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In Situ Burning for Oil Spills in Ice-Covered Waters

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Abstract

In situ burning is one of the few practical options for removing oil spilled in ice-covered waters. In many instances *in situ* burning, combined with surveillance and monitoring, may be the only response possible. As with all countermeasures in any environment, the suitability of burning a particular spill depends on the characteristics of the spilled oil and how the oil behaves in the particular ice conditions. There is an extensive body of knowledge concerning *in situ* burning of oil in ice situations, beginning with laboratory, tank and field studies in the mid-1970s in support of drilling in the Canadian Beaufort Sea. *In situ* burning research has been conducted primarily in Canada, Norway and the United States. This paper serves as a review of the subject, incorporating recent research results, summarizing the following topics:

$ The basic requirements and processes involved with *in situ* burning;
$ Trade-offs associated with burning in ice-covered waters;
$ How oil spill behavior in various ice conditions controls *in situ* burning;
$ The application of burning in various common ice situations;
$ *In situ* burning of oil spills in snow.

INTRODUCTION

The use of *in situ* burning as a spill response technique is not new, having been researched and employed in one form or another at a variety of oil spills since the late 1960s. *In situ* burning is especially suited for use in ice conditions, often offering the only practical option for removal of surface oil in such situations. Much of the early research and development on *in situ* burning focused on its application to spills on and under solid sea ice. Most recently, the research has addressed burning spills in loose pack ice. In general, the technique has proved very effective for thick oil spills in high ice concentrations and has been used successfully to remove oil resulting from pipeline, storage tank and ship accidents in ice-covered waters in Alaska, Canada and Scandinavia (Buist et al. 1994, Guénette 1997).

Although there have been numerous incidents of ship and oil well spills that inadvertently caught fire, the intentional ignition of oil slicks on open water has only been seriously considered since the development of fire-resistant oil containment boom beginning in the early 1980s. The development of these booms offered the possibility of conducting controlled burns in open water conditions. *In situ* burning operations using these booms have been conducted at three open water spills in North America in the 1990s: a major offshore tanker spill, a burning blowout in an inshore environment, and a pipeline spill into a river. The new generations of fire containment boom presently available commercially represent a mature technology: the best have been subjected to standardized testing that verifies their suitability and durability.

In situ burning of thick, fresh slicks can be initiated very quickly by igniting the oil with devices as simple as an oil-soaked sorbent pad. *In situ* burning can remove oil from the water surface very efficiently and at very high rates. Removal efficiencies for thick slicks can easily exceed 90%. Removal rates of 2000 m^3/hr can be achieved with a fire area of only about 10,000 m^2 or a circle of about 100 m in diameter. The use of towed fire containment boom to capture, thicken and isolate a portion of a spill in low ice concentrations, followed by ignition, is far less complex than the operations involved in mechanical recovery, transfer, storage, treatment and disposal. If the small quantities of residue from an efficient burn require collection (research indicates that burn residue is of low acute toxicity to marine organisms, but may smother benthic resources if it sinks), the viscous, taffy-like material can be collected and stored for further treatment and disposal. There is a limited window of opportunity for using *in situ* burning with the presently available technology. This window is defined by the time it takes the oil slick to emulsify; once water contents of stable emulsions exceed about 25%, most slicks are unignitable. Research has shown how it may be possible to overcome this limitation by spraying the slick with demulsifying chemicals.

Despite the strong incentives for considering *in situ* burning as a primary countermeasure method, there remains some resistance to the approach. There are two major concerns: first, the fear of causing secondary fires that threaten human life, property and natural resources; and, second, the potential environmental and human-health effects of the by-products of burning, primarily the smoke.

The purpose of this paper is to review the science, technology and ecological consequences of *in situ* burning as a countermeasure for oil spills in ice conditions. The main focus of this section is on marine oil spills; however, spills in snow are also covered (since many spills on ice will inevitably involve snow). Much of the content of this chapter is adapted from: an in-depth review of *in situ* burning produced for the Marine Spill Response Corporation (MSRC) (Buist et al. 1994) summarized and updated for IUPAC (Buist et al. 1999) and the USCG *In Situ* Burn Operations Manual (Buist et al. 2002). Interested readers are encouraged to refer to the original reports for fully referenced details of the summary presented here. The MSRC report is available from the American Petroleum Institute in Washington, DC and the USCG Manual is available from the USCG R&D Center in Groton, CT. Both documents are contained on a CD produced by NIST for MMS that contains a large number of the key references on *in situ* burning (Walton and Mullin 2003).

THE FUNDAMENTALS OF *IN SITU* BURNING

Requirements for ignition

In order to burn spilled oil, three elements must be present: fuel, oxygen and a source of ignition. The oil must be heated to a temperature at which sufficient hydrocarbons are vaporized to support combustion in the air above the slick. It is the hydrocarbon vapours above the slick that burn, not the liquid itself. The temperature at which the slick produces vapours at a sufficient rate to ignite is called the Flash Point. The Fire Point is the temperature a few degrees above the Flash Point at which the oil is warm enough to supply vapors at a rate sufficient to support continuous burning.

Heat transfer back to slick

Fig. 1 illustrates the heat transfer processes that occur during the *in situ* burning of an oil slick on water or ice. The rising column of combustion gases carries most heat from the burn away, but a small percentage (about 3%) radiates from the flame back to the surface of the slick. This heat is partially used to vaporize the liquid hydrocarbons that rise to mix with the air above the slick and burn; a small amount transfers into the slick and eventually to the underlying water. Once ignited, a burning thick oil slick reaches a steady state where the vaporization rate sustains the combustion reaction, which radiates the necessary heat back to the slick surface to continue the vaporization.

Flame temperatures and total heat fluxes

Flame temperatures for crude oil burns on still water are about 900° to 1200°C. But the temperature at the oil slick/water interface is never more than the boiling point of the water and is usually around ambient temperatures. There is a steep temperature gradient across the top layer of the slick; the slick surface is very hot (350° to 500°C) but the oil just beneath it is near ambient temperatures. Total heat fluxes generated by an oil pool fire are on the order of 100 to 250 kW/m^2 measured both inside and at the periphery of the fire. The higher heat flux values are associated with windy conditions that promote better combustion.

Importance of slick thickness

The key oil slick parameter that determines whether or not the oil will burn is slick thickness. If the oil is thick enough, it acts as insulation and keeps the burning slick surface at a high temperature by reducing heat loss to the underlying water. This layer of hot oil is called the "hot zone". As the slick thins, increasingly more heat is passed through it; eventually enough heat is transferred through the slick to drop the temperature of the surface oil below its Fire Point, at which time the burning stops.

The vigorous burning phase

In the final stages of burning, the “hot zone” approaches the water surface. The temperature of the layer of water directly beneath the slick, no longer insulated by a thick slick, increases. For slicks on calm water with no current, as may be the case in a drifting, pack ice cover, or in melt pools, the temperature of the underlying water can increase to the boiling point. When the water begins to boil, the steam vigorously mixes the remaining oil layer and ejects oil droplets into the flames. This results in increased burn rate, flame height, radiative output and foaming. This is called the "vigorous burning phase". This phenomenon has been observed in burns of oil on melt pools on sea ice in spring, but not when using a towed boom, probably because the water beneath the slick in the latter case does not stay there long enough to boil.

Effect of evaporation on slick ignition

Extensive experimentation on crude and fuel oils with a variety of igniters in a range of environmental conditions has confirmed the following “rules-of-thumb” for relatively calm, quiescent conditions:

- The minimum ignitable thickness for fresh crude oil on water is about 1 mm;
- The minimum ignitable thickness for aged, unemulsified crude oil and diesel fuels is about 2 to 5 mm;
- The minimum ignitable thickness for residual fuel oils, such as IFO 380 (aka Bunker “C” or No. 6 fuel oil) is about 10 mm; and,
- Once 1 m^2 of burning slick has been established, ignition can be considered accomplished.

Other factors affecting ignition

Aside from oil type, other factors that can affect the ignitability of oil slicks on water include: wind speed, emulsification of the oil and igniter strength. The maximum wind speed for successful ignition of large burns has been determined to be 10 to 12 m/s. For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water. Some crudes form meso-stable emulsions that can be easily ignited at much higher water contents. Paraffinic crudes appear to fall into this category.

Secondary factors affecting ignitability include ambient temperature and waves. If the ambient temperature is above the oil's flash point, the slick will ignite rapidly and easily and the flames will spread quickly over the slick surface; flames spread more slowly over oil slicks at sub-flash temperatures.

Flame spreading

Flame spreading is a crucial aspect of effective *in situ* burning. If the fire does not spread to cover a large part of the surface of a slick, the overall removal efficiency will be low. There are two ways in which flames spread across a pool of liquid fuel: radiant heating of the adjacent liquid oil warms it to its fire point; and, the hot liquid beneath the flame spreading out over the surrounding cold fuel.

As oil evaporation (or weathering) increases, flame spreading velocity decreases. This is because the difference between ambient temperature and the oil's flash point increases, requiring additional heating of the slick to raise the temperature of the surface of the slick. Flame spreading speeds increase with increasing slick thickness due to the insulating effect of the oil layer. For a constant slick thickness and flash point, increasing viscosity reduces flame-spreading speed. Downwind flame spreading increases with increasing wind speed. This is likely due to the bending of the flame by the wind enhancing heating of the slick. Flames tend to spread straight downwind from the ignition point without significant crosswind spread. Flame spreading upwind is slow, although the presence of a barrier or ice edge that provides a windbreak can permit rapid upwind or crosswind spreading. In general ignition of an oil slick should always take place along the upwind edge. The presence of current and regular waves (or swell) does not seem to affect flame spreading for unemulsified oils, but choppy or steep waves have been noted to curtail flame spreading.

Oil burning rates

The rate at which *in situ* burning consumes oil is generally reported in units of thickness per unit time (mm/min is the most commonly used unit). The removal rate for *in situ* oil fires is a function of fire size (or diameter), slick thickness, oil type and ambient environmental conditions. For most large (> 3 m diameter) fires of unemulsified crude oil on water, the "rule-of-thumb" is that the burning rate is 3.5 mm/min. Automotive diesel and jet fuel fires on water burn at a slightly higher rate of about 4 mm/min.

Flame heights

The thick, black smoke produced obscures flames from large oil fires making it difficult to accurately measure flame heights; however, the best available data suggests the following rules-of-thumb:

- For small and medium fires having diameters less than 10 m, flame heights are twice the fire diameter;
- For larger fires the ratio declines, approaching a value of one for very large fires.

Factors affecting residue amounts and burn efficiency

Oil removal efficiency by *in situ* burning is a function of three main factors: the initial thickness of the slick; the thickness of the residue remaining after extinction; and, the areal extent of the flame. The general rules-of-thumb for residue remaining after a successful burn are described below. Other, secondary factors include environmental effects such as wind and current herding of slicks against ice edges and oil weathering.

- for pools of unemulsified crude oil up to 10 to 20 mm in thickness the residue thickness is 1 mm;
- for thicker crude slicks the residue is thicker; for example, 3 to 5 mm for 50 mm thick oil;
- for emulsified slicks the residue thickness can be much greater; and,
- for light and middle-distillate fuels the residue thickness is 1 mm, regardless of slick thickness.

Wind and current can herd a slick against a barrier, such as an ice edge, thus thickening the oil for continued burning. As little as a 2 m/s wind is capable of herding oil to thicknesses that will sustain combustion. Indeed, the concept of "uncontained" *in situ* burning in pack ice conditions is based on the ability of a self-induced wind (drawn in by the combustion process and the rising column of hot gases), to "herd" and keep an uncontained slick at burnable thicknesses. Current can also dramatically increase burning efficiency (i.e., reduce the amount of burn residue) by herding burning oil against a barrier. The detrimental effects of current can include entrainment of residue beneath a floating barrier as the residue density and viscosity increase during the burn process, and over-washing of the burning slick, causing extinction of the flames. Excessive waves can also have a negative effect on the burning process.

The residue from a typical, efficient (>85%) *in situ* burn of crude oil up to 20 mm thick is a semi-solid, tar-like layer that has an appearance similar to the skin on an old, poorly sealed can of latex paint that has gelled. For thicker slicks, typical of what might be expected in a towed fire boom (about 150 to 300 mm), the residue can be a solid. The cooled residue from thick (e.g., >100 mm), efficient *in situ* burns of heavier crude oils can sink.

Effects of emulsification

Although the formation of water-in-oil emulsions is not as predominant a weathering process with spills in ice as it is for spills in open water, emulsions could be formed in some situations (i.e., a sub-sea blowout). The processes believed to be involved with *in situ* burning of water-in-oil emulsions are illustrated in Fig. 2. Emulsification of an oil spill negatively affects *in situ* ignition and burning. This is because of the water in the emulsion. Emulsion water contents are typically in the 60% to 80% range with some up to 90%. The oil in the emulsion cannot reach a temperature higher than 100°C until the water is either boiled off or removed. The heat from the igniter or from adjacent burning oil is used mostly to boil the water rather than heat the oil to its fire point.

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

For stable emulsions the burn rate declines significantly with increasing water content. The decrease in burning rate with increasing water content is decreased further by evaporation of the oil. The following rules-of-thumb summarize the effect of water content on the removal efficiency of weathered crude emulsions:

- Little effect on oil removal efficiency (i.e., residue thickness) for low water contents up to about 12.5% by volume;
- A noticeable decrease in burn efficiency with water contents above 12.5%, the decrease being more pronounced with weathered oils; and
- Zero burn efficiency for emulsion slicks having water contents of 25% or more. Some crudes form meso-stable emulsions that can be burn efficiently at much higher water contents. Paraffinic crudes appear to fall into this category.

Extinction of burning emulsions can be initiated by foaming action of the burning slick. The foaming is likely associated with the boiling of water. Burning emulsion slicks may foam and extinguish over one area of their surface, but be re-ignited later by adjacent flames. This can result in sudden and rapid flare-ups of flame near the end of an emulsion burn. Compared to unemulsified slicks, emulsions are much more difficult to ignite and, once ignited, display reduced flame spreading and more sensitivity to wind and wave action.

ENVIRONMENTAL AND HUMAN HEALTH RISKS

This section describes the main risks associated with *in situ* burning of spills and the safety measures used to overcome these risks. Much of the material in this section was developed for open water burn operations with towed fire boom, but is also applicable to burns in ice-covered waters. Humans and the environment may be put at risk by:

- The flames and heat from the burn;
- The emissions generated by the fire; and
- The residual material left on the surface after the fire extinguishes.

Fire and heat

Flames from *in situ* burning poses a risk of severe injury or fatality to both responders and wildlife. The threat is obvious and needs no elaboration. This section, then, focuses on the problem of the heat radiated by the burn. Risks exist both in normal operations and abnormal conditions such as tow vessel breakdown and boom failure. The risk to spill responders at the spill site is the main concern because the risks to the general public will be eliminated through the use of an exclusion zone surrounding the spill site.

Effects of heat on spill responders *In situ* burning of oil produces a large amount of heat that is transferred into the environment through convection and radiation. About 90% of the heat generated by *in situ* combustion is convected into the atmosphere. The remainder is radiated from the fire in all directions, but there is most concern with heat radiated towards responders, causing heat exhaustion and burns to unprotected skin. Of lesser concern is heat transferred downward which might affect water column resources.

The potential for causing injury to exposed workers is a function of both the level of incident radiation and the duration of exposure. Wood will char if positioned about half a fire diameter from the edge of an oil burn. The "safe approach distance" to an *in situ* oil fire for a person is from 2 to 4 times the diameter of the fire depending on the duration of exposure, as shown in Table 1.

Conservatively, it is assumed that the safe approach distance to the edge of an *in situ* oil fire is approximately 4 fire diameters**.**

It is important to recognize that the oil contained in a towed boom is relatively thick in the early stages of a burn and that this thickness is maintained through towing. If the towing were to stop or slow, or the boom were to break, this thick layer would spread quickly to cover an area several times that of the boomed oil. This will increase the fire diameter, the heat flux from the fire, and the need for workers to move further from the fire to avoid discomfort.

Environmental effects of heat Heat from the flames is radiated downward as well as outward and much of the heat that is radiated downward is absorbed by the oil slick. Most of this energy is used to vaporize the hydrocarbons for further burning, but a portion of the heat is passed to the underlying water. In a towed-boom burn or in a stationary boom situation in current, the water under the slick does not remain in contact with the slick long enough to be heated appreciably. However, under static conditions (the slick does not move relative to the underlying water - for example in a melt pool) the upper layer of the underlying water may be heated in the latter stages of the burn. In a prolonged static burn, the top few millimetres of the water column may be heated to near boiling temperatures, but the water several centimetres below the slick has been proven to be unaffected by the fire. The Alaska Regional Response Team, in their assessment of the impacts of *in situ* burning, has recognized that this heating may eliminate the small life forms that exist in the surface layer of water, but have concluded that the areas involved are small and that the lost biota will quickly be replaced, with negligible overall impact. The conclusion is that the environmental impact of the heat from an *in situ* burn is negligible.

Air emissions

Table 2 shows the components of the smoke from an *in situ* burn and their approximate proportions. (Recognize, however, that the composition of burn emissions varies with the type of oil burned and the size of the burn.) Smoke particulate is the main concern and is dealt with first in some detail.

Smoke The smoke plume emitted by a burning oil slick on water is the main concern. The concentrations of smoke particles at ground or sea level are of concern to the public and they can persist for a few miles downwind of a burn. The smoke plume is composed primarily of small carbon particles and combustion gases. Smoke particles cause the greatest risk in a plume. Carbon smoke particles are responsible for providing the characteristic black colour of the plume rising from a burn. The smoke is unsightly but more important; the smoke particles can cause severe health problems if inhaled in high concentrations. Smoke particulates and gases; however, are quickly diluted to below levels of concern. The amounts of PAHs in the smoke plume are also below levels of concern. Approximately 5 to 15 percent, by weight, of the oil burned is emitted as smoke particles.

Smoke particles are tiny specks of unburned carbon, and they vary greatly in size. From a human health perspective, the focus is on those particles that are small enough to be inhaled into the lungs, i.e., those smaller than 10 microns in diameter. These are referred to as PM-10s (PM stands for "particulate matter"). PM-10s make up approximately 90 percent of the mass of particulate emitted from an in *situ* burn. The national exposure standard that exists for PM-10s in the U.S. is the National Ambient Air Quality Standard (NAAQS), which states that PM-10 exposures of more than 150 micrograms per cubic meter (µg/m^3) averaged over a 24-hour time period can cause mild aggravation of symptoms in persons with existing respiratory or cardiac conditions and irritation symptoms in the healthy population. The NAAQS standard allows for concentrations to exceed 150 mg/m3 for hours at a time as long as the 24-hour average meets the standard; however, in the absence of any data, it was agreed to adopt a more conservative standard for *in situ* burn operations, requiring that concentrations averaged over 1 hour should not exceed 150 µg/m^3. In 1997, the U.S. Environmental Protection Agency (EPA) decided to add a PM-2.5 standard to the NAAQS. PM 2.5's make up approximately 55 percent of the particles emitted from an *in situ* burn. The PM-2.5 standard threshold is 65 µg/m^3 averaged over 24 hours. Some regions (specifically the Alaska RRT) have modified their *in situ* burn acceptance criteria on the basis of the PM-2.5 standard, using the same, conservative 1-hour exposure basis recommended for the PM-10 standard.

Particulate concentrations in the plume are greatest at the burn site, but they decline with increasing distance from the site, primarily through dilution, dispersion, and fallout, but also through washing out by rain and snow. Concentrations of PM-10 in a smoke plume are not easy to predict accurately because they are a function of many factors including soot yield, fire size, burn efficiency, distance downwind from the burn, terrain features, and atmospheric conditions (e.g., wind speed). The default adopted by the U.S. ensures smoke concentrations do not exceed the standard at downwind, populated areas by undertaking real-time monitoring of the plume. If this monitoring is not possible, the U.S. also allows for smoke plume trajectory models, with a safety factor applied, to be used to determine safe distances. Both the U.S. National Institute for Standards and Technology (NIST) and National Oceanographic and Atmospheric Administration (NOAA) have developed models to predict downwind smoke concentrations. These are sophisticated tools that require detailed spill and meteorological inputs and should be run by experts only. As an interim planning measure, general examples can be used as guides. NIST has developed a simple technique for roughly estimating the maximum distance downwind over flat or complex terrain for the concentration of soot in plumes from *in situ* burns to dilute and disperse below a given concentration. The distance beyond which the soot concentration falls below a given level depends mainly on the terrain height and the mixing layer depth relative to the elevation of the burn site, with wind speed being the next most important factor. Table 3 lists the approximate distances downwind over land for the ground-level PM-10 concentrations from 500 and 1,000 barrels per hour (bbl/hr) fires (these are equivalent to roughly 500 to 1000 m^2 (5,000 and 10,000 ft^2) fire areas, or fires that cover the back 1/4 and back 2/5 of a 500-foot, towed fire-resistant boom, respectively) to fall below 150 µg/m^3 for various terrain heights in winds from 2 to 25 knots (1 to 12 meters per second (m/s)).

If the plume passes over highly elevated terrain, the distances for the ground-level concentrations of PM-10 to decrease below 150 mg/m^3 are much greater than over flat terrain in equivalent meteorological conditions. The distance downwind for the smoke plume to dilute below 150 µg/m^3 would range from 0.5 nautical miles over flat terrain in a highly mixed atmosphere to 10 nautical miles over mountainous terrain in a very stable atmosphere. Low mixing-layer depths generally only occur at night. If the 65 µg/m^3 PM-2.5 criterion is to be applied, the mathematics of the NIST model show that the distances predicted in Table 3 should be increased by 1.5 nautical miles.

The atmosphere over water is generally less well mixed than over land and a good rule of thumb is that it takes about twice the distance over water to achieve the same decrease in smoke plume concentrations as it does over land, using the "Flat" terrain height category.

Mixing zone heights over large bodies of water are usually in the range of 150 to 300 m (500 to 1,000 feet).

Proximity to Shorelines, Towns, Airports, etc. Smoke plumes are also of concern because they obstruct visibility and, hence, may pose a safety hazard to operators of ships, aircraft, and motor vehicles in the immediate vicinity and downwind of the fire. Light scattering primarily causes the visibility reduction from the smaller smoke particles, in the 0.3 to 0.6 micron size range. A rough estimate of the visibility in a smoke plume (measured in statute miles) is 700 divided by the concentration of particulate in µg/m^3. For a concentration of 150 µg/m^3, the visibility will be about 5 miles; in a plume with a concentration of 500 µg/m^3, the visibility will be reduced to about 1 mile. It is unlikely that serious visibility effects will be caused at ground level if the appropriate upwind separation distances for PM-10 are maintained.

The smoke plume may also cause limited spatial and temporal aesthetic impacts. Even though the concentrations of particulate in the smoke plume are well below levels of concern, they can still be detected by the human nose and may cause concern in the public.

Based on very limited experience, birds and mammals are more capable of handling the temporary smoke plume than they are an oil slick. Birds flying in a smoke plume could become disoriented and suffer toxic effects; however, this risk is believed to be minimal when compared to oil coating and ingestion. The effects of *in situ* burning on marine mammals have yet to be observed; however, the effects of smoke on them is likely to be minimal, compared to the effects of contact with unburned oil.

Burn residue

As a general rule of thumb, the residue from an efficient burn of crude oil on water is environmentally inert. More specifically, the potential environmental impacts of burn residues are related to their physical properties, chemical constituents and tendency to float or submerge. Correlation between the densities of laboratory-generated burn residues and oil properties predict that burn residues will submerge in sea water when the burned oils have:

- Initial density greater than 0.865 g/cm^3 (API gravity less than about 32°) or
- Weight percent distillation residue (at >540°C) greater than 18.6 percent.

Burn residues usually submerge only after cooling. Based on modelling the heat transfer, it is likely that the temperature of a 1-cm thick burn residue will reach that of ambient water within approximately 20 to 30 minutes. Even for thicker slicks, it is likely that this cooling would occur within approximately 2 hours.

Physical properties of burn residues depend on burn efficiency and oil type. Efficient burns of heavier crudes generate brittle, solid residues (like peanut brittle). Residues from efficient burns of other crudes are described as semi-solid (like cold roofing tar). Inefficient burns generate mixtures of unburned oil, burned residues and soot that are sticky, taffy-like or liquid. Burns of light distilled fuels result in a residue that is similar to the original fuel but contains precipitated soot.

Chemical analyses of crude oil burn residues show relative enrichment in metals and the higher-molecular weight PAHs, which have high chronic toxicity but are thought to have low bioavailability in the residue matrix. Bioassays with water from laboratory- and field-generated burn residues of crude oil showed little or no acute toxicity to marine life. Localized smothering of benthic habitats and fouling of fishnets and pens may be the most significant concern when semi-solid or semi-liquid residues submerge. All residues -- whether they float or submerge -- could be ingested by fish, birds, mammals, and other organisms and may be a source for fouling of gills, feathers, fur, or baleen; however, these impacts would be expected to be much less severe than those manifested by exposure to a large, unconstrained oil spill.

BURNING SPILLS IN ICE AND SNOW

In-situ burning has been considered as a primary Arctic spill countermeasure since before the start of offshore drilling in the Canadian Beaufort Sea in the mid 1970's. Field trials at that time demonstrated that on-ice burning offered the potential to remove almost all of the oil present on the surface of landfast ice with only minimal residue volumes left for manual recovery. This area of research culminated in 1980 with a full-scale field research program on the fate and cleanup of sub-sea oil well blowouts under landfast sea ice.

Spills in Ice

Research in oil spill cleanup in pack, or broken, ice also began in the 1970's. Interest in the subject increased in the early 1980's because of proposals for offshore production in Alaska and Canada, and has become an international subject of R&D with the opening of Russian ice-covered waters for exploitation and the future potential for drilling in Norwegian ice-covered seas. Interest in the subject has been rekindled in Alaska with several recent offshore development proposals near Prudhoe Bay. Also, operators of established production facilities in Cook Inlet have an ongoing need to improve their level of understanding of alternative response strategies for spills in broken ice.

The consensus of the research to date on spill response in broken ice conditions is that *in situ* burning is a suitable response technique, and in many instances may be the only cleanup technique applicable (Shell et al. 1983, SL Ross 1983, SL Ross and DF Dickins 1987). A considerable amount of research was done on the potential for *in situ* burning in broken ice, including several smaller-scale field and tank tests (Shell et al. 1983, Brown and Goodman 1986, Buist and Dickins 1987, Smith and Diaz 1987, Bech et al. 1993, Guénette and Wighus 1996). Most of these tests involved large volumes of oil placed in a static test field of broken ice resulting in substantial slick thicknesses for ignition. The few tests in unrestricted ice fields or in dynamic ice have indicated that the efficacy of in situ burning is very sensitive to ice concentration and dynamics (and thus the tendency for the ice floes to naturally contain the oil), the thickness (or coverage) of oil in leads between floes, and the presence or absence of brash or frazil ice (which can sorb the oil). Brash ice is the debris created when larger ice features interact and degrade. Frazil ice is the “soupy” mixture of very small ice particles that forms as seawater freezes. Slush ice is formed when snow settles on open water.

The key to the success of an individual burn in a broken ice field is, in part, controlled by how well the oil is contained by the ice it is in contact with. Other factors include oil weathering processes (i.e., evaporation and emulsification) and mixing energy from waves. Field experience has shown that it is the small ice pieces (i.e., the brash and frazil, or slush, ice) that will accumulate with the oil against the edges of larger ice features (floes) and control the concentration (i.e., thickness) of oil in a given area, and the rate at which the oil subsequently thins and spreads.

Oil on Water among Pack Ice

In pack ice conditions the use of *in situ* burning is controlled, to a large degree, by the concentration and types of ice present. In general, the applicability of burning can be divided into three broad ice concentration ranges:

- Open water to 3 tenths;
- 3 to 6-7 tenths; and,
- 6-7 to 9+ tenths.

In the lowest range, the oil's spread and movement will not be greatly affected by the presence of the ice, and open water *in situ* burning techniques may be possible. This would generally involve the collection of slicks with fire boom operated by tow vessels, and their subsequent ignition. The ice concentration range from 3 to 6-7 tenths is the most difficult from an *in situ* burning perspective. The ice will reduce the spreading and movement of the slick, but not yet to the extent that it is containing the oil. The deployment and operation of booms in this ice concentration would be difficult, if not impossible. Untended booms could be deployed into the ice by helicopter, but the amount of oil that could be collected by this technique is unknown. In the highest ice concentrations, the ice floes are touching and contain the oil; if slicks are thick enough they can be burned effectively in these ice concentrations (SL Ross and Dickins 1987). Research completed last year (SL Ross and DF Dickins 2003) has shown that the following rules of thumb apply to burning thin slicks in broken ice conditions:

- The minimum ignitable thickness for fresh crude on frazil ice or small brash ice pieces is up to double that on open water, or about 1 to 2 mm.
- The minimum ignitable thickness for evaporated crude oil on frazil ice or small brash ice pieces can be higher than on open water, but is still within the range quoted for weathered crude on water, about 3 mm using gelled gasoline igniters.
- For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice. Wave action slightly reduces the burn rate on open water.
- The residue remaining on broken ice in calm conditions is about 50% greater than that on open water or 1.5 mm. The residue remaining on brash or frazil ice in waves is slightly greater than in calm conditions, at about 2 mm.

The combination of the minimum ignitable thickness rule of 3 mm for weathered oil, and the residue thickness rules infers that 3-mm slicks on brash or frazil ice can be burned *in situ* with removal efficiencies on the order of 50% in calm conditions and 33% in wave conditions. The actual thickness of an oil slick in ice conditions from a hypothetical sub-sea leak or blowout will, of course, depend on the flow rate of oil from the well or pipeline, the initial spreading of the oil droplets before they impact the ice and the rate at which the ice is drifting past the site. Whether the removal efficiencies predicted by the rules-of-thumb offer a net environmental benefit for a specific scenario is something that must be decided on a case-by-case basis.

In situ burning of oil spilled in pack ice during break-up will likely be easier than in the same ice concentration during freeze-up. In fall, the sea is constantly freezing, which generates significant amounts of slush ice which can severely hamper containment and thickening (naturally, or with booms) of slicks for burning; it is dark for much of the day, and it is cold, and only going to get colder with the onset of winter. During break-up, these is much less slush and brash ice present, the ice floes are deteriorating and melting, there is 24-hour daylight and the temperatures are warming.

Oil on Solid Ice

In-situ burning is the countermeasure of choice to remove oil pools on ice (created in the spring by vertical migration from an encapsulated oil layer or by drilling into an encapsulated oil lens in the ice sheet). There is a high degree of knowledge on the ignition and burning of oil on melt pools. For large areas of melt pools, helicopters deploying igniters would be used to ignite individual pools of oil. For smaller areas, manual ignition techniques could be employed.

Wind will generally blow oil on melt pools to the downwind ice edge, where it will be herded to thicknesses of approximately 10 mm. Individual melt pool burn efficiencies are thus on the order of 90%. The overall efficiency of *in situ* burning techniques in removing oil from the ice surface ranges from 30 to 90%, with an average in the 60 to 70% range, depending on the circumstances of the spill (e.g., melt pool size distribution vs. igniter deployment accuracy, film thickness, degree of emulsification, timing of appearance vs. break-up, etc.). For areas where the oil surfaces early in the melt, it could be possible to manually flush and/or recover remaining burn residue.

Winds and currents will herd oil in leads to the downwind edge, where it can be ignited and burned. In leads where a current herds the oil against an edge, very high removal efficiencies can be obtained.

Oil in Snow

In the case of oil spilled on the ice surface and mixed with snow, burning of oiled snow piles can be successfully achieved even in mid-winter Arctic conditions. Oiled snow with up to 70% snow by weight can be burned *in situ*. For higher snow content mixtures (i.e., lower oil content), promoters, such as diesel fuel or fresh crude, can be used to initiate combustion. For the lower concentrations of oil in snow, the technique of ploughing oiled snow into concentrated piles may be the only way of achieving successful ignition and burning. In many cases, waiting for the snow to melt could result in thin oil films incapable of supporting combustion and spread over a large ice area. For this pile technique, the oiled snow is scraped into a volcano-shaped pile, with the center of the "volcano" scraped down to the ice surface. A small amount of promoter is ignited in the center of the pile. The heat from the flames melts the surrounding inside walls of the conical pile, releasing the oil from the snow that runs down into the center and feeds the fire. This technique can generate considerable amounts of melt water, which needs to be managed.

TECHNOLOGIES FOR CONDUCTING *IN SITU* BURNS

A variety of methods are available to ignite an oil slick, including devices designed or modified specifically for ISB as well as simple, ad-hoc methods. This section describes the main types of ignition devices as well as techniques and materials that can be used to assist in the ignition process. Detailed specifications of commercially available igniter products are provided in the USCG Manual.

Two components are essential for the successful ignition of oil on water:

- Heating the oil to its flash point, such that sufficient vapors are produced to support continuous combustion
- Providing an ignition source to start burning.

For light refined products, such as gasoline and some unweathered crude oils, the flash point may be close to the ambient temperature and little if any pre-heating will be required to enable ignition. For other oil products, and particularly for those that have weathered and/or emulsified, the flash point will be much greater than the ambient temperature and substantial pre-heating will be required before the oil will ignite.

The choice of one igniter over another for a given application will depend mainly on two factors:

- Degree of weathering or emulsification of the oil, which will dictate the required energy level of the igniter
- Size and distribution of the spill, which will determine the number of ignitions required to ensure an effective burn.

Heli-torch

The Heli-torch was originally developed as a tool for burning forest slash and for setting backfires during forest-fire control operations. It was adapted for use in ISB in the mid-1980s and found to be an effective system for igniting spilled oil. The Heli-torch has been tested extensively, used in a number of field trials, and refined considerably over the years, resulting in its being viewed as the igniter of choice for ISB.

The Heli-torch emits a stream of gelled fuel, typically gasoline that is ignited as it leaves the device. The burning fuel falls as a stream that breaks into individual globules before hitting the slick, as seen during tests in Fig. 3. The burning globules produce a flame that lasts for several minutes, heating the slick and then igniting it. The globules' burn time depends upon the fuel used and the mixing ratio of the fuel and gelling powder. Although gasoline is the fuel typically used, alternatives such as diesel, crude oil, or mixtures of the three fuels have been found to produce a greater heat flux, and they should be considered for highly weathered oils and emulsions that may be difficult to ignite.

The key features of the Heli-torch are:

- Main components of the system are a storage drum to contain the gelled fuel, a pump and motor assembly and electrically fired propane jets
- System is mounted on a support frame that is slung beneath a helicopter and connected to controls in the helicopter cockpit.
- Gelled fuel is pumped on demand to the ignition tip, where the propane jets ignite it.

Using a gelling agent, which is a fine powder that forms a viscous gel when mixed with liquid, thickens the fuel. The gelling agent is added through an entry port of the storage drum, which is equipped with a hand crank for mixing. A ratio of 4 to 6 pounds of gelling agent per 55 gallons of fuel is typically used. The mixture is adequately gelled using this ratio after a few minutes of mixing at room temperatures. In near- or sub-freezing temperatures, a higher ratio and more mixing time are required to gel the fuel.

Handheld Igniters

A variety of igniters have been developed for use as devices to be thrown by hand from a vessel or helicopter. These igniters have used a variety of fuels, including solid propellants, gelled kerosene cubes, reactive chemical compounds, and combinations of these. Burn temperatures for these devices range from 650°C to 2500°C and burn times range from 30 seconds to 10 minutes. Most hand-held igniters have delay fuses that provide sufficient time to throw the igniter and to allow it and the slick to stabilize prior to ignition.

Three commercially available hand-helds are the Dome Igniter, the Simplex Model 901, and the ESSM Flare Type Igniter. Specifications and sources of supply of these devices are provided in the USCG Manual.

Ad-Hoc Igniters

For small, contained spills, simple ad-hoc techniques can be used to ignite the oil. For example, propane- or butane-fired weed burners have been used to ignite oil on water. As weed-burners or torches tend to blow the oil away from the flames, these techniques would only be applicable to thick contained slicks. Rags or sorbent pads soaked in fuel have also been successfully used to ignite small spills. Diesel is more effective than gasoline as a fuel to soak sorbents or rags because it burns more slowly and hence supplies more pre-heating to the oil.

Gelled fuel can also be used without the Heli-torch as an ad-hoc igniter. This was the method used for the test burn during the Exxon Valdez spill in 1989. Gasoline and gelling agent were mixed by hand in a plastic bag, and then the bag was ignited and allowed to drift into the slick contained within a fire-resistant containment boom.

Ignition Promoters

Ignition promoters are used to increase the ignitability of an oil slick or to promote the spreading of flame over the surface of a slick. Petroleum products, such as gasoline, diesel, kerosene, aviation gasoline, and fresh crude oil, have all proved effective as ignition promoters. Of these, the middle distillates, such as diesel and kerosene, are preferred because they burn more slowly and produce a higher flame temperature. Crude oil is also very effective as it contains a mixture of components.

Emulsion-breaking chemicals can also be considered as ignition promoters. The concept is to apply the chemical to emulsified oil to break the emulsion in-situ, thus increasing the likelihood of successful ignition. Large-scale tests have proven the feasibility of this approach and research to include emulsion-breaking chemicals in the fuel of the Heli-torch system has been undertaken. There are presently no demulsifiers on the U.S. approved list of chemicals for oil spill use; however, their use as combustion promoters (which are permitted) is not specifically excluded. Most of the demulsifiers and other ignition promoters will be consumed in the resulting fire.

When using an ignition promoter, it is important to distribute the promoter over as large an area as possible. Simply pumping it onto one location of the slick will create a thick pool of the promoter in one area and it will not promote ignition effectively.

Fire-resistant Boom

To achieve an effective burn in lower ice concentrations, boom is required to create and maintain an oil thickness that will burn efficiently. The two main requirements for a fire-resistant boom are to provide oil containment (floatation, draft, and freeboard) and to resist fire damage. This section provides a brief description of the main types of fire-resistant boom. Additional detailed specifications are provided in of the USCG Manual for products that are commercially available in the United States and that have been involved in recent fire-resistance testing.

Two main methods of providing fire resistance are used. Passive or intrinsically fire-resistant boom uses fire-resistant materials such as ceramic fibres or stainless steel. The active method keeps the boom materials within an acceptable range of temperatures by supplying coolant (usually water) to surfaces of the boom. Other ad-hoc methods of containment are also described at the end of this section.

A number of booms have been tested at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) and have been found to have similar containment limits as conventional boom, with first-loss tow speeds in the range of 0.85 to 1.0 knots when towed in calm water in a U-shape. Due to the weight of materials used for fire-resistance, the weight per unit length is generally much higher and the buoyancy-to-weight (b/w) ratio is much lower than for conventional booms of a similar size. Their lower b/w ratios means that they are generally not applicable for high sea states. Fire-resistant booms often require special handling, partly due to their higher weight and due to the use of materials that are less rugged than those used in conventional booms.

Tests to confirm fire resistance have been performed in recent years and the American Society for Testing and Materials (ASTM) International has developed a standardized test (F 2152-01). The test comprises three 1-hour burn cycles separated by two 1-hour cool-down cycles during which the boom is exposed to waves. The test is designed to simulate the stresses that a boom would receive in a typical burn scenario, where the boom is used alternately to collect oil and then contain it during a burn. A heat exposure is specified to simulate the effects of a crude oil fire; in the test either burning diesel or using a specially designed propane system that is available at OHMSETT and provides an equivalent heat can supply the specified heat. Booms are judged to have passed the test if they survive and can contain oil at the conclusion of the cyclic heat exposure.

Based on these tests, there is recognition that many fire-resistant booms have a limited life when exposed to fire, which means that an extensive ISB operation will require the periodic replacement of boom, depending on the intensity and duration of the burn.

Intrinsically Fire Resistant This type of fire boom relies on the use of fire-resistant materials to survive the effects of the burn. Two main approaches are used:

- Layers of ceramic fiber and/or stainless steel mesh surround a glass or ceramic-foam core
- Stainless steel sheet metal for the floatation chamber and all other above-water components.

The following are examples of intrinsically fire-resistant boom (listed alphabetically) that are commercially available in the United States and have been involved in recent fire-resistance testing. Any potential omission of fire boom currently on the market is not an indication that it will not be effective.

American Marine Fire Boom (Elastec/American Marine), formerly known as the 3M boom, consists of flotation sections made of rigid ceramic foam that is encased by two layers of stainless steel knitted mesh, a ceramic textile fabric and a polyvinyl chloride (PVC) outer cover. The PVC material also extends below the floats to form the skirt. A stainless steel tension cable provides strength immediately below the floatation element and a chain along the bottom of the skirt provides additional tensile strength and ballast.

Auto Boom Fire Model (Oil Stop) consists of several layers of fire-resistant material – stainless steel mesh and refractory matting – over a coated glass fabric floatation chamber. The skirt is made of a polyurethane fabric. A chain located at the bottom of the skirt, provides tensile resistance and ballast. The boom is stored on and deployed from a reel. The boom is inflated from one end as it is deployed.

PocketBoom (Applied Fabrics) consists of alternating floatation and connector sections and uses all stainless steel construction. The floatation sections are air-filled chambers at ambient pressure; these are joined by connector sections that are hinged, corrugated stainless steel attached with Navy-style connectors. An articulated box beam runs through the corrugated material to provide tensile resistance. A lifting frame and harness have been specially designed to ensure safe and effective launching and recovery.

PyroBoom (Applied Fabrics) has a freeboard constructed of a refractory material and a skirt made of a conventional urethane-coated material. Hemispherical stainless steel floats are attached to each side of the boom. Modular construction of the boom allows for its maintenance and repair in the field.

SeaCurtain FireGard (Kepner Plastics) uses a heavy-gauge stainless steel coil covered with a high temperature refractory material to make up the flotation sections of the boom. The skirt is made of a polyurethane-coated polyester or nylon fabric. The boom is designed to be stored on a reel, and as it is pulled off the reel during deployment, the stainless-steel coil springs from a flattened position and causes the boom to self-inflate.

Actively Water Cooled Actively cooled boom uses water (or other coolant) to cool the exposed surfaces of the boom and, thereby, increase the boom's fire resistance. Some boom designs in this category have relied on water simply being wicked into a protective layer, but the more common approach now is to actively pump water through a cover protecting the boom. Water is pumped from the tending vessel through a hose leading back to the boom. At the boom, various methods are used to distribute the water to cool key components.

The following are examples (listed alphabetically) of actively cooled fire-resistant boom that are commercially available and have been involved in recent fire-resistance testing. Any potential omission of fire boom currently on the market is not an indication that it will not be effective.

Hydro-Fire Boom (Elastec/American Marine) is a water-cooled, inflatable boom that is designed to be stored on and deployed from a reel. The boom is constructed much as a conventional curtain boom, but a fire-protection layer blankets the above-water portion. A chain located at the bottom of the skirt, provides tensile resistance and ballast. During use, water is actively pumped through the fire-protection layer, saturating and cooling the boom.

Water-Cooled Fire Boom (Oil Stop) is an inflatable boom with an internal water-cooling system. The flotation chamber is insulated with a ceramic blanket covered with a stainless steel mesh. The skirt is made of a polyurethane fabric. During use, seawater is pumped from the towing vessel to the boom. Within the boom, a series of hoses circulates the water through the porous cover of the boom to cool it and allow it to withstand the effects of the fire. A chain located at the bottom of the skirt, provides tensile resistance and ballast. The boom is designed to be stored on and deployed from a reel.

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TABLE 1. Safe Approach Distances for *In situ* Oil Fires

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

TABLE 2. Airborne Emissions from an In Situ Oil Fire on Water

Constituent	Quantity Emitted [b], (kg emission/kg oil burned)
carbon dioxide (CO_2)	3
particulate matter	0.05 - 0.20[c, d]
carbon monoxide (CO)	0.02 - 0.05
nitrogen oxides (NO_x)	0.001
volatile organic compounds (VOC)	0.005
polynuclear aromatic hydrocarbons (PAH)	0.000004

[a] updated from ref. 1 based on Kuwait pool fire (Allen and Ferek 1993) and NOBE data (Ross et al. 1996)

[b] Quantities will vary with burn efficiency and composition of parent oil

[c] for crude oils soot yield = 4 + 3 lg(fire diameter); yield in mass %, fire diameter in cm (Fraser et al. 1997)

[d] Estimates published by Environment Canada are considerably lower, ca. 0.2 to 3% for crude oil (Fingas 1998)

TABLE 3. Estimates for Maximum Downwind Extent of PM-10 Particulates*

Fire Size (ft^2)	Terrain Height (ft)	Maximum Distance (nautical miles) Downwind for PM-10 Concentration to Reach 150 μg/m^3 at Ground Level for Given Mixing Layer Depth Ranges**				
		0 to 350 ft	**350 to 825 ft**	**825 to 1,650 ft**	**1,650 to 3,300 ft**	**>3,300ft**
5,000	0 to 80 (Flat)	2	2	1.5	1	0.5
	80 to 825	4	3.5	2.5	2	1
	825 to 1,650	6.5	5	4	3.5	2
	> 1,650	8.5	7.5	6.5	5	4
10,000	0 to 80 (Flat)	2.5	2	1.5	1	0.5
	80 to 825	5	4	3	2	1.5
	825 to 1,650	8	6	5	4	2.5
	> 1,650	10	9	8	6	5

* Valid for wind speeds from 2 to 25 knots.

** Mixing layer depths loosely correspond to atmospheric stability class ranges as follows: Stability Class C ≈ 660 to 1,000 ft; Stability Class D ≈ 500 to 660 ft.

Figure 1. Heat and mass transfer processes involved in *in situ* burning.

Figure 2. Emulsion burning processes.

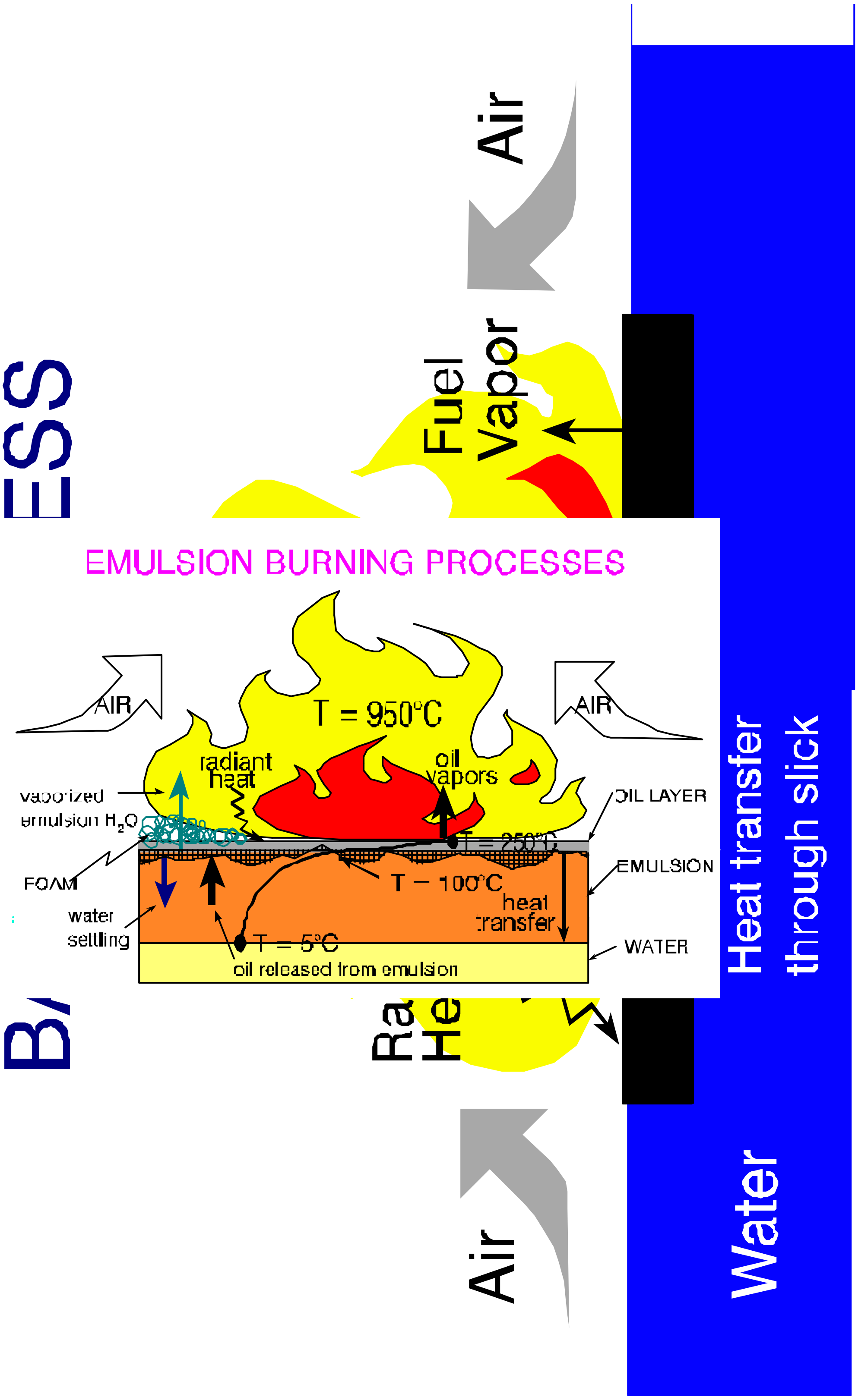

Figure 3. Heli-torch and fire resistant boom tests.