

IN-SITU BURNING



This article is a compilation of a series of 32 articles on Oil Spill In-Situ Burning that was first published in the ISCO Newsletter, starting with issue 367 of 14 January 2013, and contributed by Dr Merv Fingas of Spill Science, Edmonton, Alberta, Canada T6W 1J6 fingasmerv@shaw.ca

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IN-SITU BURNING

1. Introduction and Overview

In-situ burning is now recognized as a viable alternative for cleaning up oil spills on land and water. When performed under the right conditions, in-situ burning can rapidly reduce the volume of spilled oil and eliminate the need to collect, store, transport, and dispose of recovered oil. In-situ burning can shorten the response time to an oil spill, thus reducing the chances that the oil will spread on the water surface and thereby aiding in environmental protection. Such rapid removal of oil can also prevent the oil from reaching shorelines, which are difficult to clean. What remains after an in-situ burn are burn by-products such as carbon dioxide, water, some smoke particulate, and unburned oil (residue). Sufficient information is now available to predict levels of these emissions and calculate safe distances downwind of the fire. This serial presentation 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 an in-situ burn.

Ignition may be a concern as heavier oils may require a primer such as kerosene or diesel fuel for ignition. Heavy oils require longer heating times and a hotter flame to ignite than lighter oils. 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. It is uncertain whether oil that is completely emulsified with water can be ignited, although oil containing some emulsion can be ignited and burned. Containment of the oil on water may be necessary to carry out in-situ burning as the oil must be thick enough to quantitatively burn. Recent studies have shown thickness is not critical as once thought. The oil burn rate is a largely a function of oil type. Once burning, the heat radiated back to the slick and the insulation are usually sufficient to allow combustion down to about ½ to 1 mm of oil. 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.

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

The emissions of burning are of concern and concerns over emissions are probably the greatest obstacle to in-situ burning and are covered in this series. These emissions include 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 is a health concern close to the fire and under the plume. Particulate matter is distributed exponentially downwind from the fire.

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

VOCs - Many volatile organic compounds are emitted by fires, but in lesser quantity than when the oil is not burning. VOCs are not typically a concern, but can rise almost to health levels of concern very close to the fire.

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

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 sulphur dioxide are produced by oil fires but are significantly below any health concern level.

Table 1 provides generalizations about the burning of various fuels:

Table 1 Burning Properties of Various Fuels

Fuel	Burnability	Ease of Ignition	Flame Spread	Burning Rate* (mm/min)	Sootiness of Flame	Efficiency Range (%)
Gasoline	very high	very easy	very rapid - through vapours	4	medium	95-99
Diesel Fuel	high	easy	moderate	3.5	very high	90-98
Light Crude	high	easy	moderate	3.5	high	85-98
Medium Crude	moderate	easy	moderate	3.5	medium	80-95
Heavy Crude	moderate	medium	moderate	3	medium	75-90
Weathered Crude	low	difficult, add primer	slow	2.8	low	50-90
Crude oil with ice	low	difficult, add primer	slow	2	medium	50-90
Heavy Fuel Oil	very low	difficult, add primer	slow	2.2	low	40-70
Waste Oil	low	difficult, add primer	slow	2	medium	30-60

2 The Science of Burning

The fundamentals of in-situ burning are similar to that of any fire, namely that fuel, oxygen, and an ignition source are required.^{1,2} Fuel is provided by the vaporization of oil. The vaporization of the oil must be sufficient to yield a steady-state burning, that is one in which the amount of vaporization is about the same as that consumed by the fire. Once an oil slick is burning, it burns at a rate of about 0.5 to 4 mm per minute.

This rate is limited by the amount of oxygen available and the heat radiated back to the oil. The oil burn rate is a function of the oil type as well as conditions such as the presence of ice. The 'steady-state' burning implies that the conditions noted above are met.¹ 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 for a pool fire.^{3,4} If the oil slick is too thin, some of this heat is conducted to the water layer below it. Since most oils have the same insulation factor, most slicks must be about 0.5 to 3 mm thick to yield a quantitative burn. Once burning, the heat radiated back to the slick and the insulation is usually sufficient to allow combustion down to about 1 mm of oil. Figure 1 shows the burning of a heavy oil during the Deepwater Horizon incident.

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.⁵ The latter phenomenon is often observed when gasoline or light crudes are burning. It has been shown that diesel fuel burns differently than other fuels, with a tendency to atomize, rather than vaporize. This results in an obvious and heavier soot formation.⁶

Soot formation is an issue that has been studied by several scientists over many years.^{1,7,8} Soot formation occurs by several processes. One common process is the aggregation of molecular species into larger compounds and another process is the partial combustion of fuels. Diesel fuels and kerosene are known to burn with more soot than most other fuels.⁹ This is for several reasons, diesel fuel and kerosene can form droplets under heat and these droplets will often only burn partially, leaving carbonaceous material on the inside or even whole fuel with carbonaceous material or soot on the outside. Most other fuels will evaporate under the influence of heat and do not form significant amount of droplets such as diesel, kerosene or jet fuel.

The amount of oil that can be removed in a given time depends the fuel and on the area covered by the oil. As mentioned above, most oil pools burn at a rate of about 1 to 4 mm per minute, which means that the depth of oil is reduced by that value of millimetres per minute. As a rule of thumb, oil burn rate is about 2,000 to 5,000 L/m²-day. Several tests have shown that this does not vary significantly with oil weathering but varies with oil type.¹

Emulsified oil may burn slower as its water content reduces the spreading rate and increases the heat requirement. Chatris and co-workers carried out a study on the burning rates of gasoline and diesel fuel and found that diesel fuel burned at a rate of 0.57 kg/m²/s or 2.9 mm/min and gasoline burned at 3.5 mm/min.¹

Burn rate depends on wind velocity to a small degree.¹⁰ The burn rate for gasoline was 0.002 g/cm².s (equivalent to a pool regression rate of about 2 mm/min) at no wind velocity and this increased slightly and then returned to about the same rate at a wind velocity of 3 m/s.



Figure 1 Oil being burned during the Deep Water Horizon incident within a fire-resistant boom. This oil burn has an area of about 800 square metres which implies that the fire is consuming about 5 tons per hour of the heavy oil. This burn was ignited using a home-made igniter with a flare and a plastic jar of diesel fuel.

Burn rate depends on wind velocity to a small degree.¹⁰ The burn rate for gasoline was 0.002 g/cm².s (equivalent to a pool regression rate of about 2 mm/min) at no wind velocity and this increased slightly and then returned to about the same rate at a wind velocity of 3 m/s. Fingas measured the small scale burn rate of several heavy fuels and found that burn rates for heavy fuels varied from 0.5 to 3 mm/min.¹¹ Buist et al. found that the burn rates for many crude oils in ice was between 1 to 2 mm/min, typically half of the rate when ice was not present.¹²

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.³ 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 greater 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.³ Some 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. Many

studies have focused on flame dynamics and flame propagation.¹

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3. The Science of Burning (Continued)

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, except for heavier or emulsified oils. However, heavy oils require longer heating times and a hotter flame to ignite than lighter oils and may often require a primer such as kerosene or diesel fuel. Earlier studies appeared to indicate that heavier oils and oils with water content required greater thicknesses to ignite, however, recent testing has shown this to be incorrect.¹¹ Several workers have tested various oils to determine their ignitability with the general result that most oils are similar unless stable emulsion formation had occurred.¹³

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 and if sufficient vapors can be produced by the ignition and subsequent fire. 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.¹⁴ Alternatively weathered or heavy oils can be ignited with the addition of a primer.¹¹ At the time of the *Torrey Canyon* spill (1967), it was not known that the thickness of the oil would be a limitation. Several workers conducted studies shortly after this incident and concluded that the slicks that did not ignite were below minimum thickness.¹ Twardus conducted preliminary tests of minimum burning thicknesses and proposed that all fuels burned at the 5 mm initial thickness tried.¹⁴ Bunker C required longer heating times and the addition of a primer.

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.¹⁵ 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 limiting 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. Fingas et al. showed that thicknesses greater than about 0.5 mm burned for all types tested.^{16,17} Overall, many workers have concluded that the rule-of-thumb is that the minimum ignitable thickness of oil is 1 to 3 mm, however most did not test thin layers nor establish minimums. Fingas showed that even heavy oils at thicknesses of 0.5 mm and above could be ignited, sometimes with the aid of diesel as a primer.¹¹ Some studies have been conducted of the final thickness of burning oil on water before it is extinguished. Buist et al. 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.³ 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. **So in summary, there is no single limit of thickness to burning. For efficient burning the starting oil should be simply a few millimeters.**



Figure 2 An operations crew monitors a small burn during the Deepwater Horizon incident (Photo courtesy of Applied Fabric Technology Inc.).

It was uncertain whether oil that is completely emulsified with water can be ignited. Oil containing some emulsion was ignited and burned.¹ During the successful test burn of the *Exxon Valdez* oil, some patches of emulsion were present (probably less than 20%). While it did take longer to ignite the burn (>5 minutes), it did not affect the efficiency of the burn.¹⁸ It is suspected that fire breaks down unstable water-in-oil emulsion, and thus water content may not be a problem if the fire can be started. There is no evidence that the water is a specific factor at which emulsions can still be ignited. One test suggested that a heavier crude would not burn with about 10% water,

another oil burned with as much as 50% water, and still another burned with about 70% water.¹³ Twardus noted that mixtures containing less than 20% water ignited readily but required pre-heating.¹⁴ 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.¹⁹ Further studies indicated that stable emulsions will not burn but oil containing less than 25% water can be ignited. The burning of emulsions is probably related to their stability class.²⁰ 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. Once started, it is believed that most emulsions would burn. This certainly was the case at the Deepwater Horizon spill where some or most of the oil was emulsified, but burned well.²¹ Figure 2 shows another burn from the Deepwater Horizon spill.

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4. The Science of Burning (*Continued*)

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. 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 ranges from about 0.3 to 3% for crude oil fires and about 3 to 8% for diesel fires.²² 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. A recent study shows that overall soot percentage is most probably between 0.3 and 1% for a light crude.²²

Soot consists of agglomerates of spherical particles. Several scientists measured soot agglomerates and found that the individual spheres had radii of 5 to 25 nm (1 nm = 1000 μ m).¹ 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. Others studied soot particles and found that the aggregates ranged from 50 nm to 400 μ m with a fractal dimension of 1.8.¹ 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. A recent study of soot particles noted that small spherical particles are formed ranging in size from 200 nm to about 3 μ m.¹ These are called plerospheres. These small particles contain large amounts of trace metals as found in the originating oils.

The total heat radiated by a given burn has been measured as 1.1 MW/m².¹ Evans calculated that the heat required to vaporize the oil was 6.7 KW/m² and the heat lost from conduction through the slick to the underlying water was 2.5 KW/m².¹ 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%).³ Others calculated that 1% of heat was radiated back to the surface.¹

Thermal radiation is always an issue with fires, in the past several models for predicting radiation from hydrocarbon fires were developed.¹ Alaska North Slope oil showed a heat release rate of 176 KW/m², diesel fuel 230 KW/m², and propane, 70 KW/m². The heat radiated by a liquid propane fire enhanced by air flow and increased pressures was 180 KW/m².¹ The heat flux on booms as a result of these fires was reported as 140 to 250 KW/m² for crude oils, 120 to 160 KW/m² for diesel fuel, 60 to 100 KW/m² for propane, and 100 to 160 KW/m² for enhanced propane burning.¹

Flame spreading rates have been measured at several fires.^{3,23} 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. One scientist 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.¹ Higher heat fluxes yielded high flame spread rates. Flame velocities did not change when oil was thicker than 8 mm. Fingas and coworkers measured the flame spread rates in burning several heavy oils and Orimulsion and found that the rate was an average of 0.045 m/sec.²³ These rates ranged from 0.003 to 0.14 m/sec. It should be noted that all these rates are for flame spread on the ground and not through vapor clouds. It has been noted that at spills of gasoline, that fires have been noted as spreading through vapor clouds as fast as 100 km/hour. This is typical of flame spread through vapor clouds.

Flame heights have been measured by several authors.³ While data vary significantly, a rule-of-thumb is that the flame height of a small fire less than 10 m in diameter is about twice that of the diameter of the fire. The flame height approaches the diameter of the pool up to about 100 m in diameter. Thus an estimate of flame height for a fire in a boom with a radius of about 10 to 20 m is about 1.5 times the diameter or 15 to 30 m.

Several workers reported on findings that there is a vigorous burn phase near the end of a burn on water.³ 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 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 at sea, no vigorous burning was observed and thermocouple measurements in the water showed no increase in the water temperature.²⁴ 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. Some workers have studied a related phenomenon, sometimes known as boil-over, this occurs when water is entrained in the oil during combustion.²⁵ Boil-over typically occurs when a fuel layer is thin and is on a water layer. Heat transfer from the boiling liquid and/or flame can heat the water to boiling. When

this occurs the burning fuel is ejected and the turbulence of the fire is increased. Ferrero et al. studied this phenomenon with gasoline and diesel fuel and found that it occurs only with diesel fuel.²⁵ A related phenomenon is when water is entrained in the fuel layer. The entrained water droplets will explode if rapidly heating, thus causing what appears to be rapid boiling or even more violent behavior. This can occur with many oils, but particularly with emulsified oils. Several parties have studied the dynamics of burning and noted the above burn behaviours.¹



One group of researchers measured the radiative effect of the Kuwait oil fires at a point about 100 km downwind of the fires.¹ 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. Self-lofting is a phenomenon that may occur if a plume maintains or increases its buoyancy as a result of heat absorption from the sun.

Figure 3 Burning of a slick during the Deepwater Horizon spill. Note that the flame has not spread over the entire slick at the time this photo was taken. Also note that part of the slick appears to be a stable emulsion (reddish portion) and this would burn during this particular fire (Photo courtesy of Elastec / American Marine Inc.).

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5. The History of Burning

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.^{1,26} Failed attempts to ignite the oil spilled from the *Torrey Canyon* in 1968 were widely known.¹ 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. In the late 1970s several burn tests and studies were carried out in Canada by a consortium of government and industry agencies. Some tests in the early 1980s were performed by ABSORB (now Alaska Clean Seas) 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.¹ 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. Table 2 summarizes some of the tests and burns since the first recorded use of oil spill burning on water.¹

The largest and most extensive offshore test burn took place off the coast of Newfoundland, Canada in August 1993.^{1,27} The Newfoundland Offshore Burn Experiment (NOBE) involved 25 agencies from Canada and the United States. Two 50,000 L batches of oil were released and burned within a fire-resistant boom. During this test, more than 2,000 parameters were evaluated using various sampling 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.

A test of emissions from fires were carried out by a consortium of industry and government agencies at a test facility in Calgary Alberta.²⁸ Tests of various aspects of burning were conducted at the USCG facility in Mobile Bay, Alabama in 1991, 1992, and 1994. More than 35 burns were conducted using crude oil and diesel fuel.¹ Physical parameters were measured as well as emission data.

There are more tests – to be described in the next part of this serial. The many successful burns at the Deepwater Horizon certainly capped the history of in-situ burning.

Table 2 Summary of Burns or Tests (condensed)

Year	Country	Location/Incident	Description
1958	Canada	Mackenzie River, NWT	First recorded use of in-situ burning, on river using log booms
1967	Britain	TORREY CANYON	Cargo tanks difficult to ignite with military devices
1969	HOLLAND	Series of experiments	Igniter KONTAX tested, many slicks burned
1970	Canada	ARROW	Limited success burning in confined pools
1970	SWEDEN	OTHELLO/KATELYSIA	Oil burned among ice and in pools
1970	Canada	Deception Bay	Oil burned among ice and in pools
1973	Canada	Rimouski—experiment	Several burns of various oils on mud flats
1975	Canada	Balaena Bay—experiment	Multiple slicks from underice oil ignited
1976	U.S.A.	ARGO MERCHANT	Tried to ignite thin slicks at sea
1978-82	Canada	Series of experiments	Studied many parameters of burning
1979	Mid-Atlantic	ATLANTIC EMPRESS/ AEGEAN CAPTAIN	Uncontained oil burned at sea after accident
1979	Canada	IMPERIAL ST. CLAIR	Burned oil in ice conditions
1980-1	Canada	McKinley Bay—experiment	Several tests involving igniters, different thicknesses
1983	Canada	EDGAR JORDAIN	Vessel containing fuels and nearby fuel ignited
1983-4	Canada	series of experiments	Tested the burning of uncontained slicks
1984	U.S.A.	Beaufort Sea—experiment	Burning with various ice coverages tested
1984-5	U.S.A.	OHMSETT—experiments	Oil burned among ice but not with high water content Ice concentration not important, Emulsions don't burn
1984-6	Canada	Offshore Atlantic—experiment	Oil among ice burned after physical experiment
1985-1986	Canada - USA	several experiments in various locations	tests plus analyzed residues
1989	U.S.A.	EXXON VALDEZ	Test burn performed using a fire-proof boom
1989-1993	U.S.A.	Mobile experiments	Several test burns in newly-constructed pan
1993	Canada	Newfoundland Offshore burn	Successful burn on full scale off shore
1994, 96, 2001	U.S.A.	North Slope burns	Large scale burn to measure smoke
1994	Norway	Series of Spitzbergen burns	Large scale burns of crude and emulsions
1994	Britain	Burn test	First containment burn test in Britain
1996-97	U.S.A.	Mobile burns	Small scale diesel burns to test booms
1997	U.S.A.	North Slope tank tests	Conducted several tests on waves/burning
2002-3	Canada	Small scale tests on heavy oils	Tested procedures to burn heavy and emulsified fuels
2004	Svalbard, Norway	Burns in ice	Tested burning in frazil and brash ice
2010	U.S.A.	Deepwater Horizon Spill	successful 401 burns

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6. The History of Burning (continued)

In the last chapter we review a few of the many tests conducted on in-situ-burning. Early tests focussed on burnability in several conditions. Tests in the late 90's focussed on testing booms and measuring emissions. Such tests are shown in Figures 4 and 5.

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.¹ These tests evaluated firebooms 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 comparable to those measured in the diesel fuel fires.

Two separate fireboom test evaluations using air-enhanced propane were conducted in Fall 1998 by MAR, Inc. and S.L. Ross Environmental Research Ltd.^{1,29} Both tests were conducted at the OHMSETT facility in Leonardo, New Jersey.



Figure 4 A test of fire boom in the early 1990's. All the instruments in the foreground are to measure or capture emissions.



Figure 5 A test of fire boom at the USCG Mobile facility using the ASTM protocol. The emissions from this test would be been measured in a similar manner to that shown in Figure 4.

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 fireboom evaluation, a prototype stainless steel PocketBoom 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.

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7. The History of Burning – The NOBE Experiment

The Newfoundland Burn Experiment took place on the Grand Banks, east of the port of St. John's, Newfoundland. The experiment was conducted on August 12, 1993.^{1,30,31} Two replicate experiments were carried out wherein 50 m³ (13,200 gal) of oil was discharged into a fire-proof boom and ignited. A sophisticated array of state-of-the-art sensing, sampling and data-gathering equipment was deployed from a variety of platforms. Data was collected and analyzed to generate information on over 2000 parameters. More than 20 vessels and 5 aircraft participated in the study. Sampling near the fire and in the smoke plume was conducted from remote-controlled boats, helicopters and an ROV (submersible) that were deployed beneath the slick. At more distant locations, a tethered blimp, conventional helicopters, fixed-wing aircraft and a variety of vessels were used.



The procession was led by the 224' CCG vessel *Sir Wilfred Grenfell* that served as the supply and oil discharge vessel. The fire boom was towed directly behind the *Grenfell* with 150-ft tow lines. Two, 14-ft remote controlled boats, and a 36-ft sea truck serving as a platform for the tethered blimp, were approximately 50, 100 and 150 m, respectively, behind the apex of the fire boom. One hundred metres behind the sea truck, the secondary containment boom was towed by two, 46-ft vessels (i.e. 250 m behind the fire boom).

A number of other vessels were stationed farther from the main procession. These included several Boston Whalers from which routine sampling was conducted and other vessels that served as platforms from

which the remote controlled boats, remote controlled helicopters and the ROV were operated. The command vessel was the 272-ft CCG vessel *Ann Harvey*. Two 100-ft vessels were chartered to accommodate scientific observers and visitors.

Figure 6 A view of the Newfoundland Offshore Burn Experiment (NOBE). Only four of the 20 vessels are shown.

boats, a research vessel and from an airplane. The plume itself was sampled by two remote-controlled helicopters and a blimp. Water samples were collected from the remote-controlled sampling boats, and air and water temperatures measured from the same vessels. The fire-resistant boom was equipped with thermocouples to monitor temperatures directly impacting it and those in the water directly underneath the fire. A submersible was deployed under the burning slick to monitor temperatures and take photos. A small boat monitored and possible escaped surface material and took samples of the burn residue after the burn.

The oil was released into a fire-resistant boom and burned within it. Air emissions were monitored downwind using two remote-controlled

The oil was released from a supply-type ship. A 700-foot section of boom was used. Once sufficient oil was in the boom to sustain combustion, it was ignited using a Helitorch.

The fire-resistant boom used was a commercial version along with some experimental sections. The middle sections near the burn were equipped with a number of thermocouples to measure the temperature on the boom. The boom was backed up by another boom, an offshore type, about one kilometre down current. The fire-resistant boom was towed by a major vessel and the opening was maintained by two vessels towing outward at an angle of approximately 45 degrees. Tow vessels were equipped with current meters to ensure that they are able to maintain a forward speed of 0.5 knots. Command and control operations took place from a major vessel of the Canadian Coast Guard, the ANN HARVEY. One helicopter was used both to ignite the slick and put out flares to guide the procession into the wind. Another helicopter was used to provide photography. Two charter ships were engaged to bring out observers. They were also used as platforms for some of the documentation and air measurement. Several smaller boats were used for other sampling purposes and for controlling the remote sampling boats and a remote-underwater vessel.

Burn One was started using a Helitorch. Reports from the helicopters and both airplanes indicated that the smoke plume bifurcated after about 2 km downwind. A small part remained with the inversion layer at about 0.5 km and the main portion split with one portion turning southeast and one turning east after rising about 2 km. The average discharge and burn rate for burn 1 were 915 L/min. The fire-resistant boom was inspected after the first burn. Some signs of fatigue in the stainless steel core were observed at a point about 10 cm from the stiffeners. Some of the Nextel fire-resistant fabric was missing from these areas as well. The boom was still fit for another burn.

The crews re-fit the equipment for the second burn. The first run of the Helitorch ignited the oil. Some oil was again splashed over. The oil outside of the boom burned completely leaving only small patches of residue which drifted back into the secondary recovery

boom. The wind was 8 to 11 km/hr and this resulted in an approximate 45 degree angle for the plume. This burn was characterized by its "classical", regular plume behaviour.

The pump rate for this burn averaged 610 L/min. Pumping was stopped after 1 1/4 hours of burn time when some small pieces of the fire-resistant boom were lost. There was no oil released. The duration had already exceeded planned sampling times and most samplers had already been stopped.

Summary of Analytical Results

Oil Analysis

The oil was analyzed for physical properties and PAHs as well as for alkane proportions. A most interesting result is that the residue appears to be an oil with an evaporative loss of about 45% by weight. The residue had a density of about 0.95 g/mL and a viscosity of about 100,000 mPa.s. The distribution of alkylated PAHs in the oil was similar to that of the starting oil, but somewhat less.

Particulates

Particulates were collected by a number of means. Particulates were at moderate levels under the plume at the locations sampled by the remote-controlled boats. Particulate levels dropped to background levels at the remote sampling station about 1 km downwind. The amount of particulate material in the respirable size range was very low.

Polyaromatic Hydrocarbons (PAHs)

PAH analysis of particulate material and air itself was performed at several different sample locations and by several different means. This comparison showed that the PAH's are largely consumed by the fire. The amounts of PAHs detected at the Newfoundland burn were a fraction of that detected in previous burn trials. This may be indicative of a more efficient burn.

Aldehydes and Ketones

Aldehydes and ketones were measured using a specialized technique. Data indicate that the concentrations are near background levels and actually are higher during the times when the oil is not burning.

Dioxins and Dibenzofurans

The high-volume samples taken on the remote-controlled boats and on the downwind station were also analyzed for dioxins and dibenzofurans. The values were at background levels. This confirmed previous studies which show that dioxins and dibenzofurans are not produced by fires

Combustion Gases

Tests were made for a number of gases, but CO, SO₂ and NO_x are not above the lower detection levels. Carbon dioxide was measured around the burn and these measurements show that the CO₂ plume moves closer to the surface.

VOCs

Over 140 compounds were measured using SUMMA canisters. The levels of these compounds were even greater from an evaporating slick that is not burning.

Metals

Crude oil contains several metals in the ppm range. Metals could not be detected on soot particles.

Water-Borne Compounds

Water from under the burns was sampled and analyzed for a number of compounds. No compounds were detected in the water once the oil was on the water, during the burn or after the burn, above the background levels.

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8. The History of Burning – the Deepwater Horizon

The burning that took place at the Deepwater Horizon certainly changed the history of in-situ burning. For 35 years the history of in-situ burning had largely been that of small tests, some small burns, lots of land burns, and a few larger tests. What was needed, was a few large actual and successful burns at sea - to prove that the technique was viable. Indeed there were about 400 successful burns carried out during the Deepwater Horizon spill and this removed a large part of the oil on the water.^{21, 32} Table 3 summarizes some aspects of these burns.^{21, 32}

Table 3 Summary of the Deepwater Horizon Burns

Amount burned	35,000 to 50,000 m ³ (220,000 to 310,000 barrels)
Number of fires	411 (396 effective ones)
Time of fires (range)	10 minutes to 12 hours
Dates	April 28 to August 19, 2010 (83 days)
Location	~5-25 km (3-15 miles) from source - about ~60 km (40 miles) from shore
Average burned/fire	110 m ³ (700 barrels)
Average burn time	~ 2 hours
Most oil burned in one day	~9600 m ³ (~60,000 barrels) (June 18)
Burn teams	8 to 12
People per burn team	7 or 8
Total people involved	less than 100
Spotting aircraft	2 King Airs
Spotters	10
Fire boom used	7000 m (23,000 feet)
Types used	4 types, mostly Elastec/American Marine then Applied Fabric Technologies
Boom used per burn	~150 m (~500 feet)
Fire boom lifetimes	ranging from one to typically 12 to 14 burns
Large vessels	~ 10 supply boats and large shrimp boats
Small vessels	~ 20 rigid hull inflatable or aluminum skiffs
Igniters	1,700 handheld with gelled diesel and marine flare



Photo 7 The homemade igniter frequently used during the Deepwater Horizon spill, is lit and prepared to be put into the oil (Photo courtesy of Elastec / American Marine Inc.).

The basic technique was to collect oil in a fire-resistant boom (hereinafter called fire boom) and then ignite the oil and slowly pull the fire boom forward to push the oil to the rear or wait if the winds and currents were doing this.^{21, 32} The oil was spotted using a fixed-wing aircraft. Two shrimp boats (about 100 foot long) towed about 150 m (500 ft) of fire boom at about ½ to ¾ knot to avoid loss of the oil through entrainment under the boom. The tow lines were about 100 m (about 300 ft) for the safety of the tow crews. Once sufficient oil had been collected for a burn and marine and air monitoring approved, ignition was requested. A small boat carrying two

persons would approach from upwind and an igniter dropped over the edge of the boom. The igniters were made from a plastic jar (about 1 Litre) of gelled diesel fuel, a marine flare and some Styrofoam floats. The flare, once activated burned down to the bottle of gelled diesel fuel, which started burning and acted as a primer to ignite the oil. Figures 7 and 8 show some aspects of the burn.

Photo 8 An operations crew monitors a small burn during the Deepwater Horizon incident (Photo courtesy of Applied Fabric Technology Inc.).



Once lit the heavy, weathered oil would burn until most oil was removed. The burn was monitored from the air by trained observers and from larger vessels in the area. The amount burned was gauged by measuring the burning area in the boom and multiply by the areal burning rate.^{21, 32}

Many precautions were taken during the burn. Extensive training was given to the crews and several practice sessions were undertaken. Particulate emissions from the burns were monitored.^{21, 32}

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9. How In-situ Burning is Conducted at Sea

Several burn guidance documents have appeared in the past.³³⁻³⁶ Many of these require revision in light of the Deepwater Horizon burns. This is particularly true of the statements in these manuals as to what oils will readily burn and what will not. The Deepwater Horizon oil at the point of burning was a heavy, weathered crude and this has a positive effect in terms of the lack danger of rapid fire spread and the relative efficiency of burning.

There are several distinct steps involved in burning oil spills at sea. 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 questions to be asked before deciding to use in-situ burning at a particular spill situation are important. 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 many cases, containment will be required either because the slick is already too thin to ignite or will be too thin within hours. In other cases, such as the Deepwater Horizon, containment was used to collect the oil as well as to separate the fires from adjacent areas.

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 enough oil is collected in the boom, it is ignited using an igniter. The tow is resumed and continued until the fire is extinguished or the tow is stopped for operational reasons. The burning and progress of the tow are monitored by personnel on aircraft and/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.

The burn could be stopped in an emergency by releasing one end of the boom tow or by speeding up the tow so that oil is submerged under the water. If the burning stops because there is not enough oil in the boom, the tow can be resumed going downwind and then turning around into the wind before re-igniting. After the burn operation is finished, for the day or for the single burn, the burn residue 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 or by 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.¹ 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%.⁴⁴

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 will be given in later episodes.

During the Deepwater Horizon burns, the technique was to collect oil in a fire-resistant boom and then ignite the oil and slowly pull the fire boom forward to push the oil to the rear or wait if the winds and currents were doing this.^{21, 32} The oil was spotted using a fixed-wing aircraft. Two shrimp boats (about 100 foot long) towed about 150 m (500 ft) of fire boom at about ½ to ¾ knot to avoid loss of the oil through entrainment under the boom. The tow lines were about 100 m (about 300 ft) for the safety of the tow crews.



Once sufficient oil had been collected for a burn and marine and air monitoring approved, ignition was requested. A small boat carrying two persons would approach from upwind and an igniter dropped over the edge of the boom. The igniters were made from a plastic jar (about 1 Litre) of gelled diesel fuel, a marine flare and some Styrofoam floats. The flare, once activated, burned down to the bottle of gelled diesel fuel, which started burning and acted as a primer to ignite the oil. Figure 9 shows oil contained for the burn.

Once lit the heavy, weathered oil would burn until most oil was removed. The burn was monitored from the air by trained observers and from larger vessels in the area. The amount burned was gauged by measuring the burning area in the boom and multiply by the areal burning rate.^{21, 32}

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10. Advantages and disadvantages

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

- rapid removal of large amounts of oil from the water surface;
- significantly reduced volume of oil requiring disposal;
- high efficiency rates;
- less equipment and labor required; and
- may be only cleanup option in some situations, e.g., oil-in-ice conditions.^{1,37}



The most significant of these advantages is the capacity to rapidly remove large amounts of oil. When used at the right time, 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 98 and 99% were achieved. Figure 10 shows the small amount of residue remaining after the first burn.

Figure 10 The residue remaining after the first burn of the Newfoundland Offshore Burn Experiment. This is the remains of 50 tons of oil amounting to about 30 kg.

In ideal circumstances, in-situ burning requires less equipment and labor than other techniques. It can be applied in remote areas where other methods cannot be used because of distances and lack of infrastructure. Often not enough of these resources are available when large spills occur. Figure 11 shows burning of oil on ice in the Arctic. It would be difficult to remove the oil by any other method. Burning is relatively inexpensive in terms of equipment needed and actually conducting the burn operations.



Figure 11 Burning of oil in the Canadian Beaufort. This oil was a test spill put under the ice in the fall. In the spring, the oil resurfaces. The oil was burned as shown here.

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 few mm thick in order to ignite and quantitatively burn and must usually be contained to achieve this thickness;
- risk of fire spreading to other combustible materials; and
- burn residue must be disposed of.³⁷

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 future episodes. The second disadvantage is that the oil will not ignite and burn unless conditions are right - such as thickness. Most oils spread rapidly on water and the slick quickly becomes too thin for burning to be feasible. Fire-resistant booms can be used to concentrate the oil into thicker slicks so that the oil can be burned. While this obviously requires equipment, personnel, and time, concentrating oil for burning requires less equipment than collecting oil with skimmers. And finally, burning oil is sometimes not viewed as an appealing alternative to collecting the oil and reprocessing it for reuse.

It must be pointed out, however, that recovered oil is usually incinerated as it often contains too many contaminants to be economically reused. Furthermore, reprocessing facilities are not accessible in most parts of the world.

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11. 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 could be helpful 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 40 years. The toxicity associated with dispersant use relates to the toxicity of the dispersed oil as well as the additional toxicity caused by the dispersion. In shallow or

confined waters, dispersed oil could be toxic to aquatic life. For this reason, dispersants are not 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 into thin sheens so that the oil in thinner portions of the spill will not disperse when dispersants are applied.

Further chemical dispersions do not last long. Significant amounts of oil resurface with time. A chemical dispersion half-life may be as short as 12 hours.

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 residual oils. 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.

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 or they must be used in diversionary mode. On the other hand, while recovery using booms and skimmers is slower than removal by in-situ burning or dispersants, the oil is recovered without the potential for air and water pollution. Mechanical recovery works well in sheltered waters such as harbors and marinas where burning should not be conducted, but is impossible in high currents and waves over 2 m.

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

In some marine spill situations, the best cleanup strategy involves a combination of mechanical recovery techniques and burning for various portions of a spill. For example, burning can be applied in open water and oil that has already moved closer to shore can be recovered with booms and skimmers.

Burning could also be used on open water after the window of opportunity closes for effective use of dispersants. Burning does not preclude the use of other countermeasures on other parts of the slick. When combining different cleanup techniques, the objective should be to find the optimal mix of equipment, personnel, and techniques that results in the least environmental impact of the spill.

An approximate comparison is shown in Table 4. This table is based on a number of assumptions including that skimmer rates and dispersant effectiveness rates are average.³⁸

The table shows that burning has distinct advantages in terms of burn rate over other methods, especially for heavier oils. This is because heavier oils burn well and just as effectively as do light oils. Other methods are handicapped by increasing oil viscosity, particularly dispersants.

Table 4 Approximate Comparison of Countermeasures*

	Light crude			Heavy Crude			Bunker C		
	Presumed Effectiveness	Hours to clean	tons/hour	Presumed Effectiveness	Hours to clean	tons/hour	Presumed Effectiveness	Hours to clean	tons/hour
Brush Drum Skimmer	80	7.5	8	85	30	2	90	75	1
Large Weir Skimmer	80	1.5	40	85	0.9	71	90	18	4
Dispersants - first day	40	0.2	150	25	0.2	94	5	0.2	19
Dispersants - second day	20	0.2	75	13	0.2	47	3	0.2	10
In-situ Burning	95	0.2	356	95	0.3	238	95	0.3	238

**there are many assumptions in the table including capacities of two average skimmers, dispersant effectiveness, but the burn rate is actual. This comparison is for a 150 m boom filled over time with 75 tons of oil and removed at the operating rates*

References

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12. Assessment of feasibility of burning

When an oil spill occurs, information must be obtained on the spill location, weather conditions, and any other relevant conditions at the site. The necessary questions to be asked before deciding to use in-situ burning are outlined in Figure 12.

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.

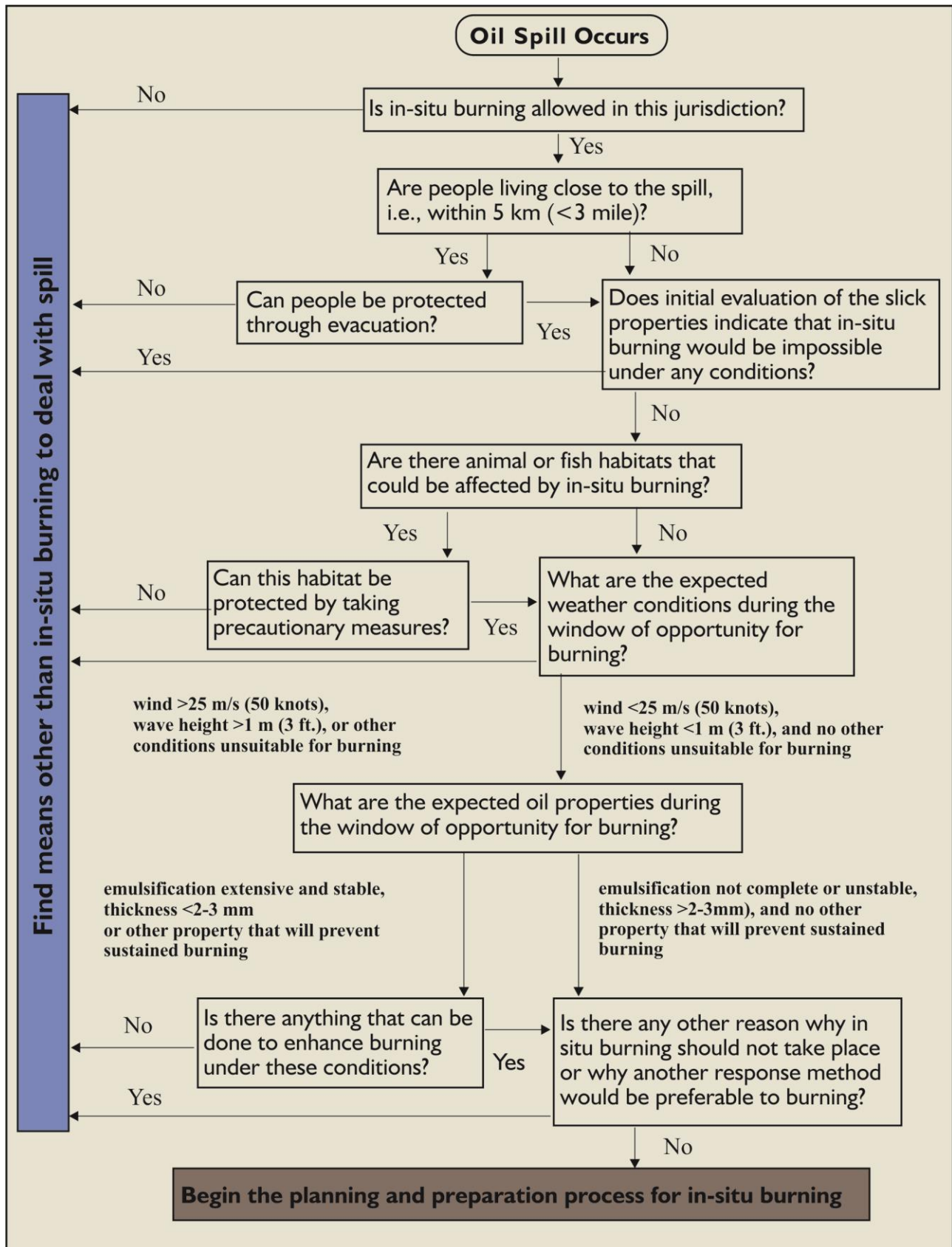


Figure 12 Logical decision-making process for an in-situ burn

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 public 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.

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

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 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 m²) would not exceed health limits for emissions beyond about 500 m from the fire. The emissions produced by in-situ burns are discussed below. 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 later in this series.

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

Public health

In general, depending on weather conditions, in-situ burning should not be carried out within 5 km of heavily populated areas. Weather conditions to be considered include the presence or absence of an inversion and the wind direction. Monitoring of oil fires, 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.¹ 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 and these are described in later episodes.

What will burn

Most oils will burn and burn quantitatively. Oils that are thick (>2 to 4 mm) will burn effectively. Oil emulsified with water will burn, once started. Therefore it is important to have some un-emulsified or unstable-emulsions to start the fire. Heavy oils will burn well and with lesser soot than light oils or fuels. The burn rate for heavy oils is lesser than that for fuels as is oil mixed with ice.

References

- 1 Fingas, M., "In-situ Burning", Chapter 23, in *Oil Spill Science and Technology*, M. Fingas, Editor, Gulf Publishing Company, NY, NY, pp. 737-903, 2011

13. Emissions – I



In-situ burning of oil spills has been tried for more than thirty years with limited acceptance as an oil spill cleanup option in certain parts of the world. Recently the Deepwater Horizon burns opened up the doors to wider acceptance. Such lack of acceptance was primarily because of the lack of understanding regarding combustion products. Extensive research was undertaken to understand emissions of burning oil. A consortium of several agencies in the United States and Canada had joined forces to study burning and to conduct large scale experiments. This effort has resulted in data which has led to broader acceptance of in-situ burning as an acceptable spill countermeasure alternative. Table 5 lists the burns monitored in the past for emission studies. Figure 12 shows some of the samplers used at a burnt test site.

Figure 12 A view of three of the downwind stations used to measure emissions at a diesel burn. Note that 15 stations were set up with more than 150 instruments. This particular burn was also used to test fire-resistant booms.

Emissions include 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, have a variety of chemicals absorbed and adsorbed. Complete analysis of the emissions from a burn involves measuring all of these components.

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 burns has involved measuring all these components. 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.¹ 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.¹ In 1993, two major burns were conducted at sea specifically to measure emissions, although many other measurements were also taken.²⁷ Further tests were conducted in 1994 and 1997.^{39,40} Heavy oil burning emissions tests were carried out in 2003 and 2004.⁴¹

Particulate Matter/Soot - All burns, especially those of diesel fuel, produce an abundance of particulate matter which is the primary 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 (35 µg/m³ for PM 2.5) 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 currently the subject of particular concern at this time.¹ It is important to note that currently the fine particles are coming under increasing scrutiny as health concerns.

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.

Table 5 Summary of Studies Used to Measure In-Situ Burn Emissions

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 to 467	70 to 60	25	40
Newfoundland	1993	2	2	(ASMB)	emissions	600 to 199	90 to 60	200	400
Mobile	1994	3	3	diesel	physics boom	231	80	95	400
Mobile	1997	9	8	diesel	tests boom	25	60	95	400
Mobile	1998	12	12	diesel	tests	25	60	67	400

Ottawa	2003	8	8	Heavy Oils	burnability	0.5 to 3	4 to 36	6	200
Ottawa	2004	10	10	Heavy Oils	burnability	1 to 4	4 to 36	6	200
Total		66	48						

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- 39 Fingas, M.F., P. Lambert, Z. Wang, K. Li, F. Ackerman, M. Goldthorp, et al., *Studies of Emissions from Oil Fires*, AMOP, 767, 2001
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14. Emissions – II

In the last episode, we reviewed the basics of oil burn emissions. It was noted that emissions include 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.¹ In this episode, we shall push further and examine more classes of emissions.

Volatile Organic Compounds (VOCs) - Volatile organic compounds are organic compounds that have high enough vapour 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. 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 [1.5 m (5 ft)] 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 have 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. Burning of alcohol-containing fuels might result in the release of more carbonyls.

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.

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

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



Figure 13 A remote-controlled helicopter emerges from a smoke plume during the Newfoundland Offshore Burn Experiment. Although the most important emissions are measured at ground (1.5 m) level, it is useful to compare these measurements to that in the smoke plume. Many compounds and gases are actually lower in the smoke plume, while the particulate levels (obviously) are very high in the smoke plume.

References

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15. Emissions – III

In the last episodes, we reviewed the basics of oil burn emissions. It was noted that emissions include 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.¹ In this episode, we shall look at how one can use the emission data to correlate and predict.

Sufficient data are now available to assemble emission data and correlate the results with spatial and burn parameters. The correlations are summarized in a reference.³⁴ 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 first 30 test burns conducted. Sufficient data were available to calculate equations for over 150 individual compounds and for all the major groups.

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 only a few cases where inversions were present.

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. The findings show 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.¹ 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.

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. There is no health concern for fixed gases such as carbon dioxide or carbon monoxide at levels measured at burns to date.

Safe Distances

Safe distances can be calculated for worst case conditions where the smoke plume does not lift or where it impacts the ground at a distance close to the fire. Such circumstances are rare however, but do occur. Figure 14 shows such a case for a test burn of diesel fuel.



Figure 14 (left) A photograph of a mid-size diesel fuel fire in which the plume does not rise due to an inversion. Such cases are rare but result in worst-case situations for emissions.

Safe distances for typical conditions where the smoke plume does not impact the ground are well within 1 km (0.6 miles). Distances greater than about 200 m (650 feet) are the closest one could safely approach most fires.

Figure 15 shows the calculated worst-case safe distances for fires. It should be noted that diesel fires produce large amounts of soot and thus worst-case safe distances are very much further than for crude oil fires.

Figure 15 (right) A nomogram to predict **worst-case safe distances**. This is for cases where the smoke plume is close to or on the ground near to the fire as shown in Figure 14. If the smoke plume rises normally, safe distance is typically a minimum of about 200 m (650 feet).

Worst-case safe distances downwind from a crude oil burn (based on PM-2.5 concentrations) can be calculated as:
 Crude worst-case safe distance = Exponential (2.64 + 0.00725*(area))
 where distance is in metres and area is in square metres

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

Diesel worst-case safe distance = Exponential (3.41 + 0.0127*(area))
 where distance is in metres and area is in square metres

Note:

To convert feet to metres, multiply by 0.305.
 To convert metres to feet, multiply by 3.28.

References

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16. Water Quality and Effects on Land and Wildlife

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.¹ Water samples from under burning oil have been analyzed and no organic compounds were detected.^{1,42,43} 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.¹ 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 aquatically 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.¹

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. Figure 16 shows the residue from the second NOBE. Figure 17 shows a residue from a heavy oil burn. 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.

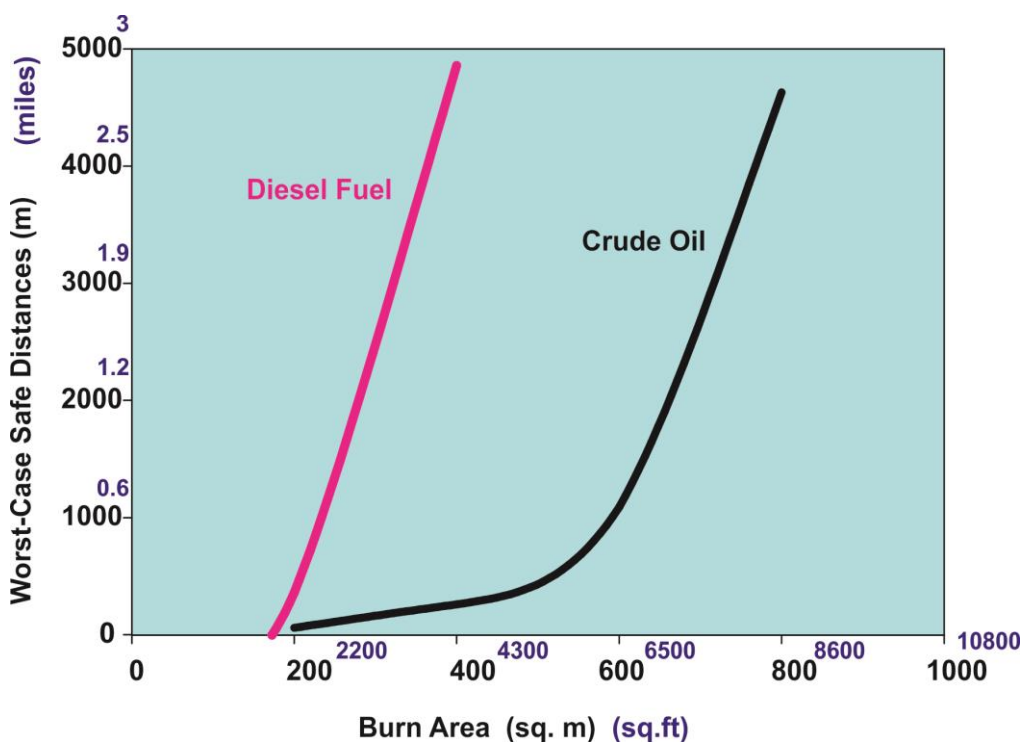




Figure 16 (left) Residue from the second NOBE burn. The residue is dense and as can be seen has a small film of water over it.

Aquatic toxicity tests performed on samples of residue have shown very low toxicity.¹ 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.¹ 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.

Figure 17 (right) Residue from burning a heavy oil. Note this residue is so solid that it can be removed as a sheet.

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. If burning on land there are some precautions that should be taken, as noted later.



Effects on birds and other species

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

References

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17. Oil Properties and Conditions

Oil spilled on water undergoes several changes with time. The processes that cause these changes include emulsification, evaporation, and spreading. 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.

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 should be 0.5 to 3 mm thick or thicker in order to be ignited and to sustain quantitative burning and a burn will be extinguished once the slick becomes less than approximately 0.5 to 1 mm thick.¹ This thickness is required for heat transfer to take place. It should be noted that this thickness is not as binding a rule as once thought. As the slick becomes very thin, the heat generated by burning is lost to the water below the slick, resulting in insufficient available heat to vaporize the constituents of the oil required to sustain combustion.¹ 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 where efficient burning takes place. In some circumstances, e.g., on dry sand or grass, oil can sometimes be ignited at lower thicknesses.

Oil weathering/volatile content

As a rule, the greater the percentage of volatile compounds in an oil, the more easily it will ignite and continue to burn. It can therefore be difficult to ignite weathered oils and heavy crude oils (No. 5 and above) and higher ignition temperatures, primers and/or longer ignition exposure times may be required.¹ During one burn test, it was found that weathered oils actually burned with an average 7% greater efficiency than fresh oils.¹

Heavy oils

Heavy oils were thought to burn poorly if at all, however results in recent years shows that these will burn quite well under most circumstances.⁴¹ Studies in the past decade have shown much more potential for burning these oils than was previously thought.⁴¹ Burning tests of bitumen, a very heavy oil, along with water have been conducted and shown useful removal potentials. The burning of heavy oils has been studied by Environment Canada over a period of 5 years.¹ Figure 18 shows the ignition of a heavy oil.



Figure 18 The ignition of a heavy oil. This is easily carried out by adding a small amount of primer such as diesel fuel (about 20 mL), and adding a small wick such as cardboard or paper towel

Heavy oils such as Bunker C burn quite well but yield a highly-viscous residue. This high-viscosity residue has a high asphaltene and resin content. There is no evidence of the presence of soluble components, thus the residue should exhibit low aquatic toxicity. Examination of the SARA content shows that the values of SARA for the residue can be used to predict burn efficiency. There appears to be a consistent reduction of

saturate and aromatic content in an oil with increasing burn efficiency. This is based on values from 10 burn experiments and 4 oil types.

The prediction equation is: $\text{Burn Efficiency (\%)} = -23000 + 230 \cdot \text{Aromatic \%} + 227 \cdot \text{Saturate \%} + 254 \cdot \text{Resin \%} + 218 \cdot \text{Asphaltene \%}$

It is interesting to note that Orimulsion (a mixture of bitumen with about 30% water) burning efficiency averages about 40 to 60% (excluding the water content of 30%), bunker C burning averages about 65% and burning bitumen averages about 12%. Orimulsion has certain peculiar burning characteristics such as popping when the water is explosively released.^{1,41} It is suggested that burning of Orimulsion actually takes place as a two-step process: first vaporization and water release and secondly, the actual combustion. Extremely weathered oils such as the bunker test oil would not burn and analysis of this showed that its calculated burn efficiency as per the equation above was calculated to be about zero. The burn rate for Orimulsion was found to be between 0.5 and 2 mm/min.⁴¹ It was found that the burn rates for heavy oils varied from 1 to 2 mm/min.⁴¹

Emissions from these heavy oil burns showed very low emissions compared to crude oils and in particular there were few volatiles and few PAHs measured in the air. The residues from all the burns were highly viscous. When cooled, all residues were solid and even 'glassy' in some cases. Analysis of the residues showed some concentration of higher-molecular weight pyrogenic PAHs.

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.¹ 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.¹ This certainly was the case during the Deepwater Horizon spill during which the burns dealt with extensive amounts of emulsified oil.

Strictly speaking, all unstable 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 - studies have shown that stable and unstable emulsions have different characteristics.⁴⁴ 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 mesostable emulsion which usually is brownish in colour and has a viscosity of about 50 times that of the starting oil. The literature has shown that the stability of an emulsion depends on the concentration of asphaltenes and, to a lesser extent, resins in the oil.⁴⁴ These compounds form a viscoelastic film at the oil water interface. 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.⁴⁴

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18. Tests on Burning Heavy Oils

Figure 19 (below) Orimulsion burning. The streaks of light are exploding water droplets. The Orimulsion was 'weathered' for 16 hours and the water largely settled out except for some water droplets. Orimulsion in this state burns very noisily as the water droplets explode.



The burning of heavy oils was studied by Environment Canada over a period of 5 years from 2000 to 2005.^{1,41} Tests began with laboratory burns using a Cleveland fire point apparatus. Dozens of tests were carried out. These tests were confirmed by using small burn pans (order of tens of cm.) in a fire-resistant fume hood. These tests established the parameters for burning a variety of heavy oils and emulsified fuels such as Orimulsion. Orimulsion is a surfactant-stabilized oil-in-water emulsion of 70% bitumen in 30% water.

Questions have long arisen over countermeasures to Orimulsion spills. In-situ burning had not been considered in the past largely because of the nature of Orimulsion and because the perception that the product could not be ignited. Even if it could be ignited, it was felt that combustion may not be sustained. The laboratory tests showed that a wide variety of heavy oils and Orimulsion would be quantitatively burned.

The laboratory tests were followed up by outdoor tests using a variety of burn pans. Four types of heavy oils, two types of Bunker C, Orimulsion, waste oil and weathered Bitumen were burned in-situ. Burning tests were conducted on two scales of approximately 1 m and 1.5 m square. Earlier tests using a 0.5 m pan, showed that this small scale was not useful. Burning was conducted outdoors in winter weather conditions. All tests were conducted on salt water which result in the separation of the bitumen from the water in the Orimulsion.

The heavy oils were ignited using a small amount of diesel fuel and a small piece of paper as wick. In all cases except for the waste oil, quantitative removal of the fuels was achieved, however in the case of Orimulsion, re-ignition may be required.

It was found that the maximum efficiency was about 70%, however the residue was largely asphaltenes and resins. Once cooled this residue could be shattered like glass and readily removed as a solid. It is believed that these tests show that many heavy oils could be burned in similar manner. The behavior of the burns depended very much on the type of oil

burned. Bunker C burns quantitatively and with only one ignition. Orimulsion may require re-ignitions to ensure a good removal. Sometimes excessive water vapour can extinguish an Orimulsion fire prematurely. Examples of test burn data are shown in Table 6.

Table 6 Example data on heavy oil burns

Burn Number	Oil Type	Starting Oil Viscosity* mPa.s	Outside Temp. °C	Initial Oil Thickness mm	Final Oil Thickness mm	Efficiency %	Burn Time minutes	Burn Rate mm/min	Flame Height m	Peak Height m	Igniter Ratio g/g oil
1	Bunker	15,330	-6	36.7	12.9	64.8	20.19	1.2	1.5	2	0.001
2	Bunker	15,330	-6	36.6	13.3	63.8	22.28	1	1	1.5	0.003
3	waste oil	16,273	-8	20.2	0	2	did not burn quantitatively				0.025
4	waste oil	16,273	-8	74	0	2	did not burn quantitatively				0.01
5	Orimulsion	255	-1	26.6	9.1	65.6	10.11	1.7	3	8	0.012
6	Orimulsion	255	-1	32.2	12.5	61.3	8.66	2.3	1.5	4	0.019
7	Bunker	15,330	1	34.2	11.7	65.9	20.9	1.1	3	4	0.002
8	Bunker	15,330	1	51.3	15.4	70	36.13	1	1.5	3	0.002
9	Bitumen	4,038,333	-6	37.8	33.2	12.3	4.82	1	1.5	2	0.057
10	Bitumen	4,038,333	-6	31.2	27.2	12.9	4.22	0.9	1	1.5	0.075
						Overall	55	average	1.5		

* all oil was weathered outside for 16 hours

Several findings resulted from these tests:

1. Ignition is best accomplished by adding a few mL (20 to 100) diesel fuel to the oil a few seconds before applying an ignition flame. This is required to start a small portion of the heavy oil. Once started, the flame will spread to adjacent areas.
2. The residue of heavy oil burns is largely resins and asphaltenes. Burning proceeds only to the point that the burn layer can produce sufficient vapors at about a temperature of 500 °C, the remainders are high-boiling-temperature residuals such as resins and asphaltenes. The residue ranged in test burns from a tarry mat to a glass-like layer.
3. Orimulsion with its water content showed a different burn behaviour. The water content caused small mini-explosions and flashing. This could sometimes prematurely extinguish the flame.
4. The burn rate of heavy oils and emulsified fuels is lower than that of crudes, and ranges from 1 to 2 mm/min.
5. Other burn parameters such as flame height and flame spreading rate were similar to that of crude.

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19. Marshes I

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

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

Figure 20 (below) shows a marsh burn.



Figure 20 A salt marsh burn in Louisiana. The high water level and topography keeps the fire contained to the oiled area.

Several cases of burning in marshes are given below:

Copano Bay⁴⁵

On January 7, 1992, an underground pipeline ruptured by Chiltipin Creek near Copano Bay, Texas, spilling 460 m³ of South Texas light crude oil into a salt marsh. Vacuum trucks, skimmer, pumps and sorbents were brought to the scene but proved to be only marginally effective. After considering various options, a decision was made to burn the oil. The oil was ignited four days after it spilled, and burned for 20 hours in various areas. The area was surveyed, and pockets of remaining oil were ignited later. At the time of the burn the marsh was covered with water from recent heavy rainfall, providing protection to plant roots and rhizomes. A study to monitor marsh plant recovery over a period of five years suggested that plant diversity in the impacted area was reduced, but that total plant biomass was similar to the control area after two growth seasons.

Rockefeller Refuge⁴⁶⁻⁴⁹

On March 13, 1995, approximately 6 m³ of condensate oil spilled from a pipeline in the Rockefeller Refuge, Louisiana, affecting 20 ha of brackish marsh. Mechanical cleanup equipment was brought on scene, but was both ineffective at collecting the oil and damaging to the marsh. In-situ burning of marshes is commonly used in that area to reduce organic debris, reduce unwanted fires, and enhance marsh growth. At the time of the spill the water layer over the marsh soil was 5 to 10 cm thick. In-situ burning of the oiled marsh was approved and conducted four days after the burn, removing the oil from 8 ha. of the impacted marsh. Studies conducted three years later concluded that the areas impacted and burned recovered better than the areas impacted but not burned. Three years after the burn, the burned areas attained the same plant density as the reference area.

Ruffy Brook^{49,50}

On July 22, 2000 a transfer pipeline near Ruffy Brook, Minnesota, failed and released over 8 m³ of medium Bow River crude oil into a marsh fed by Ruffy Brook. The spill affected approximately 3 acres of fresh water marsh, that was covered by water up to 30 to 100 cm above the marsh soil surface. Mechanical recovery was deemed difficult to deploy and potentially damaging to the marsh, so in-situ burning was conducted the same day of the spill. The burn lasted for three hours, and remaining pockets of oil were ignited over a period of three days. No secondary burning occurred during this operation. It is estimated that 80% of the oil was consumed during the burn. A significant amount of burn residue (in some places 1 cm thick) was left after the fire went out. The residue was picked up by hand three days later. There is no evidence that any residue sank. The marsh was visited a year later, and found to have recovered well, with the exception of willows, a fire sensitive species. The quick response prevented spreading of the oil and thereby minimizing damage to the marsh.

Bayou Tank Battery⁵¹

On August 17, 2002, a spill occurred at a tank battery in the Sabine National Wildlife Refuge in Southwestern Louisiana. The spill of 24 to 50 m³ crude oil ran into the adjacent marsh. Salt water spilled together with the oil, spread the oil over about 1.5 Ha of dense marsh. A burn was started on the first day. A survey indicated that most of the oil had been successfully removed from the marsh. The removal of the residue, however, proved to be difficult and took several days to accomplish using sorbents and nets. Soil samples were taken in unaffected and burn areas to assess them for metal content. Analysis of the soil samples for cadmium, chromium, copper, lead, manganese, nickel, vanadium and zinc

showed that the metal contents were relatively the same in the area under the burn and nearby. This indicated that burning, at least in this particular case, did not increase the soil metal content for those metals noted. The burn did show, however, that removal of residue is difficult and requires significant time.

Diesel Spill in Wetlands and Salt Flats, Northern Utah, ⁵²

On 21 January 2000, a release of an estimated 16 m³ of diesel occurred from a product transportation pipeline north of Great Salt Lake in Utah. Because of weather (freeze/thaw periods and wind), the product spread over 15 Ha of salt flat and wetlands during the next few days. Initial oil containment efforts were successful in reducing the risk of oil impacts in a nearby national migratory bird refuge. However, the risk remained to migratory waterfowl that were expected to arrive at the impacted wetland within approximately 6 weeks. As a result, in situ burning was proposed to remove the free-phase diesel and destroy the oiled vegetation. Upon approval of a site remediation plan and fire management plan, a Heli-Torch was used on 10 March, 2000 to initiate a burn of the most-highly impacted 5 Ha. The following month (late-April), 1.3 Ha of remaining lightly oiled vegetation were burned using drip torches and propane wands for ignition. It was estimated that 75-80% of the spilled diesel was burned in these operations. Because burning of the oil and impacted vegetation would not remove Diesel that had penetrated into the soils, bioremediation techniques were subsequently implemented to further reduce hydrocarbon levels in the soil and attain the regulatory cleanup target of 20 mg/kg total polycyclic aromatic hydrocarbons.

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20. Marshes II

Several marsh burns have been conducted around the world. These burns were largely successful and provided important information on protecting the marsh plants and the best time of year to burn. The roots of marsh plants, which also house the propagation portion of the plants, are sensitive to heat. If burning is conducted at a dry time of year, such as in late summer, these roots could be killed.⁵³ 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. 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.

Some cases of burning in marshes are given below:

Mosquito Bay ⁵⁴

On April 5, 2001, 160 m³ of condensate spilled in Mosquito Bay, Louisiana in a remote coastal marsh. The oil spill resulted from the failure of a 20-inch pipeline. The spill oiled a total of 15 Ha with heavy oil covering approximately 5 ha. The environmental conditions of the brackish tidal marsh included *Distichlis spicata* (salt grass), *Spartina alterniflora* (cord grass), and *Spartina Patters* (wire grass). The oil penetrated burrows and root cavities during the low tide. Pre-burn surveys and photo documentation were conducted. The oil was burned on April 12 and 13, approximately 7-8 days after the spill occurred. Varying daily wind speeds and tidal changes played an important role in this burn. After the burn, > 40 ha. were burned which was nearly 3 times the oiled area. Burning was effective in removing surface oil, but not subsurface oil. Vegetation died in areas of heavy oiling, but recovery occurred in light and unoiled areas. A photo of the burn is shown in Figure 21.

Tank Spill Resulting from a Hurricane ⁵⁵⁻⁵⁷

On August 29, 2005, Hurricane Katrina made landfall near Buras, Louisiana and caused an oil storage tank to rupture, spilling about 600 m³ of Louisiana Sweet Crude. Most of the oil migrated to the retention pond at the facility. During Hurricane Rita (September 24), approximately 16 to 40 m³ of oil were released into the adjacent marsh environment. A portion of the marsh was heavily oiled or moderately oiled (ca. 2 Ha and 6 ha., respectively). A total of 15.5 Ha of marsh were covered by the oil. On October 12 to 13, a burn was initiated and covered 7.9 Ha of the marsh. Test plots were sampled 9 months and one year after the burn. Re-growth from heavily and moderately-oiled plots (28 plots) were compared to two non-oiled and non-burned or reference plots. The plots were monitored for aboveground biomass, plant height and stem density. Total aboveground biomass, live biomass and dead biomass in the oil and burned zones were not significantly different than those in the reference areas after one year. Stem heights also showed recovery within one year and the number of stems of the dominant plant, *Scirpus*, in the oil and burned areas was equal to, or greater than, that in the reference areas. Complete recovery of the aboveground vegetation occurred within one year after the burn.

One of the concerns is that burns will affect the environment on a long-term basis. Otitolaju and co-workers studied a mangrove system that was affected both by a spill and a subsequent burn.⁵⁸ The refined petroleum and fire resulted in a decrease in biodiversity from about 0.8 to about 0.2. About 2 ½ to 3 months later, there were signs of recovery along with a decrease in hydrocarbon levels from about 3.7 mg/kg to 0.42 mg/kg. The recovery coincided with the loss of hydrocarbons.

Lindau and Delaune carried out field studies on the sensitivity of *Sagittaria lancifolia*, a common marsh plant, to in-situ burning of crude oil.⁵⁹ Plots (24) were constructed in a fresh marsh and schemes of control and treatments set up. Burning was carried out 3 days after oil application and at a flooding stage of 15 to 25 cm of water. Live stem count and carbon fixation were measured up to 52 weeks after the oil application. It was found that the oil application and burning had only a short-term effect on the *Sagittaria*. After 5 to 6 weeks after the burn, most indications were that the *Sagittaria* had returned to before oil and burn conditions.

The tests also showed that leaving the oil to naturally degrade may also be an option as plant recovery in the unburnt section was similar to the burnt section. The recovery in the burned section may be more rapid.

Mendlessohn and co-workers carried out a series of experiments to determine optimum water depth for burning on marsh plants.⁶⁰⁻⁶³ Three marsh types were collected, a *Spartina alterniflora* dominated marsh, a *Spartina patens* and *Distichlis spicata* co-dominated brackish marsh and a *Sagittaria lancifolia* dominated marsh. The sods were placed in metal buckets and instrumented with thermocouples. Various control and treatment procedures were applied. After burns, the vessels were returned to a greenhouse where recovery was evaluated. It was found that water depth was a key factor in the recovery of the marsh plants. When the water depth was 2 to 10 cm, the soil temperature did not exceed 40°C and there was little vegetative damage. In those test vessels where the water table was 2 cm below the soil surface there was significant vegetative damage and the soil temperatures rose to 80 to 100°C. There were different effects on the different species. *Spartina patens* and *Distichlis spicata* were less affected by these higher temperatures. The in-situ burned removed about 99% of the oil from the water or soil surfaces



Figure 21 A salt marsh burn in Mosquito Bay, Louisiana.

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21. Ignition devices I

A variety of ignition devices or methods, both commercial and non-commercial, have been used to ignite oil slicks, although the methods of igniting oil on water have not been well documented.^{1,64} Many of the methods used were modifications of ignition devices used for other purposes.

In general, an ignition device must meet two basic criteria in order to be effective. It must be safe to use and it must apply sufficient heat to produce enough oil vapors to ignite the oil. The main factor is that 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. For heavy oils, a primer, preferably diesel fuel or kerosene is used to soak in the oil for a few seconds before applying an igniter. For many oils the igniter must also transmit the heat to a low spot in the oil. Much of the heat will rise, and thus will not necessarily ignite oils without a significant vapor emission.

Commonly-available devices, such as propane and butane torches, have been used in the past to ignite oil slicks. They are more effective on thick slicks, however, as torches tend to blow the oil away from the flame on thin slicks, thus hampering ignition. Weed burners 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 devices or methods available for igniting oil slicks and the operational procedures for their use are summarized below.

Hand-Held ignition devices

Simple ignition methods such as oil-soaked paper, rags, or sorbent have been used to ignite oil at actual and test spills.⁶⁴ For example, gelled fuel in a plastic bag was used to ignite some of the oil from the *Exxon Valdez* spill.¹ 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.

As noted earlier, ignition of heavier oils is best carried out using a primer such as diesel fuel and kerosene, and a small wick such as a piece of cardboard or sorbent.¹ This enables a start similar to lighting a candle. The flames will then spread to the un-primed oil nearby. In large scale heavy oil ignition might be accomplished by applying a bit of primer and then using the helitorch. Use of a gelled fuel igniter was found inadequate to directly ignite heavy fuels without the use of a primer.¹

A variety of hand-held igniters have been devised for igniting oil slicks.^{1,64} 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.⁶⁴

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.¹ 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.

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 Environment Canada.¹ Several configurations of the igniter were built, some intended for deployment on pools of shallow water on ice. It was manufactured by Astra Pyrotechnics, Ltd. (formerly ABA Chemical Ltd.) of Guelph, Ontario, but is no longer in production. The advantage of this type of igniter is that it was built by a licensed pyrotechnic company using approved components and was licensed to be transported by truck or air freight. The DREV igniter was 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 had a 4-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 conjunction with Energetex Engineering.¹ This igniter was intended to be manufactured on site. A wire-mesh fuel basket, which contained a solid propellant and gelled kerosene, was surrounded by two metal floats. An electric ignition system activated a fuse wire allowing about a 45-second delay. The fuse then ignited a thermal igniter wire, which ignited the solid propellant, and finally ignited 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.

Another technique for igniting in-situ oil fires is the use of lasers. In the 1980s, various laser techniques were tested for igniting a variety of types of oil at different temperatures.¹ The most successful technique in laboratory tests was to use a continuous-wave CO₂ laser to heat a localized area of the oil slick. The laser heated the oil to a temperature above its fire point. The heating time varied 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 were 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 was used to aim this second laser. Despite the success of this research, this device was not made operational due to lack of funding.

A hand-held igniter was used during in-situ burning tests in 1996 off the shores of Great Britain.¹ This igniter consists of a 1-L Nalgene bottle filled with gelled gasoline or diesel fuel. The gel was made by mixing 1 L of gasoline with 0.01 kg of SureFire fuel gelling agent. 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.

A similar device was used to ignite the burns at the Deepwater Horizon spill. Gelled diesel fuel was used in this set of burns. Such a device, which is relatively easy to make and to deploy, is shown in Figure 22.



Figure 22 Operator activating an ignition device during the Deepwater Horizon spill. The device consisted of a bottle of gelled diesel fuel and a marine flare. The marine flare melts the bottle and lights the diesel fuel which acts both as primer and burn initiator.

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22. Ignition Devices II

A variety of ignition devices or methods, both commercial and non-commercial, have been used to ignite oil slicks, although the methods of igniting oil on water have not been well documented.^{1,64} Many of the methods used were modifications of ignition devices used for other purposes.

In general, an ignition device must meet two basic criteria in order to be effective. It must be safe to use and it must apply sufficient heat to produce enough oil vapors to ignite the oil. The main factor is that 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. For heavy oils, a primer, preferably diesel fuel or kerosene is used to soak in the oil for a few seconds before applying an igniter. For many oils the igniter must also transmit the heat as low as possible to the oil layer. Much of the heat will rise, and thus will not necessarily ignite oils without a significant vapor emission.

Helicopter-mounted devices

Useful, commercial devices used today for igniting oil slicks are the helicopter-mounted 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.^{1,64} This type of igniter was designed for the forestry industry and is used extensively for forest fire management. Two helicopter-based systems suitable for igniting in-situ burns are the Simplex Heli-torch manufactured by Simplex Manufacturing of Portland, Oregon and the Universal Drip Torch available from Canadian Helicopters (DNZ Group) in many locations across Canada. The Simplex Helitorch was used during the NOBE in-situ burn exercise off the coast of Newfoundland in 1993.¹ Simplex information can be found at <http://www.simplex.aero/slung/>.

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 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 separated from the helipads and helicopter refueling areas.

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 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. Figure 23 shows a HeliTorch being discharged of excess fuel before the helicopter returned to base. 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.

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.



Figure 23 A helicopter discharges remaining fuel from a Helitorch after successful ignition of an oil burn as shown behind the unit.

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23. Fire-resistant booms – Historical

As discussed in previous episodes, an oil slick should be at least 0.5 to 3 mm thick in order to quantitatively remove significant amounts of oil. It is not fruitful to burn thin slicks. 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.

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 cost considerably more than conventional booms. These booms were tested for fire resistance and for containment capability and designs are modified in response to test results.

The fire resistance of these booms had 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 24.

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.¹ In the early 1980s, Dome Petroleum Ltd. further modified the stainless steel boom. 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. The first documented use of a fire-resistant boom for burning at a major oil spill is the use of the Fire Boom at the Exxon Valdez spill.¹ This Elastec/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 metre-long flotation logs. This was caused by the use of small sections of steel wire mesh rather than using full sheets during manufacture. During the 411 burns at the Deepwater Horizon spill in the Gulf of Mexico, a variety of fire-resistant booms were used, however mostly the Hydro Fire Boom and the Pyroboom.

A standard has been devised by ASTM to test the durability of fire-resistant booms for in-situ burning.⁶⁵ The standard is

a minimum 5-hour test involving three 1-hour burning periods with two 1-hour cool-down periods between the burning periods. Booms are tested in a test tank with oil or diesel fuel. Oil is pumped into the center of the boom at a predetermined rate and is burned. The oil is continuously fed into the boom for 1 hour and then is shut off allowing the burn to die out. The boom then cools for 1 hour and is tested for two additional 1-hour burn/1-hour cooling sessions. At the start of the third burn, oil is pumped into the boom to test for gross leakage. Several booms were tested in this manner. An analogous test was developed using propane and conducted at the OHMSETT test facility.⁶⁶

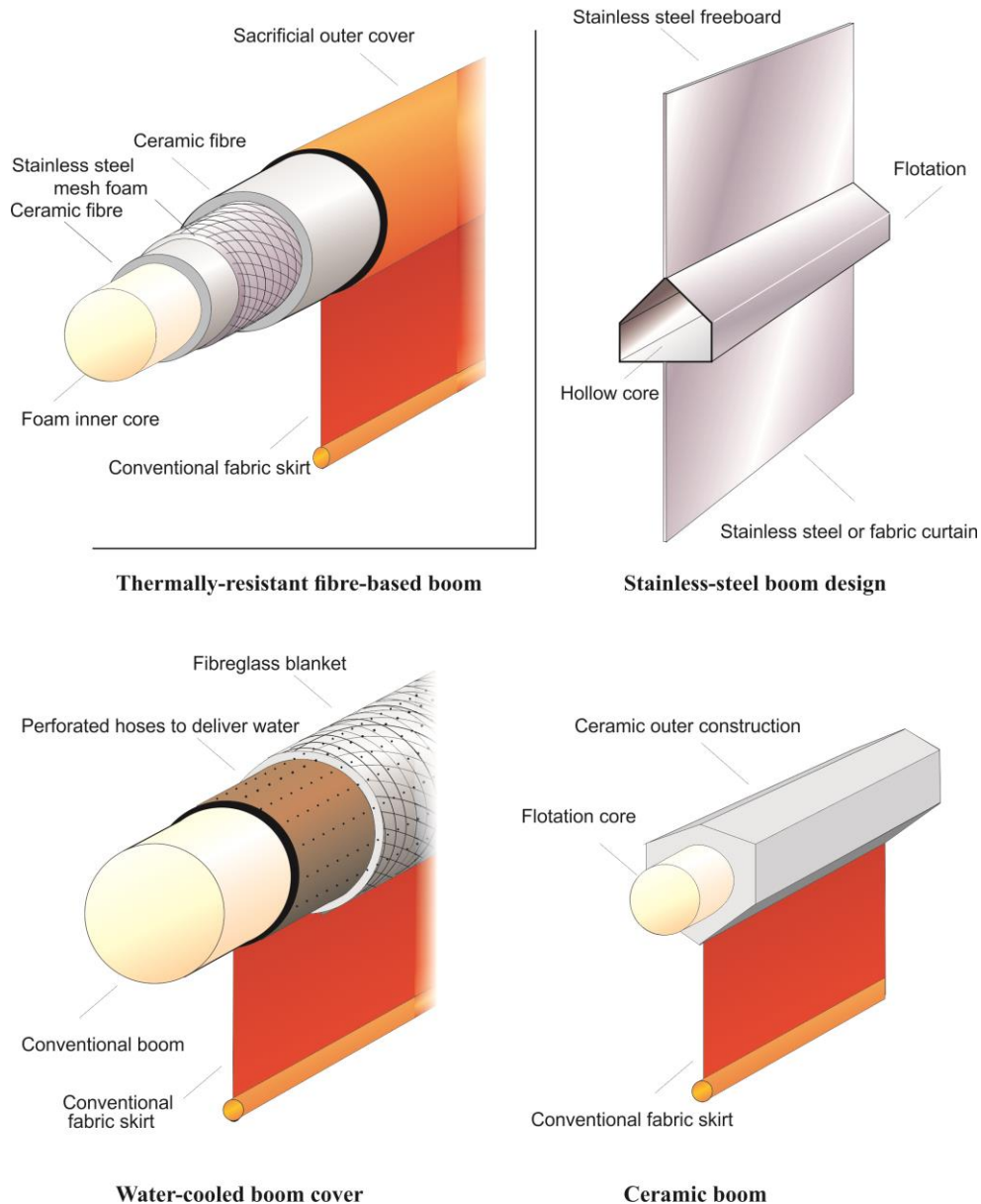
In 1994, the Marine Spill Response Corporation (MSRC) conducted at-sea towing tests of four fire-resistant booms: the American Marine (3M) Fire Boom, the Applied Fabrics PyroBoom, the Kepner Plastics SeaCurtain FireGard and the Oil Stop Auto Boom Fire Model.¹ The purpose of these tests was to evaluate 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 the fire-resistant booms currently on the market in a test tank and compared these results with previous at-sea performance results.⁶⁷ These studies determined the tow speeds at which the booms first began to lose oil ("first loss") and the speed at which a continuous, significant loss occurs ("gross loss"). It also determined the rate of loss of oil at specific tow speeds and the tow speed at which the boom physically failed, i.e., became submerged or suffered structural damage. The following are the conclusions of these tests.

- In terms of oil containment, the performance of the fire-resistant booms was similar to conventional, 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).
- 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.



Thermally-resistant fibre-based boom

Stainless-steel boom design

Water-cooled boom cover

Ceramic boom

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24. Fire-resistant booms – Commercial Products

The following is a brief description of the fire-resistant booms currently on the market. Detailed specifications for these booms can be found on the manufacturer's web sites.

American Fire Boom (<http://www.elastec.com/oilspill/fireboom/americanfireboom/index.php>) (American Marine/Elastec) 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. This boom was originally made many years ago and now has been brought back again.

The **Hydro-Fire Boom** (<http://www.elastec.com/oilspill/fireboom/index.php>) (American Marine/Elastec) 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).

PyroBoom (<http://www.appliedfabric.com/content/pages/pyroboom.php>) (Applied Fabric Technologies) 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 can be stored in a container and deployed from a large flat area or can be deployed from a reel system, which in turn is stored in a container.

PocketBoom (<http://www.appliedfabric.com/content/pages/pocketboom.php>) (Applied Fabric Technologies) is a stainless steel boom that is similar to the design of the Dome Boom but in a small version.

Spill-Tain Fire Proof Boom (<http://www.spill-tain.com/>) 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.

The booms and their testing/use in burning are illustrated in Figures 25 to 27.



Figure 25 Testing of a fire boom at the USCG Mobile Alabama facility. The testing was done using the ASTM protocol.



Figure 26 Use of the PyroBoom during the Deepwater Horizon .



Figure 27 Use of the Hydro-Fire Boom during the Deepwater Horizon burns.

25. Fire-resistant booms – 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.¹ Most commercial booms come in standard lengths of 15 or 30 m. The overall height of the boom should be equal to the maximum expected wave height (short period waves, not swell) from peak to trough.

An important factor when containing oil is the direction and speed at which the boom is being towed. The distance from the burn to the tow vessels should be far enough that the burn does not pose any danger to the tow vessel or personnel onboard the vessel. Temperature profile tests performed during trials showed that the air and water temperature ahead of the burn levels off very quickly.¹ 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 tow lines.

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.¹ 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 burning oil that splashes over the boom.

Another important factor in ensuring that the oil is properly contained for burning is the configuration of the boom. Booms can be towed in various configurations, depending on the equipment available and the weather and sea state conditions. The various conventional configurations for towing oil spill booms are shown in Figure 28.

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 28 (a). This was the configuration used during the Deepwater Horizon burns. As an alternative, a tether line or cross bridle may be secured to each side of the boom several metres behind the towing vessels to ensure that the boom maintains the proper U shape, as shown in Figure 28 (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 28C. 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 28 (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.

Bitting and co-workers tested a number of these configurations and found that many of the proposed configurations in this sub-section were viable.⁶⁸

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 28 (e). Diversion booms must be positioned at an angle relative to the current that is large enough to divert the oil, but not too large that the current would cause the boom to fail. The boom must be held in place either by anchors, towing vessels, or lines secured to the shoreline.

In nearshore situations, anchors can be used to secure booms in a stationary position. It is important, however, that a proper anchor is used particularly in high currents, to ensure that the boom will stay in place for the duration of the burn. Various types of anchors suitable for anchoring containment booms are available.¹

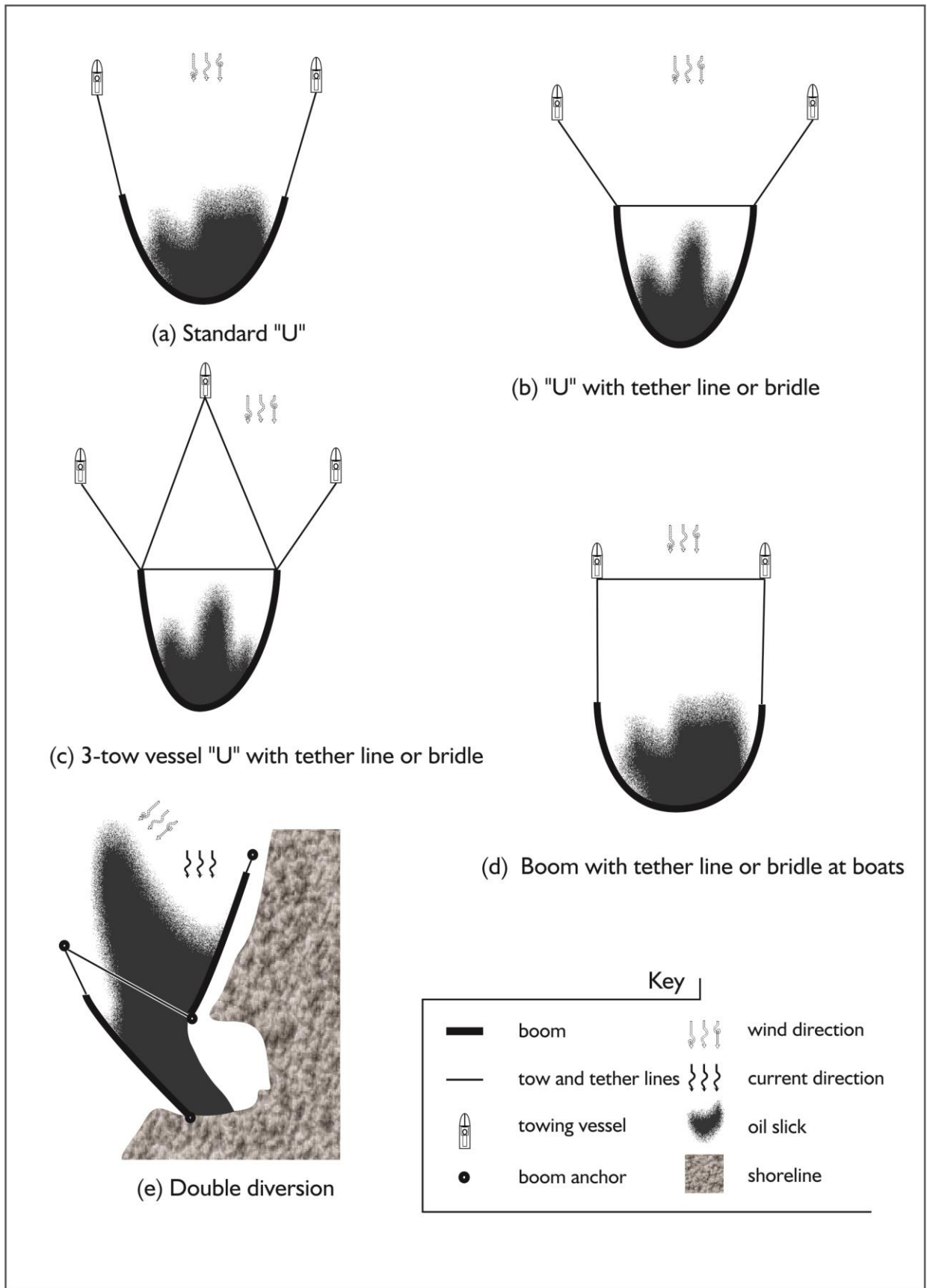


Figure 28 Possible tow configurations for fire-resistant booms

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26. Calculating the Efficiency and the Amount of Oil Burned in a Boom 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:

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

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 overflights, aerial photographs, or remote sensing devices. This area together with an estimate of the average thickness of the oil, performed either visually or by taking samples, 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.

If some of the residue sinks, which is infrequent, 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 1 to 4 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 is not affected by the oil properties, but depends primarily on the thickness of the slick and oil type. Regardless of the initial thickness of the oil, the final thickness will be in the order of 1 to 2 mm. As such, a 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.

Calculating Amount of Oil Burned

You need the burn area and time of burn (or time for each area, if the burn area varies), given the rate of burning, you can simply calculate the amount burned. The amount of oil burned:

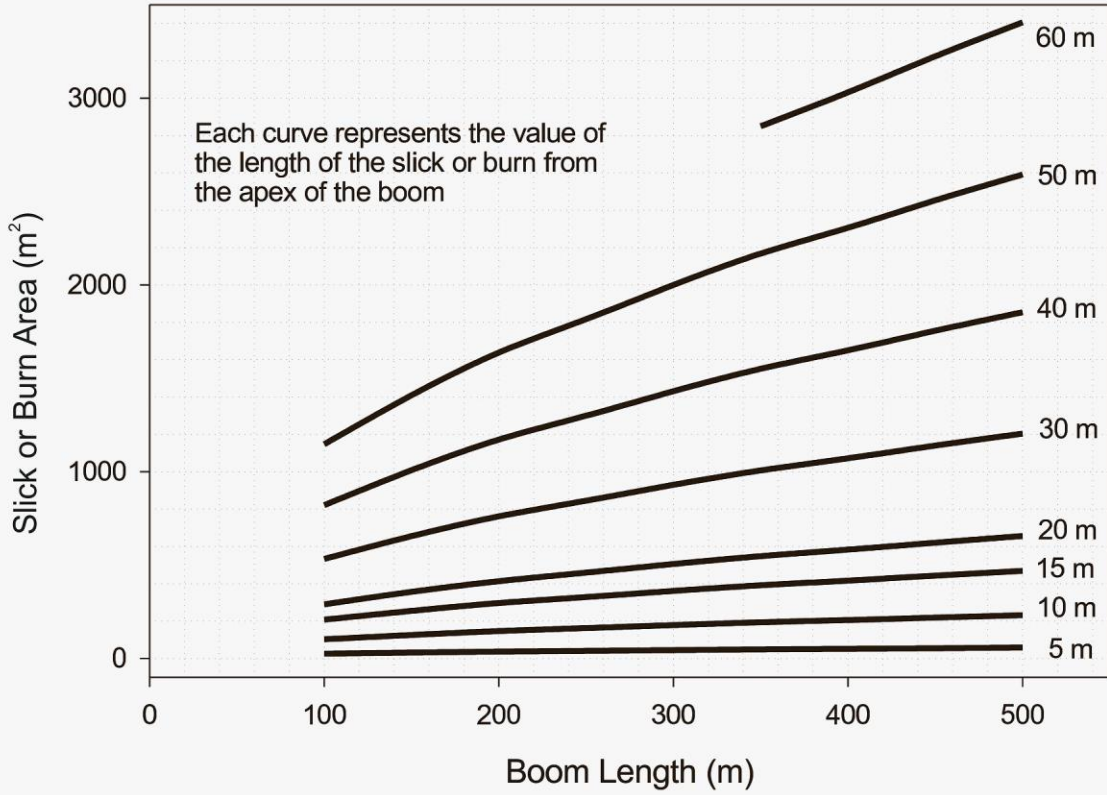
$$\text{Oil Burned} = \text{Area of burn} \times \text{time} \times \text{burn rate}$$

To practically measure the burn amount at sea follow the following process:

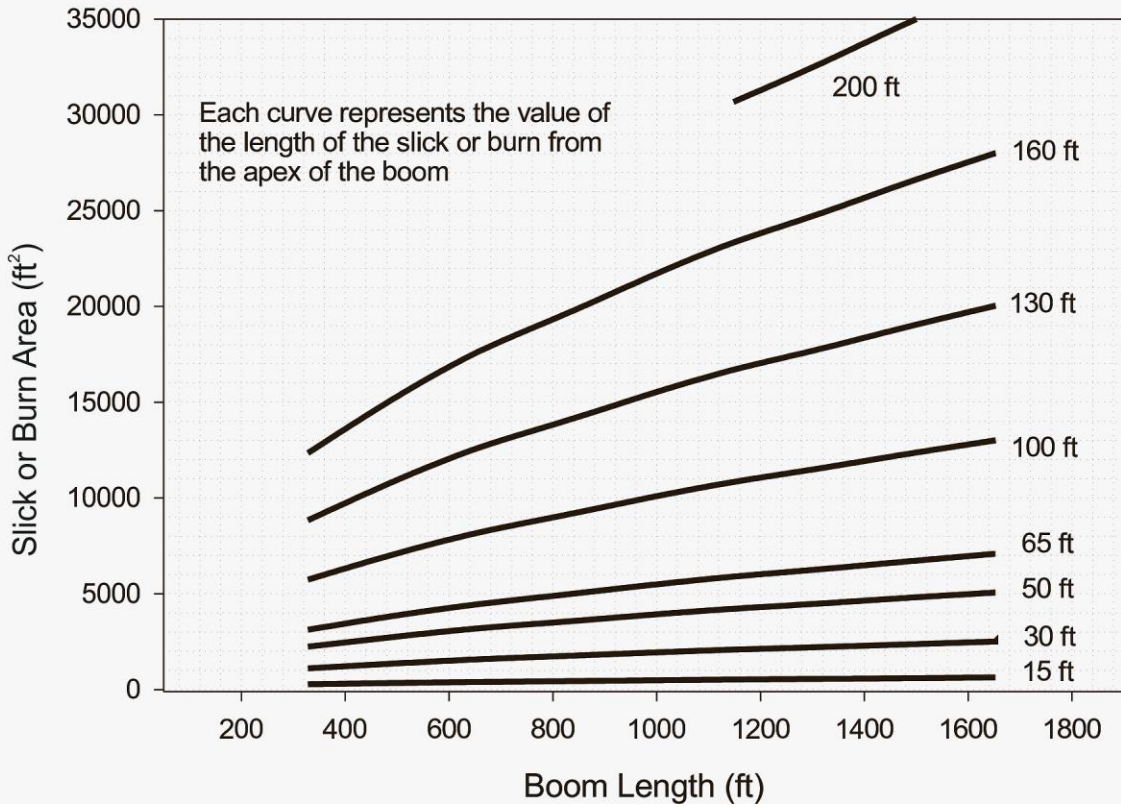
1. Record the times and the distances from the back of the boom during the burn, these will be used to calculate burn areas (may have to do at convenient time intervals if the burn area varies, which is usual),
2. Calculate the burn areas from the nomogram below (Figure 29)
3. Multiply the burn areas times the burn rates (Table 7)
4. Convert the burn rates if necessary (Figure 30)
5. Sum the amounts burned
6. Subtract the residue amount (may need to estimate).

To calculate the amount burned on land or other places where the oil is not contained, measure or estimate the area of burning as best as can be done and then use the same procedures as above.

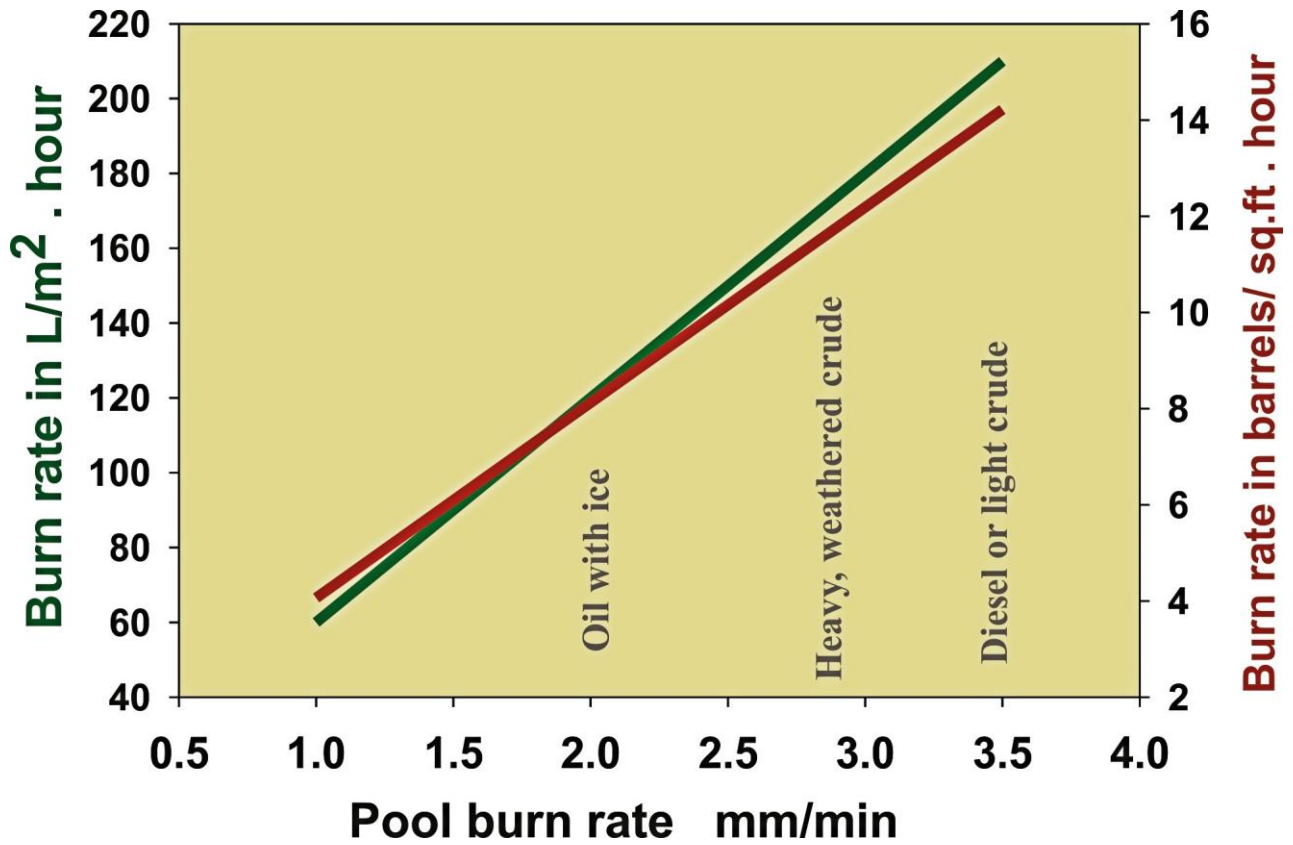
Metres



Feet



Above - Figure 29 Nomogram used to calculate burn area.



Above - Figure 30 Nomogram used to convert burn rates.

Table 7 Burn rates for various oils

Oil type	Burning Rate, (mm/min)
Gasoline	4
Diesel Fuel	3.5
Light Crude	3.5
Medium Crude	3.5
Heavy Crude	3
Weathered Crude	2.8
Crude oil with ice	2
Light Fuel Oil	2.5
Heavy Fuel Oil	2.2
Lube Oil	2
Waste Oil	1 to 2
Emulsified Oil	1 to 2

27. Burning without containment

Controlled burning of uncontained slicks is sometimes possible if the slick is thick enough to burn quantitatively 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 at the point where the oil is thickest.

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 on the sea, to prevent the fire from spreading to the source. The safest and quickest option is to move the source away from the slick. 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. Figures 31 to 33 show accidental and uncontained burns. While it is not known what conditions are best for burning uncontained oil, emulsified oil may retard the spreading of uncontained oil while it burns. In a large burn, large volumes of air are drawn into the fire, which is referred to as a "fire storm". This may provide enough force to prevent the oil from spreading.

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

In summary uncontained oil may be thick enough to burn quantitatively when:

- 1 The oil is freshly discharged, however the source of the discharge could be engulfed in fire,
- 2 The oil is very viscous and has not spread widely or has been herded together by natural forces,
- 3 The oil is very viscous because it is highly weathered and again as above, not widely spread,
- 4 The oil becomes viscous because it became emulsified,
- 5 The oil was been collected by natural phenomena such as oceanic or river fronts or Langmuir circulations, or
- 6 Possibly, that once started the air flow caused by the burn may provide a herding effect.



Figure 31 Oil burning on the water without containment from a tanker which is obscured by smoke.



Figure 32A ship on fire, note that the oil is burning on the water without containment.

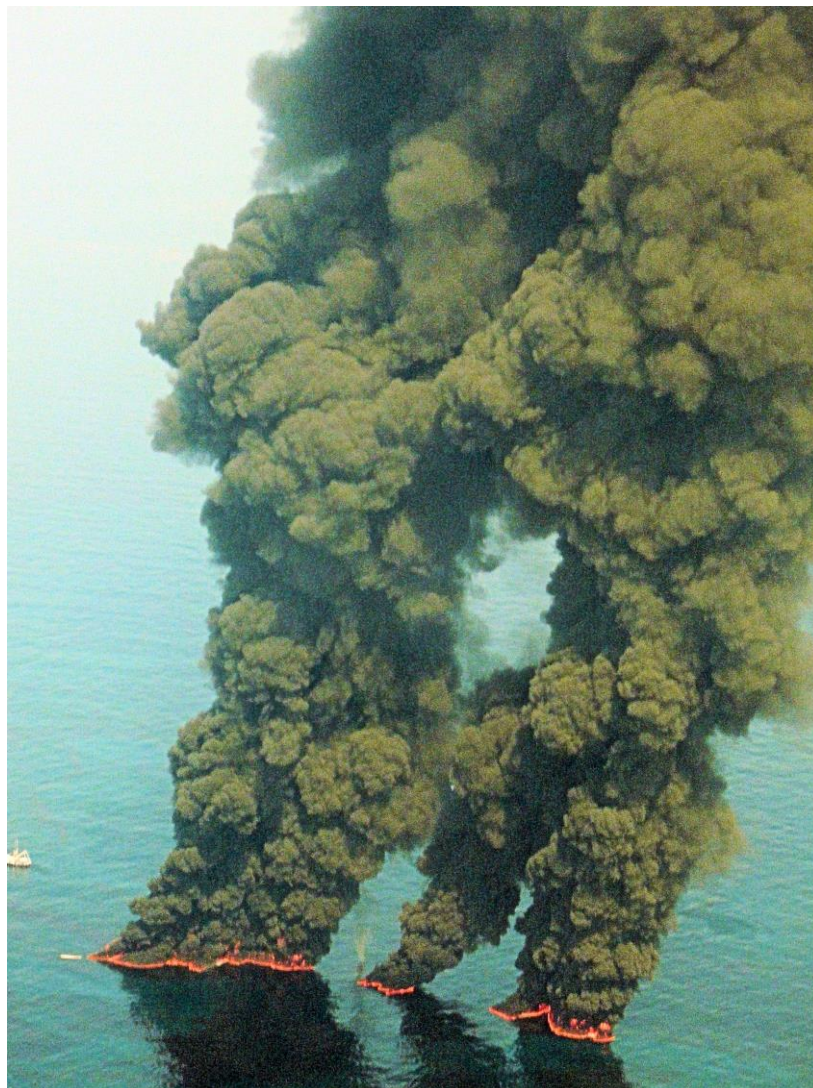


Figure 33 Burning during the Deepwater Horizon spill. The burn to the left is contained however, the two burns to the right are not contained and burn quantitatively.

28. Burning on Land and on Ice

Burning on land



Figure 34 Burning of a fuel oil spill in a drainage ditch. This is a frequently-used technique to deal with such spillage.

Burning on land is a much older and much more used technique than oil in-situ burning on water.^{1, 69} Many of the same considerations in this section, apply to land as might apply to burning on water. There are several important differences to consider, however. First, the ease of ignition and minimum burning thickness may not apply if there is combustible material such as dried grass available. Burning in cases where there is dried vegetative material or wood in the target area, is simply a matter of igniting that material. Both the dried vegetative material and oil will burn, depending on the circumstances. It should be

borne in mind that burning is often used on land to remove combustible material as a fire prevention method as well as to control certain plant species. The effects on land are a largely a function of how much heat is transferred into the soil which is also a function of how quickly the fire passes over and soil moisture content. Figure 34 illustrates burning oil spills near land.

One of the concerns of burning on land is the effects of fire on the soil structure. One such study on the effects of both a spill and the subsequent burn on the physical properties of the soil.⁷⁰ A crude oil spill occurred in Nigeria and a fire subsequently consumed most of the surface oil. The soil was sample to depth of 5 m and several measurements taken: natural moisture content, grain size distribution, consistency (Atterberg) limits, California bearing ratio (CBR) and unconsolidated-undrained triaxial compression. The findings of this study showed that the crude oil spill and subsequent fire did not have a significant impact on the foregoing soil properties. Further, very little crude oil was observed in the core samples, leading to the conclusion that the fire did not increase oil penetration or increase it significantly.

Overton and Miles conducted a series of tests in greenhouse pots with upland soil and common Bermuda grass.⁷¹ Six treatments including burning, phytoremediation and lime addition were evaluated in the pots. Soil samples were taken a number of times after treatment up to 300 days. Aromatic and aliphatic hydrocarbon content was measured in the soil samples. Data from the project suggested that there is no significant difference in aromatic and aliphatic hydrocarbon content between oil burning, non-burning and lime addition treatments.

Burning in or on ice

Figure 35 Burning oil in a lead at sea after behavior tests.

Many test burns have been conducted on or among ice floes. The ice serves as a natural barrier to the spreading of the oil. Much of the early burn work was carried out as a countermeasure for oil in ice.^{1, 72} There are hundreds of papers on oil-in-ice burning, many of these from 1974 to 1986. Figure 35 show a burn carried out in a lead in pack ice.

More recently, a group carried out an experiment of oil under and in ice near Svalbard. The oil was allowed to surface, where it was ignited with gelled hexane.⁷³ The oil was Statfjord crude, 3400 litres, and once weathered 27%, was 2480 L. The thickness was calculated to be 35 mm and covered an area of 69 m². The burn endured for 11 minutes and the 1 mm of residue yield 106 L of 0.95 g/mL density. This burn reduced the volume by 96% and the burn rate was 3.1 mm/min.



Majors and McAdams report on the burning of a small spill on the tundra in Alaska. The burn did not remove the bulk of the oil due to the low thickness of the oil.⁷⁴

Brandvik and Faksness carried out meso-scale experiments on oil in ice and developed a scheme for the burnability of oil-on-ice dependent on water content.⁷⁵

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29. Monitoring, Sampling, and Particulate Matter

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. Monitoring of PM-2.5 particulate matter in the smoke at ground level is a very necessary part of in-situ burning.

The following sampling and monitoring should be performed for any in-situ burn operation as an optional task:

- real-time monitoring of volatile organic compound (VOCs) in the smoke again at ground level
- 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.

Real-time Monitoring of PM 2.5 at Ground Level

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 2.5 μm or less (PM-2.5) should be less than 35 $\mu\text{g}/\text{m}^3$. This is the standard set out by several national authorities including the National Institute of Occupational Health and Safety (NIOSH) and described in the U.S. Code of Federal Regulations. Similar regulations exist in other countries.



Figure 36 A photograph of a cluster of real-time particulate measuring devices at a burn test site.

The devices currently used to carry out real-time monitoring of particulates are the DustTrak, and DataRAM aerosol monitors, which are capable of detecting the PM-2.5 particulates emitted by a burn. Figure 36 shows a cluster of particle-measuring instruments, these are mostly DataRAMs. 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 the some instruments

measures 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. Newer models can correct for humidity. The instrument readings should be electronically recorded and averages calculated from the recorded and corrected data..

Visual monitoring

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

30. Monitoring and Sampling

In the last episode we discussed real time monitoring of particulate matter resulting from burns. In this episode we cover conventional sampling and analysis methods.

Sampling Particulates Using Filters

Figure 37 (below): A sampling station at a burn experiment. The large devices to the right are high volume air samplers.



Particulate levels from a burn can be most accurately determined by collecting a representative sample on a quartz fibre filter using a high-volume sampling pump.^{1,76} The accumulation of particulate on the filter can be measured by differential weighing. The concentration can be calculated by dividing the weight collected by the volume of air. An added advantage of this particulate sampling method is that, after weighing, the collected particulates can be analyzed for polyaromatic hydrocarbon (PAH) compounds by gas chromatography, following a solvent extraction procedure. Other burn products of interest, such as metals, could also be analyzed.

A high-volume sampler (greater than 200 L/minute capability) is necessary for collecting particulate at a burn site in order to collect enough sample. The flow must be measured in order to calculate the concentration. The flow will decrease as the filter is loaded. For this reason, a flow rate must be recorded at both the initiation and conclusion of sampling, while the filter is in place. The flow rate is usually determined as a function of the back pressure created by the pump, although it is sometimes measured by an in-line mass flow meter.

All high-volume samplers operate on AC power due to the current required to run the pump. The unit will either have a power switch or be controlled by AC supply. There is generally a voltage regulator that can be adjusted externally. The frame for the conventional quartz fibre filter is designed to hold either a 4" diameter filter circle or an 8" x 10" filter sheet. In most cases, the total suspended particulate (TSP) fraction is being collected, for which a filter with 0.8 micron (μ) pore size is used. The collected sample can be used to determine particulate levels by differential weighing and/or can be analyzed for various burn products, usually PAHs.

VOC Sampling Using Summa Canisters

The Summa canister is one method used to collect a metered amount of whole air for laboratory analysis.¹ Air is collected in these evacuated, stainless steel canisters to be analyzed for volatile organic compounds (VOCs). In conventional high volume sampling methods, the VOCs are lost either during sampling or in transit. By contrast, the Summa canister method ensures that most of the VOCs are captured and remain stable between the sample collection on-site and the subsequent laboratory analysis. The amount of VOCs found in air samples collected close to oil burns varies, depends on several factors including fuel composition and distance from the burn.

The Summa canister is a spherical, polished stainless steel container with a single manually controlled valve. The canister must be cleaned and evacuated by an accredited laboratory before use. A pre-cleaned and pre-calibrated flow restrictor valve is affixed in order to meter the flow into the canister. No restrictor valve is necessary to collect an instantaneous grab sample. These canisters are most commonly available in sample volumes of 6 L, although 1 L and 20 L sizes, as well as less common sizes, are also available.

Both the extraction and VOC analysis of the contents of the Summa canisters should be performed by an accredited laboratory. The canister must then be cleaned and re-evacuated before it is used to collect more samples.

The main limitation of Summa canisters is that the analysis of the canisters must be done off-site so there is no on-site indication of the quality of the sample collected.

Combustion Gas Measurement

Combustion gases of concern include carbon dioxide, carbon monoxide, sulphur dioxide and nitrogen oxides.

Carbon Dioxide - Carbon dioxide is the end result of combustion and is found in increased concentrations around a burn.⁷⁷ Normal atmospheric levels are about 300 ppm and levels near a burn can be around 500 ppm, which presents no danger to humans. Carbon dioxide can be measured in a number of ways, real time instruments generally measure it using an infrared technique, discrete samples can be taken and quantified by gas chromatography and infrared open-path instruments can provide real-time measurement.

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. Carbon monoxide appears to be distributed in the same way as carbon dioxide. Measurements of carbon monoxide can be done using similar techniques as for carbon dioxide.

Sulphur Dioxide - Sulphur dioxide, per se, is usually not detected at significant levels or sometimes not even at measurable levels in the area of an in-situ oil burn. Sulphuric acid, or sulphur dioxide that has reacted with water, is detected at fires and levels, although not of concern, appear to correspond to the sulphur content of the oil. Sulphuric acid aerosols can be measured by titrating caustic solutions through which the sample air was drawn (impinger method) or using a reactive tape instrument.

Monitoring PAHs on particulates

PAHs or Poly Aromatic Hydrocarbons are aromatic compounds found in crude oil and are often produced as a result of combustion.⁷⁸ Some PAHs are toxic to man and the environment, particularly the larger PAHs. Crude oil burns result in PAH downwind of the fire, but the concentration on the particulate matter is often an order-of-magnitude less than the concentration in the starting oil and sometimes several orders-of-magnitude less. Diesel contains low levels of PAHs with smaller molecular size, but results in more PAHs of larger molecular sizes after burning. Larger PAHs are either created or concentrated by the fire. Larger PAHs, some of which are not even detectable in the Diesel fuel, are found both in the soot and in the residue. The concentrations of these larger PAHs are low and often just above detection limits. Overall, studies have shown that more PAHs are destroyed by the fires than are created.

The analysis of target PAHs and other hydrocarbons is performed on a gas chromatograph by a qualified laboratory.

Carbonyls

Carbonyls such as aldehydes and ketones are created by oil fires, but do exceed health concern levels only very close to fires.⁷⁹ Monitoring for Carbonyls is conducted using a specialized sorption tube (DNPH) and sampling pump. Analysis is conducted in the laboratory.

The methods are detailed and require experienced laboratory personnel, but are not fraught with particular difficulties. Accuracies are ensured by the use of standards and internal standards. The condition of the sample tubes is important and sample tubes must be kept frozen before use.

The particular limitation that is noted is that the sensitivity of the method depends on the amount of soot collected and small samples often have insufficient material to allow proper detection of PAHs.

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31. Safety

Safety is the utmost concern in any burn operation. The hazards involved during burn operations, in perceived order of priority include:

- 1 Vapour cloud explosion or fire spread. If there is a volatile component present, the fire can spread at an extremely fast rate. Cases exist where a gasoline and crude oil mixture after being lit spread at about 200 km/hour. Care must be taken in lighting any spill that may potentially resulting in flame spread through the vapor cloud.
- 2 Spreading of the fire to other locations. The fire may spread to oil that is adjacent to the area desired to be burned, thus endangering human safety or property.

- 3 Flash back. The fire may flash back to the area of origin, thus threatening anyone involved there with the ignition.
- 4 Smoke impact on humans or the environment. The smoke may stay close to the ground and impact humans or the environment.
- 5 Loss of containment. If a fire-resistant boom should break and there was oil or other burnable material in the area, this could cause serious safety concerns.

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 existing publications and standards.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. If on the sea, 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. If on land, surveillance of the area around the burn, before, during and after the burn is essential.

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

Any potential difficulties in a burn operation, such as encountering thick burnable slicks that could burn out of control, should be anticipated and avoided. The fire could propagate ahead of the tow vessels or to combustible amenities. 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 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.

Figure 38 Heavily weathered oil is burned inside a fire-resistant boom during the Deepwater Horizon Spill. Another burn is far in the background.



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. Several tow control methods have been suggested to extinguish the fire within a towed fire-resistant boom. The first method is to release one end of the boom tow and let the oil spread until it is too thin to burn.¹ Secondly, if the tow speed is increased to greater than containment velocities (0.4 m/s or 0.8 knots), oil will submerge under the boom and the fire is often extinguished. Since this method has not been tested and may be hard to carry out, it is not suggested as the primary technique. Another suggested method is to slow down the towing rate thereby reducing the encounter rate.¹

It is recommended that fire extinguishing equipment be available during the burn. One dedicated fire extinguishing vessel should be positioned beside the boom containing the burn. During burn operations at sea, those who must be near the burn such as the tow-boat operators can be protected by ensuring that fire monitors of sufficient capacity are available. These monitors can be left on to ensure they are ready if needed. Extra fire monitors and experienced crews should be available on the surveillance vessel to assist if a fire spreads. The fire can also be extinguished by using a firefighting foam made for liquid fuel fires 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.

References

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32 Summary and Conclusions



Figure 39 A burn progresses at the Deepwater Horizon spill in 2010. (photo by Elastec / American Marine Inc.)

In-situ burning is the oldest technique applied to oil spills and is also one of the techniques that has been explored in depth. However, only recently has in-situ burning been used on a broad scale. Burning oil on water is not intuitive and thus many people did not pursue this course of action. Recently, the successful use of in-situ burning on the Deep Water Horizon spill in the Gulf of Mexico drew attention to the technique and left a positive image of burning. In-situ burning has been used to deal with land spills for many years. Of the few documented cases, most were successful and resulted in little environmental damage.

The major issues with in-situ burning, in perceived order of importance are:

1. Safety,
2. Emissions,
3. Practicality,
4. Issues over what will burn and not burn, and under what conditions, and

5. Desirability of the technique.

Safety - Although there are many safety issues, the greatest danger is with oils that still have a large volatile content. Ignition of a vapour cloud can be very dangerous. Techniques were presented on how to deal with these types of issues. Burning is a case where the more the oil is weathered, the better and the safer. Overall, the safety issues have been identified, and measures to minimize risk have been presented.

Emissions – Emissions have been studied in depth and it has been found that the more serious emissions are the particulate matter. Particulate matter precipitates and thus after certain distances, the particulate concentration falls under the level that causes a danger to man or wildlife. Only if the smoke plume does not rise, such as if there is an inversion, does the smoke plume become a concern past about ½ km.

Practicality – The application of in-situ burning is not obvious. Using towed booms and helicopter-borne ignition devices raises the practicality of the technique to a new level. In-situ burning techniques have been developed for many situations. In many cases, these in-situ burn methods have been tested as well. More countermeasures teams are now geared up and trained to apply in-situ burning.

What will burn and under what conditions – Basically, most oils will burn on water and will burn quantitatively if over about 2 to 4 mm thick. Light and fresh oils will burn readily and can be easily ignited. Heavy oils will require a small amount of primer, such as diesel fuel, to start ignition. Once burning, heavy oils will burn well and even emulsified oil will break down and burn. Too much emphasis in the past was placed on ignition techniques and oil type and thickness

Desirability – In-situ burning permanently removes a large percentage of the oil and does so at a large removal rate. There are trade-offs of course, one being the large smoke plume. But compared to some techniques, it is quantitative and effective. Certainly there are times and places where in-situ burning should not be used. Overall, it is a very effective and powerful tool in the oil spill countermeasures tool chest.

The following Table summarizes the oil types and factors of burning. It is noted that the heavier oils often burn with less soot than lighter oils:

Table 8 Burning Properties of Various Fuels

Fuel	Burnability	Ease of Ignition	Flame Spread	Burning Rate* (mm/min)	Sootiness of Flame	Efficiency Range (%)
Gasoline	very high	very easy	very rapid - through vapors	4	medium	95-99
Diesel Fuel	high	easy	moderate	3.5	very high	90-98
Light Crude	high	easy	moderate	3.5	high	85-98
Medium Crude	moderate	easy	moderate	3.5	medium	80-95
Heavy Crude	moderate	medium	moderate	3	medium	75-90
Weathered Crude	low	difficult, add primer	slow	2.5	low	50-90
Crude oil with ice	low	difficult, add primer	slow	2	medium	50-90
Heavy Fuel Oil	very low	difficult, add primer	slow	2	low	40-70
Waste Oil	very low	difficult, add primer	slow	1 to 2	medium	15-50

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