IPIECA

IOGP International Association of Oil & Gas Producers

Controlled in-situ burning of spilled oil

Good practice guidelines for incident management and emergency response personnel

IPIECA

The global oil and gas industry association for environmental and social issues

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Preface

This publication is part of the IPIECA-IOGP Good Practice Guide Series which summarizes current views on good practice for a range of oil spill preparedness and response topics. The series aims to help align industry practices and activities, inform stakeholders, and serve as a communication tool to promote awareness and education.

The series updates and replaces the well-established IPIECA 'Oil Spill Report Series' published between 1990 and 2008. It covers topics that are broadly applicable both to exploration and production, as well as shipping and transportation activities.

The revisions are being undertaken by the IOGP-IPIECA Oil Spill Response Joint Industry Project (JIP). The JIP was established in 2011 to implement learning opportunities in respect of oil spill preparedness and response following the April 2010 well control incident in the Gulf of Mexico.

The original IPIECA Report Series will be progressively withdrawn upon publication of the various titles in this new Good Practice Guide Series during 2014–2015.

Note on good practice

'Good practice' in the context of the JIP is a statement of internationally-recognized guidelines, practices and procedures that will enable the oil and gas industry to deliver acceptable health, safety and environmental performance.

Good practice for a particular subject will change over time in the light of advances in technology, practical experience and scientific understanding, as well as changes in the political and social environment.

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Introduction

In-situ burning (ISB) is the controlled combustion or burning of spilled oil's hydrocarbon vapours in place. ISB can rapidly remove oil from a land, snow, ice or water surface, and combusts it to mostly CO_2 and water. ISB can rapidly reduce the volume of spilled oil, and thus greatly reduces the need to collect, store, transport and dispose of recovered oil. ISB can also shorten the overall response time, thus aiding environmental recovery. This guide contains information about the in-situ burning of oil spills and the scientific aspects of the burning process and its effects. It also presents practical information on the procedures and equipment required for ISB operations.

ISB is a non-mechanical response option as, for example, is the application of oil spill dispersants. However, rather than using chemicals to remove spilled oil, the oil is removed by combustion of its hydrocarbon vapours. The best spill clean-up strategy will likely involve a combination of all available response options. When combining different clean-up techniques, the objective should be to find the optimal mix of equipment, personnel and techniques that affords environmental protection and mitigates potential impacts.

- ISB can be used to remove oil spilled on hard surfaces, soils, ice and snow on land, snow and ice on water, on sea ice and on water.
- During an on-water spill, ISB can be used in open waters (whether inland or offshore).
- Burning can be repeated in cases where sufficient oil remains.
- ISB can be used in conjunction with other techniques to clean up different areas of a slick.

Ignition of volatile oils is achieved easily, while heavier oils often require the use of an accelerant or promoter, such as diesel fuel, to ignite the hydrocarbon vapours. If not enough vapours are produced, the fire will either not start or will be quickly extinguished. The amount of vapours produced is dependent on the amount of heat radiated back to the oil, which encourages further vaporization. If the oil slick is too thin, some of this heat is conducted through the slick and lost to the water layer below. Insufficient heating of a slick reduces vaporization rates and lowers vapour concentrations, until eventually, concentrations are too low to sustain combustion. Oil that is heavily emulsified with water can be ignited if sufficient heat is supplied to remove water and release hydrocarbon vapours. Containment of the oil on water may be necessary when carrying out ISB as the oil slick needs to be thick enough to ignite and sustain a burn. Once burning, the heat radiated back to the slick is usually sufficient to allow combustion down to an oil thickness of around 0.5–1 mm. The oil burn rate is largely a function of oil type and its degree of weathering.

ISB has been shown to be successful in many varying habitats. ISB on land has included burning oiled marshes, vegetation and tundra. ISB on ice has also been successfully practiced on both solid ice and among broken ice. ISB on water has been demonstrated in open water, nearshore environments, protected bays and rivers. While the fundamentals for ISB remain the same, the tactics will vary given the habitat specifics and spill circumstances. For example:

- ISB on land can involve the use of bulldozers and front-end loaders to contain and thicken spilled oil, or trenchers to cut ditches into which oil can be pooled to support ignitability;
- ISB on snow and ice may not require any further containment as the snow/ice can serve as a natural boundary;
- sea ice leads can help to create thicker pockets of oil and can also contain the oil once ignited; and
- ISB on water typically involves vessels towing fire booms at conventional speeds to both encounter and contain the oil.

Burning oil on land or wetlands is a technique that can reduce the environmental impact of oil spills. Burning vegetation is a frequent method of protecting and maintaining certain ecosystems. The important factors relating to burning are the water level of wetlands and the moisture content of soils. Burning under the correct circumstances will not affect roots and thus restoration is rapid.

Experience has shown that burns can be conducted safely for responders, the public and the environment. Set-back distances prevent exposure to high levels of heat from a burn. Firebreaks are created to avoid spreading fire to other locations.

The main advantages and disadvantages of ISB are summarized in Table 1. The most significant advantage is the capacity to rapidly remove large amounts of oil. The most discernible disadvantage is the production of dark smoke plumes, which results in public concern about aesthetics and emissions hazards.

Table 1 *Advantages and disadvantages of ISB*

Advantages	Disadvantages
• Rapid removal of oil • Minimal equipment requirement • High efficiency rates • Reduced volume of oily waste for disposal • Can be used on almost any habitat and on most oils	• Black smoke plume (aesthetics and emissions concerns) • Risk of fire spreading or loss of fire control • Residue may need to be recovered

ISB can rapidly eliminate large amounts of spilled oil; this can prevent the oil from spreading to other areas and reduces the risk of a spill contacting new habitats, such as a shoreline in offshore spills. In addition, ISB can be applied in remote areas where other techniques cannot be used due to a lack of access or infrastructure, e.g. on ice.

Burns produce particulate matter (soot). Particulate matter at ground level is a health concern, particularly when in close proximity to the fire and under the plume. The concentrations of these emissions during an ISB have been widely studied and generally found to be below the levels that are of concern to human health.

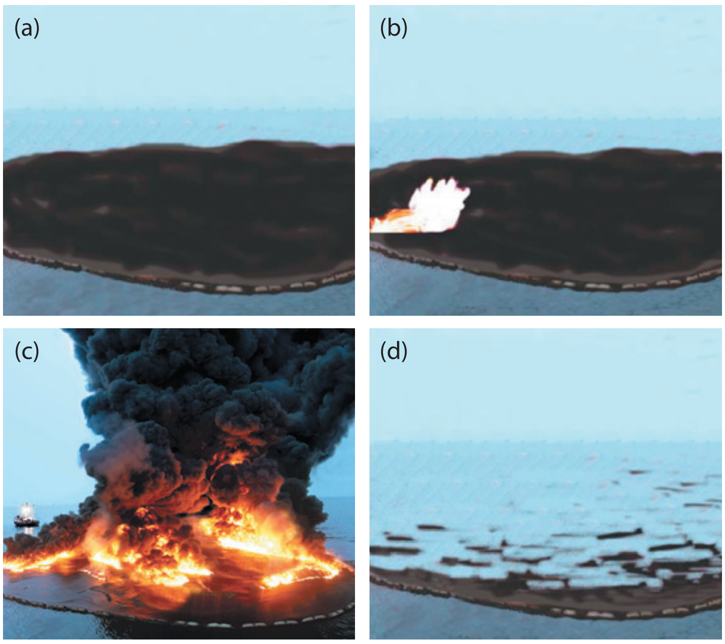
An overview of ISB

The science of burning

The fundamentals of ISB are similar to that of any fire, namely that fuel, oxygen, and heat are required for oil to ignite. In the event of an oil spill, the oil vapours provide the fuel to support combustion. Fresh oil will typically ignite once an ignition source is applied. As oil vapour burns, the heat causes more vapours to be released, known as vaporization. The vaporization process of oil must be sufficient to yield steady-state burning, in which vaporization and burn rates are relatively the same. The burn rate is limited by the amount of oxygen available and the heat radiated back to the oil. The burn rate will also rely on the type of oil and its degree of weathering, e.g. evaporation. If there are not enough vapours, the oil will not ignite or will quickly extinguish once ignited. The amount of vapours produced is dependent on the amount of heat radiated back to the oil, which is estimated to be about 2–3% of the heat produced. Fresh crude oil needs to be at least 1 mm thick to yield enough vapours to allow ignition on water, while oil that has undergone extensive weathering may need to be between 2–5 mm thick. Heavy fuel oils will need to be contained to maintain a slick thickness of around 10 mm before they can be ignited. Once ignited, the heat radiated back to a slick will usually be sufficient to allow the burn to continue until the oil slick is around 2–3 mm thick. As a slick thins, its insulating capacity weakens and more heat is lost to the media beneath the slick (e.g. soil or water), eventually resulting in insufficient heat to continue to vaporize the oil and sustain combustion.

Research has shown that virtually all oils will burn if the slick is thick enough. Oil spill containment booms and other containment methods are often used to increase a slick's thickness or to maintain it at the thickness required for burning.

The basic concepts of in-situ burning are illustrated in the photographs below and summarized in Table 2 on page 7.



Elastec Inc.

(a) *Oil collected and held by a fire-resistant boom or within a segregated area.*

(b) *Ignition—flame applied to oil creates vapour which ignites.*

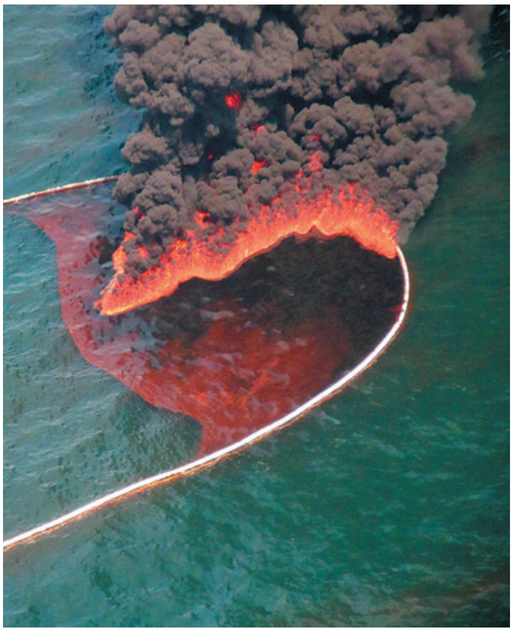
(c) *Flame spreads over slick and burns oil down to around 1 mm thickness.*

(d) *When vapour is insufficient to maintain combustion, the fire ends.*

Table 2 *Basic questions and answers about in-situ burning*

Questions	Answers
What burns?	Hydrocarbon vapours from the spilled oil.
How do burns proceed?	Heat vaporizes spilled oil for ignition, and if vapour concentrations are high enough a burn can be sustained.
How much heat radiates downward?	Only about 2% of heat produced is radiated downward and dissipates rapidly in surface waters or saturated soils.
What is the minimum slick thickness that can burn?	This depends on the oil, but it is best to have >2–4 mm for sustained burning.
What is a typical burn pattern?	Once ignited, burns will proceed downwind along a slick and reduce the slick thickness to ~1 mm before fire extinction.
What is the expected oil removal efficiency?	This depends on the initial thickness of the slick; it can be as high as 90+%.
What is a typical oil removal rate?	1 to 4 mm of oil slick thickness can be removed per minute for an oil pool (thick slick) burn.
What is a typical oil volume removal rate?	2,000 to 5,000 litres for each m^2 of a slick per day can be removed. For contained slicks on water, typical burn rates can remove ~150 m^2 of spilled oil in an hour.
How fast can a flame spread ?	Flames can move quickly for volatile oils (0.1–0.2 m/s); they can spread twice that speed downwind, and approach speeds of ~100 km/hour.
How high are flames?	The rule of thumb is ~1.5 x fire diameter.
What is the potential for soot formation?	This is greatest when the vaporization rate exceeds the burn rate (i.e. incomplete combustion due to O_2 limitation).

Weathered or emulsified oil can be difficult to ignite because much more energy is needed to remove water before it is able to heat the oil; the addition of an accelerant (e.g. diesel fuel) or promoter may therefore be necessary to achieve ignition. Boom tows containing both unemulsified oil and emulsified oil on a water surface can be burned by first igniting the unemulsified portion. The heat from burning the unemulsified oil causes the water content to be released from the emulsified oil, and eventually the oil vapours become sufficient to support ignition. Once ignited, most water-in-oil emulsions will continue to burn. The photograph on the right shows the progression of a burn as it spreads from the unemulsified oil to the emulsified oil (red colour); this eventually led to both oils burning simultaneously.



Elastec Inc.

A burn of unemulsified and emulsified oil

Elastec Inc.

An example of residue from a highly effective multi-hour burn at sea.

Incomplete combustion results in material being left behind after a fire is extinguished. This is known as burn residue. Residue can range from brittle or stiff toffy-like material to a liquid similar to the original oil. Highly efficient burns of heavy crude oil can result in the formation of dense residue that sinks into the water column. The small amounts of residue present after such an on-water burn (see photograph) typically represent $<0.1\%$ of the oil burned.

Ignition and burning requirements

In general, most oils on water will burn if slicks are more than 2–4 mm thick. On land or wetlands, the situation is similar, although oil with a thickness of 1 mm or less can be burned in a sustained manner on grassland because of heat from the burning of vegetative fuels. Heavy oils will require a small amount of primer (promoter or accelerant), such as diesel fuel, to start ignition. A promoter or accelerant would be applied to just a few spots on a slick which are judged to be near or on the thickest portion. Easy ignition of the promoter or accelerant can heat the underlying oil and increase its vaporization rate and its potential for ignition. Once burning, heavy oils will burn well, and even emulsified oil can break down and burn. Table 3 shows the ignition characteristics of various oils. These characteristics are independent of whether the oil is on land or on water.

Table 3 *Burning properties of various oils*

Oil	Overall burnability[a]	Ease of ignition	Flame spreading speed	Burning rate[b] (mm/min)	Sootiness of flame[c]	Efficiency[d] (%)
Gasoline	very high	very easy	very rapid	4	medium	95–99
Diesel fuel	high	easy	moderate	3.5	very high	90–98
Light crude	high	easy	moderate to rapid	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	moderate	add promoter	slow	2.5 to 3	low	60–90
Crude oil with ice	moderate	difficult, add promoter	slow	2	medium	50–90
Light fuel oil	moderate	difficult, add promoter	slow	2.5	low	50–80
Heavy fuel oil	moderate	add promoter	slow	2 to 3	low	60–90
Diluted bitumen (dilbit)	moderate	easy, if fresh	moderate	2 to 3	medium	40–60
Weathered dilbit	moderate	add promoter	slow	2 to 3	medium	50–70
Emulsified oil	low	add promoter	slow	2 to 3	low	30–70
Bitumen	low	add promoter	slow	2 to 3	low	30–50
Used oil	very low	add promoter	slow	1 to 2	medium	15–50

(a) Overall burnability is a general reflection of the ease of ignition, burn sustainability and its efficiency of oil removal. (b) Typical rates only. To convert rate to litres/m^2/hour multiply by 60. (c) A descriptive label to reflect the degree of combustion and quantity of soot in a burn plume (therefore, the darkness or sootiness of a smoke plume). (d) Efficiency of a burn is estimated here from historic information based largely on reported residue amounts.

ISB decision making

When an oil spill occurs, information must be obtained on the various factors that would influence the decision as to whether or not an ISB operation should be considered. Such factors include regulatory requirements, safety, oil properties, environmental and weather conditions, resources and geographical location. The main considerations are listed in Table 4.

Table 4 *Factors in the selection of burning as a spill response option*

Appropriateness	Feasibility
Is the location suitable for burning? • Distance from populated areas • Burn distance from other combustibles • Distance of smoke plume trajectory from residences	Is the oil burnable? • Oil can be ignited (<25–30% evaporated) • Oil is thicker than 2–3 mm • Emulsification: <20–25% water
Is burning feasible, and can burning be carried out safely?	Weather forecast? • Winds <18 knots for ignition/ <20 knots for a sustained burn • If booms are necessary, is wave height <1 m?
Legislation and regulations • Can necessary permissions be obtained? • Can stipulated conditions be met?	Equipment availability?
What are the results from a net environmental benefit analysis (NEBA)—i.e. is burning the best option in this case?	

An ISB feasibility analysis will often include an evaluation of the geographic location and any pre-existing prohibitions. For example, ISB approvals may be constrained when requested in close proximity to:

- human habitation; and
- industrial facilities with fire safety hazards, e.g. petroleum loading, production or exploration facilities, areas designated for military target practice or areas of former munitions dumping.

Sensitive areas, such as shorelines, nature preserves, bird colonies, or national or state/provincial parks could be of regulatory concern, yet these areas are often good candidates for ISB when minimal intrusion and rapid oil removal is desired.

Decision making using net environmental benefit analysis

The net environmental benefit analysis (NEBA) process can help to identify appropriate response strategies that result in the lowest overall environmental and socio-economic impact. The NEBA process is used for pre-spill contingency planning and for decision making during a response. NEBA considers and compares the advantages and disadvantages of different spill response techniques with those of taking no response action, taking account of the operating conditions and anticipated effectiveness of each technique and actual spill circumstances, including location. No single response technique is completely effective or risk-free. Any response operation will likely involve a combination of response techniques, because:

- each technique has different strengths and weaknesses relative to the circumstances of the spill;
- spill circumstances change over time; and
- larger spills with greater spatial extent of slicks may benefit from various techniques used in different locations simultaneously.

NEBA should be conducted with appropriate regulatory agencies and other stakeholders as part of spill contingency planning (see IPIECA-IOGP 2015).

Regulatory approvals

Most countries have not yet established approval processes for conducting ISB. In the USA, which has the most developed regulatory guidance and approval process for ISB:

- ISB is now included in many multi-state, regional contingency plans, and the process for obtaining approval to conduct ISB operations has been relatively well-defined on a regional basis under the US National Contingency Plan;
- response decision making for ISB reflects the scale of a spill or intended burn: larger spills involve more agencies, and approval requests receive greater scrutiny; small spills and burns may be handled by local emergency responders and firefighters; and
- pre-approval zones for streamlined decision making have been identified for coastal areas on a regional basis.

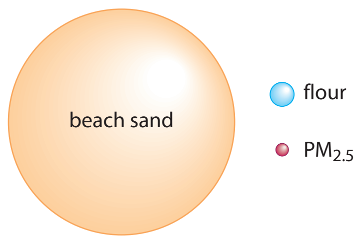
As more countries seek to use ISB in oil spill response operations, it is anticipated that an approval process will be developed, similar to the dispersant use approval process, which would entail government and stakeholder engagement. Many state/provincial governments already have provisions for using prescribed burning to manage land, and the in-situ burning of spilled oil may fit into these provisions.

In general, regulatory agencies are most concerned with operational safety (i.e. fire control and responder safety) and public safety (i.e. fire control and the potential for effects from smoke plumes on air quality and health) during response operations. See *Operational monitoring for safety and burn control* (page 34) for information on safety. Some jurisdictions have waived air quality limits for special cases, such as during an emergency.

Human health and environmental concerns

The primary health concerns relate to emissions produced by ISB. Data indicate that the combustion of oil yields mostly CO_2 and water to the atmosphere (up to 85% of emissions), inert carbon particles, i.e. soot, which colours the smoke plumes (around 10%), and small amounts of various other gases and PAHs (polycyclic aromatic compounds—organic compounds containing carbon and hydrogen). Of the soot particles, attention is focused mostly on a class of small particulate matter, $PM_{2.5}$—the 2.5 µm-sized particles (Figure 1).

Figure 1 *Relative particle sizes*
(based on data courtesy of the National Wildfire Coordination Group)



Inhalation of $PM_{2.5}$ could be a health concern to vulnerable groups, such as the elderly, the very young, and those with compromised lung function. Public health concerns with $PM_{2.5}$ are linked to longer-term exposure rather than to short-duration events (e.g a burn); however, exposure to sufficient quantities can lead to irritation of the eyes, nose, throat and respiratory tract, and can aggravate existing conditions such as asthma. These effects are usually temporary and should resolve after exposure stops.

It should be noted that:
- hydrocarbons will evaporate from oil slicks, whether burned or not;
- monitoring data consistently show that concentrations of emission constituents decline quickly as the distance from a burn increases; and
- data from monitoring of the Kuwait War oil fires and Deepwater Horizon incident do not indicate that the concentrations of emission constituents released from burning are of concern with regard to human health.

The gases and emissions to the atmosphere that may arise from ISB are described in Box 1. There has been interest in whether ISB generates dioxins or dibenzofurans. Analysis of particulates precipitated downwind and residue from several fires has found dioxins and dibenzofurans to be at background levels, indicating no production during ISB.

Box 1 *Gases and other emissions to the atmosphere resulting from ISB*

- **Carbon dioxide (CO_2):** carbon dioxide is the end result of combustion and is produced during in-situ burning. Normal atmospheric levels are about 300 ppm (parts per million), and levels close to a burn can be around 500 ppm, which presents no danger to humans. Concentrations at ground level are typically much higher than in the plume.
  In addition to the release of CO_2 and water (which constitutes ~85% of smoke plume contents), and particulate matter (PM, soot in the plume), a small number of other low-concentration emissions are produced by ISB.
- **Polyaromatic hydrocarbons (PAHs):** the concentration of PAHs, both in a plume and as particulate precipitation at ground level, is often an order of magnitude less than the original concentration of PAHs in the spilled oil. This includes the concentration of multi-ringed (5 or 6 rings) PAHs, which are destroyed by the fire.
- **Volatile organic compounds (VOCs):** when oil is burned, these compounds evaporate and are burned or released. The concentration of volatile compounds at several test burns was relatively low compared to an evaporating, unburned slick.
- **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 produced at very low concentrations and are below health concern levels even close to the fire.
- **Carbon monoxide:** carbon monoxide levels are usually at or below the lowest detection levels of most instruments and thus do not pose any hazard to humans. The gas has only been measured when a burn appears to be inefficient, such as when water is sprayed into the fire.
- **Sulphur dioxide (SO_2):** this is usually not detected at significant levels, and sometimes not even at measurable levels in an in-situ oil burn. SO_2 reacts with water to produce sulphuric acid, which can be detected at levels lower than the sulphur content of the spilled oil.
- **Other gases:** attempts were made to measure oxides of nitrogen and other fixed gases. None were detected in several experiments.

Other topics of concern related to ISB include potential water quality and environmental effects (see Table 5). Information from past burns and tests indicate that ISB has little effect on water quality. Studies have shown that no measurable quantity of oil is released to the water column during burning. For oil spills on water that are not burned, there is greater potential for impacts on water quality. For spills on land or shorelines, the removal of surface oil by burning is a positive outcome, and the effects of heat and fire control can be addressed in planning and execution. The distance of ISB operations from vulnerable groups is a key operational control point to limit any potential for exposure.

Table 5 *Topics of concern related to the use of ISB*

Concern	Mitigation
Public Health	• A burn should be greater than 1 km from any residence of the general public that is downwind of a burn plume so that exposure to PM does not exceed thresholds.
	• A burn should be greater than 4 km from multiple residences of the general public that are downwind of a burn plume, to account for additional time for sheltering in place or temporary evacuation.
Air quality	• Predict emissions and safe distances.
Water quality	• Studies show that effects are negligible.
Effects on land	• Habitat and season dependent, but can be accommodated by burn design and timing.
Effects on birds/animals	• Habitat and season dependent, but can be accommodated by burn design, timing and hazing.
Heating of surface water layers and surface soils	• Water is a strong heat sink. Studies show that burns have negligible effects on surface waters or soil temperatures.

Operational feasibility for ISB

There are several key points to be considered when determining the operational feasibility for ISB. Responder safety should always be the first priority when evaluating ISB feasibility. Trained responders will be required, with preference being given to those who are experienced in the use of ISB. Appropriate equipment necessary for ignition and containment will be required. Responders and equipment will need to be ready and available within the ISB window of opportunity. An organizational structure should be in place to ensure good communication and reporting. Roles include 'burn boss', 'ignition crew', fire control team, etc. The spill circumstances (e.g. oil type, behaviour and properties, location, weather conditions, etc.) will influence the likelihood of a successful burn, burn strategy and tactics, and possibly influence regulatory approvals for carrying out ISB.

Oil behaviour and properties

As soon as oil has been spilt, it begins to undergo a series of changes in state, influenced by the conditions in which it was spilt; this is known as weathering. Weathering is the alteration of the physical and chemical properties of oil through natural processes, including spreading, evaporation, dissolution, photo-oxidation, emulsification, sedimentation and biodegradation.

Further information on oil behaviour and properties can be found in ITOPF's Technical Information Paper, *Fate of Marine Oil Spills* (see the *Bibliography* on page 39).

To determine whether ISB will be feasible on a particular oil slick, it is important to understand how these processes change the properties of the particular spilled oil and ultimately affect the oil's ability to ignite and sustain the burn. Understanding a particular oil's properties prior to an event, e.g. the tendency for the oil to emulsify, or the percentage rate of evaporation at various temperatures, will expedite the decision making process during an incident.

A key oil property for burning is its volatility. As a rule, the greater the percentage of volatile compounds in an oil, the more easily it will ignite and continue to burn. The rate of evaporation depends on ambient temperatures and wind speed. In general, oil components with a boiling point <200°C will evaporate within 24 hours. It can therefore be difficult to ignite weathered oils (since most of the more volatile compounds will have vaporized) and heavy crude oils which contain minor amounts of volatile compounds. Higher ignition temperatures, the addition of fire promoters or accelerants and/or longer ignition exposure times may be required.

Emulsified and heavy oils

In general, unstable oil emulsions can be ignited and will sustain burning as the emulsion will be quickly broken down during the burning process. By contrast, stable oil emulsions are difficult to ignite because of the large amount of energy required to heat the water (so that it vaporizes) and then heat the spilled oil. Additional energy is therefore required to vaporize oil in the emulsion before burning can be sustained.

Test burns have shown that, once emulsified oil is ignited and has burned for long enough, the heat from the burn will break down the emulsion and allow the slick to continue to burn. Emulsified oil can be burned alongside unemulsified oil, as the heat from burning the unemulsified oil will break down the emulsion (see photograph on page 7).

Heavy oils do not contain many lighter-weight, volatile hydrocarbons. However, it is now accepted that heavy oils—once considered to burn poorly, if at all—will burn well under most circumstances. Burning tests of bitumen (very heavy oil) along with water have been conducted and show a useful burn rate potential. Heavy oils, such as Bunker C, burn quite well. Heavy oil burns produce low emissions compared to crude oil burns and, in particular, fewer volatile compounds and PAHs are released into the air. The residues from heavy oil burns are highly viscous, and when cooled may be solid and even 'glassy' in some cases.

Treating agents

The use of chemical additives (treating agents) to promote ignition, enhance burning or aid smoke management has been investigated over the years. These agents include emulsion breakers, herding agents, ferrocene, combustion accelerants or promoters, and sorbents (see descriptions below). Note that the use of all but sorbents for oil spill response is likely to require advance approval by the designated government agency/agencies. Few are approved for use at the present time.

- **Emulsion breakers and inhibitors** are used to either break down water-in-oil emulsions as they weather, or to prevent emulsions from forming. They have not been used extensively in field trials and are rarely used for on-water or shoreline spills. They would not be needed for spills on land.
- **Herding agents** have been developed and tested to increase the thickness of oil slicks on water so that the slicks are thick enough for burning. Outdoor tests in pack-ice conditions and in open waters has shown herders to be effective at thickening slicks. Herders work most effectively in calm conditions; winds greater than 1.5 m/s or the presence of waves could overcome their slick-thickening effect.
- **Ferrocene** has been used in wildland firefighting to reduce and eliminate soot production from burns. Tests have shown that, when mixed with spilled oil, ferrocene is highly effective at dose percentages from 1–2%. It is denser than oil and water, so for on-water spills it is usually pre-mixed and applied just before burning; timing such an application can therefore be difficult. Ferrocene can also be encapsulated so that it floats, and in this way can be added to an on-water burn after ignition, although this is not currently an established practice.
- **Accelerants or promoters** (primers) are agents which, when applied to selected spots on an oil slick, are intended to provide sufficient hydrocarbon vapours for ignition. Once ignited, the heat from the primer burn is intended to increase the vaporization of spilled oil and support continued burning.
- **Sorbents**, such as peat moss, have proven useful by acting as wicking agents for oil sorbed into debris and soils, and can increase oil removals by encountering and acquiring more oil to burn.

Influence of environmental conditions

Spill circumstances and forecast weather conditions can influence the decision as to whether or not ISB operations should be conducted. The following are examples of specific weather phenomena and their potential impacts on ISB operations:

- Wind speed, gusts and shifts in wind direction, plus for on-water spills, wave height and geometry and water current can all jeopardize the safety and effectiveness of a burn operation.
    - Strong winds can make it difficult to ignite the oil, or make a burn difficult or dangerous to control. In general, oil can be ignited and burned at wind speeds less than 10 m/s (<18 knots); however, lower winds speeds are preferred (<5 m/s and <10 knots) for fire control.
    - Tank tests have shown that at wind speeds greater than 15 m/s (>30 knots) flames do not propagate upwind. This effect can either add to fire control or constrain oil removal depending on the location of the burn in a slick.
    - At higher wind speeds, the concentration of vapours becomes difficult to maintain, and burns can be extinguished.
- Tank tests have shown that air temperatures from -11 to 23°C and water temperatures from -1 to 17°C did not affect the ability to burn.
- Rain can lower the efficiency of a burn due to the cooling effect of water droplets plus the potential for disruption of a slick which reduces vaporization.
- For on-water spills, higher sea states can make it difficult to contain the oil to create the thicker slicks necessary for maintaining adequate vapour concentrations. Waves greater than 1 metre in height can weaken the wave conformance of containment booms and lead to failure.
- Ice has a minimal effect on the ability of a slick to burn on land. On water, ice can dampen waves and help to contain a slick, thereby enhancing the ability to burn.

- Water, ice and snow on land can act as insulators, protecting soils and plants from any downward radiated heat.

Burning can be conducted safely at night if the slick properties and weather conditions are well-known. There are examples of burns carried out safely at night on nearshore and marsh spills. In these cases, the concentrations and location of oil were known, and precautions were taken to ensure that the fire did not spread to surrounding areas. Burning at night is a relatively safe choice for cases of thicker, uncontained spills at sea, especially if the spill is offshore, its extent is well-known and vessel traffic is directed away. However, towing booms at night would be unsafe under most conditions.

Successful burning in wetlands is well documented and important information is available on the protection of marsh plants and the best times of year to carry out a burn. For example:
- Flooding is a useful technique for flushing oil out of a wetland to burn, while protecting the roots of plants from heat and increasing fire control. Flooding can sometimes be accomplished by placing a berm across drainage ditches or pumping water onto higher-elevation areas. Care should be taken to ensure that flood water is of similar salinity to that normally present in the wetland, and that natural drainage conditions are returned after burning.
- Burning is best conducted when a wetland is wet and soils are saturated, e.g. in spring. It has been observed that water-saturated soils provide sufficient insulation from the heat of a burn, so that temperatures remain below those known to affect soil biota and plant roots. A NEBA analysis will help the decision making process in dry seasons or times of the year.

Ice and snow during cold periods in temperate climes, alpine areas, or in the Arctic or Antarctic can serve as a natural barrier to the spreading of spilled oil. Ice and snow also function as barriers to oil penetration into soils and to soil heating from burns. Many burns have been conducted with oiled snow, on ice, or among ice floes (see photographs on the right). Much of the early ISB research was carried out in Canada to develop a countermeasure for spilled oil in sea ice. Burns can be conducted when the oil is:
- contained in close pack-ice conditions (pack ice of 7/10 coverage or greater);
- contained in drift-ice conditions and is of a sufficient thickness to sustain a burn (drift ice of 2/10 to 6/10 coverage);
- contained in a fire-resistant boom (generally in open water up to 1/10 ice coverage);
- trapped along an ice floe or herded by wind, and has sufficient thickness to support a burn;
- contained in melt pools on top of ice sheets; and
- contained in open fractures or leads in ice.

Environment Canada

Left: burning an oil spill that is entirely contained by ice rubble.

Below: burning oil in an ice lead after a spill experiment.

Environment Canada

ISB application

An important advantage of ISB is that it is a useful response option whether on land, on water, or on snow or ice. This section describes how ISB is applied in each operating environment.

On-land spills

Burning oil on land is an established and more frequently used technique than ISB on water. Unique considerations for ISB on land include the following:

- The effect of oil and heat on soil and vegetation is a prime consideration. Certain types of vegetation are very sensitive to fire, while others are not or may be fire-dependent.
- The burn history of a location (i.e. the use of ISB or prescribed burning in the past) should be reviewed and considered. The history of fire behaviour and habitat recovery is useful to help estimate future fire effects and recovery. Prescribed burns are conducted frequently in many countries to achieve or maintain a wildland habitat (e.g. grasslands, rangelands, forests) and address concerns with invasive species. Extensive literature and expertise are available on prescribed burning, which can be used to support ISB on land.
- The impact and after-effects from exposure of the subsurface soils (including plant roots, tubers, and microorganisms) to heat: this is highly influenced by soil moisture, depth of oil sorption, and fire intensity. If fire damages soils and roots, etc., revegetation will be commensurately slower. Standing water and saturated soils should provide adequate insulation from heat.
- The amount of oil that has penetrated into soils, and the depth of penetration, before and after the proposed fire: if there is little penetration before the fire, burning will be able to remove more oil. Spills to peat bog habitats have been a concern due to observations of fires in dry peat habitats that were difficult to extinguish. However, water-saturated peat cannot burn, so spills in areas of saturated peat could be candidates for ISB.

In terms of burn operations, many of the same considerations apply to land as might apply to burning on water. There are, however, several important differences:

- The ease of ignition and oil thickness may not be a significant concern if combustible material (vegetative fuel), such as dried grass, is available. Burning where there is dried vegetative material or wood is simply a matter of igniting that material.
- Fire control procedures on land differ from those on water. First, a firebreak is needed around the perimeter of the proposed burn area. Sometimes natural barriers, such as rivers, roads, etc. can serve as firebreaks. Once the firebreak is established, ignition is typically begun in the downwind position to give greater control as the fire must fight its way against the wind. Once ignited, the fire should be monitored, especially near firebreaks.
- Sufficient resources should be available to extinguish the burn and prevent uncontrolled fire propagation. Such resources usually include a fire truck with trained firefighters. After the main burn is extinguished, the location should be monitored for several hours until hotspots have cooled and there is no danger of reignition (flare-ups).
- After the burn is completely extinguished, post-burn monitoring should include a walk-through of the area with collection of samples for post analysis, as well direct observation of the surface layers. Details to be recorded include whether: (1) oil has been burned completely; (2) burn residue is present that could interfere with plant regrowth; (3) oil has penetrated into the soil; and/or (4) there is unburned oil remaining which needs treatment (and if so, could this oil be burned?).

The creation of a firebreak can pose a problem in wetlands as the periphery often contains sensitive vegetation. Two methods for creating firebreaks in wetlands include using airboats to lower vegetation height and/or wetting a periphery around the oiled vegetation.

On-water spills

The basic process is as follows: (a) collect oil behind a fire-resistant containment boom; (b) slowly pull a fire-resistant boom against the water current to push oil into the boom apex and increase the thickness of the oil; and (c) ignite the oil. In most cases, a fire-resistant boom is deployed downwind of the spill and a tow is put in place. When enough oil is collected in the boom, it is ignited as shown in the photograph on the right. If burning extinguishes because there is not enough oil in a boom, the burn can be resumed by heading vessels and towing booms downwind and then turning around into the wind, before re-igniting. Fire control on water can be achieved in an emergency by releasing one end of a boom or by increasing the tow speed to force boom failure. Either action results in rapid thinning of the oil slick, a decrease in vaporization and a decline in burning.

US Coast Guard

Vessel coordination between towing, ignition and support during an on-water burn operation.

The boom normally remains deployed until the fire is extinguished. The burning and progress of the tow should be checked frequently by personnel either onboard aircraft or on a larger vessel.

Another potential situation for on-water burns is where oil has been spilled onto or among sea ice and become encapsulated. If accessible, volatile oil on a surface can be ignited directly with or without the use of an accelerant. Burns have been conducted in various types of sea ice conditions which provide a form of containment (frazil, brash, drift and pack ice) (Buist, *et al.*, 2013). If spilled oil becomes encapsulated, oil will not be accessible until warmer weather when melt channels form in the ice and oil can migrate to the ice surface.

Nearshore and shorelines

Barriers such as shorelines, breakwaters, sandbars or sea ice can help to contain the oil so that it can be burned without the use of fire booms. In these habitats, shorelines can include cliffs, rocks, gravel, piers, breakwaters or sandy slopes. If a spilled oil slick is thick enough to release sufficient vapours for ignition, and other relevant circumstances support burning, a burn will be feasible. There should be a safe distance between the spilled oil and any combustible materials, such as wooden structures and areas of habitation. Nearshore burning has been successfully conducted in the Arctic, particularly in cases where the oil is contained by a shoreline. If there is an onshore wind, oil will be concentrated against the shoreline, increasing its thickness and sustaining a longer burn.

There can be cases where oil becomes stranded on shores that can be dangerous for responders to access to carry out mechanical response operations. Burning could therefore be the only viable clean-up solution, with its smaller logistical needs and potential for remote ignition. Firebreaks in these locations can be comprised of the surf zone and unvegetated shore areas which have been cleared of unoiled debris. The window of opportunity for ISB is between the outgoing and incoming tides.

Uncontained slicks on water

Four uncontained burns at sea

US Coast Guard.

Two opportunities may exist to burn uncontained slicks on water: (1) in zones of convergences; or (2) when spill conditions generate many thick on-water slicks. Zones of convergence are surface phenomena, driven by winds, which naturally collect the spilled oil into thicker concentrations, that can be suitable for burning. Controlled burning of uncontained slicks is rare, but sometimes possible if a slick is thick enough. If an oil slick is already fairly thick, it may be advisable to burn as much as possible as a first response, and then bring in fire booms to thicken the remaining parts of the slick for a second burn.

When burning an uncontained slick, personnel must ensure that there is no direct connection between the oil to be burned and its source, so that the fire is prevented from spreading uncontrollably. In the Macondo incident, some spilled oil was ignited without containment (see photograph on the left). These uncontained burns increased the number of burn operations conducted and the volume of oil removed by ISB.

Operational hazards and considerations

The burning of oil on land may involve hazards that are not encountered during burning at sea. For example, the sea acts as a barrier between offshore burns and the shoreline, helping to prevent the uncontrolled spreading of fire; for on-land burns, however, there is no ‘gap’ between the burn area and other possible combustible land/objects nearby. Special precautions must therefore be taken when initiating a burn on land. Hazards in, or close to, the burn area that should be considered include:

- other unintended combustibles;
- physical hazards, such as debris, barbed wire, etc.;
- areas with poor footing, holes or steep slopes; and
- areas where vehicles may become stranded.

Smoke control (smoke management)

The possible health effects from exposure to a smoke plume should be assessed to determine the preferred burn strategies. The size and trajectory of smoke plumes can be influenced by decreasing the size of individual fires, and burning in different wind directions and at different times of day. Generally, a safe distance for the general public is a minimum of 1 km downwind from a burn (see Table 5 on page 12) and is based on conservative estimates of dilution for $PM_{2.5}$ concentrations to below the 24-hour exposure threshold of less than 35 µg/m^3. The same threshold applies to responders working at a burn site, although when using appropriate PPE any exposure should be minimal or negligible.

Biota

Consideration should be given to the variety of biota that may be present when responding to oil spills, whether conducting burns or not, including:

- birds, especially when nesting;
- sensitive plant species during growing seasons;
- burrowing and nesting animals when not dormant;
- migrating species and those which are trying to use a spill area for foraging and feeding; and
- the impact of smoke plume particulates on neighbouring habitats.

The use of NEBA during oil spill contingency planning can help to evaluate factors such as those listed above in advance of a spill. Rapid oil removal by ISB can limit and/or prevent exposure to the oil. Burn planning should account for:

- local wildlife, e.g. consideration should be given to scaring (hazing) operations; and
- protected species, which should be taken into account during burn design and execution; protected species may also require specially trained and licensed persons.

It should be recognized that some terrestrial habitats need fire as part of their life cycle, e.g. some pines for propagation, and many grasslands.

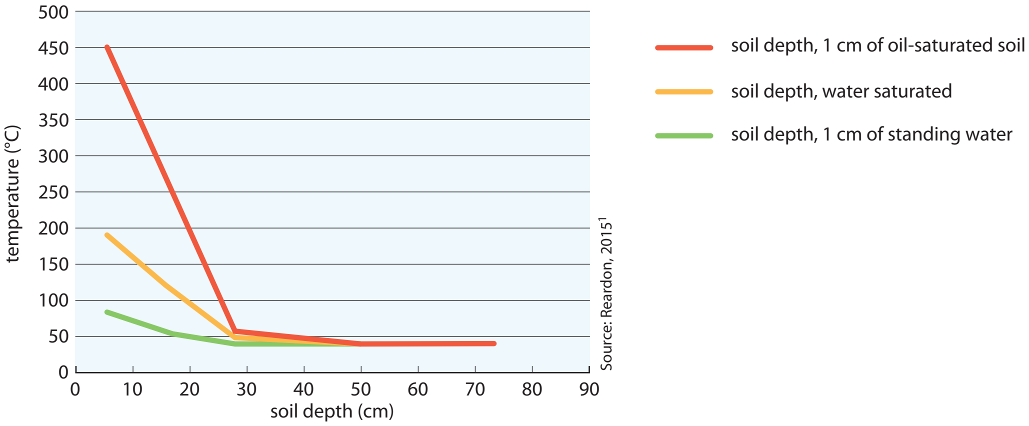
Soil heating

Soil heating has the potential to affect vegetation through changes in soil property and damage to plant structures below ground, such as roots and tubers. Damage to, and mortality of, soil micro-organisms and vegetation cells is expected above a temperature threshold of 60°C. In addition to the depth and degree of soil heating, the effects of fire on vegetation are also dependent on the properties of different species, such as their rooting depth and sensitivity to heating. To improve the ability to assess the potential outcomes of ISB, information on the effects on plants and animals, and on the fire regimes of plant communities in the USA is available from the Fire Effects Information System (FEIS) and may be applicable for other locations with similar plant communities. The FEIS database is available at www.feis-crs.org/beta.

Observations of intense energy released by flaming combustion of petroleum fuels during ISB suggest severe soil heating. However, the heating that results from the transfer of heat from the flaming combustion zone into the soil below is influenced by several factors including soil moisture. Research has shown that a small percentage of total energy emitted during burning is transferred downward into the soil, and when soil moisture is present, temperatures are limited to less than 100°C until this moisture is either transported out of the soil or is moved lower in the soil profile.

The results of laboratory oil burns on soil cores demonstrate the effects of soil water on heat transfer to and within soil (see Figure 2 on page 20). Maximum soil surface temperatures were influenced by the level of water saturation; however, with the exception of temperatures resulting from one diesel-saturated soil treatment, maximum soil temperatures at depths greater than 2 cm were lower than 60°C due to the high soil moisture content. The results support the use of ISB conducted over a range of high soil moisture levels.

Figure 2 *Laboratory oil burn data showing the effects of soil moisture on soil heating*



Weather conditions

Some weather conditions can influence burn planning and execution due to safety and $PM_{2.5}$ exposure concerns, for example an air temperature inversion, either present or forecast, which constrains the rise of a smoke plume and the dilution of plume constituents. The photograph below shows the effects of windy conditions and an inversion on a smoke plume, which moved laterally along the ground for about a kilometre.

A smoke plume moving along the ground due to lateral winds and a temperature inversion.

Environment Canada

Another example is a weather front that is forecast to move into a spill area within the next 12 hours; such a phenomenon can result in rapidly shifting winds (speed and direction) or precipitation. Depending on the intended scale and duration of the burn, it may therefore be advisable to complete the burn in advance of the weather front to eliminate potential complications arising from rain or snow on the slick, the impact of winds on fire control, and concerns regarding smoke plume trajectories near sensitive populations.

[1] Reardon, James, 2015. Forester at US Forest Service's Fire Laboratory in Missoula, Montana. Personal communication on results from soil core burns conducted for the American Petroleum Institute.

Planning a burn

Every ISB should be preceded by the preparation and approval of a burn plan which describes, at a minimum, the spill circumstances, the intended burning activities and pertinent safety precautions. A general plan or template burn plan can be prepared in advance that contains as much of the information as practical from Table 6 to aid rapid preparation of an incident-specific burn plan.

Table 6 *Generic burn plan content*

General content	Plan components
Objective for burn and expected results	Communications plan, including local fire department contacts: • key agency personnel • plans for public notices
Burn site physical and legal description with maps and photos: • spill circumstances and oil weathering state • hazards or concerns in burn area • wildlife of concern in burn area*	
Responder Team assignments and contact information	Ignition plan
Equipment and supplies: • ignition** and fire control • vehicles/vessels • air support • PPE • tools for mop-up and clean-up	Health and Safety Plan, including: • fire control/extinction (if needed) • escape plan for responders with map(s) • evacuation plans for nearby residents • navigation rules for on-water vessels, and traffic control for on-land locations
Firebreak design, location and creation, plus perimeter watch	A go/no-go checklist
Information on smoke management and plume trajectory prediction	Surveillance and monitoring plan
Plan preparation date and approval signature(s)	Post-burn activities: • mop-up • clean-up and residue recovery

* This may require the writing and utilization of a 'Best Management Practice' (BMP) for the wildlife/species involved. For example, see: https://awionline.org/sites/default/files/uploads/documents/govleg-bestpracticesseaturtles-102011.pdf

** refer ASTM F1990 - 07(2013): *Standard Guide for In-Situ Burning of Spilled Oil: Ignition Devices.*

Equipment, vessels and vehicles for the burn crew

Sufficient equipment, vessels and/or vehicles should be available for the ISB fire crew to enable them to respond to any potential incident, including the possibility of escaped fire in multiple directions. During a land or onshore burn, at least two individuals should be in each vehicle, and their movements monitored from a safe location. Crew members should carry shovels, rakes and specialized snuffer tools. After the burn operation has been completed, the recovery of residue may require other tools and containers for collection and disposal.

Smoke management

The possible impacts of the smoke should be estimated and considered. Smoke from a burn plume can be managed by decreasing the size of fires, burning under different wind directions, and during different times of day.

Evacuation and safety zone

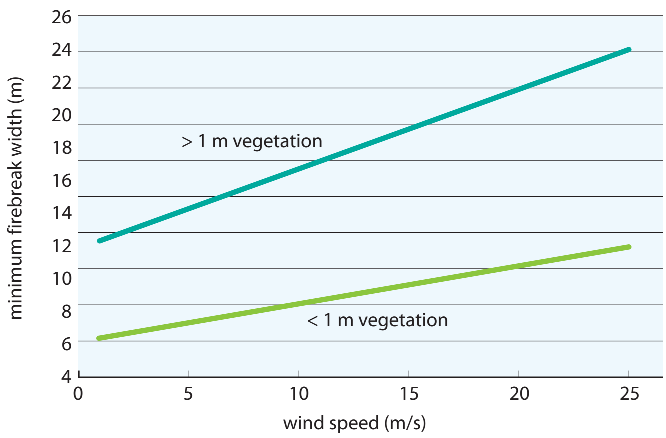
As a safety precaution, an evacuation plan and safety zones should be identified to support the potential evacuation of members of the public from the areas surrounding the planned fire. The plan should be sufficient to cover a worst-case scenario. One rule of thumb is that a safety zone should be large enough so that the distance between the firefighters and flames is at least four times the maximum flame height. Another rule of thumb is that an evacuation zone in the downwind area must be a minimum of 10 times the length of the downwind distance of the fire area, or a minimum of 1.5 kilometres (one mile). The upwind evacuation distance is the length of the downwind distance of the burn area. Prior to the commencement of any burns, the evacuation zone(s) should be clearly communicated and briefed to all personnel working in the burn area.

Firebreaks

A firebreak should be established around any land or shoreline burn to protect the surrounding area from potential spreading fire. The width and length of a break depends on terrain, wind, soil and vegetation moisture, and plant height. A minimum width is about 6 m (15–20 feet). There are de facto firebreaks in on-water operations, i.e. vessel set-back (tow) distances and ability to release booms.

The calculator for estimating firebreak width for a downwind firebreak is shown in Figure 3. Since the downwind width of a firebreak is more than the minimum upwind distance, the fire area and its firebreaks will form a quadrilateral shape.

Figure 3 *Firebreak width versus wind speed for burns*



Various situations and approaches exist for creating a firebreak on land or shores, including:
- an already burned area with little to no oil or vegetative fuels;
- mowed and/or wet land;
- natural topography changes (such as rivers);
- tilled ground;
- roads; and
- firebreak construction using a bulldozer, grader, etc.


US National Park Service


Environment Canada

Left: a firebreak created by mowing a field, and the burning of a pipeline spill in winter where a snow-covered road provides a firebreak.

Firebreaks for on-water burns are primarily safety setback distances between the pair of vessels towing the fire booms and from any adjacent vessels.

See the *Bibliography* on page 39 for sources of information on land burns and firebreak design.

Fire control

A plan and resources must be assigned to address the possibility that fire could escape beyond the planned burn site. For on-land and onshore burns this may include details of firefighting resources, the provision for removal of un-oiled debris, and the establishment of firebreaks.

One technique used for on-land burns is to spray or flood water to wet the intended burn site. This can also assist in lifting oil from the land surface for removal by burning.

For on-water burns, the most common means of fire control is the release of one end of a towed fireboom to enable the slick to spread and thin and, by so doing, lower the concentration of ignitable vapours. Another option is to instigate boom failure for the same effect (e.g. by increasing tow speeds). An option for smaller-scale effect is for a vessel to rapidly transit near the boom and burning slick such that its bow wave disrupts the adjacent slick and the sustainability of the burn.


US National Park Service


Minnesota Pollution Control Agency

Far left: a water tanker is ready to provide fire control.

Near left: aerial spraying of fire retardant in advance of an inland burn.

Using a drip torch to ignite a prescribed burn.

US National Park Service

Ignition plan

The ignition plan should describe the method(s) of ignition, ignition equipment, site access, the line of ignition and location, safety zones, and the time and rate at which ignition is to be carried out. The above items apply to land, onshore and on-water burns. The direction of approach for ignition will be influenced by wind and current direction when on water, while influenced by wind, terrain slope and vegetation when on land. The drip torch is the most frequently used method of igniting on-land burns (see photograph on the left). A flare attached to a container of gelled fuel is the most frequently used method of igniting on-water burns.

Implementing a burn

The conduct of ISB operations must meet regulatory requirements. Different levels of government may already have procedures in place for the approval of prescribed burning. An ISB plan and its execution should be coordinated with, or linked to, relevant prescribed burning plans in a particular jurisdiction.

Pre-burn safety briefing

In advance of every burn, there should be a safety briefing for in-field responders. Such briefings usually aim to provide the most recent information on weather status, spill status and ignition plans, together with communications and emergency reminders.

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Ignition

Upon a signal from the 'burn boss', the ignition crews will begin their task of applying a heat source to a slick to begin the burn. The photographs below show ignition for a spill on water (left) and a spill on land (right). Stable emulsions can be very difficult to ignite because the water in the oil will act as a heat sink; consequently, a higher amount of energy is needed to heat and vaporize the oil before burning can be sustained.

Near right: example of a floating hand-held igniter using a marine flare, diesel fuel and a gelling agent.

Far right: the tip of a flare is used to ignite oil as frozen soil warms.

Elastec Inc.

US National Park Service

Burn monitoring

The fire should be monitored visually and with the use of particulate monitors commensurate with the scale of the spill and burn, and the weather conditions. Photographs using GPS, and time-annotated photographs are helpful to document the progress of burn operations. Patrols should be conducted around firebreaks, with appropriate caution, to assess fire control. Monitoring of on-land burns can be carried out in vehicles or from aircraft. Monitoring of on-water burns can be carried out from vessels or from aircraft. Particulate monitors can be fixed/mobile or ground/plume level. See *Operational monitoring for safety and burn control* on page 34.

Extinguishing the remaining flames post-burn, during mop-up operations.

US National Park Service

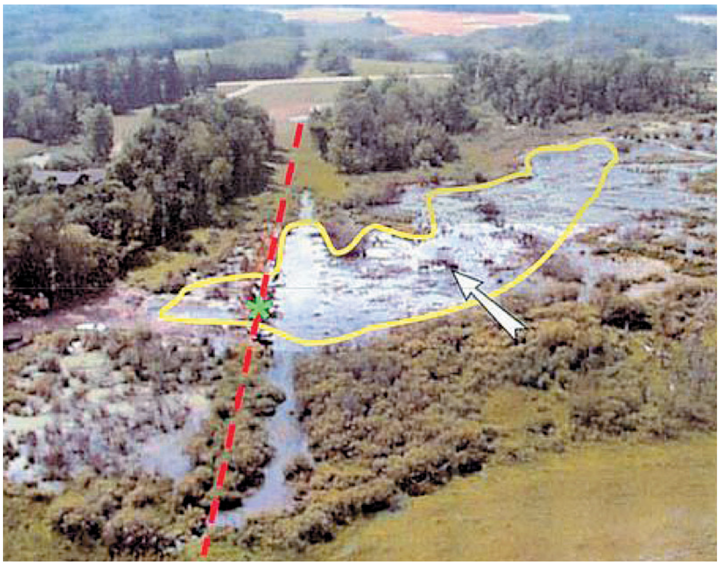
Mop-up or site clean-up

A check and clean-up of a burn site is made after a burn. This includes wetting any smouldering spots or potential flare-up sites. Any heavy oil burn residue that is deemed to have the potential to suppress future revegetation should be noted for post-burn attention. This step is more important for on-land and onshore burns because of the potential for fire flare-up from still burning or smouldering vegetative fuel and remaining spots of oil.

Post-burn actions

Several activities may be conducted, as required, after the conclusion of burn operations in an oil spill response. Key among these are reporting, emergency site stabilization, post-burn monitoring for habitat recovery, and recovery aid through rehabilitation.

Example photo-documentation of a burn site.



Jacqui Michel, RPI

Operational summary reports

Summary reports are a stipulation of most burn plans and would be provided to the approving government agency/agencies. Such reports contain a summary of site conditions prior to the burn, documentation of burn execution, estimates of oil removal, observations of fire behaviour (of special interest for on-land or shoreline burns), and details of any loss of fire control and commensurate actions to regain control. Operational summary reports are often accompanied by photographic documentation. For example, in the photograph on the right, the oiled area that resulted from a pipeline spill is outlined in yellow, and the pipeline route is indicated in red. The detail in a burn summary report should reflect the scale of a spill and the complexity of the burn.

Emergency stabilization

Emergency stabilization after an on-land or onshore burn involves any immediate restorative action that may be required for a burn area to ensure that there is minimal impact on drainage patterns, soil conditions and vegetation. This activity relates only to short-term needs to stabilize land or shorelines until further restoration can be conducted or until the area recovers naturally. This step does not apply to on-water burns.

Post-burn observations and recovery monitoring

Depending on the scale of a spill and subsequent land or onshore burn, the burn area should be monitored to ascertain the effectiveness of the oil removal and to observe progress with revegetation and re-establishment of the habitat for an agreed-upon time after completion of the burn. Periodic visits to ascertain and document recovery are recommended. If an area is slow to re-establish, seeding or other forms of rehabilitation may be desired.

Post-burn observations after an on-water burn are focused primarily on estimating the degree of oil removal and determining the practicality of any residue recovery.

Rehabilitation

Rehabilitation is a longer-term activity to facilitate restoration of an inland or onshore burn area, which may be agreed to in a burn plan or afterwards (up to three or even five years). This includes restoring vegetation and soil or drainage patterns on a longer-term basis, e.g. by seeding, adding soil conditioners, modifying drainage patterns, etc. This step does not apply to on-water burns.

The burn area should be surveyed for any dense residue covering areas of vegetation. If residue is found that may inhibit the recovery of vegetation, it should be treated, recovered or tilled. Soil amendments and re-seeding may be desired.

The photographs below and on page 27 show the situations before a burn, and afterwards/during post-recovery monitoring subsequent to a spill, at three different locations.

Right: (a) the vegetation on a slough before a burn; and (b) the vegetation on the same slough one year after the burn.

(a)

Jacqui Michel, RPI

(b)

Jacqui Michel, RPI

NOAA

NOAA

Left: (a) aerial view of a marsh spill resulting from the overflow of a settling pond; and (b) an aerial view of a burn on the same marsh.

NOAA

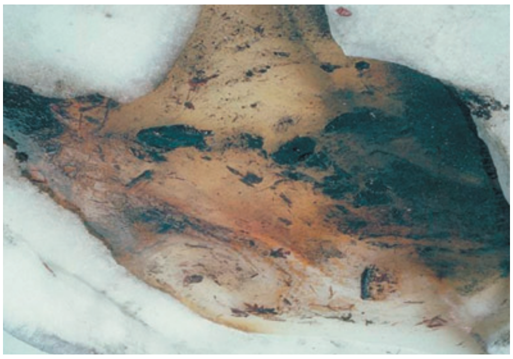
NOAA

Left: (a) the surface of a marsh as the burn is extinguishing; and (b) the surface of the same marsh three weeks post-burn.

Burn residue

The residue from a burn consists of partially burned oil, oil depleted of volatiles, and/or precipitated soot. It appears similar to weathered oil of the same type and is typically viscous and dense (see examples below). Residue excludes unburned oil. The residue in the photograph on the right was estimated to be around 20 kg or about 0.05% of the original oil amount.

The density of burn residue depends on how heavy the original oil was and the completeness of the burn. An efficient on-water burn of a heavier crude oil will produce a dense residue which could sink and pose a threat to benthic species from smothering. However, sinking is rare and has only been recorded in a few burns worldwide. Results from several tests have shown that burn residue is less toxic to aquatic biota than weathered oils.



NOAA

Environment Canada

Far left: residue from a fuel oil burn on snow and ice.

Near left: residue in a boom apex after a 50-tonne burn.

The decision to recover residue mechanically or leave it to degrade naturally depends on the total quantity of residue, whether it is dense enough to sink (if ISB was conducted on water), and where it is expected to go if it is not recovered. Other considerations include the immediate availability of equipment and personnel, as these might already be deployed in other recovery efforts, and the conditions for safe residue-recovery operations. Residue recovery considerations can be part of an overall ISB decision-making process using NEBA.

Options for the recovery of burn residue include the following:

- Depending on the quantity, residue could be mechanically recovered or transferred using either a vacuum suction system or a submersible pump, or be manually transferred with shovels and buckets.
- An on-water option is to herd the oil residue into one area using pumps or water hoses deployed from a small boat. Once herded, it may be possible to re-ignite the residue or to ignite it along with newly collected oil to further reduce the volume of residue to be recovered.
- Residue on water can also be collected in a backup boom, and recovered using sorbents or skimmers suitable for heavy oil.
- On land, residue is more readily recovered using mechanical means. It may be preferable to leave residue in place after burns in habitats that are sensitive to trampling (e.g. wetlands).

It is possible for unburned oil to remain after a burn and, if present in sufficient thickness and quantity to support ignition, this oil could be subsequently burned.

ISB equipment

Two main types of equipment are needed for ISB: an ignition system (i.e. the device itself, together with an associated carrier or launcher if applicable) and, for spills on water, a containment boom.

Ignition devices

A variety of ignition devices and methods have been used to ignite oil slicks. Many of the methods used are modifications of ignition devices used for other purposes. In general, ignition devices must meet two basic criteria:

1. They should be safe to use.
2. They should be capable of producing sufficient heat to ignite oil vapours from a slick.

Helicopter underslung ignition devices

Helicopters are sometimes used for transporting ignition devices. Often referred to as 'helitorches', these underslung devices dispense packets of burning, gelled fuel. This type of igniter was designed for the forestry industry and has been used extensively for forest firefighting. Special training is recommended for pilots expected to handle helitorches. Two helicopter-based systems are shown below.

Clean Caribbean and Americas

OSRL

Far left: a helicopter with empty torch tank detached prior to its return to base.

Near left: a helicopter carrying an underslung drip torch and releasing gelled fuel in flight.

Handheld and mobile platforms for igniters

Handheld ignition devices are many, and extend from the very simple (e.g. matches) to the complex (underslung drip torches, flame throwers, and plastic spherical device launchers). Hand-held devices are available for igniting land burns, as shown in the photographs at the top of page 30. Caution must be exerted in igniting materials at close proximity, especially if volatile components are present. Gasoline or light crude oils should not be ignited at close proximity. Furthermore, it should be noted that the spread of fire through a vapour cloud, such as those that arise from gasoline or similar fuels, can be as fast as 50 m/s (100 knots).

Near right: a member of an ignition team igniting a prescribed fire by flare gun.

Far right: use of a power torch to ignite a prescribed burn.

US National Park Service

National Wildfire Coordinating Group

Mobile launch platforms for ignition devices on land include vehicles or rotary wing aircraft. The photograph below right illustrates a side-mounted chute designed to release plastic spherical igniters from a helicopter. These igniters are filled with potassium permanganate; on release, they are injected with glycol which reacts with the potassium permanganate to create an exothermic reaction for ignition. After a 20–40 second delayed ignition as the two constituents react, a sustained flame is produced which last for approximately two minutes.

Near right: all-terrain vehicle (ATV) carrying gelled fuel for release from a drip torch along a designated ignition line.

Far right: a side-mounted launcher for deploying plastic spherical igniters for aerial ignition.

National Wildfire Coordinating Group

US National Park Service

Non-commercial ignition devices

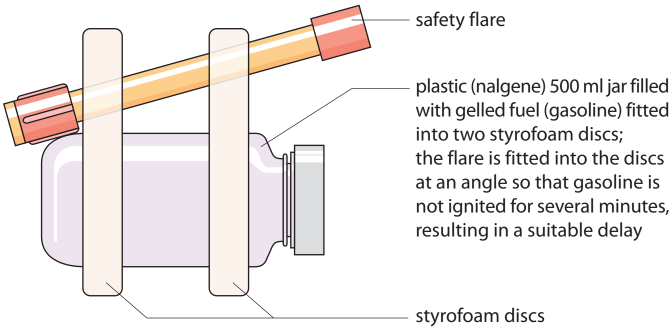
Simple and informal ignition methods such as oil-soaked paper, rags or sorbent have been used to ignite oil at actual and test spills. A variety of handheld igniters have been devised for igniting oil slicks. These devices:

- can be thrown into a slick from a vehicle, vessel or helicopter;
- often have delayed ignition switches to allow enough time to throw the igniter and, if required, allow it to float into the slick; and
- 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 ranging from 1,000 to 2,500°C.

It should be noted that diesel oil is much preferable to, and safer than, gasoline for soaking materials or for use as a base for the gelled fuels in handheld igniters.

An example of a handheld igniter, which has been used during several ISB tests, is illustrated in Figure 4, below. It consists of a plastic bottle filled with gelled gasoline or diesel fuel. The bottle and a standard 15-cm marine handheld distress flare are secured side by side within two polystyrene foam rings. The flare is lit and the device is thrown into the slick, where it burns for approximately 60 seconds before melting the plastic bottle and lighting the gelled gasoline, which in turn ignites the oil.

Figure 4 *An igniter constructed from a plastic jug and flare*



Source: Environment Canada

A similar device to that shown in Figure 4 was used to ignite the burns during the Macondo spill response. Such devices, which are relatively easy to make and to deploy, are shown in the photographs below.

US Coast Guard

US Coast Guard

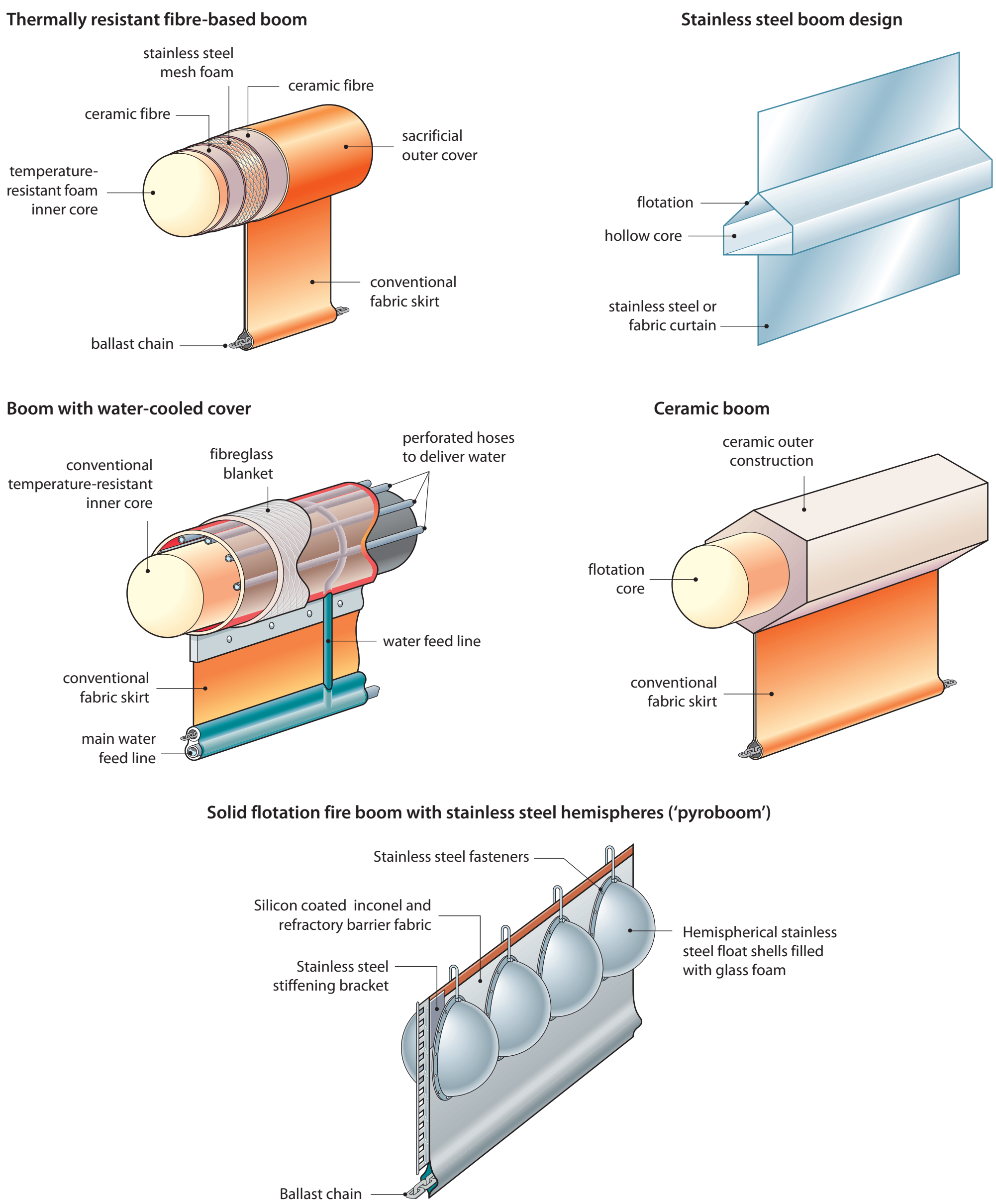
Far left: one of the igniters used in ISB operations during the Macondo spill response.

Near left: lighting the fuse (flare) of an igniter before releasing the device onto the water.

Fire-resistant booms

The primary requirement for a containment boom (and its components) used in ISB operations is the ability to withstand heat for long periods of time. Fire-resistant booms are generally designed to survive multiple burns, after which they are then disposed of, or refurbished. Several types of fire-resistant boom designs are shown in Figure 5 below. To ensure that the boom used in an ISB operation will be able to withstand multiple burns, a standard test has been devised by ASTM to assess durability. The minimum standard is a five-hour test involving three 1-hour burning periods with two 1-hour cool-down periods between the burning periods.

Figure 5 *Types of fire-resistant booms*



The containment ability of a fire-resistant boom is also important. Studies have determined the tow speeds at which booms begin to lose oil ('first loss') and the speed at which a continuous, significant loss occurs ('gross loss'). The rate of loss of oil can also be determined at specific tow speeds, as can the tow speed at which the boom physically fails, i.e. the speed at which the boom becomes submersed or suffers structural damage. Details on deployment and towing are provided in Appendix 2.

Conventional booms

A conventional boom cannot usually contain burning oil as the construction materials will either burn or melt, compromising the boom's ability to contain oil. Conventional booms can be used to corral a slick until a fire-resistant boom can be obtained, or they can be used as side extensions to a fire boom over longer towing distances.

Support vessels for ISB on water

Vessels play an important role in a successful ISB operation. Vessels are required to bring equipment and personnel to the burn site, to tow booms and to carry monitoring equipment. Barges and small boats may also be required for standby fire safety and monitoring operations, as well as being used for residue recovery and for storing equipment and residual oil.

A sufficient number of vessels must be available to transport and deploy the length of containment boom required at the burn site. Support vessels should also be appropriate for the task:

- Vessels must have a large enough deck space to carry the boom, as well as any equipment and materials required for handling the boom. They must also be able to move steadily and manoeuvre effectively at a slow speed (<0.5 m/s).
- A vessel with a low freeboard enables easier access to the water surface and is recommended for recovering burn residue. A barge or landing craft used in conventional oil spill response is ideal.

Support aircraft for ISB

Aircraft play an important role in successful ISB operations. Fixed and rotary wing (helicopter) aircraft can be used for surveillance and aerial photo-documentation of a spill site, and to provide an ignition platform, aid slick targeting for vessels or other aircraft, support burn extinguishing operations and carry monitoring equipment. For all aircraft operations, reliable air-to-ground communications are essential.

Aerial surveillance along the burn perimeter.

Minnesota Pollution Control Agency

Operational monitoring for safety and burn control

Monitoring helps to provide information on the effectiveness of a burn, and is an aid for vigilance regarding the safety of nearby responders and observation of fire control. Table 7 summarizes the key aspects of a burn operation that should be monitored.

Table 7 *Aspects to be monitored during ISB operations*

Aspect	Targets of observation	Interpretation
Fire safety	Proximity of personnel to the burn	Danger to humans, infrastructure and amenities
	Fire control and movement	
Fire boom containment integrity	Loss of a boom's ability to contain the slick	Provide early warning to vessel operators and responders
Burn effectiveness	Oiled area ignited and burning over time	Efficiency of oil removal; volume of oil removal
Burn emissions	Particulates	Monitor human exposure

Exposure of responders to heat

The safety and heat exposure limitations for responders must be thoroughly understood. A rule of thumb for responders is to stay back from a fire at a distance equivalent to four times the maximum flame height. The flame spreading rate is usually about 0.02–0.16 m/s; however, this rate can increase with wind. Other considerations include:

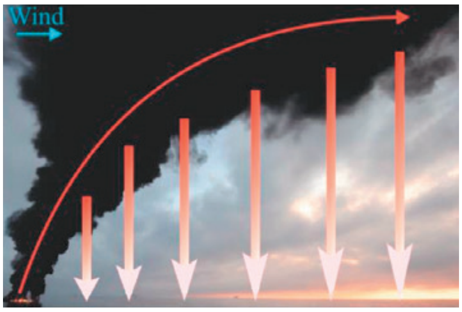
- On land, fires can move rapidly where combustible materials such as trees and grass are nearby. An adequate firebreak should be in place prior to ignition to provide fire control and protection against heat.
- Crews onboard vessels involved in tow operations can be in danger of being exposed to fire or flames if the fire should move up the boom. This could occur if thick patches of oil are encountered and the flame spreads along these thicker patches. The flames would not spread towards the towing vessels if the boom is moving at a speed of at least 0.4 m/s (0.7 knots) in an upwind direction. In highly variable winds, caution must be taken to ensure that thick concentrations of oil are not encountered at low boom-tow speeds.

The behaviour and distribution of ISB emissions

The primary health concerns related to ISB arise from the emissions produced by a burn. Empirical measurements of emissions reveal that their concentrations dissipate rapidly in the atmosphere and as the distance from the burn site increases. Ensuring that the burn remains at the minimum distance away from populated and sensitive areas will help to mitigate safety concerns. Emissions levels and safe distances downwind can be estimated for burns of various sizes and types. For example, a crude oil burn (500 m^2) would not generate concentrations of emissions that exceed health limits beyond around 500 m from the fire. The key combustion products that result from petroleum burns are predominantly carbon dioxide and water, and by-products, i.e. particulates (soot), organic compounds and gases.

Tracking the behaviour of burn emissions is an important aspect of ISB monitoring. The most important emissions are the soot particles (PM): these rise and are then are precipitated back to the ground (Figure 7). It is estimated that before a plume travels 1 km, half of any particles are precipitated downward (depending on wind speed). Some PM remains aloft with a smoke plume for a long time. The plume itself is not dangerous to humans as long as it rises in altitude and does not lead to exposure levels of concern.

Figure 7 *Behaviour of different combustion emissions in a burn plume*



a) *Particulates along with adsorbed organics, e.g. PAHs, rise and are then precipitated downwind.*

b) *Water vapour and light gases rise and are widely transported and diffused.*

Merv Fingas

c) *Carbon dioxide and other heavy gases rise and then slowly sink, and may cycle through the fire.*

d) *Organic gases, such as VOCs and carbonyls are widely diffused and diluted.*

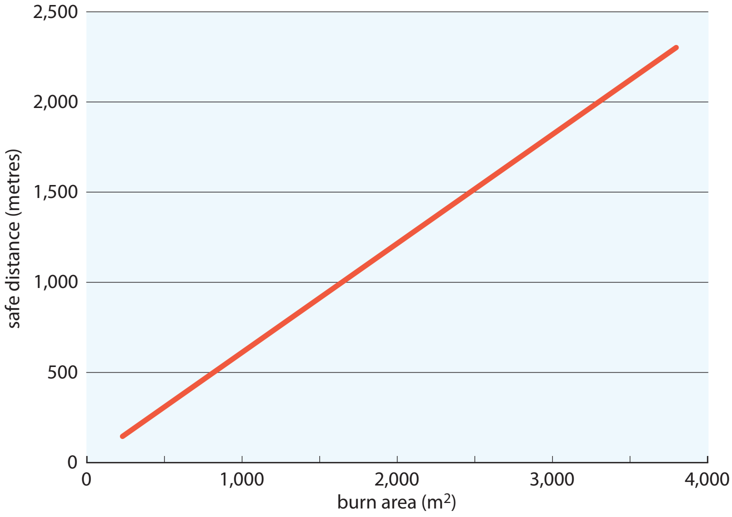
Particulate matter

ISB produces particulate matter, which is the primary emission of concern from an oil fire with respect to human health. Particulate matter is distributed exponentially downwind from the fire. Concentrations at ground level (1 m) can be above health concern levels (35 µg/m^3) even as far downwind as 500 m from a small crude oil fire. Of greatest concern are the smaller, or 'respirable', particulates, i.e. the $PM_{2.5}$ fraction (particles of size less than 2.5 µm). It should be noted that these particles are often not visible as a smoke plume even if concentrations are above threshold levels.

Safe distances

Sufficient data are available to predict concentrations for more than 150 individual compounds and for all the major chemical compound groups. The data have been collected with wind speeds between 2 to 5 m/s (4 to 10 knots) and with no inversions. The prediction equations for several common emission groupings and specific compounds are given in literature referenced in the *Bibliography* on page 39.

Figure 8 *Safe downwind distances for burn areas of varying sizes*



Safe distances downwind from a crude oil burn (based on $PM_{2.5}$ concentrations) have been estimated from several on-water test burns, during which winds varied from ~2 to 10 m/s (~4 to 20 knots)—see Figure 8. A safe operational distance is defined as the downwind distance after which no particulate respirators would be needed. Although the results are based on data from on-water burns, the distance estimates are also applicable to on-land burns, at the various burn sizes. However, it should be noted that:

- higher winds could increase these distances while lower-speed winds would decrease the distances; and
- these distances are not applicable during inversions because the smoke plume could be forced to ground level.

Monitoring and sampling for emissions

A well-planned monitoring programme, in which data are recorded before, during and after a burn, will help to document the burn operation and help to answer any questions arising after a burn operation. At the minimum, monitoring and sampling should include:

- visual monitoring of the smoke plume, its trajectory and its possible impacts on humans or sensitive environments (time and physical locations should be documented); and
- monitoring of 2.5 µm ($PM_{2.5}$) particulates downwind of the burn at a receptor height of 1.5 m, and in particular between 1 to 3 kilometres downwind of the burn, and at the receptor height, at any potential human impact locations.

Shifting weather conditions can dramatically change the precipitation of particulate matter in a plume. In some cases, a plume can drop to ground level. Weather officials should be consulted for forecasts of weather and wind, and for information on the potential for atmospheric inversion.

Visual monitoring

Visual monitoring of the trajectory of a smoke plume and its passage over land, population centres, and other points of concern should be noted, timed and recorded. This information is beneficial for answering questions on any potential for exposure to emissions from an in-situ burn. The prime areas of deposition should be surveyed after a burn to check for soot deposits. If soot is found, it should be sampled for possible analysis if deemed necessary.

Real-time particulate monitoring

If required by regulators, or if a forecasted burn plume trajectory indicates the potential for exposure of sensitive populations, real-time monitoring of emissions should be performed downwind of the fire and at a point closest to populated areas. Concentrations of particles downwind can vary over time, and a reading can exceed the recommended maximum value on one occasion and then be at baseline values the next. Background values should be measured and subtracted from the observed values. The instrument readings should be electronically recorded and time-weighted averages calculated from the recorded and corrected data. Some instruments provide running average readings which are applicable to real-time use. For monitoring of particulate matter, it is generally accepted that the concentration of particles having diameters of 2.5 µm or less ($PM_{2.5}$) should be less than 35 µg/m^3 over a 24-hour period. This is a standard used by several national authorities.

There are several methods for collecting and analysing samples to evaluate emissions from ISB. See the *Bibliography* on page 39 for sources of information on sampling emissions.

US National Park Service

Air quality monitoring station at Great Smoky Mountains National Park, North Carolina and Tennessee

Operational monitoring

The purposes of operational monitoring are:
- to guide successful ignition;
- to provide documentation of burn operations and burn progress;
- to estimate the area of oil burning at specific time intervals to estimate the total amount burned (The nomogram in Appendix 1 can be used to estimate the area of a burn and the volume of oil removed. Each burn location should be recorded at approximately 10-minute intervals for small, short burns. Larger, longer burn can have longer intervals. Photographs should be taken of burn operations at periodic intervals; use of a camera that has a time and GPS stamp is recommended);
- on land or shorelines—to assure the safety of burn crews and their vehicles; to track the trajectory of a smoke plume and its proximity to human habitation; and to enable advance alerts for danger and take action, as necessary (for example to instigate an evacuation or to extinguish a burn early);
- at sea—to provide direction to the towing vessel crews to optimize the encounter rate with spilled oil to increase the volume of oil collected in a fire boom for removal by ISB.

At sea, two surveillance tactics should be considered:
1. aerial surveillance; and
2. surveillance from a larger vessel.

There is a greater range of view from an aircraft than from a surface vessel; this may be advantageous when observing boom performance and burn operations. A larger, non-towing vessel can provide a good view of the tow operation from the water surface and could be equipped with extra fire monitors for firefighting capability. Such a vessel also provides a means of rescue if a towing vessel gets into difficulty.

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www.firelab.org/project/fofem

Appendix 1: Estimation of the amount of oil burned and the burn efficiency

At sea, the area of oil burning inside a boom is recorded along with the burn duration using a template similar to that shown Figure A1 on page 43. These details can be used to calculate the amount of oil burned. The area can be calculated from Figure A1 in conjunction with Table A1. Burn rates are listed in Table 3 on page 8.

The procedure is as follows:
Using the charts of the boom fills recorded during the burn, the fill area is estimated using Table A1. The time over which burning took place for this fill level is then multiplied by the burn rate for that type of oil (see Table 3) to give the amount of oil burned. All times and boom fill amounts are calculated this way and then summed; the final result provides an estimate of the amount of oil to be burned or consumed.

The volume of oil burned can be calculated using Equation 1, as follows:

Equation 1: **Burn volume = Area x time x rate x conversion factor**
where the conversion factor for metric units is **0.001** to give a volume in m^3, and in US customary units is **0.0006** to yield a volume in barrels (area in square feet, but burn rate in mm/minute).

Example:
During a burn, nomograms of the type shown in Figure A1 showed that, for 21 minutes, there was removal of approximately one half of a 150 m boom filled with medium crude oil.

- Using Table A1, it can be seen that the area is about 1,220 m^2, and Table 3 indicates that the burn rate is about 3.5 mm/min.
- The amount burned is thus calculated as: 1,220 x 21 x 3.5 x 0.001 = 89.7 m^3 (560 barrels).

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 using Equation 2 (below), where v_{oi} is the initial volume of oil to be burned and v_{of} is the volume of residual oil remaining after burning:

Equation 2:
$$E = \frac{v_{oi} - v_{of}}{v_{oi}}$$

The initial volume of oil, v_{oi}, can be estimated in a number of ways:

- If the spill source is known, as in the case of a vessel or storage depot, the volume spilled can be estimated from the tank size and the amount of oil remaining in the tank.
- In the case of an offshore rig, the discharge rate can be used to estimate the initial volume. This volume, combined with the slick area and an estimate of the average thickness of the oil, can then be used to estimate the volume of a slick.

In the case of burning at sea using a containment boom, the amount burned versus an estimate of the residue can constitute the inputs to Equation 2. Spills on land or marshes cannot be estimated in the above ways since much of material burned may be vegetation.

Figure A1 *Nomogram used to record burn areas and subsequently calculate burn areas*

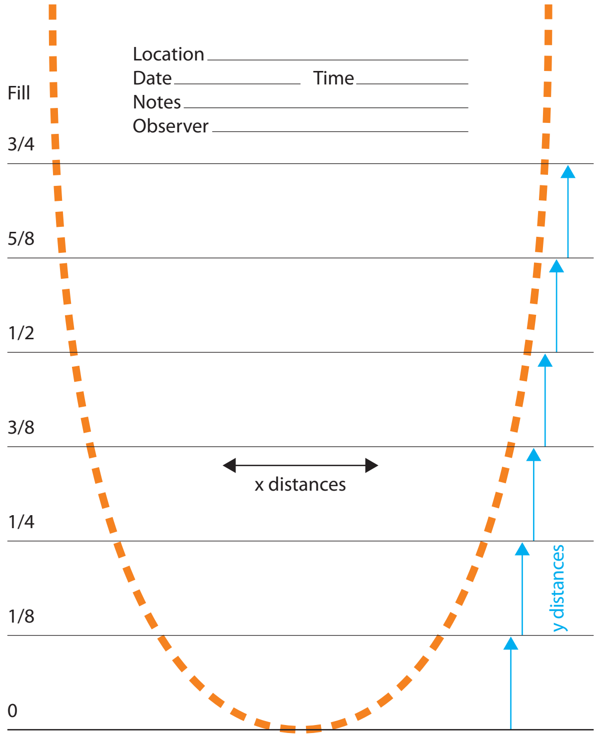


Table A1 *Boom fill-to-area conversions for a u-shaped boom*

a) Metric Units: Boom sizes = 150 m – 50 m opening and a 200 m – 66 m opening

Degree of fill		Length (m)	Width (m)	Burn area (m^2)	Length (m)	Width (m)	Burn area (m^2)
3/4	three quarters	51	48	2,020	68	64	3,590
5/8	five eighths	43	46	1,610	57	61	2,860
1/2	one half	34	44	1,220	45	59	2,170
3/8	three eighths	26	41	860	35	55	1,530
1/4	one quarter	17	38	530	23	51	940
1/8	one eighth	9	32	220	12	43	390

b) US customary units: Boom sizes = 500 ft – 166 ft opening and a 700 ft – 233 ft opening

Degree of fill		Length (m)	Width (m)	Burn area (m^2)	Length (m)	Width (m)	Burn area (m^2)
3/4	three quarters	165	156	21,000	231	218	41,200
5/8	five eighths	137.5	149	16,800	193	209	32,900
1/2	one half	110	142	12,700	154	199	24,900
3/8	three eighths	82.5	132	9,000	116	185	17,600
1/4	one quarter	55	122	5,500	77	171	10,800
1/8	one eighth	27.5	102	2,300	39	143	4,500

Appendix 2: Boom deployment and towing configurations

Deployment of booms for ISB

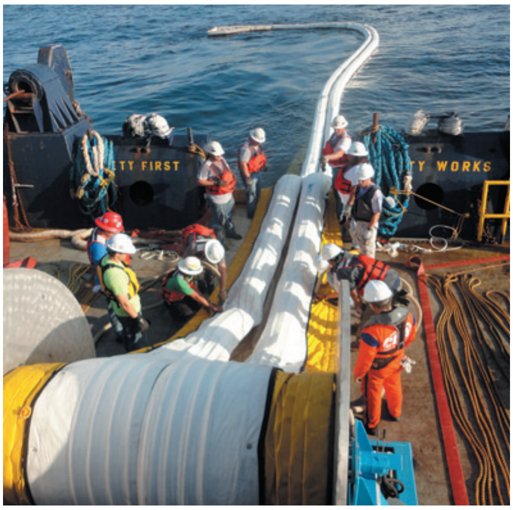
The deployment procedures for fire-resistant containment booms depend on the type of boom used. Water-cooled booms are typically inflatable and can therefore be stored on, and deployed from, a reel. However, these booms sometimes require a large deck space for the proper installation of the water-cooling equipment as the boom is removed from the reel.

Stainless steel booms and thermally resistant booms are rigid and therefore need to be stored in sections within a container. They will also require deck space to connect the sections during deployment. Because of their rigidity and weight, a winch or crane is normally required to assist in their deployment.

Booms can be damaged during deployment and recovery. Care must be taken to ensure that the boom is moved slowly and handled carefully. For example, the cinch and choker attachment of a crane can damage a boom and it is therefore better to use a web belt to lift the boom. The photographs below show different boom deployment methods.

Near right: deployment of a boom from the rear of a supply vessel.

Far right: deployment of a fire-resistant boom using a crane.



Elastec Inc.

Desmi-AFTI

Containment booms normally come in sections joined by a connector. Many fire-resistant booms are equipped with standard connectors or can accommodate adapters that can fit standard connectors. These connectors allow different types of booms to be joined together easily and securely. If more than one type of boom is used for containment, the connectors on these booms should be checked first to ensure that they can be properly joined.

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

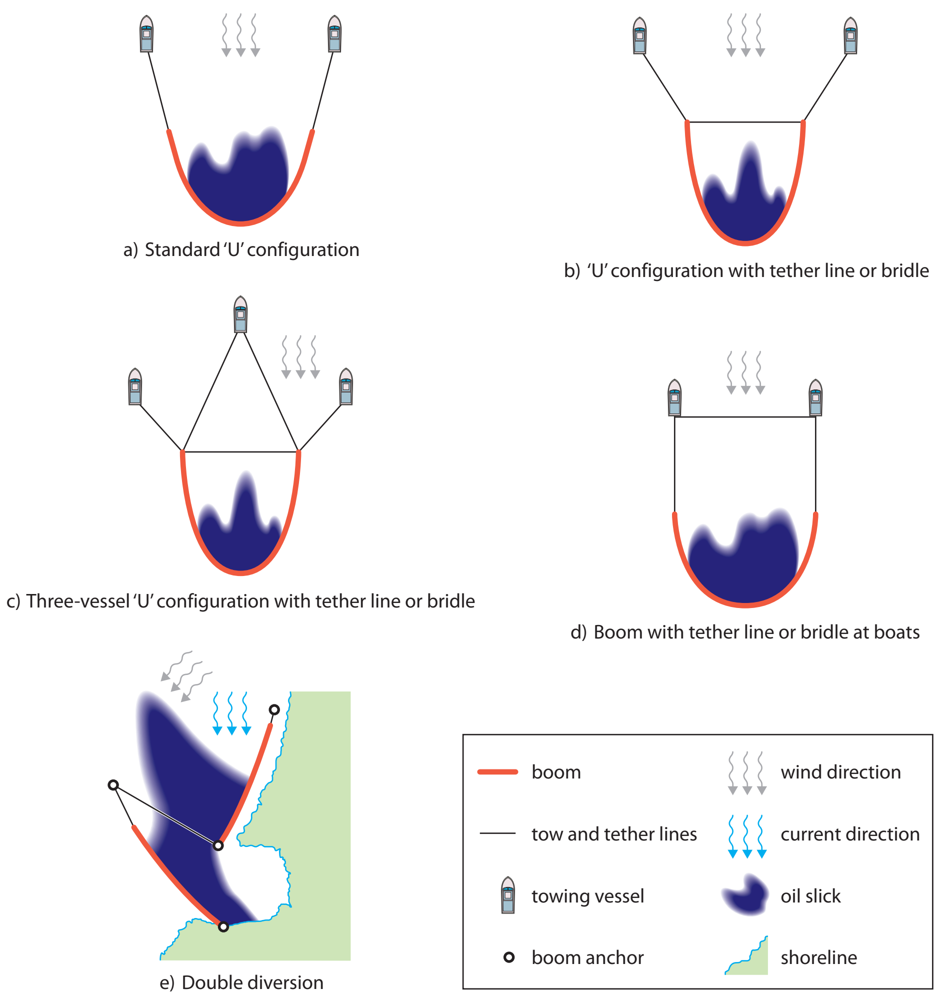
- The deployment vessel situates itself far enough downwind from the oil so that there is enough time to deploy the boom before approaching the oil.
- The deployment vessel aligns itself so that its bow is facing upwind.
- Before the first part of the boom is deployed from the deck, a tow line for the towing vessel is attached to the end.

- The boom is deployed from the vessel stern so that the wind causes the boom to trail behind.
- When the last section is deployed, the end of the boom is attached with a towline to the deployment vessel, which can then become one of the towing vessels. If another towing vessel is to be used, this towing vessel picks up the tow line from the deployment vessel.
- The tow line at the other end of the boom is then attached to the second towing vessel.
- The second towing vessel heads upwind until the proper U configuration is formed.

Fire boom towing configurations

The size of boom required for an in-situ burn depends on the amount of oil to be burned. In general, the length of boom used ranges from 150 to 300 m (500 to 1000 feet). Most commercial booms come in standard lengths of 15 or 30 m (50 or 100 feet). Generally, the oil in the boom should fill no more than two-thirds of the area of the catenary, the typical U shape that a towed oil boom takes (Figure A2).

Figure A2 *Tow configurations that can be used to tow fire-resistant booms*



a) Standard 'U' configuration

b) 'U' configuration with tether line or bridle

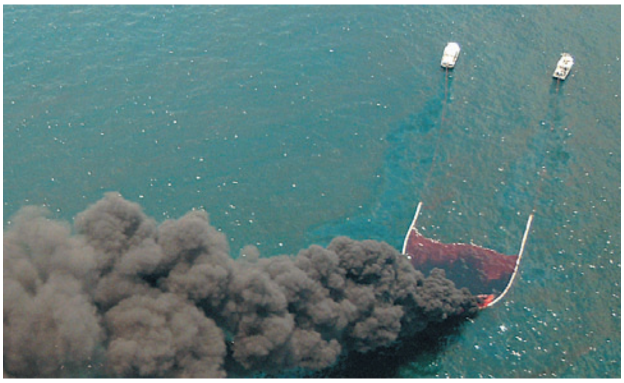
c) Three-vessel 'U' configuration with tether line or bridle

d) Boom with tether line or bridle at boats

e) Double diversion

Based on information courtesy of Environment Canada

An on-water in-situ burn within a fire-resistant boom deployed in the standard 'U' configuration.



Elastec Inc.

Tow lines from tow boats should generally be at least 75 m (150 feet) long. The boom should always be towed into the wind so that smoke will pass behind boats. 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.

In general, booms should be towed at a speed of <0.4 m/s (<0.7 knots) to prevent the oil from splashing over the boom or becoming entrained beneath. Additional considerations are described below:

- The standard boom configuration consists of 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 A2 (a).
- 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 A2 (b). This tether line or cross bridle is useful in maintaining the correct opening for the boom tow as well as preventing the accidental formation of a 'J' configuration.
- 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 A2 (c). 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.
- The tether line can also be attached to the vessels as shown in Figure A2 (d). The advantage of this method is that boat operators can detach the tether line very quickly in the case of an emergency.
- If the oil is nearshore, 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 A2 (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 would be held in place either by anchors, towing vessels or lines secured to the shoreline.

The towing speed may have to be increased periodically if a burn begins to fill more than two-thirds of the boom space. If contained oil becomes 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 uncontained oil could potentially be ignited by the burning oil inside the boom or by ignited oil that splashes over the boom.

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