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COVER

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.

IN SITU BURNING OF OIL SPILLS:
A HISTORICAL PERSPECTIVE

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SUMMARY

The history of *in situ* burning is reviewed and perspectives on the key developments are given. The development of knowledge and techniques are noted and documented.

INTRODUCTION

In situ burning of oil spills has been tried over the past thirty years but has only recently been accepted as an oil spill cleanup option in some countries. The lack of acceptance of burning as a cleanup option is largely because of the lack of understanding of the combustion products and the principles governing the combustibility of oil-on-water. There remain several barriers to the full acceptance of burning, especially concern over emissions, but also the ability to retain oil slicks that are thick enough to burn.

This paper reviews the history and the state-of-the-art in burning to shed light on what is known and what remains to be researched. 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. Unfortunately, the progress has not been linear over the years and often efforts have been wasted on concepts or theories that yielded no benefit to the practical application of burning. The main cause of this is the interdisciplinary nature of oil spills. Researchers and engineers often are unaware of findings and concepts in each others fields. The practical approaches usually win out for funding, often at the detriment of advancement in the field. This paper will focus on the advancements and the progress made through the years and not the difficulties encountered on the way. Table 1 highlights some of the *in situ* burns and experiments over the past 30 thirty years.

PHILOSOPHY AND USE OF BURNING

Outside of Arctic regions, deliberate burning has not been used to a large extent. Several reviews contain histories of deliberate and accidental burns[1,2]. Often accidental burns were viewed as being detrimental to the situation and efforts to put out the burn were paramount to mounting other measures. Needless to say, a large release of oil from a stricken tanker would be motivation to stop a fire; however, such a threat was not always imminent. The current instinct is to put out the fire

irrespective of the situation. Underlying this action, appears to be the view that burning is bad and results in negative effects on the situation and on the environment.

The acceptance and use of burning in a given country often depended on the success (or failure) of initial attempts to use the technique. The first recorded burn was in Northern Canada in 1958, where a log boom was used to successfully contain oil for *in situ* burning on the Mackenzie River. After this, many burns were conducted in Canada, most often without any form of documentation. 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 resulted in mixed results. Consequently, burning has not been tried again in Britain until recently.

In recent years, the understanding of *in situ* burning has matured to the point where it will be accepted in several jurisdictions[3-5]. Burning is now an "approved" technique requiring authorities permission in most western countries. Despite, the newly-gained acceptance, there a no to few actual uses of *in situ* burning on open waters. It should be noted that *in situ* burning still has wide application on spills on land and on small waterbodies. *In situ* burning is used extensively in the petroleum-producing regions of Canada and the United States to deal with oil spills.

WHAT WILL BURN

In earlier years, theories varied as to the burnability of oils[6,7]. 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 in sufficiently thick slicks. The "prime rule" of *in situ* burning is that oils will ignite if they are at least 2 mm to 3 mm thick. They will continue to burn down to slicks about 1 mm to 2 mm thick. The reason that these thicknesses are required is heat transfer. Sufficient heat is required to vaporize material for continued combustion. For very thin slicks, most of the heat is lost to the water and combustion is not sustained.

The effect of weathering on oil combustion is to increase the difficulty with which the material is ignited. Weathered oil requires a longer ignition time and somewhat higher ignition temperature. This is not a problem for most ignition devices because they generate sufficient temperature and have sufficient burning time to ignite most oils.

The effect of water content on oil ignition is similar to that of weathering. It is known that oil that is completely emulsified with water cannot be ignited. Oil containing some emulsion can be ignited and burned. The successful test burn of the *Exxon Valdez* oil had some emulsion present (probably less than 20%) and this did not affect either the ignitibility or the efficiency[8]. It is suspected that fire breaks down the water-in-oil emulsion, thus water content may not be a problem given that the fire can actually be started. At what point an emulsion can be ignited is not known. One test suggested that a heavier crude would not burn with about 10% water, another burned with as much as 50% and still another burned with about 70% water. Extensive studies on emulsions have shown

that there are different categories and the results above may only relate to the stability of the emulsion[9]. There still remains extensive work to solve this problem.

Only limited work has been done on burning oil on shorelines. Because sub-strata are generally wet, minimum thicknesses are thought to be similar to those for on water--2 mm to 3 mm. Oil is sometimes deposited in layers much thinner than this. Burning may cause the part of the oil to penetrate further into the sediments. Where shorelines are close to human settlements and other amenities, burning would not be considered.

EMISSIONS FROM OIL SPILL BURNING

The concern over atmospheric emissions remains the biggest barrier to the widespread use of burning. Unfortunately, burning of all kinds, is in today's times, a questionable process because of concern over combustion by-products. Analysis is still difficult, although technology does permit analysis of key compounds and comparison to ambient levels of pollution.

Early papers on the topic 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 PAHs. Only recent studies have explored hundreds of compounds to delineate the concerns with emissions. The following paragraphs summarize the current state-of-knowledge in the field[10-12].

All burns, especially those of diesel fuel produced an abundance of particulate matter. The concentrations of particulates from diesel at the same distances were approximately 4 times that for similar-sized crude oil burns. Concentrations of particulate matter with diameters of 10 μm or less (PM10) were sometimes about 0.7 of the total particulate concentration (TSP), as would be expected, but sometimes were the same as the TSP. The same is true of the PM2.5 concentrations.

Crude oil burns result in polycyclic aromatic hydrocarbons (PAH) downwind of the fire, but the concentration on the particulate matter is often an order-of-magnitude less the concentration in the starting oil. Diesel fuel contains low levels of PAHs with smaller molecular size, but results in more PAHs of larger molecular sizes. Larger PAHs are either created or concentrated by the fire. Larger PAHs, some of which are not even detectable in the diesel fuel, are found both in the soot and in the residue. The concentrations of these larger PAHs are however low and often just above detection limits. Overall, more PAHs are destroyed by the fires than are created.

One-hundred and forty-eight volatile organic compounds (VOC) were measured from samples taken in recent studies. The concentrations of VOCs are about the same in a crude or diesel burn. Concentrations appear to be under human health limits even at the closest monitoring station (about 30 m). VOC concentrations are about three times higher when the oil is not burning and is just evaporating. Unfortunately, this is difficult to measure at all burns.

Particulates precipitated downwind and oil residue were analyzed for dioxins and dibenzofurans, very toxic substances often produced by the burning of organic chlorine-containing compounds. The levels of these toxic compounds were at background levels indicating no production by either crude or diesel fires.

Oil burns produce low amounts of the small aldehydes (e.g., formaldehyde, acetaldehyde) and ketones (e.g., acetone). These would not be a health concern even close to the source fire. Carbonyls from crude oil fires are at very low concentrations.

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. There is no human danger in this level. 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 of the plume. Distribution along the ground is broader than for particulates.

Carbon monoxide levels are usually at or below the lowest detection levels of the instruments and thus do not pose any hazard to humans. The gas only has 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 contents of the oil. Attempts were made to measure oxides of nitrogen and other fixed gases. None were measured in about 10 experiments.

A concern about burning crude oil lies with any "hidden" compounds that might be produced. One study was conducted several years ago in which soot and residue samples were extracted and "totally" analyzed in various ways. The study was not conclusive; however, no compounds of the several hundred identified were of serious environmental concern. The soot analysis revealed that the bulk of the material was carbon and that all other detectable compounds were present on this carbon matrix in abundances of parts-per-million or less. The most frequent compounds identified were aldehydes, ketones, esters, acetates and acids. These are formed by incomplete oxygenation of the oil. Similar analysis of the residue shows that the same minority compounds are present at about the same levels. The bulk of the residue is unburned oil.

The quantity of soot produced by *in situ* oil fires is unknown. No measurement techniques exist because the emissions from fires cover a large area. Estimates of soot production vary from 0.2 % to 3% of the starting oil volume, however some older techniques reported numbers as high as 16%. These estimates are complicated by the fact that particulates precipitate from the smoke plume. This appears to occur at an exponential rate from the fire outwards. Some researchers have tried to estimate soot production by performing a carbon balance. They measure the soot quantity and the carbon dioxide concentration at the same point in the smoke plume. The soot production is estimated by taking the percentage of soot versus 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 on quantity of soot production is required.

IGNITION

Much of the earlier work focused on the ignition of slicks[13,14]. The thinking was that proper ignition was the key to successful burning of oil on water. Studies conducted in the last ten years have shown that ignition is relatively unimportant. Research has shown that slick thickness is the major factor and ignition is only important under certain circumstances. Heavy oils require longer heating times and a hotter flame to ignite compared to lighter oils. Many ignition sources can supply sufficient heat for sufficient length of time.

Several igniters have been developed. A simple device consisting of juice cans and propellant was developed by Dome petroleum and was known as the "Dome" igniter. Environment Canada and the Canadian military developed a device with a sophisticated time fuse. This device was commercialized under the name "Pyroid" but did not continue in production. Some of these devices are used from time to time for experimental spills. Work also was conducted on developing a laser ignition device, although a working unit was not completed. The state-of-the-art in ignition technology is a device called the "heli-torch". It is a helicopter-slung device which distributes packets of burning, gelled fuel.

Actual burns at some incidents and experiments have been ignited using much less sophisticated means. The *Edgar Jordain* spill was lit using a roll of diesel-soaked toilet paper. The east coast oil burns were lit using oil-soaked sorbent. The test burn at the *Exxon Valdez* spill was ignited using a lunch "baggie" filled with gelled gasoline. This illustrates the ease and lack of sophistication that is required to ignite oil slicks.

EFFICIENCY AND BURNING RATES

In early years, it was presumed that burn efficiency was somehow related to oil type. It is now known that burning efficiency is simply a matter of initial thickness and of encounter. Efficiency is largely a function of oil thickness. Oil thicker than about 2 mm to 3 mm can be ignited and this will burn down to about 1 mm to 2 mm. If we ignite a slick at, lets say, 2 mm and this burns down to 1 mm, our efficiency can be at most 50%. However if we ignite a pool of oil 20 mm thick and this burns down to 1 mm, our efficiency of removal is about 95%. Current research has shown that other factors such as oil type and water content only marginally affect these values.

The residue from oil spill burning is largely unburned oil with some lighter or more volatile products removed. It is adhesive and because of this, somewhat easy to recover with manual techniques. Recent concern has been raised over the fact that these may sink, but this is only speculation and has only occurred on two spills.

Most oil pools burn at a rate of about 3 mm/min to 4 mm/min. This means that the depth of oil is reduced by 3 mm/min to 4 mm/min. Several tests have shown that this does not vary significantly with oil type, weathering and water content. As a rule of thumb, one can burn about 5000 litres per-square-metre per-day (or about 100 gallons-per-square-foot per-day).

BURNING TECHNIQUES

Containment is usually required to concentrate oil slicks so that they are of sufficient thickness to ignite and burn efficiently. Lightweight and fire-resistant booms now exist which make burning very feasible. The trial burn conducted at the *Exxon Valdez* site illustrates how oil spills can be burned without threatening the spill source. Two fishing vessels towed a fire-resistant boom using long tow lines. The boom was towed slowly through the slick until the boom-holding capacity was reached. The oil-filled boom then was towed away from the main slick and the oil ignited. Fire could not spread to the main slick because of the distance.

Burning *in situ* without the benefit of containment boom can be done only if sufficient thickness (2 mm to 3 mm) exists to ignite the oil. For most crude oils this only occurs for a few hours after the spill event. Oil on the open sea rapidly spreads to equilibrium thicknesses. For light crude oils this is about 0.01 mm to 0.1 mm, for heavy crudes and heavy oils this is about 0.05 mm to about 0.5 mm. These are far too thin to ignite.

Log booms were first used to contain oil for burning and this was successful. In the early 1970s Environment Canada initiated several projects to develop fire-resistant containment techniques, water spray and air jet were examined but abandoned because of the impracticality of this approach. Several series of stainless steel booms were built and also different versions of ceramic booms. Alaskan workers and 3M pioneered the development of a flexible fire-resistant boom and this product continues until today. Dome petroleum pursued one of the stainless steel booms and this product has been recently been re-engineered into a smaller product.

Lately much work has been conducted on fire-resistant booms. This has been highlighted by two series of tests of these at Mobile, Alabama to test the fire resistance and further testing of the same booms at OHMSETT (the National Oil Spill Response Test Facility in Leonardo, New Jersey) for the usual containment parameters. These tests have highlighted several insights about fire-resistant booms. First, a simple fire-resistant blanket over the top of a standard boom will not function well for the purpose. 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 is still needed.

CONCLUDING REMARKS

Progress has been immense in the ability to apply *in situ* burning. Better information transfer is still needed. It has been noted that literature in the field and general scientific literature often is not used. On the positive side, more spill workers are accepting burning as a technique and are receptive to information on the technique.

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Table 1. Historical Burns and Spill Studies

Year	Location	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	*Torrey Canyon*	Cargo tanks difficult to ignite with military devices	There maybe limitations to burning
1969	Holland	series of experiments	Igniter KONTAX tested, many slicks burned	Burning at sea is possible
1970	Canada	*Arrow*	Limited success burning in confined pools	Confinement may be necessary for burning
1970	Sweden	*Othello/Katelysia*	Oil burned among ice and in pools	Can burn oil contained by ice
1970	Canada	Deception Bay	Oil burned among ice and in pools	Can burn in ice and in pools
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.	*Argo Merchant*	Tried to ignite thin slicks at sea	Not able to burn thin slicks on open water
1976	Canada	Yellowknife - experiment	Parameters controlling burning not oil type alone	Parameters controlling burning not oil type alone
1978-82	Canada	series of experiments	Studied many parameters of burning	Found limitations to burning was thickness
1979	Mid-Atlantic	*Atlantic Empress/ Aegean Captain*	Uncontained oil burned at sea after accident	Uncontained slicks will burn at sea directly after spill
1979	Canada	*Imperial St. Clair*	Can readily burn fuels with ice	Can readily burn fuels amongst 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

Year	Location	Description	Events	Lessons
1983	Canada	*Edgar Jordain*	Vessel containing fuels and nearby fuel ignited	Practical effectiveness of burning amongst ice
1983	U.S.A.	Beaufort Sea - experiment	Oil burned in broken ice	Ability to burn in broken ice
1984	Canada	series of experiments	Tested the burning of uncontained slicks	Uncontained burning only possible in few conditions
1984-5	U.S.A.	Beaufort Sea - experiment	Burning with various ice coverages tested	Burning with various ice coverages possible
1984-6	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	Ease of burning amongst ice
1985	Canada	Esso - Calgary - experiments	Several slicks in ice leads burned	Ease of burning in leads
1986	Canada	Ottawa - experiments/analysis	Analyzed residue and soot from several burns	Analysis shows PAH's about same in oil and residue
1986	U.S.A.	Seattle and Deadhorse - experiment	Test of the heli-torch and other igniters	First demonstrations of heli-torch 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 PAH's and others - not major problem
1989	U.S.A.	*Exxon Valdez*	A test burn performed using a fire-proof boom	One burn demonstrated practicality and ease
1991	U.S.A.	First set of Mobile burns	Several test burns in newly-constructed pan	Several physical findings and first emission results
1992	U.S.A.	Second set of Mobile burns	Several test burns in pan	Several physical findings and emission results
1992	Canada	Several test burns in Calgary	Emissions measured and ferrocene tested	Showed smokeless burn possible

Year	Location	Description	Events	Lessons
1993	Canada	Newfoundland Offshore burn	Successful burn on full scale off shore	Hundreds of measurements, practicality demonstrated
1994	U.S.A.	Third set of Mobile burns	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 and emulsions	Large area of ignition results in burn of emulsions
1994	Norway	Series of Spitzbergen burns	Try of uncontained burn	Uncontained burn 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 Mobile burns	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 strongly constraining on burning
1998	U.S.A.	Fifth set of Mobile burns	Small scale diesel burns to test booms	Emissions measured and booms tested