code of Federal Regulations*, “Protection of Environment”, U.S. National Archives and Records Administration, Washington, DC, 1991.
- Ontario Ministry of Natural Resources (OMNR), “Ignition Devices - Helitorch”, *Specialized Fire Equipment Manual*, March, 1990.
- Pilewskie, P. and F.P.J. Valero, “Radiative Effects of the Smoke Clouds from the Kuwait Oil Fires”, *Journal of Geophysical Research*, Vol. 97, No. D. 13, pp. 541-544, 1992.
- PROSCARAC (Prairie Regional Oil Spill Containment and Recovery Advisory Committee), “Anchor Design and Deployment Review”, prepared by Paul Wotherspoon & Associates Inc., Calgary, AB, 1992.
- Punt, M., “The Performance of a Water Jet Barrier in a River, *Spill Technology Newsletter*, Vol. 15(1), 1990.
- Ross, S.L., G.P. Canevari, and Consultchem, *State-of-the-Art Review: Emulsion Breaking Chemicals*, Canadian Petroleum Association Report, Calgary, AB, 1992.
- Schulze, R. (ed.), *1997/1998 World Catalogue of Oil Spill Response Products - Sixth Edition*, World Catalog Joint Venture, Port City Press, Baltimore, MD, 1997.

- Sloan, S.L., D.F. Pol, and A.B. Nordvik, "Phase 2: At Sea Towing Tests of Fire Resistant Oil Containment Booms", Marine Spill Response Corporation, MSRC Technical Report Series 95-001, Washington, DC, 82 p., 1995.
- Smith, N.K. and A. Diaz, "In-place Burning of Crude Oils in Broken Ice", *Proceedings of the 1987 Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 383-387, 1987.
- Snider, J. "Research Needs Associated with In Situ Burning - Report of the Environmental and Human Health Panel", in *In Situ Burning Oil Spill Workshop Proceedings*, N.H. Jason (ed.), National Institute of Standards and Technology, Gaithersburg, MD, pp. 3-10, 1994.
- Sorensen, C.M. and G.D. Feke, "The Morphology of Macroscopic Soot", *Aerosol Science and Technology*, Vol. 25, pp. 328-337, 1996.
- Swift, W.H., C.J. Touhill, and P.L. Peterson, "Oil Spillage Control", *Chemical Engineering Progress Symposium Series* 65(97): 265-273, 1968.
- Tennyson, E.J., "In Situ Burning Overview", in *In Situ Burning Oil Spill Workshop Proceedings*, N.H. Jason (ed.), National Institute of Standards and Technology, Gaithersburg, MD, pp. 21-27, 1994.
- Thompson, C.H., G.W. Dawson, and J.L. Goodier, "Combustion: An Oil Mitigation Tool", prepared by Pacific Northwest Laboratory (operated by Battelle) for U.S. Department of Energy, Division of Environmental Control Technology, Washington, DC, 554 p., 1979.
- Twardawa, P. and G. Couture, "Incendiary Devices for the In Situ Combustion of Crude Oil Slicks", National Defence Research Establishment, Valcartier, QC, 56 p., 1983.
- Twardus, E.M., "A Study to Evaluate the Combustibility and Other Physical and Chemical Properties of Aged Oils and Emulsions", Environment Canada, Environmental Protection Service, Manuscript Report EE-5, Ottawa, ON, 1980.
- Twardus, E.M. and T.A. Bruzustowski, "The Burning of Crude Oil Spilled on Water", *Archivum Combustionis*, Vol. 1, No. 1&2, pp. 49-60, 1981.
- Walker, A. H., J. Michel, G. Canevari, J. Kucklick, D. Scholz, C.A. Benson, E. Overton, and B. Shane, "Chemical Oil Spill Treating Agents: Herding Agents, Emulsion Treating Agents, Solidifiers, Elasticity Modifiers, Shoreline Cleaning Agents, Shoreline Pre-treatment Agents and Oxidation Agents", MSRC Technical Report Series Report 93-015, Marine Spill Research Corporation, Washington, DC, 1993.
- Walton, W.D., W.H. Twilley, R.H. Hiltabrand, and J.V. Mullin, "Evaluating a Protocol for Testing Fire-Resistant Oil-Spill Containment Boom", in *Proceedings of the Twenty-first Arctic and Marine Oilspill*
- Walton, W.D., W.H. Twilley, N.P Bryner, L. DeLauter, R.H. Hiltabrand, and J.V. Mullin, "Second Phase Evaluation of a Protocol for Testing Fire-Resistant Oil-Spill Containment Boom", in *Proceedings of the Twenty-second Arctic and Marine Oilspill Technical Seminar*, Environment Canada, Ottawa, ON, pp. 447-466, 1999.
- Walton, W.D., "Status of Fire Boom Performance Testing", *Spill Science and Technology Bulletin*, Vol. 8, No. 4, pp. 361-365, 2003.
- Wu, N., M. Baker, G. Kolb, and J.L. Torero, "Ignition, Flame Spread and Mass Burning Characteristics of Liquid Fuels on a Water Bed", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 769-793, 1997.

8.1. Some Specific References to Inland Burning

- API (American Petroleum Institute), 1999. *Compilation and review of data on the Environmental Effects of* In Situ *Burning of Inland and Upland Oil Spills.* API Publication Number 4684. Prepared by Research Planning, Inc. American Petroleum Institute. Washington, DC, USA. 186p.

- API (American Petroleum Institute), 2002. *Use of* In Situ *Burning as an Oil Spill Response Tool: Follow-up of Four Case Studies.* API Publication Number 4724. Prepared by Research Planning, Inc. American Petroleum Institute. Washington, DC, USA. 73p.
- Eufemia, Steven J., (1994). Brunswick Naval Air Station JP-5 aviation fuel discharge in-situ burn of fuel remaining in fresh water marsh, April 6-8, 1993. Proceedings of the In Situ Burning Oil Spill Workshop. NIST Special Publication 867. National Institute of Standards and Technology. Gaithersburg, MD, USA: 87-90.
- Fritz, David, 2003. *In Situ Burning of Spilled Oil in Freshwater Inland Regions of the United States.* Spill Science and Technology Bulletin (August, 2003)
- Gonzalez, M. F. and G. A. Lugo, (1994). Texas marsh burn, Removing oil from a salt marsh using in situ burning. Proceedings of the In Situ Burning Oil Spill Workshop. NIST Special Publication 867. National Institute of Standards and Technology. Gaithersburg, MD, USA: 77-85.
- Lin, Q., I.A. Mendelssohn, K. Carney, N.P. Bryner, and W.D. Walton, "In-Situ Burning of Oil in Coastal Marshes: I. Vegetation Recovery and Soil Temperature as a Function of Water Depth, Oil Type and Marsh Type", *Marine Pollution Bulletin*, in Press, 2004a.
- Lin, Q., I.A. Mendelssohn, K. Carney, N.P. Bryner, and W.D. Walton, "In-Situ Burning of Oil in Coastal Marshes: II. Oil Spill Cleanup Efficiency as a Function of Oil Type, Marsh Type and Water Depth", *Marine Pollution Bulletin*, in Press, 2004b.
- Lindau, C.W., R.D. Delune, A. Jugsujinda, and E. Sajo, "Response of Spartina Alterniflora Vegetation to Oil and Burning of Applied Oil", *Marine Pollution Bulletin*, Vol. 38, No. 12, pp. 1216-1220, 1999.
- Lindau, C.W., R.D. Delune, and A. Jugsujinda, " Marsh Sensitivity to Burning of Applied Crude Oil", *Spill Science and Technology Bulletin*, Vol. 8, No. 4, pp. 401-404, 2003.
- May, Victoria L. and James R. Wolfe, (1997). Field experience with controlled burning of inland oil spills. Proceedings of the 1997 International Oil Spill Conference. American Petroleum Institute. Washington, DC, USA: 811-816.
- Mendelssohn, I. A., M. W. Hester, and J. W. Pahl, 1996. Environmental effects and effectiveness of *in situ* burning in wetlands: Considerations for oil-spill cleanup. Louisiana Oil Spill Coordinator's Office/Office of the Governor, Louisiana Applied Oil Spill Research and Development Program. Baton Rouge, Louisiana, USA. 53p.
- Pahl, James W., Irving A. Mendelssohn, and Thomas J. Hess, (1997). The application of in-situ burning to a Louisiana coastal marsh following a hydrocarbon product spill: Preliminary assessment of the site recovery. Proceedings of the 1997 International Oil Spill Conference. American Petroleum Institute. Washington, DC, USA: 823-828.
- Tunnel, John W. Jr., Beau Hardegree, and David W. Hicks, (1995). Environmental impact and recovery of a high marsh pipeline oil spill and burn site, Upper Copano Bay, Texas. Proceedings of the 1995 International Oil Spill Conference. American Petroleum Institute. Washington, DC, USA: 133-1
- Zengel, S.A., J. Michel, and J.A. Dahlin, "Environmental Effects of In Situ Burning of Oil Spills in Inland and Upland Habitats", *Spill Science and Technology Bulletin*, Vol. 8, No. 4, pp. 373-377, 2003.

9. Glossary

Aromatics - A class of hydrocarbons considered to be the most immediately toxic hydrocarbons found in oil and that are present in virtually all crude oils and petroleum products. Many aromatics are soluble in water to some extent, thereby increasing their danger to aquatic organisms. Certain aromatics are considered long-term poisons and often produce carcinogenic effects. Aromatics are characterized by rings containing benzene, which is the simplest aromatic.

Asphaltenes - These are the larger polar compounds found in oil, so named because they make up the largest percentage of the asphalt used to pave roads. Asphaltenes often have very large molecules (or a high molecular weight). If there are enough asphaltenes in an oil, they greatly affect how the oil behaves when spilled.

Barrel - This is a unit of liquid (volumetric) measure for petroleum and petroleum products, equal to 35 Imperial gallons, 42 US gallons, or approximately 160 litres (L). This measure is used extensively by the petroleum industry. There are approximately 7 to 9 barrels (245 to 315 Imperial gallons) of oil per metric ton, depending on the specific gravity of the crude oil or petroleum product.

Boiling point - it is the temperature at which the vapor pressure of a liquid is equal to the atmospheric or external pressure. The boiling point of crude oils and petroleum products may vary from 30 to 550 C but is of little practical significance in terms of oil spill cleanup. (See also **Flash point**.)

Boom failure - This refers to the failure of a containment boom to contain oil due to excessive winds, waves, or currents or improper deployment. Boom failure may be manifested in oil underflow, oil splashover, submergence or planing of the boom, or structural breakage. (See also **Critical velocity**, **Entrainment failure**, **Head wave**.)

Bridle - When using a containment boom, in some configurations a bridle or cross bridle, also called a **tether line**, 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.

Bubble barrier - A method for containing oil consisting of an underwater air delivery system which creates a curtain of rising bubbles that deflects the oil. The system has been used with some success in relatively calm harbors.

Bunker C - A very viscous fuel oil (No. 6 fuel) used as a fuel for marine and industrial boilers.

Burn efficiency - When carrying out in-situ burning of an oil spill, this is the percentage of the oil removed from the water by burning. It is the amount (volume) of oil before burning, less the volume remaining as a residue, divided by the initial volume of oil.

Burn rate - When carrying out in-situ burning of an oil spill, this is the rate at which oil is burned within a given area or the rate at which the thickness of the oil diminishes. In most situations, the burn rate is approximately 3.75 mm/min.

Carbonyls - This is a class of compounds containing the C=O group. The class includes aldehydes, (formaldehyde, acetaldehyde, etc.) and ketones (acetone, etc.).

Catenary - This is the geometric form, which resembles a parabola, that a rope or chain takes when suspended from both ends.

Controlled burning - This refers to a fire or burn that can be started and stopped by human intervention and can be managed to a certain degree throughout the burn.

Critical velocity - This is the lowest speed or velocity of the water current that will cause loss of oil under the skirt of a containment boom. Critical velocity varies with specific gravity, viscosity, and thickness of the oil slick contained by the boom, and the depth of the skirt and position of the boom in relation to the direction of the current. For most oils, when the boom is at right angles to the current, the critical velocity is about 0.5 m/sec (1 knot). (See also **Boom failure**.)

Emulsification - This is the process whereby one liquid is dispersed into another liquid in the form of small droplets. Water-in-oil emulsions are sometimes stable and create special cleanup problems. (See also **Water-in-oil emulsion**.)

Emulsion breakers and inhibitors - These are chemical agents used to prevent the formation of water-in-oil emulsions or to cause such emulsions to revert to oil and water. Several formulations can perform both functions.

Entrainment failure - This is a type of boom failure resulting from excessive current speed or velocity. The head wave formed upstream of the oil mass contained within a boom becomes unstable and oil droplets are torn off and become entrained or drawn into the flow of water beneath the boom. (See also **Boom failure**, **Critical velocity**.)

Fire point - This is the lowest temperature at which the vapor above a test liquid will sustain burning for 5 seconds (ASTM-D92).

Fire-resistant containment booms - These are floating devices, constructed to withstand high temperatures and heat fluxes used when burning oil on water. These booms restrict the spreading and movement of oil slicks while increasing the thickness of the slick so the oil will ignite and continue to burn. The types of commercial fire-resistant booms are water-cooled, stainless steel, thermally resistant, and ceramic booms.

Fire storm - This is a very rapid rate of burn, which may occur in a very large burn when large volumes of air are drawn into the fire by the convection of the fire itself.

Flame contact probability - This is the probability that oil will be contacted by the flame during burning.

Flash point - This is the lowest temperature, corrected to a barometric pressure of 101.3 kPa, at which the liquid gives off sufficient vapors to ignite when exposed to an ignition source such as an open flame. A liquid is considered to be flammable if its flash point is less than 60ºC.

Freeboard - This is the part of a floating containment boom that is designed to prevent waves from washing oil over the top of the boom. The term freeboard is also used to describe the distance from the water surface to the top of the boom. Freeboard is generally also applied to the distance from the deck to the water line of a vessel such as a ship or barge.

Fuel oils - These are refined petroleum products with specific gravities of 0.85 to 0.98 and flash points greater than 55 C. This group of products includes furnace, auto diesel, and stove fuels (No. 2 fuels), industrial heating fuels (No. 4 fuels), and various bunker fuels (No. 5 and No. 6 fuel oils).

Gasolines - These are a mixture of volatile, flammable liquid hydrocarbons used primarily for internal combustion engines and characterized by a flash point of approximately -40°C and a specific gravity of 0.65 to 0.75.

Improvised booms - These are booms constructed from readily available materials such as railroad ties and logs. Improvised booms can be used as temporary containment structures until more suitable commercial booms arrive at the spill site. They can also be used in conjunction with commercial containment booms to divert oil into areas where the commercial booms are positioned.

In-situ burning - This is an oil spill cleanup technique that involves controlled burning of the oil directly on the water surface. It does not include burning oil or oiled debris in an incinerator.

Insulation factor - This is the amount of heat transfer between oil and water as a result of oil on the water surface.

Kerosene - A flammable oil characterized by a relatively low viscosity, specific gravity of approximately 0.8, and flash point close to 55°C. Kerosene lies between the gasolines and fuel oils in terms of major physical properties and is separated from these products during the fractional distillation of crude oils.

Light ends - This is a term used to describe the low molecular weight, volatile hydrocarbons in crude oil and petroleum products. The light ends are the first compounds recovered from crude oil during the fractional distillation process and are also the first fractions of spilled oil to be lost through evaporation.

Metric ton (tonne) - This is a unit of mass and weight equal to 1,000 kilograms. In Canada, the metric ton is the most widely used measure of oil quantity by weight. There are approximately 7 to 9 barrels (245 to 315 Imperial gallons) of oil per metric ton, depending on the specific gravity of the crude oil or petroleum product.

Oxygenated compounds - These are hydrocarbon compounds containing oxygen. They may be the result of incomplete combustion.

Paravanes - These are rigid metal boom-towing sections that attach at the rear mouth of a conventional boom as an untested boom configuration when burning oil.

PM-10 - This is particulate matter consisting of small respirable particles with a diameter of 10 μm (micrometers or microns) or less. Ten micrometers is a critical size below which human lungs are affected. For monitoring of particulate matter in the smoke plume from oil fires, it is generally accepted that the concentration of PM-10 particles should be less than 150 $\mu g/m^3$ for a 24-hour period. Particulate matter is the main public health concern when oil or petroleum products are burned.

PM-2.5 - This is particulate matter consisting of small respirable particles with a diameter of 2.5 m (micrometers or microns) or less, which are particularly dangerous to human lungs. For monitoring of particulate matter in the smoke plume from oil fires, a standard of 65 $\mu g/m^3$ for a 24-hour period has been proposed. Particulate matter is the main public health concern when oil or petroleum products are burned.

Polar compounds - These are hydrocarbon structures found in oil that have a significant molecular charge as a result of bonding with compounds such as sulfur, nitrogen, or oxygen. The 'polarity' or charge carried by the molecule results in a behavior that is different from that of unpolarized compounds under some circumstances. In the petroleum industry, the smallest polar compounds are called resins which are largely responsible for oil adhesion. The larger polar compounds are called asphaltenes because they often make up the largest percentage of the asphalt commonly used in road construction. (See also **Asphaltenes**, **Resins**.)

Polyaromatic hydrocarbons (PAHs) - These are common compounds found in oil. They contain multiple benzene rings that may be formed by combustion. Crude oils and residual oils contain varying amounts of these compounds, some of which may be toxic to humans and aquatic life.

Pour point - The pour point of an oil is the lowest temperature at which it will flow under specified conditions. The pour point of crude oils generally varies from -57º to 32ºC. Lighter oils with low viscosities have lower pour points. Pour point is highly variable and dependent on measurement conditions.

Residue - This is the material, excluding airborne emissions, remaining on or below the surface after an in-situ burn takes place. It is largely unburned oil with some lighter or more volatile products removed.

Resins - These are the smallest polar compounds found in oil. They are largely responsible for oil adhesion. (See also **Polar compounds**.)

Saturate group - This is a group of hydrocarbon components found in oils that consists primarily of alkanes, which are compounds of hydrogen and carbon with the maximum number of hydrogen atoms around each carbon. The term saturated is used because the carbons are 'saturated' with hydrogen. The saturate group also includes cyclo-alkanes, which are compounds made up of the same carbon and hydrogen constituents but with the carbon atoms bonded to each other in rings or circles. Larger saturate compounds are often referred to as waxes. (See also **Aromatics**.)

Slick - This is the common term used to describe a thin film of oil, usually less than 2 µm (0.002 mm) thick, on the water surface.

Sorbent - This is a substance that either adsorbs or absorbs another substance. Specifically, it is a natural organic, mineral-based, or synthetic organic material used to recover small amounts of oil that have been spilled on land or water surfaces or stranded on shorelines.

Specific gravity - This is the ratio of the weight of a substance such as an oil to the weight of an equal volume of water. Buoyancy is intimately related to specific gravity - if a substance has a specific gravity less than that of a fluid, it will float on that fluid. The specific gravity of most crude oils and refined petroleum products is less than 1.0 and therefore these substances generally float on water.

Tension member - This is the part of a floating oil containment boom that carries the load placed on the barrier by wind, wave, and current forces. Tension members are commonly made of wire cable due to its strength and stretch resistance.

Tether line - When using a containment boom, in some configurations a tether line, also called a bridle or cross bridle, is often secured to each side of the boom behind the towing vessels to ensure that the boom maintains the proper U shape.

Vapor flashback - This occurs when flames spread rapidly through vapors when highly volatile oils such as fresh, very light crudes, gasoline, or mixtures of these in other oils are being burned.

Vapor pressure - This is a measure of how oil partitions between the liquid and gas phases, or how much vapor is in the space above a given amount of liquid oil at a fixed temperature.

Viscosity - This is the property of a fluid, either gas or liquid, by which it resists a change in shape or movement or flow. Gasoline has a low viscosity and flows readily, whereas tar is very viscous and flows poorly. The viscosity of oil is largely determined by the amount of lighter and heavier fractions that it contains. Viscosity increases as oil weathers and as the temperature decreases, with a lower temperature giving a higher viscosity. (See also **Light ends**, **Volatility**.)

Volatile organic compounds (VOCs) - These are organic compounds with vapor pressure high enough to cause the compounds to vaporize at normal temperatures.

Volatility - This is the tendency of a solid or liquid substance to pass into the vapor state. Many hydrocarbons with low carbon numbers are extremely volatile and readily pass into a vapor state when spilled. For example, gasolines contain a high proportion of volatile constituents that pose considerable short-term risk of fire or explosion when spilled. On the other hand, bunker fuels contain few volatile hydrocarbons as they are removed during the fractional distillation refining process.

Water-in-oil emulsion - This is a type of emulsion in which droplets of water are dispersed throughout oil. It is formed when water is mixed with a relatively viscous oil by wave action. This type of emulsion is sometimes stable and may persist for months or years after a spill. Water-in-oil emulsions containing 50 to 80% water are most common, range in consistency from grease-like to solid, and are generally referred to as “chocolate mousse”. (See also **Emulsification**.)

Weathering - This refers to a series of processes whereby the physical and chemical properties of oil change after a spill. These processes begin when the spill occurs and continue indefinitely while the oil remains in the environment. Major processes that contribute to weathering include evaporation, emulsification, natural dispersion, dissolution, photo-oxidation, sedimentation, adhesion to materials, interaction with mineral fines, microbial biodegradation, and the formation of tar balls or tar mats. (See also **Emulsification**.)

APPENDIX A - In-situ Burn Evaluation Sheet

In-situ Burn Evaluation Sheet

(Fingas, M. and M. Punt, 2000)

Form completed by ___________________________Date ___________ Time _________

Name of incident (e.g., tanker, platform or location name) ___________________________

Date of incident __________________Time of incident ___________________

Type of incident: tanker grounding ___ tanker transfer ___ tanker collision ___
tanker explosion ___ blow out ___ other _____________________

Spill location: latitude _______________longitude ___________________

Type of product released ____

Estimated volume of product released ____________________

Estimated area covered by the slick ________________

Is source still releasing product? yes ___ no ___
If yes, at what estimated flow rate ____

Is source and/or slick burning on its own? yes ___ no ___

Condition of the oil

	Current	24 hour forecast	48 hour forecast
date and time			
thickness range			
emulsification (% of slick and water content)			
weathering (%)			
type of slick (check one)			
• one large slick			
• large patches			
• several small patches			
• thin strips			
• other			

Description of estimated trajectory of spill (also attach maps showing current, 24-hour and 48-hour estimated positions)

____
____
____

Location of nearest land to the spill site ________________________________

Distance from spill site _______

Location of land area(s) expected to be oiled by slick within the first 48 hours after spill incident

Location	Distance from spill	Est. date and time of oiling

Name and location of communities near the spill site [within 100 km (60 miles)]

Name of community	Location	Distance from spill

Name and location of inhabited sites near the spill site [within 100 km (60 miles)]

Name of inhabited site	Location	Distance from spill

Location and type of environmentally sensitive area(s)/population(s) [within 100 km (60 miles)]

Type of area or population	Location	Distance from spill

Location and type of other areas that could be effected (e.g., parks, archeological sites, anthropogenic structures) [within 100 km (60 miles)]

Type of area	Location	Distance from spill

Weather and sea conditions

	Current	24 hour forecast	48 hour forecast
date and time			
air temperature			
water temperature			
wind speed			
wind direction			
skies (check those that apply):			
• clear			
• partially cloudy			
• overcast			
• rain			
• fog			
• storm			
tide (check one)			
• slack			
• incoming			
• outgoing			
dominant current speed			
dominant current direction			
sea state (check one)			
• calm			
• choppy			
• swell			
waves (check one)			
• < 0.3 m (1 ft)			
• 0.3 - 1 m (1 to 3 ft)			
• > 1 m (3 ft)			

Tidal projection

Next high tide at _____________ (date) ___________ (time)

Next low tide at _____________ (date) ___________ (time)

Location of nearest oil spill response equipment depot

Location __________________________ Distance from spill ________________

Location of specific response equipment (indicate if specific equipment will not be required)

Equipment	Description and number required	Location	Time required for deployment
vessels			
remote sensing aircraft			
helicopters			
tug boats			
fire-resistant boom			
conventional boom			
igniters			
skimmers			
sorbent			

APPENDIX B - Equipment for In-situ Burning

Equipment for In-situ Burning

The list of equipment for in-situ burning below is not complete, but rather a reference for the reader to start developing his/her own research.

Fire-resistant Booms

American Marine (3M) Fire Boom - http://www.elastec.com/fire.html

Auto Boom™ Fire Model - http://www.oilstop.com/FireBoom.htm

Hydro-Fire Boom - http://www.elastec.com/hydro.html

PocketBoom® - http://www.appliedfabric.com/firebarriers.htm

PyroBoom® - http://www.appliedfabric.com/firebarriers.htm

SeaCurtain FireGard™ Boom Systems - http://www.kepnerplastics.com/firegard1.html

The reader is encouraged to browse *The Oil Spill Equipment and Pollution Clean Up Contractors Directory* (http://www.cleanupoil.com/equipment.htm) or *The World Catalog of Oil Spill Response Products* (published annually)

APPENDIX C - Duties of Helitorch Operating Team

Duties of Helitorch Operating Team

(Fingas, M. and M. Punt, 2000)

The **Helitorch Supervisor** is responsible for the following aspects of the ignition operations:

- coordinating all ignition, suppression, and support operations;
- keeping the in-situ burn On-Scene Commander informed about ignition requirements, the ignition team's readiness, and any problems associated with the ignition operations;
- ensuring that all personnel involved with the helitorch operation are properly trained on all operation and safety aspects, are fully aware of their duties, and are briefed on upcoming ignition plans;
- arranging the transportation of mixing crew and helitorch unit to the burn site;
- ensuring that the torches and kits are in serviceable condition;
- ensuring that the operation and safety plans are adhered to;
- ensuring that proper equipment, including safety equipment, is available and used by all personnel throughout the burning operations;
- ensuring that all dangerous goods documents are properly completed and that the appropriate dangerous goods signs are in all vehicles transporting dangerous goods;
- ensuring that sufficient gasoline, Sure Fire, and propane are on-site before burn setup;
- briefing the ignition helicopter pilot on the planned ignition operations and the aircraft/pilot checklist;
- certifying the checklist and ensuring that it is placed in the helitorch accessories kit;
- designing the ignition plan, including the location and layout of the mixing/loading area;
- keeping all unauthorized personnel outside of the mixing/loading area;
- ensuring that a fire-proof area is set up close to the mixing/loading site for the disposal and burning of unused gelled fuel;
- maintaining radio contact between the mixing/loading area and the ignition helicopter pilot and hook-up operator.
- supervising mixing of fuel to desired gel;
- documenting the ratio of fuel-to-gelling agent used, and the results obtained;
- supervising the loading and moving of full fuel barrels from the mixing site to the loading site;
- supervising the cleanup of the site after the burn and removal of all unused fuel and gelling agent;
- keeping track of the propane bottles and fuel used and advising the hookup operator of when to change the propane bottles; and,
- completing the post-burn report.

The Helitorch Supervisor must also be familiar with the following:

- the Gasoline Handling Act;
- the dangers of static electricity when working with fuels;
- the proper grounding techniques when transferring fuels and moving fuel containers;
- the extinguishment of gasoline and electrical fires;
- the use and placement of fire extinguishers;
- the treatment of burns and other injuries;
- the use of first aid kits, eye wash systems, and burn treatment kits; and,
- the safety practices associated with helicopters, including proper sling hand signals.

The Safety Officer reports directly to the helitorch supervisor on all aspects of safety related to the ignition operations, and must ensure that all safety features are in place and that all safety practices are carried out. It is required that this person be familiar with the following:

- the Gasoline Handling Act;
- the dangers of static electricity when working with fuels;
- the proper grounding techniques when transferring fuels and moving fuel containers;
- the extinguishment of gasoline and electrical fires;
- the use and placement of fire extinguishers;
- the treatment of burns and other injuries;
- the use of first aid kits, eye wash systems, and burn treatment kits; and,
- the safety practices associated with helicopters.

The Ignition Helicopter Pilot is responsible for:

- flying the helicopter and operating the helitorch in the air;
- ensuring that the helicopter is serviceable, capable of performing the assigned duties, and has 50-amp service available to power the helitorch operation;
- being thoroughly briefed and fully understanding the ignition plan, helitorch operation, and the radio policies and procedures to be used during the ignition operations;
- knowing the location of all helipads in the burn vicinity and the location of alternate landing sites;
- completing and signing the aircraft/pilot checklist;
- conducting a dry run flight over the burn area prior to commencing the ignition operations;
- directing the ignition operation from the ignition helicopter;
- communicating any problems to the Helitorch Supervisor;
- ensuring that no fuel drips outside the intended burn area; and,
- discussing the fire behavior, ignition pattern, ignition intensity, and helitorch efficiency with the helitorch supervisor.

The Pilot must be trained and fully briefed on the operation and safety aspects associated with the helitorch system to be used during the burn. This will normally involve a training session with a representative from the company that manufactures the helitorch. If the company representative is not available, this training should be performed by the helitorch supervisor who should be well briefed in the operational and safety aspects of the helitorch. This training must involve information on the potential problems that may be encountered while operating the helitorch in the air. The Pilot should also be familiar with procedures for mixing and loading fuel.

The Hook-up Operator is responsible for:

- assembling and testing the helitorches;
- maintaining equipment, conducting inspections, and servicing equipment;
- checking the helicopter hook position (i.e., whether it should be parallel or at right angles to the torch frame and adjusting the cable connectors to the pear ring assembly accordingly);
- connecting and disconnecting the torches from the helicopter;
- maintaining radio contact with the pilot and helitorch supervisor during hook-up operations;
- helping to transport the full fuel barrels from the mixing area to the loading site; and,
- monitoring and changing the helitorch propane tanks when necessary.

The Fuel Mixers are responsible for performing the following duties:

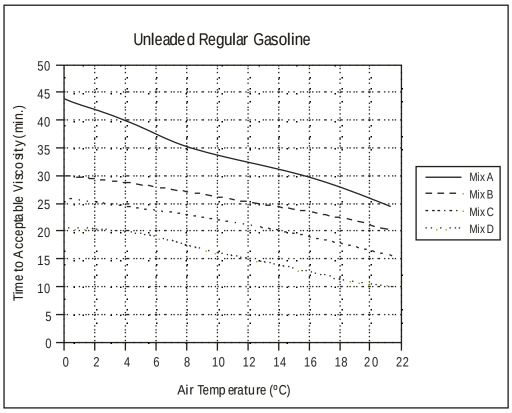
- setting up the mixing and loading areas;
- properly mixing the fuel with the gelling agent according to the Helitorch Supervisor's instructions;
- carrying the full barrels to the loading area;
- aiding in the retrieval of the torch unit after use; and,
- assisting the Hook-up Operator where required (the Fuel Mixers should be familiar with the Hook-up Operator's duties); and,
- cleaning up the site.

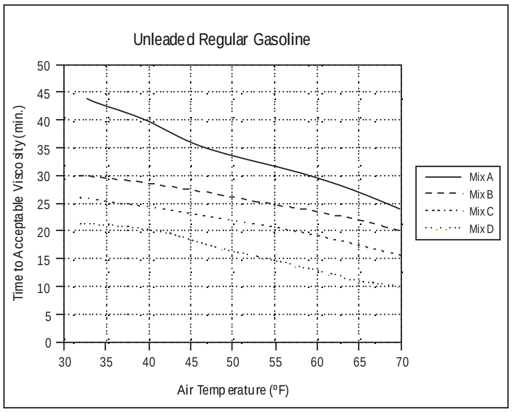
APPENDIX D - Helitorch Gelled Fuel Mixing Charts

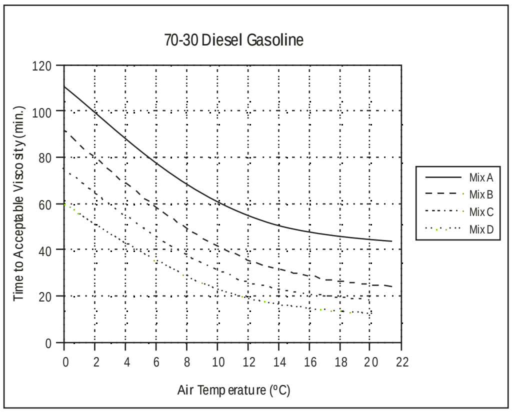
SUREFIRE Gel Ratios *(Fingas, M. and M. Punt, 2000)*

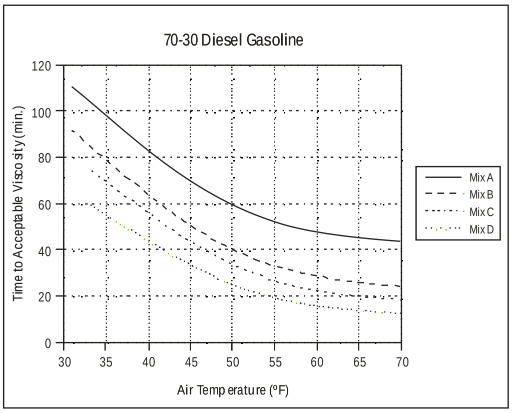
Using the following table, select an appropriate mixing ratio, then locate the graph for the type of fuel to be gelled. The time for the gelled fuel to reach the acceptable viscosity can then be determined from the mix type and air temperature.

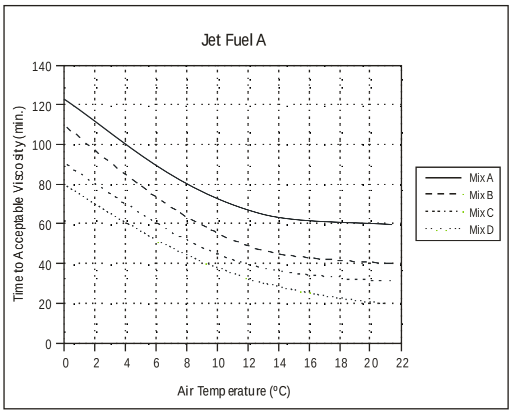
Mixture	Mixing Ratio (weigh of SureFire/volume of fuel)		
	g/L	lb / U.S. gal	lb / Imp. gal
A	5.9	0.05	0.059
B	7.9	0.066	0.079
C	9.9	0.083	0.099
D	11.9	0.1	0.119

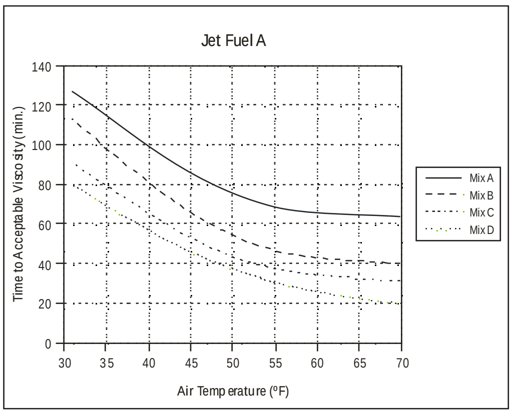












APPENDIX E - In-situ Burn Equipment Requirements Checklist

In-situ Burn Equipment Requirements Checklist

Burn Equipment Checklist

Vessels and Aircraft	Safety Equipment
Tow vessels	Fire pump for each tow boat
Command vessel	Fire hoses
Surveillance aircraft	Fire nozzles
Helicopter for igniter	Fire extinguishers
	First aid kits
	Fire blankets for tow boats
	Extra radios
Containment Equipment	Ignition Equipment
Full length of fire-resistant boom	Hand-held igniters
Extra lengths	Helitorch and accessories
Towing paravanes	
Towing cables	Residue Cleanup Equipment
Bridles	Sorbents
Attachment shackles	Shovels or bailers
Anchors - if needed	Drums or other recovery collection containers
Equipment for backup boom if needed	Heavy oil skimmer – if necessary
	Pumps and hoses for skimmer
General Supplies	Helitorch Equipment
Burn plan	Helitorch unit
Safety plan	Helicopter connecting harness
Radios	Fuel gellant
Contact lists	Fuel mixture
	Fire extinguishers
Monitoring Equipment	Hard hat
Portable monitors	Gloves
PAH Sampling pump/filters	Goggles
Summa canister	Protective clothing
Recording notebook, pens	Safety boots
	Respirators
	Propane bottle
Personal Protection Equipment	Personal Cleanup Equipment
Respirators	Sorbents, rags, towels
Boots, gloves	Citrus cleaner
Special clothing	Garbage bags
Duct tape for sealing	Soap, warm water
Goggles	Extra clothing

ARPEL

Regional Association of Oil and Natural Gas Companies in Latin America and the Caribbean

Established in 1965, ARPEL is an association of 30 state owned and private oil and gas companies and institutions with operations in Latin America and the Caribbean, which represent more than 90 percent of the Region's upstream and downstream operations. Since 1976, ARPEL holds formal UN-ECOSOC special consultative status.

ARPEL works together with its members –through its various Committees and Working Groups- on issues that contribute to sustainable development in the Region:

- *Economic issues*: regional energy integration, pipelines and terminals, downstream and fuels
- *Environmental issues*: climate change, atmospheric emissions, oil spill contingency plans and best practices in environment and occupational health and safety management.
- *Social issues*: corporate social responsibility and relations with indigenous peoples

ARPEL develops a proactive attitude on issues of interest to the industry and produces documents representing the views of its members. It also promotes interaction among its members and with governments building alliances and establishing agreements with international organizations with the aim of presenting and developing a regional perspective. To accomplish its objectives, ARPEL organizes regional workshops and symposia to share information and best practices and develops technical documentation for capacity building and information exchange on the issues of interest to its members. To support its management ARPEL has an interactive Portal in which all documents developed by ARPEL Technical Committees and Working Groups are available for its Members. This tool also facilitates the virtual interaction within the ARPEL community and with those stakeholders that interrelate with it.

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