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U.S. Coast Guard and Minerals Management Service sponsored fire-resistant oil spill containment boom performance test using a non-commercial test boom at the Coast Guard Fire and Safety Test Detachment, Mobile, AL, August 1997. William D. Walton, Photographer.

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## WINDOW OF OPPORTUNITY FOR *IN SITU* BURNING

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### INTRODUCTION

Thick, fresh slicks can be ignited very quickly 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<sup>3</sup>/hr can be achieved with a fire area of only about 10,000 m<sup>2</sup> 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, followed by ignition, is far less complex than the operations involved in mechanical recovery, transfer, storage, treatment and disposal. However, there is a limited window of opportunity for using *in situ* burning with the presently available technology. This window is partly defined by the type of oil spilled and its evaporation rate; the prevailing meteorological and oceanographic conditions; and, the time it takes the oil slick to emulsify. Once water contents of stable emulsions exceed about 25%, most slicks are unignitable.

The purpose of this paper is to review the current knowledge of limitations imposed by oil slick properties, weather and sea conditions and operational/equipment factors on the use of *in situ* burning as a countermeasure for oil spills on water. Environmental impact limitations are not discussed. Much of the content of this paper is updated from an in-depth review of *in situ* burning produced for the Marine Spill Response Corporation (MSRC) in 1994[1]. Interested readers are encouraged to refer to the original report for fully-referenced details of the summary presented here.

### THE FUNDAMENTALS OF *IN SITU* BURNING

#### Requirements for Ignition

In order to burn oil spilled on water, 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. There are two properties of an oil that are often used as an indication of its ignitability: flash point and fire point. 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

Most heat from a burning oil slick is carried away by the rising column of combustion gases, but a small percentage (about 1% to 3%) radiates from the flame back to the surface of the slick. This heat is partially used to vaporize the liquid hydrocarbons which 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

Flame temperatures for crude oil burns on water[2] are about 900 °C 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 thickness of the slick; the slick surface is very hot (350 °C to 500 °C) but the oil just beneath it is near ambient temperatures.

## 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 to the water; eventually enough heat is transferred through the slick to allow the temperature of the surface oil to drop below its fire point, at which time the burning stops.

## 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.

## Factors Affecting Quantity of Residue and Burn Efficiency

Oil removal efficiency is a function of three main factors: the initial thickness of the slick; the thickness of the residue remaining after extinction; and, the areal coverage 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 barriers and oil weathering.

The following rules-of-thumb apply for the residue thickness at burn extinction:

- for pools of unemulsified crude oil up to 10 mm to 20 mm in thickness the residue thickness is 1 mm;
- for thicker crude slicks the residue is thicker, for example, 3 mm 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.

The residue from a typical, efficient (>85%) *in situ* burn of crude oil 10 mm to 20 mm thick is a semi-solid, tar-like layer that has an appearance similar to the skin on a 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 mm to 300 mm), the residue can be a solid. The cooled residue from thick (>100 mm), efficient *in situ* burns of heavier crude oils can sink in fresh and salt water[3] .

### 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. The reason for this is that the difference between ambient temperature and the oil's flash point increases, requiring additional heating to raise the temperature of the slick surface. 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 edge that provides a wind break can permit rapid upwind or cross-wind spreading. 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.

## LIMITATIONS TO SUCCESSFUL *IN SITU* BURNING IMPOSED BY SLICK PROPERTIES

### 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, volatile crude oil on water is about 1 mm;
- the minimum ignitable thickness for aged, unemulsified crude oil and diesel fuels is about 2 mm to 5 mm;
- the minimum ignitable thickness for residual fuel oils, such as Bunker “C” or No. 6 fuel oil, is about 10 mm; and,
- once 1 m<sup>2</sup> of burning slick has been established, ignition can be considered accomplished.

### Other Factors Affecting Successful 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. Secondary factors include ambient temperature and waves.

- The maximum wind speed for successful ignition of large burns has been determined to be 10 m/s to 12 m/s.
- 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.

### Effects of Water-in-oil Emulsion Formation

Emulsification of an oil spill negatively affects *in situ* ignition and burning. This is because of the water in the emulsion. Stable 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 the adjacent burning oil is used first 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. Chemicals called "emulsion breakers", which are common in the oil industry, also may be used.

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

- 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 stable 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[4].

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.

#### Emulsion Breakers

The idea of applying emulsion breakers to a slick to break the emulsion *in situ*, remove water, and extend the window of opportunity for successful ignition of the slick is being actively researched. Recent large-scale tests in Alaska[5,6], the U.K.[7] and Norway[8,9] indicate that the technique shows great promise, although there is strong evidence that the technique is highly oil-specific and surfactant-dependant.

A recently-completed study of emulsion burning with Alaskan oils[6] is summarized below to illustrate the potential for chemical treatment to extend the window of opportunity for *in situ* burning and the challenges remaining.

Four oils were selected for an initial set of quiescent laboratory test burns (40 cm diameter): Drift River crude from Cook Inlet, Endicott and Pt. McIntyre crudes from the North Slope, and IF-30, a common bunker fuel for vessels. As expected, the ignition and burning of all four oils was limited by the formation of water-in-oil emulsions. As has been noted in other studies[10,11], the burning of emulsions *in situ* was found to be oil-specific, with some oils (e.g., Drift River - see Table 1 below) being much easier to ignite and burn than others (e.g., Pt. McIntyre). Evaporation also appeared to play a strong role in emulsion burning; increased weathering decreased ignitability and burn efficiency. Increased water content also reduced ignitability, oil burn rate and burn efficiency. The application of chemical breakers to emulsions of the four oils extended the limits of ignition and burning. The efficacy of emulsion breaker addition in extending the limits of ignition and efficient burning appeared to be oil-related. The use of an emulsion breaker considerably extended the limits for some oils (e.g., Drift River) but only had a marginal effect on others (e.g., Pt. McIntyre).

Table 1: Efficacy of emulsion breaker addition summary

Oil Type	Maximum Ignitable (% weathered/% water)	Maximum Ignitable with Emulsion Breaker Added (% weathered/% water)
Drift River crude	35.4% evap. / 25% H <sub>2</sub> O	35.4% evap. / 60% H <sub>2</sub> O
Endicott crude	fresh / 25% H <sub>2</sub> O	9.1% evap. / 60% H <sub>2</sub> O
Pt. McIntyre crude	fresh / 25% H <sub>2</sub> O	fresh / 40% H <sub>2</sub> O 18.2% evap. / 25% H <sub>2</sub> O
IF-30 fuel oil	fresh / 25% H <sub>2</sub> O	fresh / 40% H <sub>2</sub> O
Milne Pt. crude		
- lab scale	40.7% evap. / 60% H <sub>2</sub> O	40.7% evap. / 60% H <sub>2</sub> O
- mid scale	27.6% evap. / 60% H <sub>2</sub> O	27.6% evap. / 60% H <sub>2</sub> O
ANS crude		
- lab scale*	28% evap. / 25% H <sub>2</sub> O	28% evap. / 60% H <sub>2</sub> O
- mid scale	20.4% evap. / 25% H <sub>2</sub> O	20.4% evap. / 60% H <sub>2</sub> O

*In situ* burning of emulsions also was sensitive to ambient temperature. Generally, at higher temperatures, ignition of emulsions became easier and burn efficiency increased. This effect appeared to be oil-specific as temperature increases had large effects on the burning of emulsions of some oils (e.g., Drift River and Endicott) but almost no effect on others (e.g., Pt. McIntyre).

For the lab-scale burns (40 cm diameter) in wave conditions of normally unignitable emulsions of ANS, the addition of a chemical breaker was successful in promoting emulsion ignition. Manually mixing the emulsion breaker chemical was found to be somewhat more effective than the natural mixing of the emulsion breaker with wave action alone. The results indicated that mixing energy supplied either manually or by the waves was necessary for the chemical to work.

The small-scale lab tests with the Milne Pt. crude revealed that it has a low to moderate tendency to form emulsions and their tendency and stability increased with degree of weathering; it responded well to treatment with emulsion breakers; it was highly ignitable and burned readily, even at high degrees of weathering and with high emulsion water contents; and, it burned well in waves.

The mid-scale (1.7 m diameter) burn tests, in a newly-constructed wave tank in Prudhoe Bay, showed that larger oil and emulsion slicks of ANS and Milne Pt. crudes could be successfully burned in waves. Emulsified slicks of ANS crude with water contents greater than 25% required treatment with emulsion breakers and a period of settling for successful ignition and efficient burning. The Milne Pt. emulsions ignited and burned easily without treatment. A mid-scale test slick of 60% water emulsion of weathered ANS crude was successfully burned in the highest waves tested, with an oil removal efficiency of 79%, after treatment with emulsion breakers. A similar test slick of 60% water emulsion of weathered Milne Pt. crude was successfully burned in the highest waves tested, without the need for treatment with emulsion breakers, with an oil removal efficiency of 83%. At this larger scale, increasing wave steepness (or wave energy) appeared to reduce both burn rates and burn

efficiencies of the unemulsified oil slicks. For emulsified slicks, increasing wave steepness did not appear to appreciably affect the oil burning rates, but did reduce the oil removal efficiencies.

The results of this research have indicated that the concept of applying emulsion breakers to extend the window of opportunity for *in situ* burning still has merit. It is clear that the efficacy of the technique is dependant on oil type and degree of weathering. It was also dependant on the specific emulsion breaker used.

The results of the study are not, in themselves, sufficient to conclude that the operational use of emulsion breakers offshore is feasible. In order to implement emulsion breaker addition as a technique to extend the window of opportunity for *in situ* burning (ISB) operations offshore several areas still need to be researched. These include:

- exploring the regulatory regimes covering the application of emulsion breakers to oil slicks, and, if required, obtaining approval for specific chemicals being considered for ISB;
- investigating and developing systems for the application, and perhaps mixing, of emulsion breakers at dose rates on the order of 1:500 onto contained slicks at sea;
- conducting large-scale trials in realistic wave conditions (i.e., on the order of 0.6 m to 1 m high) to fully prove the operational feasibility of burning water-in-oil emulsions *in situ*. Although ideally these trials should be conducted at sea, tests in a large pit or other water body could serve as a substitute. These tests are necessary to confirm that in an offshore environment the emulsion breaker can be applied and work effectively over a large area of slick; that the flames will spread from an area ignited with a heli-torch to cover the entire slick; and, that an efficient burn will result that removes a significant amount of the oil.

Other research programs underway on the subject of burning water-in-oil emulsions *in situ* include small-scale testing of a number of crude oils produced on the Outer Continental Shelf of the United States to determine their burning characteristics[10,11], studies of the fundamentals of emulsion burning[12], and studies of the ignition and flame spreading characteristics[13] of emulsions.

#### LIMITATIONS TO *IN SITU* BURNING IMPOSED BY OPERATIONAL CONSTRAINTS

There are two basic scenarios for the application of controlled *in situ* burning in spill response operations: the "batch" mode and the "continuous" mode. The "batch" mode consists of six discrete steps: 1) oil is collected in a section of fire-resistant boom towed by two vessels until the back third of the boom is filled; 2) the filled boom is manoeuvred to a safe distance crosswind; 3) the contained oil is ignited; 4) the oil is burned and then extinguishes; 5) the residue is collected, if necessary and the boom inspected for damage, and replaced if necessary; and, 6) the boom is maneuvered back into the slick to begin collecting the next batch of oil.

In the "continuous" mode the fire-resistant boom is positioned a safe distance down drift from a continuing oil leak, such as a blowout, and oil is burned continuously or intermittently as it accumulates in the back of the boom. An alternative to controlled burning is the ignition of uncontained oil slicks that are thick enough to support combustion.

### Capabilities and Limitations

The oil removal rate for the "batch" mode is constrained by the rate at which the towed boom can encounter oil (estimated from the tow speed--a maximum of 0.35 m/s, the width of the mouth of the boom and the average thickness of the slick through which the boom is being towed); and, the time required to manoeuver the boom to a safe area, ignite and burn the oil, recover the residue, inspect and perhaps replace the boom, and return to the oil collection area[14]. The oil removal rate for the "continuous" mode is constrained by the rate at which the boom system collects the leaking oil and the ability to keep the boom on station in the oil slick.

There is limited data on the effects of sea state on *in situ* burning. What little experience exists suggests that the sea-state limit for effective burning is from 1 m to 2 m significant wave height or less. Of course, burning will not be effective if the fire boom fails to hold oil in these sea conditions.

Winds of approximately 30 km/hr to 40 km/hr are considered to be the upper limit for ignition of oil pools in the absence of waves. These constraints reflect both the current state-of-the-art in proven ignition and fire containment booms systems, as well as the environmental conditions under which most oils will be quickly weathered beyond a combustible state.

Another important environmental factor controlling burning is the presence of good visibility. For a safe and effective burn to take place it should be possible to see 1) the oil to be collected, 2) the vessels towing the fire containment booms, and 3) the proximity of the intended burn location relative to the spill source, other vessels in the area, and other potentially ignitable slicks. As a guide, VFR (visual flight rules) flying conditions (greater than 4 km visibility and a minimum 300 m ceiling) could be used. If helicopters are to be used, VFR flying conditions must exist both at the site and at the helicopter base. If burning is to be conducted at a remote, fixed, continuous source of spilled oil (e.g., an offshore blowout), it may be feasible to burn spilled oil safely at or near the source during limited visibility conditions (e.g., less than VFR flying conditions, dusk, dawn, etc.).

### THE FUTURE

*In situ* burning is a potentially valuable tool for oil spill response. If used prudently, it can make a significant contribution as one facet of an overall spill response operation. For spills in ice-covered waters it may be the only removal option. Although a considerable body of knowledge exists on the use and impacts of *in situ* burning, continued research is warranted, particularly on better understanding the fundamentals of emulsion burning; developing catalogues of the *in situ* burning characteristics of various oils; the use of emulsion breakers to extend the window of opportunity; and, developing better, longer-service-life fire containment booms.

Most importantly, *in situ* burning needs to be used on real spills; it is only through operational usage that practitioners will gain the knowledge to ascertain the place of burning in an overall oil spill response.

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