ADVANTAGES AND DISADVANTAGES OF BURNING SPILLED OIL

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ABSTRACT: *The full potential for in situ burning as a controlled oil spill response technique is a subject of growing interest throughout the world. Information now available from burning oil during accidental fires, war-related fires in Kuwait, spillage from the* Exxon Valdez, *and controlled test burns, permits an objective and comprehensive assessment of both the positive and negative aspects of in situ burning. A thorough analysis has been made of direct and indirect impacts and concerns typically associated with the decision, to burn or not to burn. These factors, together with the comparative costs of various response techniques, have been identified and described to provide spill control planners and response organizations with a means of assessing the potential use of burning to clean up offshore oil spills.*

The response options available during a major offshore oil spill normally involve mechanical cleanup (containment and recovery), the application of chemical dispersants, and the use of in-situ burning. Depending on the nature and location of the spill, the environmental conditions, and the availability of personnel and equipment, it is sometimes necessary to resort to other options. These might include the decision to monitor and wait and/or to institute shoreline protection and cleanup activities. The goal, of course, is to prevent as much oil as possible from moving into nearshore and shoreline areas, where impacts are normally most severe and costly.

When physical removal, burning, or chemical dispersion can be used effectively offshore, one must still consider the operational, environmental and financial constraints of each mode of response. A comparison of response techniques reveals that each mode has a unique window of opportunity and that in situ burning, under the right conditions, provides an efficient means of eliminating large quantities of oil quickly and with minimal logistical support.[3]

The objectives of this paper are to identify and examine those issues that pertain to the "right conditions" for burning spilled oil, and to provide a balanced perspective on its advantages and disadvantages. These considerations are realistically compared with the impacts of not burning and of other sources of combustion products.

Operational considerations

At an operational level, most questions, doubts, or concerns involving in-situ burning fall in the categories of feasibility and safety. The primary issues for these categories are presented below, and they are summarized (along with environmental and financial issues) in the Tables 3 and 4 at the end of the paper.

Feasibility.

Oil condition. Most crude and refined oils will burn on water if the oil layer thickness is at least several millimeters and the ignition area and temperature are great enough to vaporize the oil for continued combustion. Experience has shown that about 0.1 inch (2 to 3 millimeters) of oil thickness is needed to prevent excessive heat loss from the oil layer to the water below. Combustion ceases quickly when the average film thickness is reduced to approximately 1 to 2 millimeters. The critical film thickness for sustained combustion increases by a few additional millimeters as the concentration of water in the oil being burned increases.

The uptake of water (emulsification), the evaporation of lighter volatiles, and the thinning of spilled oil layers can be significant deterrents to the successful use of controlled burning. Burning at sea must therefore be recognized as an effective response tool when the oil is relatively fresh (typically less than 1 to 2 days old), containable (in order to maintain combustion thicknesses), and relatively low in water content (preferably less than 20 to 30 percent). From a more positive viewpoint, these same constraints can simply mean that burning may work best early during a sudden batch spill, or as an ongoing response technique during a continuous spill, and when containment is practical with fire resistant booms or other natural or man made barriers.

Conditions for effective containment vary depending on the specific equipment used and the skills of those using it. It is generally recognized that most booms will suffer significant losses of oil due to entrainment and/or splashover as short period wind-waves build to about 2 to 3 feet (0.6 to 0.9 meter). As wind and sea conditions approach a Beaufort scale wind force of 4 to 5 (that is, with wind waves well in excess of a meter and winds of 15 to 20 knots or more), containment for ignition purposes is extremely difficult.

Under certain conditions burning can be accomplished without containment, and in some cases with relatively high water contents. Experience during accidental spills and controlled tests[14] reveals that thermally induced winds can help maintain adequate film thicknesses, and emulsions often can be ignited with the use of larger-than-normal ignition areas.[9,11,13] Field tests also have shown that emulsions can be broken with emulsion breakers and then burned efficiently.[12]

Each of the above favorable and unfavorable aspects of burning must be considered carefully in each potential spill scenario. When conditions are right for effective and safe ignition, burning can eliminate spilled oil at approximately 0.07 gallons/minute/square foot, or about 100 gallons/day/square foot (about 4,100 liters/day/square meter).[4,5] These elimination rates mean that a single 500 foot (152 meter) fire

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boom, positioned in a U configuration to intercept an ongoing spill, could provide enough burn area to sustain an elimination rate of 15,000 barrels (or 2,385 cubic meters) per day. Three such U configurations working in a collection-relocation-and-burn mode could eliminate approximately 8,000 barrels (1,272 cubic meters) of oil during a 12 hour period with only one U configuration burning at a time.[6]

Availability of equipment. When oil and environmental conditions are acceptable for a successful burn at sea, one must still have the equipment necessary in a time frame that meets the above constraints. Some might argue that this is a negative aspect regarding burning. However, the same argument could be applied to mechanical cleanup and dispersant application as well. Obviously, without the equipment, the response technique would not even be attempted. An exception, of course, is the use of uncontained burning where fire boom need not be available, and a floating ignition device is quickly fabricated on location.

A more realistic basis for examining the pros and cons of burning from an equipment standpoint would be to assess the type, amount, and cost of such equipment, as well as the logistics needed to support a burn operation. The costs are considered separately toward the end of this paper.

An effective burn at sea would normally involve 300 to 500 feet (92 to 152 meters) of fire boom; two boom towing vessels (typically 30 to 40 feet, or at least 10 meters in length) with twin propellers, tow posts, and tow lines at least 500 feet (about 152 meters) long; and a means of ignition (either hand held devices or a helicopter deployed Heli torch). The two boom towing vessels would drag the fire boom in a U configuration at approximately three-fourths knot or less in order to intercept and hold the oil in the downstream apex of the boom. The surface collection operations could be guided from above with spotter aircraft (possibly the ignition helicopter), and ignition could be initiated while the boats are intercepting oil (Figure 1) or after the oil is captured and relocated a safe distance from the source and other floating oil layers (Figure 2).

Depending on the location of the burning operations from shore and the expected duration of such activities, backup support in the form of additional fire boom, relief vessels, and fuel and supplies might be brought in later. Backup support could be expanded to include a supply barge/vessel for equipment storage, food and shelter, or helicopter support. In any event, a very significant amount of oil can be eliminated through burning with a relatively short length of fire boom, two boats, and a simple means of igniting the contained oil. Such an operation was conducted during Day 2 of the *Exxon Valdez* spill in which up to 30,000 gallons (about 114 cubic meters) of crude oil were burned in less than an hour with an efficiency of approximately 98 percent.[4]

Availability of trained personnel. As with the issue of equipment, any response option is best carried out by knowledgable, experienced personnel. Some people believe that only highly trained combustion specialists can conduct in-situ burning; this is simply not the case. In fact, with relatively little training, it is quite easy to safely and efficiently burn spilled oil at sea.

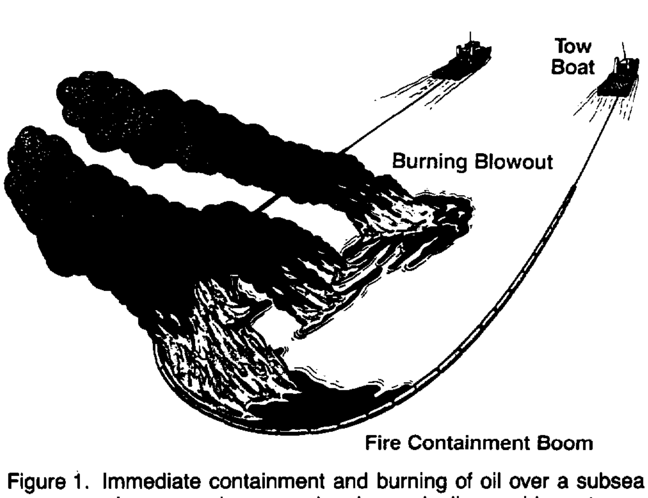

Figure 1. Immediate containment and burning of oil over a subsea source, such as a sunken vessel, subsea pipeline, or blowout

Personnel in such an operation would not have to handle pumps, skimmers, hoses, and storage containers, nor would they need to handle dispersant application equipment (such as pumps, spray arms, or nozzles). The basic skills are an ability to tow boom in a U configuration and to minimize the losses of any contained oil by using proper conventional boom towing techniques. Throughout the ignition and sustained combustion phases of a burn, the operators of the tow boats would simply maintain a proper speed (typically about a half knot) and direction in order to keep the oil contained until the burn is over. The following section on safety addresses safe operating procedures during these phases. With an understanding of a few simple, though important, concepts regarding safety, the technique of burning spilled oil is quite simple and may be accomplished safely by personnel with no prior burn experience. Field personnel can be properly trained within a few hours to understand and be able to implement a safe and effective in-situ burn at sea.

Safety.

Oil location. The decision to burn spilled oil is strongly tied to the location of the intended ignition and the region of influence throughout the burn period. The ability to ignite and sustain combustion safely, effectively, and with minimal disturbance of other spill control measures must include careful consideration of the burn location and its proximity to shorelines, docks, forests, and coastal communities; sensitive biological resources; other vessels in the area; and the source of the spill or any potentially ignitable slicks nearby. Therefore, any burn operation at sea must include good communications and navigational equipment to ensure that the burn and its products of combustion do not impact people, natural resources, equipment, or facilities located, downstream or downwind of the operation.

The obvious negative aspect of any in situ burn is the potential for an accidentally ignited secondary fire. This risk is of relatively little concern during a contained petroleum fire at sea since the burning operation would be surrounded by water; flame and smoke would remain at safe distances from people, wildlife, and equipment; and the fire could be extinguished quickly at a sudden unexpected change in wind or currents. For single contained burns (Figure 2), the duration of each burn would likely be on the order of an hour or less. Even for an ongoing burn (Figure 1), the burning oil within a boom could be extinguished by allowing the boom to drift open (thereby allowing the oil to spread out and thin) or by moving ahead rapidly, thereby forcing the oil to entrain and extinguish itself as it passes beneath the boom.

All issues related to the proper positioning of an in situ burn can be anticipated and used to prepare meaningful guidelines for the safe and effective use of controlled burning. Planners can consider sensitive resources or population centers during the identification of acceptable burn sites or zones; they can anticipate smoke plume trajectories with the use of atmospheric dispersion models and consideration of prevailing wind conditions; and they can establish specific criteria in advance for the ways in which burning would or would not be considered for certain types and locations of oil spills. The maintenance of safe working distances for personnel on location, the adherence to approved burn zones and conditions offshore, and the ability to extinguish a burn quickly if needed all reduce the risk of secondary fires to an acceptable level. As with most response techniques, well planned and practiced procedures can provide a reliable margin of safety so that the potential benefits of that technique will consistently outweigh the risks.

Oil ignition. Those unfamiliar with the controlled burning of oil on water often believe that ignition is either too difficult (because the oil is too old and/or thin) or too dangerous (because the oil is fresh and highly volatile). Each of these conditions can certainly exist, but neither is necessarily a disadvantage. In fact, it is quite fortunate that oil can be too old and/or too thin to burn, since such constraints provide a natural margin of safety against the accidental or premature ignition of an oil layer. One simply works around this constraint by recognizing that there is a window of opportunity within which an oil spill is still fresh enough to ignite, and that a too-thin slick can be thickened with natural or man made barriers to support combustion.

During the early stages of a spill's burn window there is, of course, a danger of accidental ignition. One need not be a professional fireman to believe the "no smoking" sign when filling a car's fuel tank! The risk of unwanted ignition during a spill response should always be foremost in the thinking of response personnel, be they involved in mechanical cleanup, dispersant application, personnel evacuation, lightering operations, or in situ burning. Normal precautions against unwanted igni-

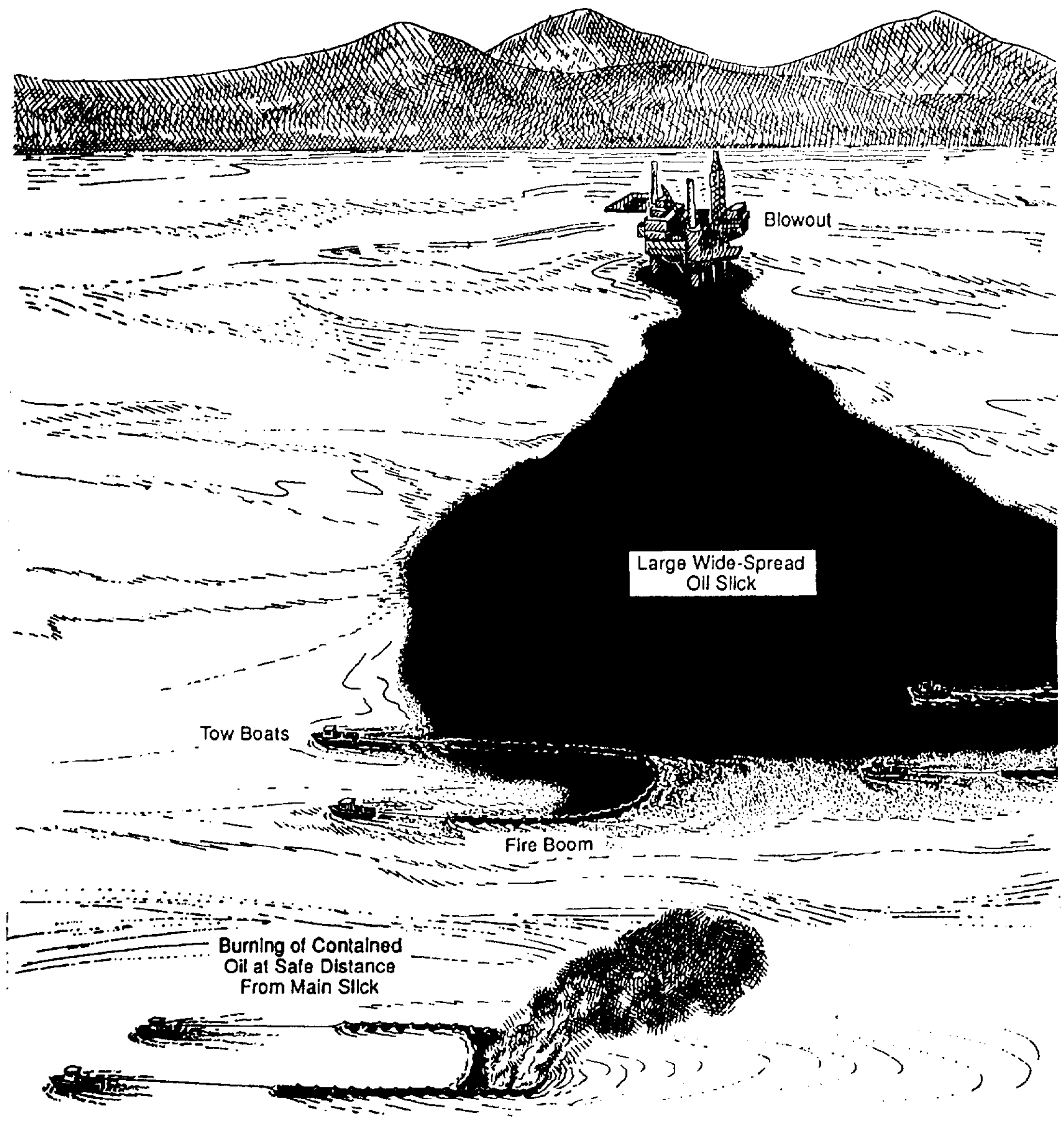

Figure 2. Collection, relocation, and burning of oil away from spill source

tion include testing and monitoring for explosive vapor levels; positioning vessels, aircraft, and personnel to avoid unexpected dangerous vapor levels; and initiating controlled ignition with proven techniques and equipment.[1,2,4,7]

A contained oil layer is often ignited with a device from a safe distance so that personnel and equipment are sufficiently removed from any direct or indirect effects of combustion. Small makeshift igniters—such as a gasoline-soaked roll of toilet paper, rag or sorbent, or a small plastic bag filled with gelled fuel—could be released well upstream of the target oil and allowed to float back into the oil. Similarly, specially designed pyrotechnic devices (such as a Pyroid igniter or Dòme igniter[1] could be released by hand from a vessel or from a helicopter, thereby putting considerable distance between personnel doing the ignition and the oil layer. Better yet is the simple and inexpensive technique involving the aerial release of gelled fuel from a Heli-torch.[1,4]

The technology for safe and effective ignition of oil has been developed and proven. The use of such technology, together with common sense and good judgment, will ensure that burning is accomplished at the right time and place.

Cost considerations

The cost of recovering or eliminating spilled oil offshore is typically 10 to 100 times less than removing the same oil from shorelines. The actual cost of shoreline cleanup obviously depends on the location, nature, and amount of shoreline contaminated. Such costs often include the direct costs of mechanical cleanup and bioremediation efforts, as well as the indirect cost of damage claims, fines, environmental restoration, or long-term biological studies. Relatively minor shoreline operations may cost as little as $100 per barrel of oil spilled. More commonly, however, shoreline cleanup and restoration will often run from several hundred to several thousand dollars per barrel of oil recovered.[8] In extreme spill events, such as the *Exxon Valdez* spill in 1989, such costs may be on the order of $10,000 to $100,000 per barrel of oil recovered.

The next logical question is: "How much does it cost to eliminate oil through in situ burning at sea, and how does that cost compare with mechanical removal and dispersant application techniques?" A thorough answer to this question is clearly beyond the intent of this paper.

However, it is possible to provide approximate comparative costs based on representative performance characteristics for mechanical, dispersant, and burning operations on a specific type of spill. To meet this objective, typical volume control rates for each mode of response are used along with the required resources (vessels, aircraft, or personnel) to provide an estimated 8,000 to 10,000 barrel recovery (or elimination) capability within a 12-hour workday.[3,6]

Some of the key parameters selected for this assessment include:

- Mechanical. Recovery efficiency 33 to 67 percent; throughput efficiency 50 to 80 percent; and sufficient vessel, skimming, transfer, and storage capability to encounter, recover, and store oil/water based on the above volume control objectives and efficiency constraints
- Dispersants. Large fixed wing aircraft delivery of six 5,000 gallon (18,925 liter) payloads of dispersant; dispersant-to-oil treatment ratio about 1:20; and a dispersant efficiency of 50 to 70 percent
- Burning. Sufficient fire containment boom (1,500 feet) to allow three 500 foot U configurations to alternately collect and burn oil; burn rate 0.07 gallons/square foot/minute; burn efficiency 95 percent; aerial ignition with helicopter deployed Heli-torch; and one burn allowed per hour while the other two U configurations are involved with oil collection and relocation for burning

Based on the above performance characteristics, approximate costs were determined for all vessels, aircraft, and equipment needed to carry out each response mode and achieve the estimated control rate of 8,000 to 10,000 barrels of oil over a 12 hour period. Included in these estimates were the costs to dispose of mechanically recovered oil and water, current costs to purchase and transport chemical dispersant, and the costs of replacing fire containment boom after one day of use (minimum) and three days of use (maximum). The following cost estimates are based on a range of typical daily use rates associated with each offshore mode of response.

- Mechanical: $100 to $150 per barrel of oil recovered and disposed of
- Dispersants: $50 to $100 per barrel of oil dispersed
- In situ burning: $20 to $50 per barrel of oil burned

It should be recognized that the cost estimate for mechanical removal could conceivably be cut in half if the recovered oil/water could be easily reprocessed and reused. The same recovery/disposal estimate, however, could go up by a factor of 2 to 3 for a highly weathered and contaminated oil requiring special handling and disposal.

Air pollution considerations

Expected emissions. One of the major concerns about in-situ burning of oil spills is the impact of the smoke emissions on air quality. Except for recent measurements of the smoke from the Kuwait oil fires,[19,21,22] and several studies of small-scale burns of crude oil in test tanks,[10,17,18] little data exist on the emission characteristics of oil fires in large scale open water environments. The concern remains that in situ burning merely substitutes one pollution problem (air) for another (water). It is important to recognize that unburned spilled oil presents air quality problems of its own. The volatile fraction of crude oil (approximately one third by volume) contains many toxic hydrocarbons which would normally evaporate and could create hazardous air concentrations in the vicinity of the spill. In situ burning would eliminate most of these vapors.

The major combustion products from the burning of crude oil (composed mostly of hydrocarbons) are carbon dioxide (CO_2) and water (H_2O). However, a number of minor combustion products are produced which cause concern as pollutants. Sulfur and nitrogen in the fuel are combusted to sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Since the oil would be burned in an enclosed boom and the oxygen supply is inefficiently mixed, some carbon monoxide (CO) and a large amount of soot particles (primarily graphitic carbon) would be produced. Some hydrocarbons are likely to escape combustion and be emitted in the smoke plume. Polycyclic aromatic hydrocarbons (PAHs) also pose a concern since they are among the most hazardous compounds present in crude oil. While in situ burning would consume most of the PAHs in the fuel, a small amount could be expected to escape combustion. PAHs are also produced by high temperature, oxygen poor combustion processes and would likely be emitted. Although all of the above mentioned pollutants are potentially hazardous, the rapid rise of the hot smoke plume and subsequent dilution would be expected to keep ground level concentrations well within ambient air quality standards.

Based on previous measurements of emissions from oil pool fires in Kuwait and from test burns of crude oil in tanks, it is expected that the emissions from an in situ oil spill burn would have the following general characteristics.

- Combustion should be relatively efficient, with about 90 to 95 percent of the carbon burned emitted as CO_2, about 1 percent as CO, and about 0.5 percent as hydrocarbon vapors.
- Particle emissions will likely amount to about 5 to 10 percent of the fuel burned, with roughly half the particulate mass emitted as soot.
- Sulfur will be emitted in proportion to the sulfur content of the fuel, mostly in the form of SO_2.
- NO_x will be emitted roughly in proportion to the nitrogen content of the fuel, and combustion temperatures will be too low to produce much excess NO_x.
- The smoke should be highly absorbing (that is, black), with a mean particle size of about 0.5 micron (μm).
- Peak concentrations in the smoke near a typical contained in situ burn (about one fourth to one half mile downwind) should be of the order of 100 parts per million (ppm) for CO_2, 1 ppm for SO_2 and CO, 50 parts per billion (ppb) for NO_x, and about 1,000 micrograms per cubic meter ($\mu g/m^3$) for particles.

Results from previous studies. Perhaps the greatest demonstration of the effectiveness of in situ burning occurred during the aftermath of the Gulf War when more than 700 oil wells in Kuwait were sabotaged and set afire by the retreating Iraqi army. Imagine the impact if 6 million barrels of crude oil per day had been spilled rather than burned. Over the entire course of the disaster, an estimated one billion barrels of oil were burned. By contrast, the *Exxon Valdez* spill released 250,000 barrels of oil and, although more than two billion dollars was spent on cleanup, only a small fraction of the spilled oil was recovered.

As part of the U.S. efforts to assess the environmental consequences of the Kuwait oil fires, a number of air sampling programs were conducted from both airborne platforms and ground-based samplers. Of most relevance to the issue of in situ burning were the measurements of smoke plumes from individual well fires conducted with the University of Washington's research aircraft.[19,22] Among the individual plumes sampled were two fires that were burning in large pools of oil on the ground. A variety of gaseous and particulate species were measured, with particular emphasis on the various forms of carbon emitted. By accounting for all the carbon in the emissions (the carbon content of the crude oil was known to be 85 percent), the emission factor (grams of species emitted per kilogram of oil burned) could be determined for any pollutant measured concurrently in the smoke.

Table 1 shows the results of measurements from the two pool fires expressed as emission factors and as the percentage of the total carbon emitted. The results show that about 96 percent of the carbon burned is emitted as CO_2, 2 to 3 percent as soot, about 1 percent as CO, and less than a percent as organic vapors and particles. The smoke particles emitted were equivalent to 4 to 5 percent of the fuel burned and, although some of the minor constituents were variable, on average were composed of about 45 percent soot (elemental carbon), about 4 percent organic carbon, about 6 percent sulfate, a few percent salt, and a rather large fraction of unidentified material, possibly mineral particles which were suspended in the oil. The low amounts (about 0.5 percent) of organic species, both gaseous and particulate, emitted indicate that very little of the oil escaped combustion, while the relatively higher amounts of soot and CO produced are indicative of the oxygen-starved nature of the pool fire environment. This is in contrast to the emissions from spraying well fires, which produced less soot (about 1 percent) but more unburned hydrocarbons (2 to 6 percent). The implication for in situ burning is that other than the organic residue remaining on the surface, very little of the toxic hydrocarbon species present in the oil will be emitted to the air despite the appearance of the black smoke plume emitted from the fire. Furthermore, the remaining toxic materials are dispersed, diluted, and eventually deposited over a very large area rather than highly concentrated in a single area along a shoreline as is often the case in an unburned spill.

Recent studies by the National Institute of Standards and Technology of the burning of Louisiana crude oil on water in a large open pan (approximately 2,500 ft^2 surface area) also measured a variety of chemical species in the emissions.[18] Volumes of oil burned ranged from

Table 1. Emission factors for gases and particles in the smoke plume of two crude oil pool fires in Kuwait

				Carbon species						
				Gaseous species				Particulate species		
Location	Units	SO_2	NO_x	CO_2	CO	NMHC	CH_4	Organic aerosol	Soot (elemental carbon)	Total sub-3.5 μm particles
Pool fire in Minagish oil field	g C/kg burned	—	—	824	5.6	2.0	0.7	1.6	16.3	—
	g species/kg burned	70	0.83	3021	13	2.3_1	0.9	1.9_1	—	43
	percent of total C emitted	—	—	96.9	0.7	0.2	0.1	0.2	1.9	—
Pool fire in Magwa oil field	g C/kg burned	—	—	805	9.5	2.8	1.8	2.8	28.2	—
	g species/kg burned	32	0.39	2952	22	3.3_1	2.4	3.3_1	—	52
	percent of total C emitted	—	—	94.7	1.1	0.3	0.2	0.3	3.3	—

1. Assumes average hydrocarbon composition is CH_2

about 8 to 90 barrels. The smoke particle emission factors measured were somewhat higher (average smoke yield of 11.7 percent) than those measured by the University of Washington in Kuwait. [This difference is probably due to the different particle sampling devices used in the two studies. In the Kuwait studies the University of Washington used a device which sampled only particles with aerodynamic diameters less than 3.5 μm (in the respirable size range with slow settling velocities and long residence times in the atmosphere). For NIST's Louisiana crude burns, particles up to 10 μm were collected, and a significant fraction (about 20 to 30 percent) of the smoke mass was found in particles of 5 to 10 μm.] Extensive ground based sampling for a variety of toxic compounds including PAHs revealed very low concentrations (usually undetectable amounts) at ground level in the vicinity of the fire due to the rapid rise of the smoke. PAH samples collected in the smoke plume using a sampler suspended from a small tethered blimp also contained concentrations barely above their detection limits. Samples of the burn residue were also analyzed for PAH and found to be somewhat enriched (by a factor of 2 to 5) over the PAH content of the original oil in contrast to the factor of 10 to 20 found in small-scale lab tests by Benner et al.[10]

Amounts emitted from a typical in situ burn. If we consider 10,000 barrels/day as an example of a reasonable elimination rate for a single burn operation, emission factors can be used to calculate the release rate of any of the pollutants listed in Table 1. It is simply the product of the emission factor (in grams per kg of fuel burned) and the fuel burn rate (in kg per unit time). The results of these calculations are shown in Table 2, where the amounts of pollutants produced are compared to emissions from other common sources like wood stoves, powerplants, and slash burning. The results show that in situ burning does not produce unusually large emissions compared with the other ongoing sources. For example, although CO_2 is a greenhouse gas, the amount released from an occasional in situ burn is insignificant compared to the normal consumption of 60 million barrels of petroleum products worldwide each day. Similarly, slash burning (usually occurring on several tens to several hundred acres per fire) is conducted on more than 100,000 acres per year in Oregon alone, while wildfires typically consume more than 10 million acres of forest per year in North America. The significance of large quantities of rapidly dispersed combustion products from in situ burning should be weighed against the consequences of oil possibly moving into sensitive shoreline environments.

Concerning the emission and fate of the PAHs, a mass balance or budget can be calculated for the fate of those compounds in the starting oil, smoke, and residue. Since no data exist for large burns in realistic situations at sea, several lab tests provide the only usable results. Benner et al. burned small amounts of Alberta sweet crude oil in a small (0.6 m diameter) pan and analyzed the smoke particles and residue for their PAH content.[10] The oil contained 0.144 percent PAH, the smoke averaged 0.51 percent, and the residue averaged 0.065 percent. For the selected burn of 10,000 bbl (1.37×10^6 kg), the starting oil would have a PAH content of 1,970 kg. If 11.7 percent of the oil is converted to smoke particles, 1.6×10^5 kg of smoke would be produced, with a PAH content of 0.51 percent (816 kg). A conservative estimate for the amount of residue produced would be 5 percent (6.8×10^4 kg), and if the PAH content is 0.065 percent, then 44 kg of PAH would remain in the residue. From the original 1,970 kg of PAH, 41 percent is released in the smoke, 2.2 percent left behind in the residue, and 56 percent is consumed by the fires.

Although reduction of total PAH is expected, the laboratory tests suggest that the PAHs emitted in the smoke are enriched in higher molecular weight PAHs, which are believed to be more toxic. On the other hand, the results from the larger-scale tests suggest that this

Table 2. Calculated rates of emissions for an in-situ burn of 10,000 bbl/day (57,000 kg/hr)

	Average emission factor (g/kg fuel burned)	Emission rate (kg/hr)	Comparable emissions from other known sources
CO_2[22]	2986	1.7×10^5	~2-acre slash burn[16,26]
CO[22]	17.5	998	~0.2-acre slash burn[16,26]
SO_2[22]	51	2907	7,400 kg/hr (avg. coal-fired powerplant),[1,20]
Total smoke particles[18]	117	6670	~7-acre slash burn[25]
Sub-3.5 μm smoke particles[22]	48	2736	~4.5-acre slash burn[16,26]
Sub-3.5 μm soot[22]	22	1254	~32-acre slash burn[16,26]
Sub-3.5 μm organic aerosol[22]	2.6	148	99 kg/hr (emissions from cigarette smoke in Los Angeles area)[15]
NMHC[22]	2.8	159	Equivalent to natural emissions from a living 11,000-acre forest[23]
PAHs[10]	0.4	23	Equivalent to ~12,000 wood stoves[10]

1. Value is the average of the hourly emissions from four different plants ranging from 600 to 2,100 megawatts

enrichment was much less than observed in the lab burns. Therefore, using the lab results in our above example represents a conservative estimate until measurements can be performed on a realistic fire. As far as PAH deposition is concerned, the main advantage of burning is that it dilutes the smoke into a large volume of air and disperses the particles over a very large area compared to an unburned spill. The remaining PAH in the surface residue can easily be recovered by mechanical means at the end of the burn, resulting in a very small net PAH release compared to an unburned spill.

Water pollution considerations

The effects of in situ burning on the ocean itself and/or its inhabitants are minimal and of very little environmental significance. Typically 97 to 98 percent of the heat produced during a burn is directed upward and outward so that any heat absorbed by the underlying water is generally negligible. This is particularly true where currents are continually causing an exchange of water below the burning oil. The movement of soluble petroleum components into the water column is also of little concern since the effects of reduced surface area and exposure time (by containment and burning) should easily compensate for any thermally induced enhancement of oil solubility.[24]

A final potential impact could result from the soluble petroleum components or negatively buoyant portions of burn residue following a burn. Most controlled burns to date have resulted in only a few percent of the original oil volume left as a taffy-like, floating residue which is easy to collect and requires relatively small volumes for temporary storage. As larger controlled burns are conducted and monitored, additional information will be collected on the significance of residue decomposition and sinking if such residue is not recovered following a burn.

Each of the above effects on the ocean or its inhabitants should also be examined in light of the potential region of influence from each effect. Even if thermal, solubility, and/or sinking phenomena involved significant pollutant-exchange processes, the scale of such an influence (compared to the volume of water or resources threatened) would be extremely small.

Table 3. Summary of advantages of in-situ burning

Advantage	Explanation
High elimination rate	The rate of removal is approximately 0.07 gallons/minute/square foot (or about 100 gallons/day/per square foot) for most relatively fresh crude oils. A single 500-foot-long fire boom in a towed U configuration can easily provide enough "oil area" to sustain an elimination rate of 500 gallons/minute.
High efficiency of burn	The volume of oil eliminated depends upon the original thickness of oil, which is commonly burned to an average thickness of about a tenth of an inch (2 to 3 millimeters) or less. Oil layers of about 4 inches (~100 millimeters) or more can result in an efficiency of removal of 98 to 99 percent.
Storage for recovered oil and water not needed	Nearly all of the contained oil is removed from the surface, therefore eliminating the need for storage barges, bladders, or tanks. If the small quantities of burn residue are recovered upon completion of a burn, such viscous, taffy-like material can be collected easily with nets and stored in open-top containers.
Minimal disposal and cleanup needed	The most costly task involving the disposal of large volumes of oil/water/debris is eliminated (disposal would only involve the recovered burn residue). The cleanup of equipment after the response is minimal since there are few, if any, recovery, transfer and storage systems involved.
Versatility	In-situ burning can be used on fresh water or salt water; on lakes, streams, and oceans; onshore; or on wetlands/marshes with only a few inches of water. Burning can be used on calm water and in sea conditions approaching a Beaufort scale wind force of 4 to 5. The burning of spilled oil can be used under tropical and arctic conditions, and is particularly effective with solid and some broken ice conditions.
Potential for night operations	Burning close to spill sources that are fixed in location, exposed to currents of a knot or less, and/or are already burning will commonly allow for the controlled positioning of fire containment boom near or around the source during periods of darkness or other limited visibility.
Minimal logistics	Two boats towing fire containment boom in a U configuration can accomplish a typical at-sea burning operation. When aerial ignition is unavailable or unnecessary, the contained oil can be ignited with small hand-held igniters released from one of the tow boats. Very little equipment and few personnel are needed to maintain a highly efficient elimination of oil. Backup support (such as spotter aircraft, vessels, fire boom, personnel) can be mobilized as time and conditions permit.
Ease of control	The size (or area) of each burn can be controlled easily by adjusting the speed of the boom-towing boats. Overall volume control rates (described above) can be doubled easily by slowing the tow boats and allowing the burn area to double. The burn can be reduced by speeding up and reducing the burn area, or the fire can be extinguished by towing the boom fast enough to force the contained oil beneath the boom.
Minimal environmental impact	The overall impacts of combustion products, thermal effects, and floating burn residue are minimal in light of their short-term, localized influences and the ease with which such influences can be controlled. The location and timing of in-situ burning, for example, can be controlled in order to minimize any potential exposure of onsite personnel, communities, or wildlife. The rapid dilution and dissipation of pollutants and thermal effects, together with the number and size of spill events worldwide, suggest that the long-term effects of burning oil spills are of little consequence to the atmosphere and ocean.
Low cost	In-situ burning of spilled oil is likely to run between $20 and $50 per barrel of oil eliminated (based on the described use of fire boom in a towed U configuration). Based on comparable spill events and volume control rates, the cost of controlled burning is likely to be less than half that for chemical dispersion, and less than a third that for mechanical recovery offshore and disposal of the recovered oil.

Table 4. Summary of disadvantages of in-situ burning

Disadvantage	Explanation
Oil condition constraints	Oil to be burned must be thick enough (that is a minimum of 1/10 inch or 2 to 3 millimeters, and preferably several inches); it must be low in water content (preferably less than 20 to 30 percent); and it must contain sufficient volatiles to allow ignition and sustained combustion.
Containment is usually necessary	Because of the above thickness constraint, specially designed and constructed booms must be available to contain and thicken the oil and to withstand the temperatures and physical-chemical reactions created by the combustion of oil.
Limited window of opportunity	Because of the weathering and emulsion that occur quickly at sea, burning must be conducted as early as possible (preferably within the first 12 to 24 hours of exposure). Highly flammable oils spilled onto relatively calm seas will often remain ignitable for a couple of days or more. In very cold climates, particularly when oil is thick and trapped on, in, or under ice or snow, the "burn window" may extend to months and even years.
Visual impact	Nearly everyone is offended by the appearance of black smoke, particularly if such emissions are unnecessary and/or if they could conceivably interfere with one's ability to breath, see, or function normally. Efforts are underway to reduce soot emissions during in-situ burning by physical and chemical means; however, the best way to handle this short-lived, visual impact is to conduct burns where and when the smoke will be dissipated quickly and/or blown away from any populated areas.
Localized reduction of air quality	Typically 90 to 95 percent of the carbon burned during an oil fire on water is emitted as CO_2. Particulate emissions may account for 5 to 10 percent of the fuel burned, with about half of this mass released as soot. These and other emissions (such as CO, SO_2, or NO_x) are rapidly dispersed and diluted downwind of the fire. Fortunately, the products of combustion released to the atmosphere during a typical controlled burn exist with significant concentrations for a very short time (usually minutes to a few hours at most), any fallout of particulate material is low in toxicity (compared to the original oil), and all emissions are generally released over water sufficiently removed from populated areas.

Conclusions

Tables 3 and 4 present a summary of the primary advantages and disadvantages of in situ burning. For many offshore oil spill scenarios, the advantages of controlled burning appear to outweigh the disadvantages. Burning offers a logistically simple and highly efficient means of eliminating large quantities of oil quickly and cheaply. In situ burns can be conducted on oil within a fire containment boom, on oil that is wind or current herded against other barriers such as ice or shorelines, or on large uncontained layers of oil that are still thick enough to support combustion. The versatility of burning, together with its potential for operations at night or during periods of reduced visibility, provides spill response personnel with a control technique that has a broad range of applicability with minimal backup support. A major advantage is the lack of dependence on skimming, transfer, and storage equipment for recovered oil and water. During a major spill, burning can proceed as efforts are made to secure additional equipment for the recovery of what little floating residue remains on the surface.

Personnel with minimal background and experience can conduct in-situ burning safely because burning requires simple and easily taught concepts involving the towing of boom, as well as the ignition of oil while all personnel and equipment are kept at a safe distance from the fire. Burns can be conducted when and where other techniques are less effective (or unavailable), or they can be used simultaneously with other techniques by confining each type of response to a properly designated segment of the spill or geographic region.

In situ burning is limited by the same wind and sea constraints as most conventional containment systems, it is dependent on a proper oil thickness, and the oil must not be heavily emulsified. As a result, burning often has a window of opportunity involving only a few hours to a day or two of oil exposure and seas where the short period wind waves are around three feet (about a meter) or less in height. The use of in situ burning must also include a continuous monitoring of the proximity of the burn to all facilities and population centers toward which the controlled burn or its smoke plume could move. Planners and responders should consider these constraints carefully so that specific guidelines and procedures are established in advance for the timely use of in-situ burning techniques.

What often appears to be the most significant adverse impact of burning is the black smoke released to the atmosphere. These emissions (both particulates and gaseous), however, would represent insignificant contributions to the atmosphere even if a major burn were conducted every day. Compared to the ongoing emissions from wildfires and slash burns alone, the products of combustion from even a 10,000 barrel burn every day would be many orders of magnitude less. The issue really comes down to a balance of priorities among the people of a given region of potential oil spill impact. Decisions need to be made before a spill event on whether they want a short-term, minor impact to the air or a relatively long-term, potentially major impact to the shoreline. Burning, along with mechanical recovery and chemical dispersants, must be planned for in advance so that the best mix of personnel and equipment can be activated without delay during the critical first few hours of a major spill event.

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