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## IN-SITU BURNING OF OIL SPILLS - AN OVERVIEW

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### Introduction

In-situ burning is an oil spill cleanup technique that involves controlled burning of the oil at or near the spill site. While it has been tried over the last 30 years, it has only recently been accepted as an option for cleaning up oil spills in some countries.

The reluctance to use burning as a cleanup option despite some obvious advantages is largely because the combustion products produced when oil is burned and the principles governing the combustibility of oil on water have been poorly understood. There are still several barriers to the full

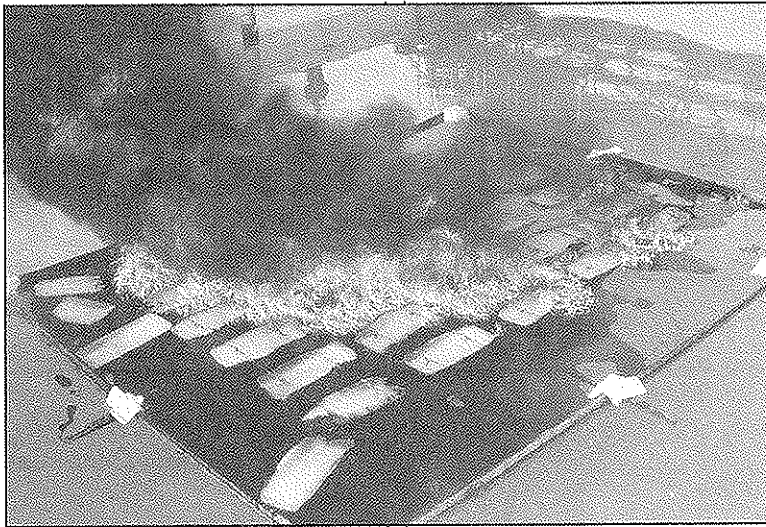
acceptance of burning, especially concern over emissions and the ability to retain oil slicks that are thick enough to burn.

The history of burning is full of reversals, re-directions, and re-inventions. Often a concept for ignition or containment reappears on the market or on a research list years after its initial introduction.

Unfortunately, progress has been sporadic over the years and efforts have often been

misplaced on concepts or theories that yielded no benefit to the practical application of burning. In other words, the more interesting approaches usually win out for funding, often at the cost of advancement in the field. This is primarily due to the interdisciplinary nature of the oil spill field and the fact that researchers and engineers are often unaware of findings and concepts in each other's areas of expertise. This has led to a fragmented approach.

**This article provides an overview of the use of in-situ burning as an oil spill cleanup option. It reviews the history and state of the art in burning and looks at what is known and what remains to be researched. Other topics covered include the emissions produced when oil is burned, ignition, burn efficiency and burn rate, and burning techniques. The focus is on advancements and progress over the years and not on the difficulties.**



*In 1984, tests of oil burning in ice were conducted at the OHMSETT facility in New Jersey.*

## Philosophy and Use of Burning

Outside of Arctic regions, there has not been much deliberate burning of oil spills. Several reviews contain histories of deliberate and accidental burns (Thompson et al., 1979; Buist et al., 1994).

Accidental burns were often viewed as detrimental to the spill situation and efforts to put out the fire were seen as necessary before attempting cleanup. Needless to say, a large release of oil from a stricken tanker would be motivation to extinguish a fire, although such a threat was not always imminent.

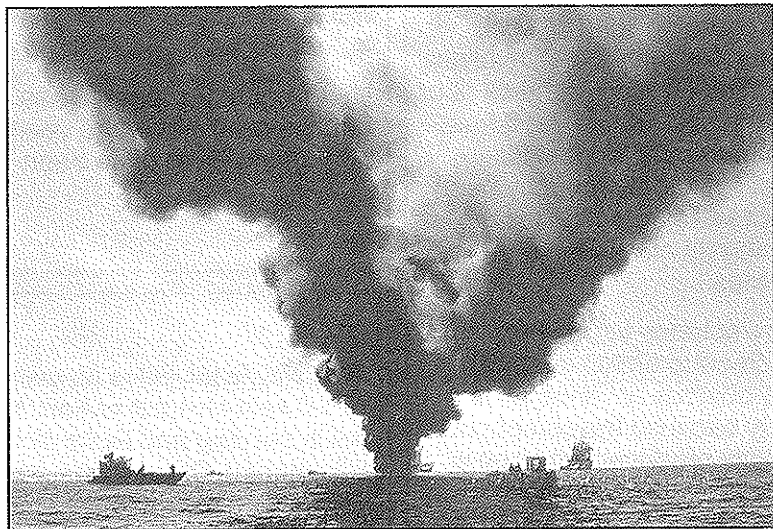
The current instinct is still to put out a fire at the scene of an oil spill regardless of the situation. Underlying this appears to be the view that burning is bad and harms the environment and perhaps could also aggravate the spill or salvage operation.

The acceptance and use of burning in a given country has often depended on the results of initial attempts to use the technique. The first recorded burn was in 1958 on the Mackenzie River in Northern Canada where a log boom was used to successfully contain oil for in-situ burning (McLeod and

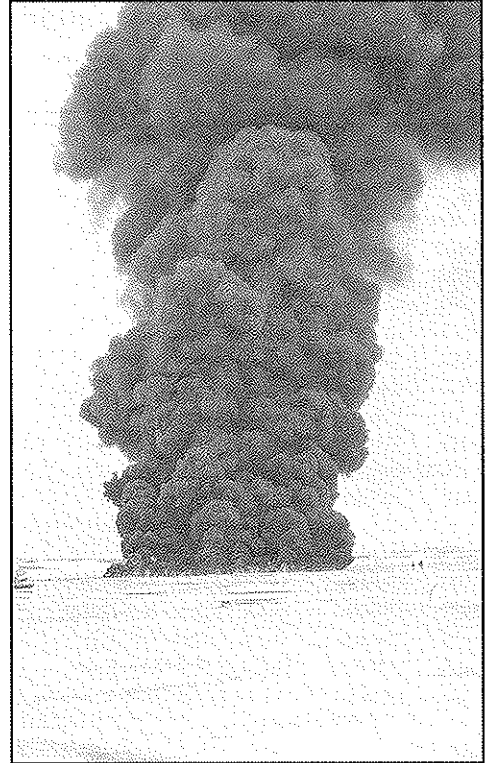
McLeod, 1972). After this, many burns were conducted in Canada, although they were seldom documented. Similarly, several successful burns in Sweden and Finland resulted in the use of burning on many occasions in those and surrounding countries. In Britain, extensive efforts to ignite the *Torrey Canyon* spill and the vessel itself brought mixed results. Consequently, burning has not been tried again in Britain until recently.

## Advantages

With the development of fire containment booms, in-situ burning can be carried out quickly, safely, and effectively and has some obvious advantages. When used at the right time, i.e., early in the spill before the oil weathers and loses its highly flammable components, and under the right conditions, in-situ burning can be very effective at rapidly eliminating large amounts of



*Interesting phenomena are sometimes observed during test burns. During the second burn of the Newfoundland experiment, the smoke plume bifurcated.*



*Oil appears on top of the ice in Balaena Bay in 1975 after penetrating through the ice during spring melting. This oil was later burned (shown on right), marking a new capability for dealing with oil in ice.*

spilled oil, especially from water. This can prevent oil from spreading to other areas and contaminating shorelines and biota.

Compared to mechanical skimming of oil, which generates a large quantity of oil and water that must be stored, transferred, and disposed of, burning generates a small amount of burn residue. This residue is relatively easy to recover and can be further reduced through repeated burns.

While the efficiency of a burn varies with a number of physical factors, removal efficiencies are generally much greater than those for other response methods such as skimming and

the use of chemical dispersants. During a series of test burns conducted off the coast of Newfoundland in 1993 (The Newfoundland Offshore Burn Experiment or NOBE), efficiency rates of 98 and 99% were achieved.

In-situ burning can be applied in remote areas where it would not be practical to use other techniques. In some circumstances, such as when oil is mixed with or on ice, burning may be the only available option.

In recent years, the understanding of in-situ burning has matured to the point where it is accepted in several jurisdictions (Addassi, 1997; Alyeska Pipeline Service

Company, 1997; ASTM, 1997). Burning is now an "approved" technique requiring permission from authorities in most western countries.

Despite its newly gained acceptance, in-situ burning has rarely been carried out on open waters. It is widely used, however, on spills on land and small water bodies and in the petroleum-producing regions of Canada and the United States to deal with oil spills.

Some in-situ burns of accidental oil spills as well as some research trials over the past 30 years are highlighted in Table 1.

**Table 1 Historical Burns and Spill Studies**

Year	Country	Description	Events	Lessons
1958	Canada	Mackenzie River, NWT	First recorded use of in-situ burning on river using log booms	In-situ burning possible with use of containment
1967	Britain	<i>Torrey Canyon</i>	Attempted to ignite cargo tanks with military devices	There may be limitations to burning
1969	Holland	Series of experiments	Igniter KONTAX tested, many slicks burned	Burning at sea is possible
1970	Canada	<i>Arrow</i>	Limited success burning in confined pools	Confinement may be necessary for burning
1970	Sweden	<i>Othello/Katylisia</i>	Oil burned among ice and in pools	Oil contained by ice can be burned
1970	Canada	Deception Bay	Oil burned among ice and in pools	Oil among ice and in pools can be burned
1973	Canada	Rimouski - experiment	Several burns of various oils on mud flats	Demonstrated high removal rates possible, >75%
1975	Canada	Balaena Bay - experiment	Multiple slicks from under-ice oil ignited	Demonstrated ease of burning oil on ice
1976	U.S.A.	<i>Argo Merchant</i>	Tried to ignite thin slicks at sea	Not able to burn thin slicks on open water
1976	Canada	Yellowknife - experiment	Studied parameters controlling burning	Oil type is not only parameter controlling burning
1978-82	Canada	Series of experiments	Studied many parameters of burning	Found thickness was limitation to burning
1979	Mid-Atlantic	<i>Atlantic Empress/ Aegean Captain</i>	Uncontained oil burned at sea after accident	Uncontained slicks will burn at sea directly after spill
1979	Canada	<i>Imperial St. Clair</i>	Fuels burned in ice	Fuels can be burned readily among ice
1980	Canada	McKinley Bay - experiment	Several tests involving igniters, different thicknesses	Test of igniters, measured burn rates
1981	Canada	McKinley Bay - experiment	Tried to ignite emulsions	Noted difficulty in burning emulsions
1983	Canada	<i>Edgar Jordain</i>	Vessel containing fuels and nearby fuel ignited	Practical effectiveness of burning among ice
1983	U.S.A.	Beaufort Sea - experiment	Oil burned in broken ice	Oil can be burned in broken ice
1984	Canada	Series of experiments	Tested the burning of uncontained slicks	Uncontained burning possible only in a few conditions
1984-85	U.S.A.	Beaufort Sea - experiment	Burning with various ice coverages	Burning is possible with various ice coverages
1984-86	U.S.A.	OHMSETT - experiments	Oil burned among ice but not with high water content	Ice concentration not important - emulsions don't burn
1985	Canada	Offshore Atlantic - experiment	Oil among ice burned after physical experiment	Demonstrated ease of burning among ice
1985	Canada	Esso - Calgary - experiments	Several slicks in ice leads burned	Demonstrated ease of burning in ice leads
1986	Canada	Ottawa - experiments/ analysis	Analyzed residue and soot from several burns	Analysis shows PAHs about same in oil and residue
1986	U.S.A.	Seattle and Deadhorse - experiments	Test of the Helitorch and other igniters	First demonstrations of Helitorch as practical
1986-91	U.S.A.	NIST - experiments	Many lab-scale experiments	Science of burning, rates, soot, heat transfer
1986-91	Canada	Ottawa - analysis on above	Analyzed residue and soot from several burns	Found PAHs and others - not major problem
1989	U.S.A.	<i>Exxon Valdez</i>	Test burn using a fire-proof boom	One burn demonstrated practicality and ease of burning
1991	Canada	Several test burns in Calgary	Emissions measured and ferrocene tested	Showed smokeless burn possible
1991	U.S.A.	First set of burn trials, Mobile, Alabama	Several test burns in newly constructed pan	Several physical findings and first emission results
1992	U.S.A.	Second set of burn trials, Mobile, Alabama	Several test burns in pan	Several physical findings and emission results
1993	Canada	Newfoundland Offshore Burn (NOBE)	Successful full-scale burn offshore	Hundreds of measurements, practicality demonstrated
1994	U.S.A.	Third set of burn trials, Mobile, Alabama	Large-scale diesel burns to test sampler	Many measurements taken
1994	U.S.A.	North Slope burns	Large-scale burn to measure smoke	Trajectory and deposition determined
1994	Norway	Series of Spitzbergen burns	Large-scale burns of crude oil and emulsions	Large area of ignition results in burn of emulsions
1994	Norway	Series of Spitzbergen burns	Attempt at uncontained burn	Uncontained oil largely burned
1996	Britain	Burn test	First containment burn test in Britain	Demonstrated practicality of technique
1996	U.S.A.	Test burns in Alaska	Igniters and boom tested	Some measurements taken
1997	U.S.A.	Fourth set of burn trials in Mobile, Alabama	Small-scale diesel burns to test booms	Emissions measured and booms tested
1997	U.S.A.	North Slope tank tests	Conducted several tests on waves/burning	Waves not a strong constraint on burning
1998	U.S.A.	Fifth set of burn trials in Mobile, Alabama	Small-scale diesel burns to test booms	Emissions measured and booms tested

## What Will Burn?

In earlier years, theories varied as to the burnability of oils (Twardus, 1980; Twardus and Brzustowski, 1981). Some of the early papers suggested that some oils would not burn in-situ. In fact, most if not all oils will burn on water or land if the slick is thick enough. The prime rule of in-situ burning is that oils will ignite if they are at least 2 to 3 mm thick and will continue to burn down to slicks about 1 to 2 mm thick. This thickness is required in order for heat transfer to take place. Sufficient heat is required to vaporize material so the fire will continue to burn. In very thin slicks, most of the heat is lost to the water and vaporization/combustion is not sustained.

Weathering of oil makes it more difficult to ignite. Weathered oil requires a longer ignition time and somewhat higher ignition temperature. This is also the case for oil that contains water. Oil containing some emulsion can be ignited and burned, although oil that is completely emulsified with water may not ignite at all.

A successful test burn was carried out on the oil from the *Exxon Valdez* despite patches of emulsion (probably less than 20%) which did not affect the efficiency of the burn, although it did take longer for the oil to ignite (Allen, 1990). As it is suspected that fire breaks down the water-in-oil emulsion, water content may not be a problem if the fire can actually be started.

It is not known at what point an emulsion can be ignited. One test suggested that a heavier crude would not burn with about 10% water (Smith and Diaz,

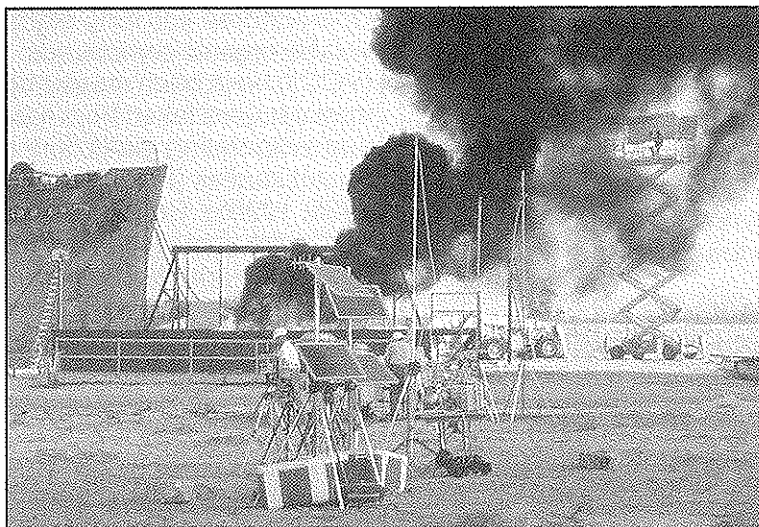
1987). Another oil burned with as much as 50% water and still another burned with about 70% water (Twardus, 1980). Extensive studies have shown that there are different categories of emulsions and the above results may only relate to the stability of the emulsion (Fingas et al., 1998a). Extensive work is still required in this area.

Only limited work has been done on burning oil on shorelines. Because substrata are generally wet, minimum oil thicknesses are probably similar to those required on water, that is from 2 to 3 mm. Oil is sometimes deposited in much thinner layers than this. Burning may cause portions of the oil to penetrate further into the sediments. If shorelines are close to populated areas and other amenities, burning is not an option.

## Emissions from In-situ Burning

The release of soot and gaseous emissions into the atmosphere or water remains the biggest barrier to the widespread use and acceptance of burning oil as a spill cleanup technique. Today, burning of any kind is viewed as a questionable process because of concern over toxic combustion by-products. Analysis is still difficult, although monitoring technology is now available to analyze key compounds of the smoke plume and compare their levels to ambient levels of pollution.

Early papers on oil burn emissions did not report on extensive experiments, but focused either on simple measurements or predictions of the types of emissions that could be encountered. Some papers focused only on sulphur dioxide, others on polyaromatic



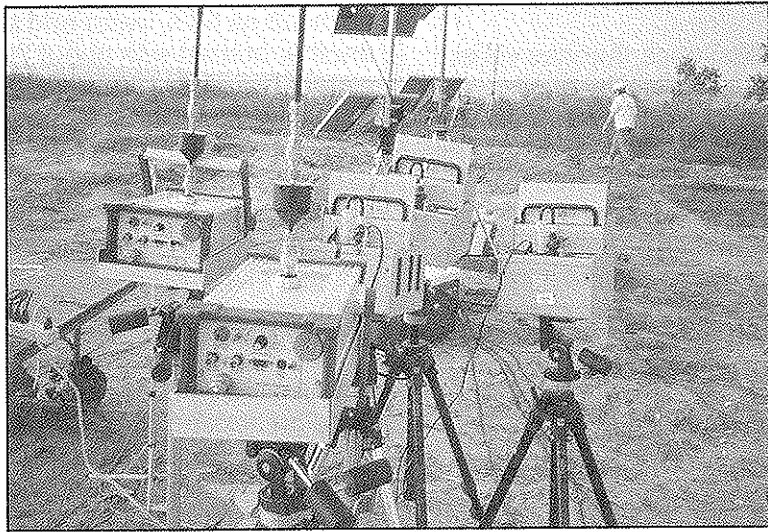
*The United States Coast Guard test facility in Mobile, Alabama was used over several years to test various aspects of in-situ burning. This photograph shows an array of air-sampling equipment used during testing of a fire-resistant boom at the facility in 1997.*

hydrocarbons (PAHs). Only recent studies have explored hundreds of compounds to delineate the concerns with emissions. The current state of knowledge in the field is summarized in this section (Lambert et al., 1998; Fingas et al., 1995; 1998b).

All burns, especially those of diesel fuel, produced an abundance of particulate matter. Particulate matter at ground level is a health concern close to the fire and under the plume. Concentrations of particulates in emissions from burning diesel were approximately four times that from similar sized crude oil burns at the same distance from the fire.

Particulate matter is distributed exponentially downwind from the fire. The greatest concern is the smaller or respirable particles with a diameter of 10  $\mu\text{m}$  or less, referred to as PM-10. Concentrations of PM-10 particulate matter were generally about 0.7 of the total particulate concentration (TSP) of all particulates measured, but sometimes were the same as the TSP. The PM-2.5 concentrations may be 0.5 of the TSP, but again, were sometimes the same concentration as the TSP.

Crude oil burns produce polyaromatic hydrocarbons (PAHs) downwind of the fire, but the concentration of PAHs on the particulate matter is often an order-of-magnitude less than in the original oil. Diesel fuel contains low levels of PAHs with smaller molecular size, but when burned, more PAHs of larger molecular sizes are either created or



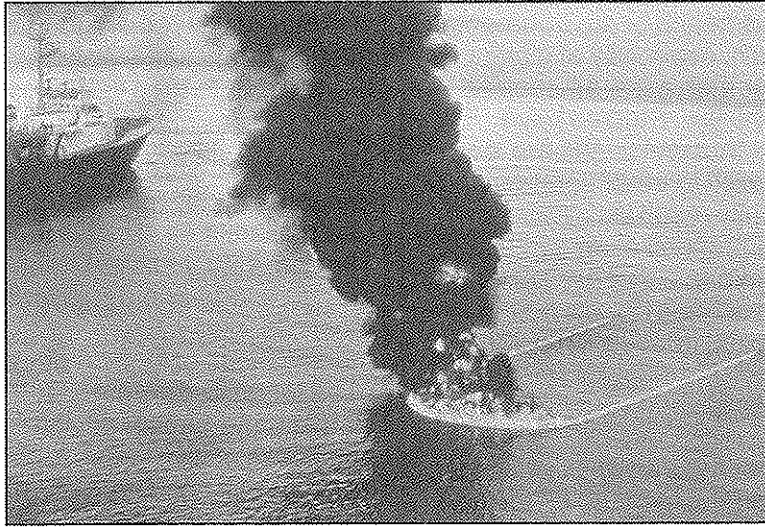
*A close-up of real-time aerosol monitors used at the U.S. Coast Guard testing facility in Mobile, Alabama in 1997.*

concentrated by the fire. Larger PAHs, some of which are not even detectable in the diesel fuel, are found in both the soot and the residue, although at low concentrations and often just above detection limits. Overall, more PAHs are destroyed by the fires than are produced.

One-hundred and forty-eight volatile organic compounds (VOCs) have been measured from samples taken from fires and evaporating slicks during recent studies (Fingas et al., 1995; 1998b). Concentrations of VOCs are about the same from both crude and diesel burns. Concentrations appear to be under human health levels of concern even at the monitoring station closest to the fire (about 30 m). VOC concentrations are about three times higher from an evaporating slick than from burning oil. Unfortunately, the amount of oil that has evaporated is often not measured before the burning starts.

Dioxins and dibenzofurans are highly toxic substances often produced by burning organic compounds containing chlorine. Particulates precipitated downwind and residue from several fires have been analyzed for dioxins and dibenzofurans. These toxic compounds were at background levels at many test fires, indicating no production by either crude or diesel fires.

Oil burns produce low amounts of partially oxidized material, sometimes referred to as carbonyls or by their main constituents the small aldehydes (formaldehyde, acetaldehyde, etc.) or ketones (acetone, etc.). Carbonyls from crude oil fires are at very low concentrations and are not a health concern even close to the fire. Carbonyls from diesel fires are slightly higher but are still below health concern levels.



*A field trial of in-situ burning using a fire-resistant boom was conducted in Norway in 1991.*

Carbon dioxide is the end result of combustion and is found in increased concentrations around a burn. Normal atmospheric levels are about 300 ppm and levels near a burn can be around 500 ppm, which presents no danger to humans. The three-dimensional distributions of carbon dioxide around a burn have been measured. Concentrations of carbon dioxide are highest at the 1 m level and fall to background levels at the 4 m level. Concentrations at ground level are as high as 10 times that in the plume and distribution along the ground is broader than for particulates.

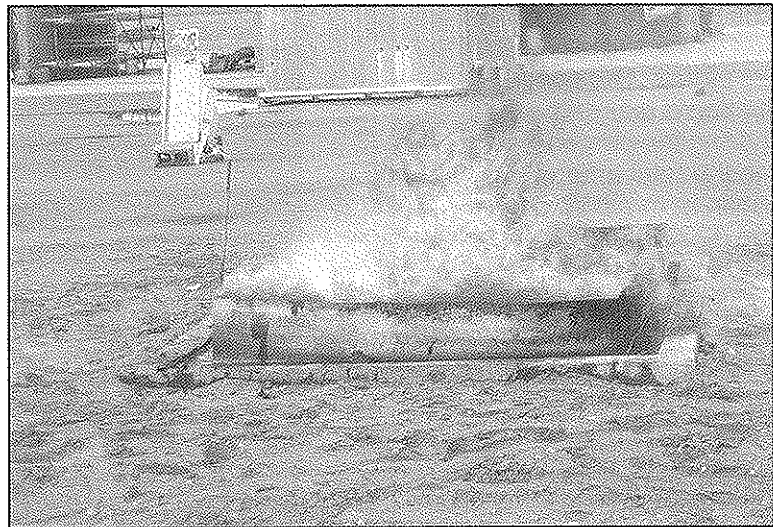
Carbon monoxide levels are usually at or below the lowest detection levels of the monitoring instruments and thus do not pose any hazard to humans. The gas has only been measured when the burn appears to be inefficient, such as when water is sprayed into the fire. Carbon monoxide appears to be distributed in the same way as carbon dioxide.

Sulphur dioxide, per se, is usually not detected at significant levels or sometimes not even at measurable levels. Sulphuric acid, or sulphur dioxide that has reacted with water, is detected at fires and levels, although not of concern, appear to correspond to the sulphur content of the oil. Attempts were made to

measure oxides of nitrogen and other fixed gases. None were measured in about 10 experiments (Lambert et al., 1998; Fingas et al., 1998b).

There is a concern that "hidden" compounds might be produced when crude oil is burned. In one study conducted several years ago, soot and residue samples were extracted and "totally" analyzed in various ways. While the study was not conclusive, no compounds of the several hundred identified were of serious environmental concern (Lambert et al., 1998; Fingas et al., 1998b).

The soot analysis revealed that the bulk of the material was carbon and that all other detectable compounds were present on this carbon matrix in abundances of parts-per-million or less. The most frequent compounds identified were aldehydes, ketones, esters, acetates, and acids which are formed by incomplete oxygenation of the oil.



*A land-based test of in-situ burning was conducted in Calgary in 1991. In this test, ferrocene was added to reduce soot and emissions were measured using monitoring stations shown in the background.*

Similar analysis of the residue showed that the same minority compounds were present at about the same levels. The bulk of the residue is unburned oil without some of the volatile components.

The amount of soot produced by in-situ oil fires is not known. There are no accurate measurement techniques because the emissions from fires cover such large areas. Estimates of soot production vary from 0.2 to 3% of the volume of the original oil, with some older techniques reporting numbers as high as 16%. A good estimate at this time is 0.2 to 2% of the original oil volume for crude oil and about 5 times that amount for diesel fuel. These estimates are complicated by the fact that particulates appear to precipitate from the smoke plume at an exponential rate from the fire outwards.

Some researchers have tried to estimate soot production by performing a carbon balance, measuring the amount of soot and the concentration of carbon dioxide at the same point in the smoke plume. The soot production is estimated by comparing the percentage of soot to the total amount of carbon in both the soot and carbon dioxide. This technique results in high estimates of soot production and is flawed because the soot is largely confined to the smoke plume but the carbon dioxide is emitted over a very wide sector. Further work is required on estimating the amount of soot produced.

In summary, current thinking on burning oil as an oil spill cleanup technique is that the

airborne emissions are not a serious health or environmental concern, especially at distances greater than a few kilometres from the fire. Studies have shown that emissions are low compared to other sources and generally result in concentrations of air contaminants that are below health concern levels 500 m downwind from the fire.

### Ignition

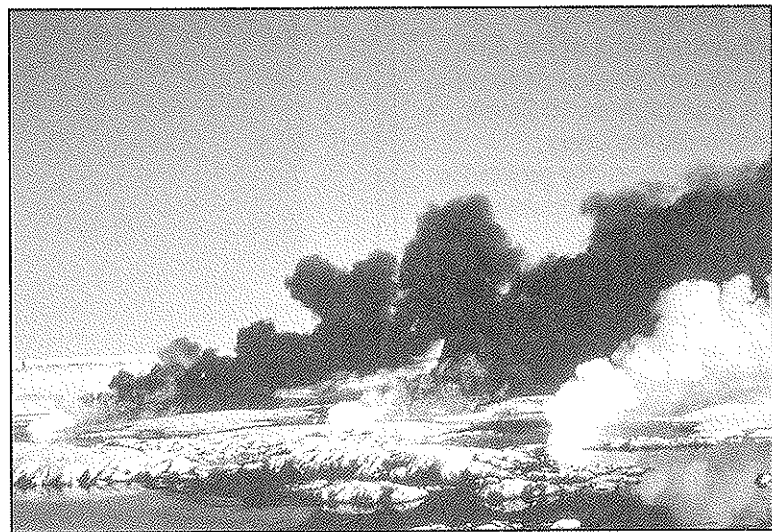
Much of the earlier work on in-situ burning focused on ignition of slicks as being the key to successful burning of oil on water (Meikle, 1981; Allen, 1986). Studies conducted in the last ten years have shown that slick thickness is the major factor and ignition is only important under certain circumstances.

Research has shown that most oils will ignite if they are at least 2 to 3 mm thick and will continue to burn down to slicks about 1 to 2 mm thick. The thicker the slick, the more easily and quickly it will ignite. In

general, heavy oils and weathered oils require longer heating times and a hotter flame to ignite than lighter oils.

A variety of ignition devices, both commercial and noncommercial, have been used to ignite oil slicks. These can generate sufficient heat and burn long enough to ignite most oils. Many are modifications of ignition devices used for other purposes. A simple hand-thrown device consisting of wire-mesh fuel baskets with solid propellant and gelled kerosene surrounded by metal floats was developed by Dome Petroleum Ltd. in Calgary, Alberta and Energetex Engineering of Waterloo, Ontario. This unit was called the Dome igniter or "tin-can" igniter.

Environment Canada and the Canadian military developed a device with a sophisticated time fuse which was commercialized under the name "Pyroid" but is no longer manufactured. Work was also conducted on developing a laser ignition



*Several igniters were tested in 1980 at McKinley Bay in the Canadian Beaufort Sea.*



device, although a working unit was not completed. Some of these devices are used from time to time for burn trials.

Fires at accidental oil spills and during tests have been ignited using much less sophisticated means. For example, a lunch "baggie" filled with gelled gasoline was used to ignite some of the oil from the *Exxon Valdez*. The oil spill in the Arctic from the *Edgar Jordain* was lit using a roll of diesel-soaked toilet paper. A series of experimental burns off the coast of Nova Scotia in 1986 were lit using oil-soaked sorbent.

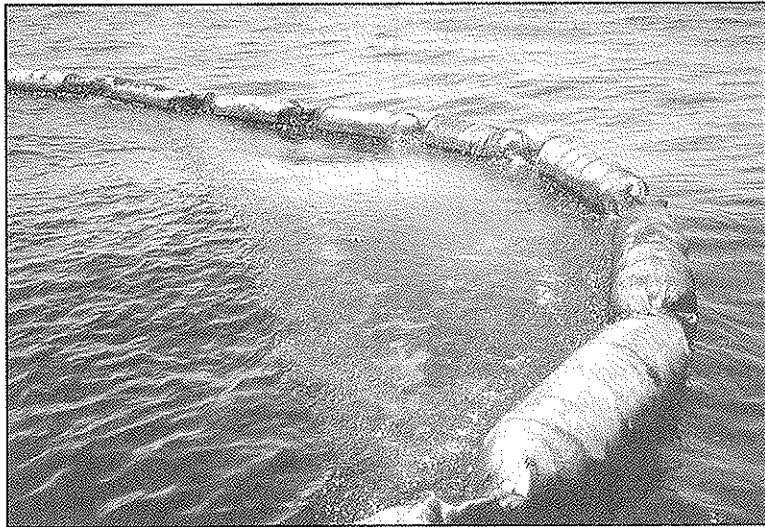
The state of the art in ignition technology is the helitorch igniter. It is a helicopter-slung device that distributes packets or globules of burning, gelled fuel. This type of igniter was designed for the forest industry and is used extensively for forest fire management.

## Burn Efficiency and Burn Rate

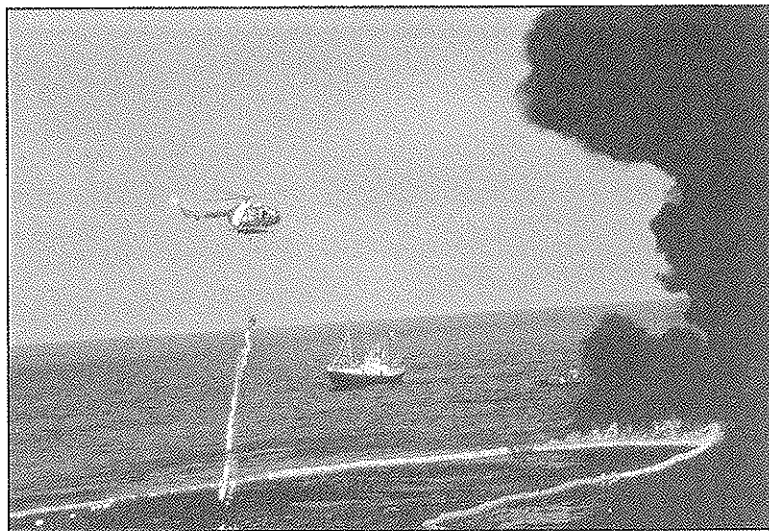
Burn efficiency is measured as the percentage of oil removed during the burn compared to the amount of residue left after the burn. In early years, it was presumed that the efficiency of a burn was somehow related to the type of oil being burned. It is

now known that burning efficiency is a function of the initial thickness of the oil slick and of the probability that the oil will be contacted by the flame during burning (referred to as the "contact probability").

Oil thicker than about 2 to 3 mm can be ignited and will burn down to about 1 to 2 mm. If a 2-mm thick slick is ignited and



*Burn residue remaining in fire-resistant boom after the first Newfoundland test burn. The residue represented less than 0.1% of the volume of the starting oil.*



*A helicopter equipped with a Helitorch is shown here igniting oil during the major Newfoundland burn experiment conducted in 1993.*

burns down to 1 mm, the most efficiency that can be expected is 50%. If a pool of oil 20 mm thick is ignited, however, and burns down to 1 mm, the efficiency of removal is about 95%. Recent research has shown that other factors such as the type of oil and its water content only marginally affect these values.

The residue from burning oil is largely unburned oil with some lighter or more volatile products removed. This residue is adhesive and can therefore be recovered manually. Residue from burning heavier oils and from very efficient burns may sometimes sink in water,

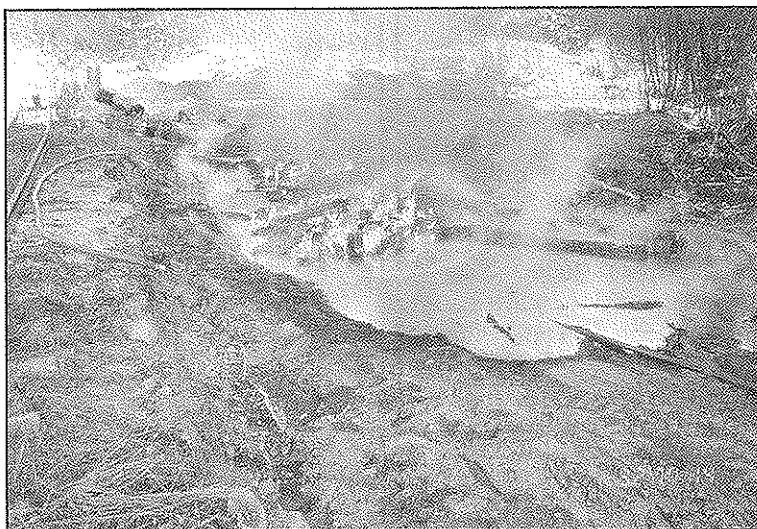
although this is rare as the residue is only slightly denser than sea water.

Most oil pools burn at a rate of about 3 to 4 mm per minute. In other words, the depth of oil is reduced by 3 to 4 mm a minute. When the slick becomes very thin in the final stages of burning, the rate decreases to about 1 mm/minute until the slick becomes less than 1 mm thick. Several tests have shown that this does not vary significantly with the type of oil, the degree of weathering, and the water content of the oil. The standard burn rate is about 5000 L of oil/m<sup>2</sup>/day (or about 100 gal/ft<sup>2</sup>/day).

### Burning Techniques

Burning in-situ without the benefit of containment boom can be done only if the oil slick is thick enough to ignite (at least 2 to 3 mm). For most crude oils, this thickness is only maintained for a few hours after the spill occurs. Due to the effects of wind and waves, oil on the open sea rapidly spreads to equilibrium thickness which is about 0.01 to 0.1 mm for light crude oils and about 0.05 to 0.5 mm for heavy crudes and residual oil. Such slicks are far too thin to ignite and the oil must be contained so it is thick enough to ignite and burn efficiently.

Oil is sometimes contained by natural barriers such as shorelines, offshore sand bars, or ice. Oil can be burned against a shoreline if it consists of cliffs, rocks, or sandy slopes or is in a remote area which is not close to combustible materials such as forests, grass cover, or wooden structures. Several experiments and burns

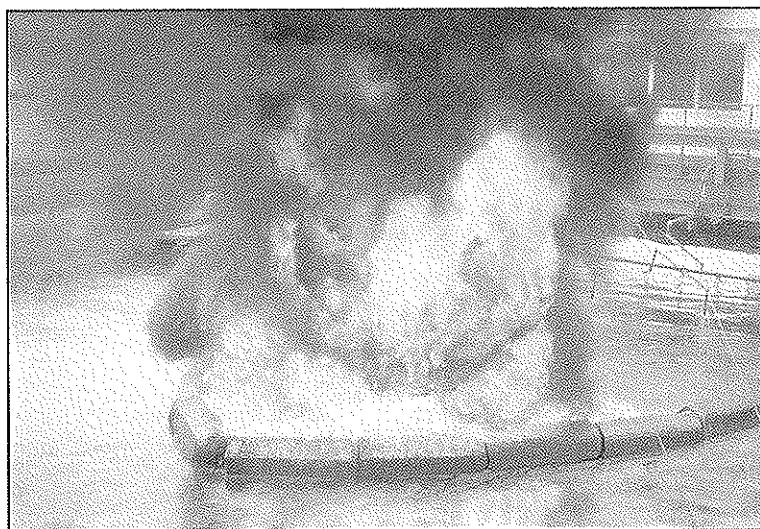


*Burning is used to remove old Bunker C oil that leaked from sunken rail cars at the edge of Lake Bennett in Northern British Columbia in 1993.*

of accidental spills have shown that ice acts as a natural boom so that in-situ burning can be carried out successfully for spills in ice.

Log booms were first used to contain oil for burning and this was successful. In the late 1970s, Environment Canada developed a series of ceramic, stainless steel designs as well

as those that used air or water sprays to contain oil during burning (Meikle, 1983; Buist et al., 1983.) In the early 1980s, Dome Petroleum Ltd. further modified the stainless steel boom developed by Environment Canada and this has recently been re-engineered into a smaller product.



*This test of a ceramic fire-resistant boom took place in the OHMSETT facility in New Jersey in 1982.*

Alaskan workers and 3M pioneered the development of a flexible fire-resistant boom. A variation of the 3M Boom is now constructed and marketed by American Marine, Inc. under license from 3M and this product, along with some experimental prototype sections, was used during the Newfoundland Offshore Burn Experiment (NOBE) in 1993.

Lightweight and fire-resistant booms are now available that make burning very feasible. Three different types of fire-resistant boom are currently available: water-cooled booms, stainless steel booms, and thermally resistant booms. Thermally resistant booms are similar in appearance and handle like conventional booms, but are built of many layers of fire-resistant materials. Fire-resistant booms require special handling, especially stainless steel booms, because of their size and weight.

Recently, much work has been conducted on fire-resistant booms. This has been

highlighted by two series of tests at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama to test the fire resistance of these booms.

These booms were also tested for strength, integrity, and oil containment capabilities during tow tests at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility in Leonardo, New Jersey.

These tests have provided several insights about fire-resistant booms. First, a simple fire-resistant blanket over the top of a standard boom does not prevent the boom from burning. Second, heavy metal booms may be impractical in operational situations, despite their outstanding ability to withstand fire. Third, water-cooled booms, although functional in test situations, may not be practical in open burn situations. Obviously, more development work is needed.

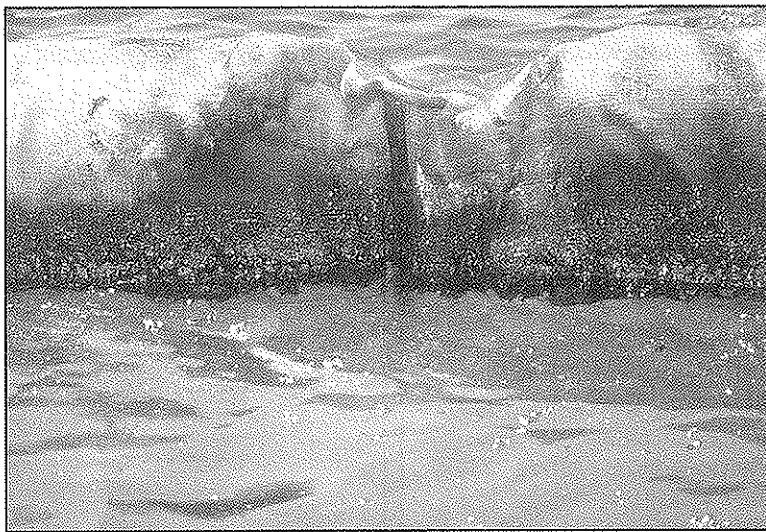
Booms can also be used to isolate the oil from the source of the spill. The test burn conducted at the *Exxon Valdez* site in 1989 illustrates how oil spills can be burned without threatening the source of the oil. Two fishing vessels slowly towed a fire-resistant boom on long tow lines through the slick until the boom's holding capacity was reached. The oil-filled boom was then towed away from the main slick and the oil ignited. The distance ensured that the fire could not spread to the main slick.

## Conclusions

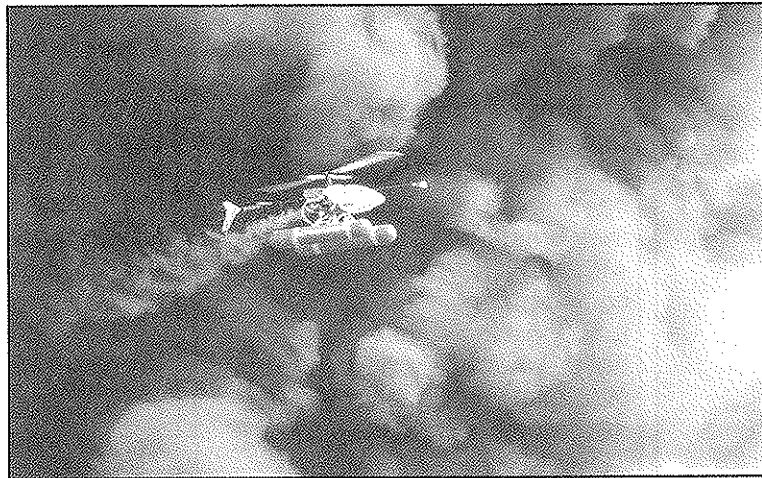
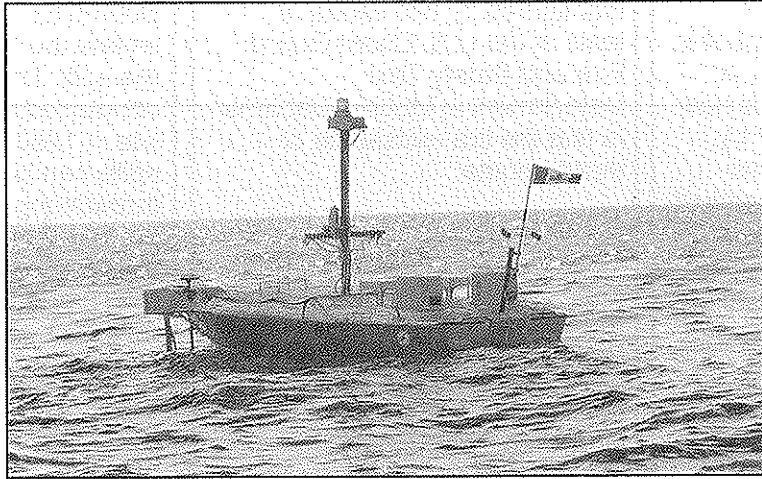
Much progress has been made in the ability to apply in-situ burning as an oil spill countermeasure. Significant advances have been made in the development of techniques and equipment for the safe and effective ignition and controlled burning of spilled oil.

More spill workers are accepting burning as a technique and are receptive to new information. It has been noted, however, that literature in the field and general scientific literature is often not used and better information transfer between scientists and response workers is still needed.

The use of burning as an oil spill countermeasure is a series of trade-offs between concerns over the emissions produced, the environmental impact of a spill, the advantages of being able to remove large amounts of oil in a short period of time, and maintaining the safety of both spill workers and the source of the spill.



*A close-up of the fire-resistant boom after the first burn in the Newfoundland burn experiments.*



*Remote-controlled equipment was used to sample air and water during the Newfoundland burn experiments. The sampling boat (on top) contained 30 samplers for air and water. The mini-helicopter leaves the plume after sampling the smoke (at bottom).*

The potential for in-situ burning must be determined based on specific conditions at the time of the spill, bearing in mind that oil can only be burned efficiently for a limited time after the spill. If a decision is delayed, burning becomes increasingly difficult and perhaps even impossible. There are situations such as major spills in remote areas

where burning may provide the only means of eliminating large amounts of oil quickly and safely.

In some situations, burning may be used in combination with mechanical recovery and the use of chemical dispersants. The ultimate goal, however, is to find the right combination of equipment, personnel, and techniques to ensure that an oil

spill will have the least environmental impact.

In-situ burning can be an invaluable tool in attaining that goal.

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