

IN-SITU BURNING

THE FATE OF BURNED OIL

REGULATORY AND SCIENTIFIC AFFAIRS DEPARTMENT
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Regulatory and Scientific Affairs Department

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Overview

- The American Petroleum Institute (API) commissioned the preparation of two booklets to help bridge the gap in the understanding of *in-situ* burning use, effectiveness, and effects.
- This booklet (first of two) focuses on *in-situ* burning effects, risks, and the fate of oil once it has been burned.
- This series was developed as a training tool or planning tool for *in-situ* burning. It is not exhaustive, and is **NOT** an operations manual. Each spill is unique and decision makers must use their judgment to meet legal and environmental requirements.
- Crude oil is a complex mixture of thousands of different compounds, composed primarily of carbon, hydrogen, sulfur, nitrogen, and oxygen. Hydrocarbons (composed solely of carbon and hydrogen atoms in various combinations) are the most abundant compounds found in crude oils.
- *In-situ* burning (ISB) is considered as effective as mechanical recovery options on open water when the oil is contained; under these circumstances both methods can result in 80 to 90 percent removal. However, for spills on water, only 20 percent of the total discharge is typically contained and thus available for recovery or burning.
- Burning can be effective, but needs to be conducted as quickly as possible if weather conditions are favorable (before the oil has emulsified or spread so far that collection of significant quantities is too difficult).
- ISB aims to remove at least 90% of the discharged oil (that has been contained for burning) from the environment, whether on land or on water. The overriding goal is to accomplish this removal while minimizing adverse environmental effects and ensuring that any resultant air pollution does not jeopardize human health.
- ISB may be useful during a continuous release situation from an offshore production platform when the necessary burn equipment can be brought on scene.
- *In-situ* burning can be a very effective tool on shore and in marsh areas, where the oil is contained by the environment and other response options are limited by topography.
- ISB has always been considered as a primary Arctic spill response countermeasure. High ice concentrations contain oil for burning while rendering offshore mechanical recovery difficult or ineffective. ISB is the countermeasure of choice for removal of oil pools on ice and may also be effective for oiled snow.
- On water, most burns produce small amounts of taffy-like or brittle oil residues that can be recovered manually, although, in some cases, the burn residues from crude oil and heavy refined oils may sink after cooling.
- In open water, unrecovered residue may float to nearby shorelines where it can be manually removed. Recovery of sunken residue is very difficult and thus not likely to be undertaken.
- Burn residue tends to be sticky and, on land, may adhere to vegetation and sediments. Removing thick residues may be required.

- Burn residues can be chemically characterized as weathered oil, with most of the light fractions burned off. Thus, further changes in composition will be slow.
- On open water, burn residue from an effective burn presents a minimal environmental risk because of the small amount of residue (1-10 %) present relative to the initial volume burned. During an incomplete burn, the volume of remaining oil and partially burned oil may be a greater percentage and more difficult to remove using standard removal techniques.
- Exposure to burn residue may affect biologically sensitive resources. On open water, effects may occur if the residue is ingested (by birds or sea turtles). The residue may also physically coat and smother animals and habitats. Chemical and physical impacts to biologically sensitive resources on land are essentially the same, but include potential impacts to soils and vegetation from both the burn and burn residue. The chemical toxicity effects of burn residue are generally less than the effects from the original oil.
- *In-situ* burning may be used to quickly remove oil from the environment thereby eliminating the need for further handling and storage of oil and minimizing further impacts.
- Burning oil (on land and on water) produces plumes of airborne emissions composed of a wide variety of gases as well as particulate matter (soot). The most abundant components within the smoke plume are CO₂, water vapor, CO, SO₂ and unburned carbon particles.
- Air pollution from a burn is usually short-lived, and, depending on wind speed, the smoke plume is often dispersed within 10-20 miles (16-32 km) from the burn site. Additionally, the environmental impacts from ISB are often far less than if the oil were allowed to weather, spread, or remain in the environment.
- One major concern with *in-situ* burning, and the decision to burn or not to burn, is the potential for human health effects of inhaled smoke particles, carbon monoxide, sulfur dioxide, PAHs, VOCs, and metals. The effects will depend on the amount of burn products inhaled and the length of exposure, both of which are related to proximity to the burn, the volume of oil burned, burn efficiency, burn duration, wind direction and speed, and atmospheric stability, as well as a person's age and overall health, prior to exposure.
- Individuals most likely to be affected by the burn by-products are those people who are sensitive individuals, such as children or those with heart or lung disease.
- Worker health and safety is also of primary importance during a burn and individuals associated with the response must have up-to-date 40-hour Occupational Safety and Health Administration (OSHA) hazardous materials training as well as other more specialized training. The concerns can include:
 - Fire control - preventing unwanted ignition or secondary fires
 - Ignition control – using specialized equipment and trained personnel requires additional safety precautions
 - Vessel Safety – at sea, a burn requires several vessels to work together often under difficult circumstances. Boom handling for corralling the spilled oil should also be conducted by experienced, trained personnel

- Personnel exposures – response personnel may be in danger from the fire or flames, exposure to high concentrations of particulate matter, or other health and safety issues such as working in extreme heat or cold conditions,
- Modeling the *in-situ* burn plume can provide critical information to help responders determine potential for general public impacts from exposure to the burn smoke. Models available to estimate the dispersion of *in-situ* burn products include, for example:
 - National Institute of Standards and Technology’s (NIST) ALOFT (A Large Outdoor Fire plume Trajectory) model
 - US EPA’s ISCST3 (Industrial Source Complex, Short Term) model
 - US EPA’s CTDMPLUS (Complex Terrain Dispersion Model PLus algorithms for Unstable Situations)
 - Offshore and Coastal Dispersion (OCD) model
 - Earth Tech, Inc’s. CALPUFF model, adopted by U.S. EPA
- The Special Monitoring of Applied Response Technologies (SMART) protocol establishes a monitoring system for rapidly collecting and reporting real-time information on *in-situ* burning or dispersant operations.
 - This monitoring information system is designed for use during either land or water spill response operations, using a minimum of three separate teams for the monitoring task.
 - Prompt notification needs to be given to the Monitoring team when *in-situ* burning is being considered to give them enough time to activate and arrive on scene.
- *In-situ* burning has been widely used on land spills with numerous examples of success. There is limited experience from a few on-water efforts, but controlled testing has confirmed it can be a viable option.
- *In-situ* burning can provide net environmental benefit (e.g., tradeoffs are worth it). Removal of bulk oil by ISB can enhance the recovery rate of impacted areas, and lessen the overall environmental effects of an oil spill. Issues surrounding effects of residual oil or exposures to smoke plumes are far more manageable and environmentally less hazardous than the long-term impacts of persistent oil slicks or heavily oiled shorelines.

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Section I—Introduction

You are in the midst of a large oil spill and it's your first month on the job. Approximately 20,000 gallons (476 bbl/65 tons) of a medium weight crude oil has been discharged into the environment and the responders are looking for options to remove this oil that will also minimize the potential impacts to the environment. One of the possible strategies is to burn the oil in place (i.e., *in-situ* burn - ISB). You want to verify the appropriateness of this removal method for today's specific spill conditions, identify and present any pros and cons, additional operational requirements, worker health and safety issues, public health issues, monitoring requirements, etc.

Needless to say, time is of the essence. You have had basic oil spill response training, and you have heard of ISB, but have never been involved in an ISB-related response. During your training, you remember that there were several guidance documents that have been developed to assist responders in understanding the concept of ISB...

Purpose of This Booklet

This scenario may not be real, but the circumstances are possible. ISB is a response option that has been used far less frequently than mechanical countermeasures (booms, skimmers, etc.) and consequently, familiarity with ISB operations is limited. There are ISB "experts" in the US and international responder tools, but the intentional practice of this response tool remains relatively limited for both water and land situations. As our network of experienced oil spill responders retire, their knowledge and hands-on experiences with the various response tools like ISB may be lost. This document was designed to capture that knowledge and present it clearly and concisely so you will have the necessary information to understand issues associated with fate and effects of oil to which ISB has been applied. It is not a set of instructions for carrying out a specific ISB.

During the 1998 *In-situ* Burning of Oil Spills Workshop (Walton and Jason, 1999), participants worked to determine the state of knowledge and the research needs of the user community regarding ISB. The participants believed that the "...lack of adequate knowledge by public and other decision-makers was a major impediment to acceptability and utilization of *in-situ* burning" (Walton and Jason, 1999). They determined that the knowledge-base for burn residue and air impacts is mostly adequate, but this information needs to be presented such that decision-makers better understand the function of *in-situ* burning and the tradeoffs facing them in using this technique when responding to an oil spill.



An oil slick undergoing an *in-situ* burn.

This booklet is a reference document for oil spill response decision-makers, to **provide an accurate synthesis of available information concerning of the fate and effects of burned oil on water, on land, and in the air.**

This booklet also identifies and explains specific terms associated with oil that may be used by technical experts during planning or response operations. The first time a new technical term is used within this booklet, it will appear in **ALL CAPS** signifying that a more detailed explanation or definition is present in the right or left margin near where the word(s) is first used within the main text.

A second booklet, “A Decision-maker’s Guide to *In-situ* Burning,” discusses the operational issues and concerns associated with an *in-situ* burn on land or on water.

Who Gets to Make the Decision to Conduct an ISB?

In the United States, the use of ISB as an oil spill response tool is regulated by both federal and state laws. Regional Response Teams (RRT), made up of federal and state agencies, have developed guidelines that provide a common decision-making process to evaluate the appropriateness of using ISB during a spill response. The decision to use ISB is not defined by the spill volume or intensity, but is based primarily on the viability of the countermeasure based on the incident-specific conditions.

The **UNIFIED COMMAND (UC) FEDERAL ON-SCENE COORDINATOR (FOSC)** must consider ISB a practical option for the incident-specific conditions. Before initiating an ISB, the Unified Command should conduct a consultation with Regional, State, and Local Air Quality Officials. Because the smoke from an ISB has a much greater ability to migrate than the oil slick itself, careful consideration of potential air quality impacts on neighboring States, regions, and countries is especially important. Finally, the UC then consults with meteorologists, response contractors, and experts on burning to further determine ISB viability for the incident-specific conditions. The UC will seek approval/concurrence of the RRT members prior to initiating the burn (where feasible).

In many states, the decision to conduct an ISB on land does not always require concurrence by the RRT; however, it is strongly recommended that the RRT be notified.

The **Federal On-Scene Coordinator (FOSC)** is the pre-designated, senior government authority during oil and hazardous materials spill. This position’s authority is designated under the National Contingency Plan.

The **Unified Command** is composed of FOSC, State on-scene coordinators, Local agency, and a responsible party (RP) representative.

Section II—Oil Chemistry Review

What is Oil?

Decision-makers need a comprehensive understanding of the oil itself in order to understand the behavior of any ISB by-products and the potential impacts from an *in-situ* burn.

Oil is not one compound nor chemical, but a complex mixture of thousands of different compounds, primarily comprised of carbon, hydrogen sulfur, nitrogen and oxygen (NRC, 2003) in various combinations within the oil. Once it is exposed to the atmosphere, oil undergoes seven weathering processes: **SPREADING, EVAPORATION, DISSOLUTION, NATURAL DISPERSION, EMULSIFICATION, PHOTO-OXIDATION, SEDIMENTATION, and BIODEGRADATION**. The rate and extent of these weathering processes vary by the type of oil, air/water temperatures, wind, and wave conditions (for on-water spills).

Because the composition of crude oil differs, and these are significantly different from refined products, spill responders must have a clear understanding of the type of oil that has been discharged. For instance, one crude oil may have many components that evaporate quickly, whereas another may be composed of many heavy components that can persist in the environment for a long time. A more detailed discussion on oil chemistry can be found in the booklet, “Fate of Spilled Oil in Marine Waters: Where Does It Go? What Does It Do? How Do Dispersants Affect It? An Information Booklet for Decision-Makers” and is available from API Publications at www.api.org.

HYDROCARBONS are the most abundant organic compounds in crude oil (NRC, 2003). There are essentially three groups of hydrocarbon components in every crude oil:

1. Lightweight components (low molecular weight)
 - contain 1 to 10 carbon atoms (C1 to C10);
 - evaporate and dissolve more readily than medium or heavy-weight components, and also leave fewer residual compounds (often called residue) than medium or heavy-weight components;
 - are thought to be more **BIOAVAILABLE** to animals (readily taken up by an organism) than medium or heavyweight components;
 - are potentially flammable and readily inhaled, so they are of concern relative to safety and their potential **TOXICITY** to animals and humans; and

Evaporation is the preferential transfer of light- and medium-weight oil components from the liquid to the vapor phase. During the first 24 to 48 hours of a spill, evaporation is the single most important weathering process from the standpoint of volume reduction. It is often the primary process involved in the natural removal of oil from the water/land surface

Spreading is the movement of the entire slick horizontally along the surface of the water or land. Spreading dominates the initial stages of a spill and involves the whole oil (the oil is not partitioned chemically at this point).

Dissolution is the transfer of the oil components from a surface slick into solution in the water column. This is a relatively insignificant weathering process and most dissolution takes place within the first 24 hours following the discharge.

Natural Dispersion occurs as the oil slick forms small oil droplets that become incorporated into the water column as a dilute oil-in-water suspension. Natural dispersion reduces the volume of oil on the water surface but does not affect the chemical composition of the oil.

Emulsification is the mixing of water droplets into oil. Emulsification tends to increase the total volume of the oil, often by a factor of two to four. Water-in-oil emulsions are highly viscous and further weathering of the emulsified oil can be significantly reduced.

Photo-oxidation transforms the oil into other by-products during exposure to sunlight. It occurs at the very surface of the oil and plays a relatively minor role in the overall weathering of the oil. This process may continue over a period of several weeks to months.

Sedimentation is the incorporation of oil (on water) into both suspended and bottom sediments.

Biodegradation is the process whereby naturally occurring bacteria and fungi consume hydrocarbons as a food source. Carbon dioxide and water are produced as by-products. This is a significant, but relatively slow, process in oil weathering.

Hydrocarbons are chemical compounds composed solely of carbon and hydrogen.

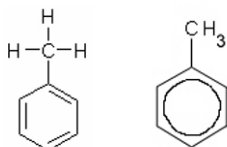
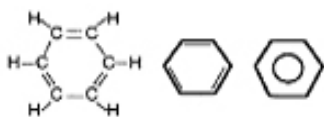
To be **Bioavailable** is to be in a form that is conducive to uptake (e.g., ingestion, inhalation) by organisms.

Bioavailability is the tendency of a substance (in this case, individual oil components) to be taken up by a biological organism (Rand and Petrocelli, 1985).

Toxicity represents the degree of danger a substance poses to animal and plant life. Acute toxicity occurs quickly and often quantified as death. Chronic toxicity occurs over the life of an organism, typically quantified as impacts to reproduction, growth, or behavior.

Mono-aromatics are a class of hydrocarbons characterized by a single ring with six carbon atoms. Mono-aromatics are considered the most acutely toxic components of crude oils, and are also associated with chronic and carcinogenic effects. Many mono-aromatics are also soluble in water.

Benzene and Toluene are petroleum hydrocarbon mono-aromatic components that are characterized by single rings of six carbon atoms.



- must be present in order for the oil to ignite easily
2. Medium-weight components (medium molecular weight)
 - contain 11 to 22 carbon atoms (C₁₁ to C₂₂);
 - evaporate or dissolve more slowly than lightweight components, over several days;
 - may leave behind additional residual compounds which can appear as a coating or film;
 - are regarded as more potent toxins than the lightweight components; but
 - are not as bioavailable as lower-weight components, resulting in lower exposure rates for organisms.
 3. Heavyweight components (high molecular weight)
 - contain 23 or more carbon atoms (\geq C₂₃);
 - undergo little to no evaporation or dissolution;
 - can cause long-term ecological/biological effects via smothering or coating by residual compounds; residuals may remain in the water column and sediments indefinitely (Helton, 1996); and
 - are not very bioavailable, resulting in much lower exposure rates for organisms when compared to light or medium components.

The effects of spilled oil depend on the chemical composition of the oil itself. Some components that are considered harmful (i.e., **MONO-AROMATICS** such as **BENZENE** and **TOLUENE** in the C₁ to C₁₀ range) have a high volatility and are readily taken up through the skin or through inhalation; but, unless the concentration of oil is very high, they will usually evaporate before becoming widely available to organisms in the water column. The air surrounding the spill may contain harmful concentrations of the volatile materials if wind is still. Other oil components may also be considered harmful, but their molecules are very large, making them less soluble in water. Because these components are less soluble, they are also less biologically available to organisms in the water column. The two classes of oil components thought to be the most bioavailable, thus most hazardous for water column organisms, include many of the lightweight components in the C₁ to C₁₀ range and the two and three-ring **POLYCYCLIC AROMATIC HYDROCARBONS** (PAHs). (NRC, 2003; Neff and Sauer, 1995) Potentially hazardous levels of bioavailable oil components such as these usually exist in the water column for only a short period of time after a spill.

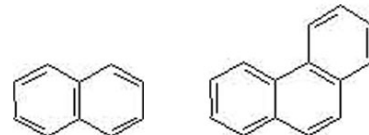
How Does Burning Change the Oil?

The primary goals of oil spill response techniques are to recover (or reduce the quantity of) the oil and reduce the environmental impacts from the spill. With *in-situ* burning, **ON LAND** or **ON WATER**, the overall goal is the removal of as much oil as possible from the environment (**NOTE**: the amount removed is based, in large measure, on the volume of oil that can be contained to sustain ignition). ISB rapidly changes large quantities of spilled oil into its primary combustion products - water and carbon dioxide, plus a smaller percentage of other unburned or residual by-products, including soot (NRT, 1992).

Practically speaking, ISB does not completely remove spilled oil from the environment, since even an effective burn will leave behind burn residue, and produce gases and large amounts of black smoke or soot. The residues have the potential to negatively impact natural resources.

Because *in-situ* burning of oil generates large amounts of black smoke, there is a visual impact leading to concern about the effects of the smoke plume on downwind human populations and biological resources. One of the primary concerns in the decision to burn is the smoke plume and the **PARTICULATE MATTER**, which consists of small particles (less than 10 microns in diameter) that are referred to as "**PM-10**." Particles smaller than 10 microns are easily inhaled and drawn deeply into the lungs where they can lodge and cause damage. The particulate matter in the smoke is composed primarily of elemental carbon. It is generally long-term exposure over months to years to PM-10s that affects health. However, short-term exposure to high concentrations can aggravate symptoms in sensitive individuals with existing heart or lung ailments.

Polycyclic Aromatic Hydrocarbons (PAHs) refer to aromatic oil components that are composed of two or more six-carbon rings. Some PAHs are associated with carcinogenic effects. Solubility in water and bioavailability decrease as PAH size increases



Examples of two common PAHs
Naphthene (left) and Penanthrene
(right)

On Land includes a wide range of habitats, such as salt marshes, wetlands, ponds, grasslands, timberlands, and open fields.

On Water means spills on the ocean, coastal waters, estuaries, bays, freshwater lakes, and rivers.

What do we mean by an EFFECTIVE burn?

Determining if a burn is effective is a relative evaluation. The overall burn efficiency is affected by a number of factors: oil thickness, oil discharge conditions (continuous versus instantaneous release), oil encounter rates, wind and weather conditions, extent of weathering of the oil (how much the oil has already evaporated), as well as the ability to initiate and maintain the burn. The oil (on water or on land) needs to be contained and appropriate slick thickness maintained to sustain a burn.

For traditional on-water countermeasures (booms, skimmers and other storage devices), a 20% recovery rate is considered effective based on historical open water operations. However, under ideal conditions, on-water and on-land recovery operations can achieve much higher removal rates. For on-water/on-land ISB, a 50% removal rate is considered a marginal burn (Etkin and Tebeau, 2003). When all conditions are right and the oil can be contained, a 90% or greater removal rate on water can be expected. Under ideal conditions, ISB can achieve removal rates of 98% or better (from conversations with A. Allen, March 6, 2003). **The bottom line is that total effectiveness in ISB is only as good as the initial booming; if you can't contain the oil and maintain the proper thickness, then the burn efficiency will be reduced.**

Ian Buist of S.L. Ross states that an effective burn is one where 85% of the oil is removed (Buist, 1998).

Particulate Matter is the general term used for a mixture of solid particles and liquid droplets found in the air. **PM-10** refers to coarse particulate matter 10 microns or less in diameter that is potentially harmful if inhaled (See Section VI for more information on this topic).

Some particulates are directly emitted into the air. They come from a variety of sources such as cars, trucks, buses, factories, construction sites, tilled fields, unpaved roads, stone crushing, and burning of wood. Other particulates may be formed in the air from the chemical change of gases. They are indirectly formed when gases from burning fuels react with sunlight and water vapor. These can result from fuel combustion in motor vehicles, at power plants, and in other industrial processes. From <http://www.epa.gov/air/urbanair/pm/what1.html>.

Condensates are liquid petroleum products that are co-produced from gas wells. Condensates have a narrower carbon number range than crude oil, typically extending from C6 to C30. These hydrocarbon mixtures generally exhibit an API gravity of greater than 45°, are not considered extremely viscous at normal ambient temperatures and they are relatively volatile and soluble in water (Nakles, 2001).

The smoke plume may also contain gases, some of which are hazardous when inhaled or allowed to contact the skin. The gases emitted during a burn consist primarily of carbon dioxide, water vapor, carbon monoxide, nitrogen oxides, sulfur oxides, and volatile organic compounds. The two substances of greatest concern for human health are PAHs and carbon monoxide. Refer to Section VI of this booklet for more information on this.

Previous studies have shown that it is primarily personnel working at the burn site who may be exposed to dangerous levels of components within the smoke plume (See Section VI). OSHA requirements limit their exposures. The on site decision maker should take both worker and civilian populations into consideration in authorizing an *in-situ* burn.

Section III—Burn Residue On Water

How Burn Residue Behaves On Water

In-situ burning of oil on water under ideal circumstances can be very efficient, removing up to 90-98 percent of the oil that is contained for burning. Light oils such as diesel or **CONDENSATE**, and fresh oils have the highest burn efficiencies; whereas, heavy crude oils, heavy refined products, and weathered oils tend to have lower burn efficiencies. Even with high removal efficiencies, there is usually some residue left at the end of the burn. This section describes the nature of these residues and how they are expected to behave.

During a burn, heated oil forms vapors that sustain ignition. Researchers have concluded that the vaporization process includes enhanced evaporation of the lighter components as well as vaporization of the whole oil (SL Ross, 2002). That both processes are working is indicated by the fact that burn residues contain some lighter ends but are very chemically and physically different from the original oil. In general, the burn residue has a greater quantity of the heavy components than lighter components and is more viscous than the original oil.

Experiments demonstrate that on-water *in-situ* combustion ceases when the burning oil slick reaches about 1 mm in thickness for light and intermediate refined oils and light crude oils. For thicker oil slicks and heavier oils, the residue at the end of the burn is expected to be 3-5 mm in thickness. For emulsified oil slicks, the residue can be even thicker (Buist, 1998).

Various terms have been used to describe *in-situ* burn residues, depending on the oil type, thickness, degree of weathering, and efficiency of the burn. Examples of how previous ISB efforts have described burn residues include:

- **Semi-solid, tar-like layer that had the appearance similar to the skin on a poorly sealed can of latex paint that has gelled** – this description was provided by Buist (1998) from several laboratory experiments using a thin slick of crude oil. During these tests, Buist also reported that the residues from burning diesel had no solids.
- **Tarry lumps** - From three experimental burns of a medium crude oil off Canada (Fingas *et al.*, 1994).
- **Stiff, taffy-like burn residue that could be picked up easily** – From a test burn of 15,000-30,000 gallons of North Slope crude oil from the *Exxon Valdez*, resulting in 300 gallons of burn residue (Allen, 1990).
- **Brittle solid similar to peanut brittle** – From burning emulsified North Slope crude in outdoor pits (Buist *et al.*, 1994).
- Other descriptors of burn residue are **solid, semi-solid, hard, asphaltic**, and combinations of all the terms listed above.

One of the major concerns about burn residue is the potential for it to sink. Early experiments were conducted with thin slicks, and sinking of the residue was not reported. However, two spills of heavy crude oil in the early 1990s, where the oil burned and large amounts of the burn residues sank, triggered research into the **DENSITY** of burn residues.

Recent experiments yielded the following results when burning thicker slicks of 5-15 cm. This slick thickness is thought to be more representative of the thickness of oil that would be contained and burned in fire-resistant booms (SL Ross, 2002):

- Of 100 international crude oils tested, about half of the burn residues would tend to float and half tend to sink in seawater. About 60 % of the crude oil residues would tend to sink in fresh water.
- Many times, the hot residues floated at first, but began to sink after they cooled. Typical burn residues are expected to cool within 30 minutes.

The researchers found a good correlation between the densities of the burn residue versus the original oil. Based on these laboratory tests, * crude oils with densities greater than 0.864 g/cm³ (or an API gravity less than 32°API) will produce burn residues that may sink in seawater (SL Ross, 2002). In general, these tests determined that medium and light crude oils, condensates, and light and intermediate refined products are likely to produce floating burn residues, but heavy crude oils and heavy refined products are expected to produce burn residues that will sink.

Density is a measure of the weight of a specific volume of a solid, liquid, or gas relative to water. The greater the density of a resultant burn residue, the more likely it is to sink.

If the density of residue is greater than the density of water, it will sink. Note that seawater is denser than freshwater so a specific residue might float on seawater but sink in freshwater.

***NOTE:** Do NOT assume that laboratory tests will be accurate predictors of what will happen at all real open-water burns.

Likely Fate of Residues That Are Not Recovered

Floating tarry or solid burn residues can easily be recovered from the water surface under many circumstances (where contained). They can be collected with pitchforks, dip nets, and other hand tools, while sticky residues are often recovered with sorbent materials. Liquid residues could be recovered using skimmers, but they are usually very viscous and difficult to pump using existing skimming equipment. Also, skimmers are not very efficient at picking up small, scattered patches of oil.

Two possible methods to recover sinking residues have been proposed (SL Ross, 2002), the most promising is to use netting suspended under the fire-resistant boom to collect the oil as it sinks.** Another method is using “oil-snare walls,” which have sorbent snares, or pompons, tied to a wooden or steel frame. The frame could be placed down current from the burn area to catch the oil as it started sinking. However, there are many logistical problems in using this approach in open water with waves and currents.

****NOTE:** To date, no one has actually designed a prototype system nor tested this approach.

Even under the best conditions, some of the burn residue will be unrecoverable. Therefore, responders need to know the fate of burn residue in open water environments. The first step is to understand the chemical composition of the residues.

Experiments and test burns show that the burn residues for crude oils are similar in composition to heavily weathered oil: (1) the burn residues are mostly devoid of light ends (since most have boiled off at 204°C); (2) a small fraction of the medium-weight compounds (that boil off between 204°C and 538°C) will remain in the residue; and, (3) the majority (75-95 percent) of the residue will be composed of the heavy ends (Buist and Trudel, 1995).

With highly weathered oil, additional weathering of both sinking and floating residues will likely be slow. Weathering rates will also be reduced because the residues form relatively large physical lumps or thick sheets that are less biodegradable. (For more on microbial degradation, refer to Scholz et. al., 1999.) Thus, unrecovered burn residues are likely to persist for long periods of time. Residues may eventually strand on shorelines where they could be recovered, or sink and be deposited on the sea floor as intact, increasingly unreactive masses. The amount of residue depends on the volume of oil burned and the burn efficiency; where it ends up depends also on weather, current/tides, and response operations specifics.

Environmental Concerns of Burn Residues from On Water ISB

There are several ways in which unrecovered burn residue can directly and indirectly affect the environment. These include impacts and injuries to wildlife resources and habitats from:

- direct contact (coating);
- ingestion;
- stranding/smothering; and
- toxicity effects from water soluble components.

Direct Contact (coating)

Sticky burn residues that float can foul the feathers of birds and the fur of marine and terrestrial mammals (e.g., seals, otters). Birds are particularly at risk because even small amounts of oil can interfere with a bird's ability to thermo-regulate and maintain buoyancy (Leighton, 1995). In tests with seven crude oils and one diesel, Buist and Trudel (1995) reported that burn residues from the heavier oils formed brittle, non-sticky residues that would not stick to feathers and fur; conversely, the lighter crude oils and diesel did produce sticky burn residues. By comparison, the risk of birds and mammals directly contacting, and being impacted by, clumps of burned oil residue is small relative to the possibility of contacting and being impacted by unburned, sticky oil since unburned oil will have spread over a large area. (Please note that even small amounts of any type of floating oil, however, can significantly impact birds under certain conditions, such as when both oil and birds are concentrated in convergence zones.)



Bird Coated in Heavy Oil.

Ingestion

Currently, there are no data on the effects to birds from ingesting burn residue, such as would occur during preening. We can expect, however, that burn residue ingestion will result in similar types of effects as weathered oils (Leighton, 1995), including a wide range of internal injuries. Again, the risk from residues would be less than that of a slick because of the reduced volume of material on the water.

Floating burn residues can affect sea turtles because they feed on objects floating at the water surface. Sea turtle contact with, and ingestion of, pelagic tar has been well-documented (Witham, 1978, 1983; Vargo *et al.*, 1986; Van Vleet and Pauly, 1987). Turtles have ingested tar balls that blocked their mouth cavities and digestive tracts, and contact with floating tar coats their flippers and then their mouths as the turtles attempt to clean their flippers. Large quantities of tar have been known to physically immobilize smaller turtles.



Oiled green sea turtle (from http://www.aida2.org/english/projects/talamanca/impact_environmental.php)

Photo Credit – Florida Marine Research Institute

Stranding/Smothering

Floating burn residues could eventually strand on the shoreline. Impact severity would be a function of the amount of oil that came ashore as well as the habitat type. Smothering of intertidal organisms could occur. While cleanup crews would normally be deployed to remove oil that stranded shortly after a burn, small



Oiled, stranded dolphin

amounts of oil that stranded over large areas and long periods of time could be difficult to distinguish from chronic oil pollution if that were a problem in the area.

A major concern about sinking oil residues is their potential for physical smothering and coating of animals and habitats on the seafloor. The biggest risk from a large burn of heavy oil inside bays and estuaries would occur if residue could concentrate in important habitats. A recent study of spills of non-floating oils by the National Research Council (NRC, 1999) found that there were few effective technologies for containing and recovering liquid sunken oil. Removal of viscous and semi-solid or solid burn residue would be even more difficult than sunken oil.

Burn residues could smother or coat animals that live on and in the seafloor if sufficient quantities of residues sink and remain where these benthic organisms are located. In one documented South Korean case, approximately 500,000 gallons (11,900 bbl/1,625 tons) of heavy oil were burned and the residue sank, affecting nearby caged crabs (Moller, 1992). Generally, the amount of residue expected from intentional burning of oil at sea is very small and this residue will tend to spread over large areas of the seafloor. Based on the South Korean case, it was concluded that residues of small intentional burns will have very localized physical impacts. However, if a large amount of oil is to be burned in an area with slow currents or low flushing rates, the potential for a significant amount of residue to accumulate on the seafloor and affect benthic resources must be assessed.

Relative Toxicity of Soluble Components of Burn Residues

It is well documented that burn residues have lower concentrations of total PAHs, but often have a higher proportion of the high molecular weight PAHs within that total, compared to the fresh oil. This relative enrichment of high molecular weight PAHs is a result of preferred evaporation and combustion of the light-weight PAHs and, in some cases, accumulation of PAH-containing soot particles over the burn area.

Burn residues from a 1993 Canadian open-water test burn were collected and used in bioassay testing. The residues were mixed in water for 48 hours, and the water was used in three kinds of bioassays: rainbow trout (96-hour exposure in freshwater), stickleback (96-hour exposure in seawater), and sea urchin fertilization (20 minute exposure in seawater). All of the tests showed no toxicity (Blenkinsopp *et al.*, 1997). In Australia, bioassays using crude oil burn residues created in the laboratory showed no acute toxicity to amphipods and very low sublethal toxicity (burying behavior) to marine snails (Gulec and Holdway, 1999). Based on these limited tests and the chemical composition of

the burn residues, they are expected to yield little or no chemical toxicity.

The oil remaining after a burn differs in composition from the parent oil. One difference is that the burn residue is depleted in short-**ALKANES** and **CYCLOALKANES** relative to the parent oil (Evans *et al.*, 1986). A comparison of concentrations of **VOLATILE ORGANIC COMPOUNDS** (VOCs) from the original oil to the burn residue shows a reduction in these toxic components (Evans *et al.* 1986). Some of the reduction can be attributed to evaporation. Both lower and higher molecular weight PAHs have been shown to be reduced in the burn residue relative to the parent oil (Lin *et al.* 1992). On the other hand, the latter authors found that some metals were enriched in the burn residues by a factor of 2 to 4.

Section IV—Burn Residues On Land

How Burn Residues Behave On Land

Burning of oil spilled on land occurs more often than at sea. Thus, there is more information on burn residue behavior on land. “On land,” as used here includes a wide range of habitats, such as salt marshes, wetlands, ponds, grasslands, timberlands, and open fields. There can be a layer of water between the soil and oil. In fact, a layer of water is preferred because it can protect the soil from damage from both the oil and the heat of the burn.

Many of the residue behaviors and issues discussed in Section III for spills on water also apply to spills on land. Sinking of burn residues is still of concern in small waterbodies, and because freshwater is less dense than seawater, more burn residues could be expected to sink. Spills on land tend to be thicker since there is less spreading (compared to spills on water), resulting in thicker burn residues. However, thicker layers of oil have higher burn efficiencies, so the overall net result is likely to be higher overall removal rates. Table 1 summarizes the likely behavior of burn residues on land from different oil types.

During a burn, organic material (plants and animals) in the affected area can be consumed by the flames; depending on conditions, root matter may be protected. This can include grasses, shrubs, and other vegetation. Soils that are heavy with organic matter can also be impacted by a burn.

Burns of oil directly on the ground can behave differently depending on the physical aspects of the site. If the ground is water-saturated or frozen, there is little risk of the spilled oil penetrating into the ground and contaminating the soils and the underlying water table. If the ground is dry and permeable, the fresh oil can soak in, requiring the construction of trenches and ditches to collect the oil

Alkanes are any of a group of open chain hydrocarbons whose molecules contain only single bonds. Alkanes have the general chemical formula C_nH_{2n+2} .

Cycloalkanes are **ALICYCLIC** hydrocarbons with a saturated ring. From: www.dictionary.com.

Alicyclic hydrocarbons have properties of open-chain (aliphatic) compounds, in spite of having a 6-carbon ring. From: www.wordreference.com.

Volatile Organic Compounds (VOCs) are substances containing carbon and different proportions of other elements such as hydrogen, oxygen, fluorine, chlorine, bromine, sulfur, or nitrogen; these substances easily become vapors or gases and can cause adverse health effects.



Oil spilled on land.

Table 1. Behavior of Burn Residues for Different Types of Oil for On Land Burns.

Oil Type	Behavior of Burn Residue On Land
VERY-Light Oils	Will burn, will not leave a significant amount of residue
Diesel-Like Products and Light Crude Oils (Diesel, No. 2 Fuel Oil, Light Condensate, West Texas Crude Oil)	Burn residue is mostly unburned oil that penetrated into the ground, root cavities, and burrows, with a small amount of soot particles that can be enriched in heavier PAHs. Remains liquid; can be recovered with sorbents and flushing.
Medium Crude Oil and Intermediate Products (South Louisiana Crude Oil, IFO 180, Lube Oils)	Burn residue can be pockets of liquid oil, solid or semi-solid surface crusts or sheets, and heavy, sticky coating on sediments. Liquid oil can be flushed. Semi-solid and solid residues can be manually picked up. Remaining residues can be tilled in appropriate habitats.
Heavy Crude Oils and Residual Products (Venezuela Crude, San Joaquin Crude, No. 6 Fuel Oil)	Difficult to burn, so often have to add a lighter oil to start the burn. Leaves heavy, sticky residue that is a mix of unburned oil and semi-solid burn residue, requiring extensive cleanup. Some of the starter fuel can remain and contaminate the ground.

Peat habitats are soil material consisting of partially decomposed organic matter; found in swamps and bogs in various parts of the temperate zone. It is formed by the slow decay of successive layers of aquatic and semiaquatic plants, e.g., sedges, reeds, rushes, and mosses

Fens are areas of flat, highly fertile agricultural land with a high water table that were once marsh lands. Fens are common features in England.

A **Tundra** is defined as the treeless plains of Northern North America where the subsoil is perpetually frozen.



ISB in Ice.

on the water table prior to burning. There are special concerns about burning oil on highly organic substrates, such as the **PEAT**, **FEN**, and **TUNDRA** habitats. The heat of the burn can liquefy the oil and cause it to soak deeply into the peat when the water table is low. Degradation rates in peat, with low oxygen and acidic conditions, can be very slow. For example, studies of a crude oil spill in a peat bog in Canada found high levels of lightly weathered oil to depths of more than 15 inches (40 cm) 15 years after the spill and burn (Blenkinsopp *et al.*, 1996). Nevertheless, burning can be a preferred response option, especially in remote areas. Because peat is so soft, manual clean up could cause more damage to the marsh/bog and also result in pockets of oil collecting in footprints and other tracks.

Oil spills on snow can produce large volumes of oil-contaminated snow. Burning of oil-contaminated snow is similar to burning oil on water, as the snow melts, oil is released onto a pool of water where it is ignited by the heat of the burn. The main differences are that oil mixed in snow does not form an emulsion (since there is no mixing

energy or liquid water) and the evaporation rates are slower. Therefore, burns of oil-contaminated snow can be very efficient, producing less residue. Residue can easily be collected and properly disposed of when oiled snow is collected and burned in special burn pits.

Likely Outcome of Residues That Are Not Recovered On Land

Where the oil remains on the surface, it is often possible for crews to go back into the burned area and conduct additional cleanup. Liquid residues can be flushed to collection sites for recovery by sorbents or vacuum systems. Sticky or solid residues can be manually picked up at sites with access by foot. On barren areas, agricultural areas, and habitats with sparse or annual vegetation, the site can be tilled and fertilized to speed the degradation of light residues. However, ISB is often used in areas with difficult access, so the residues will not be completely recovered.

Most crude oil residues have the composition of weathered oil, and further weathering rates are relatively slow. Their thickness and hard surface also slow weathering rates. Because of these factors, responders often till and fertilize burn areas, to break up the oil and increase the rate of microbial degradation and enhance the rate of plant recovery.

The fate of the oil remaining at ISB sites varies by habitat (Dahlin *et al.*, 1999). At one end of the spectrum are the low oxygen, cold, and acidic peat habitats in the sub-Arctic and Arctic regions. Weathering rates under these conditions are extremely slow (decades), particularly where the oil concentrations are high and the oil has penetrated into the peat. At the other end of the spectrum are agricultural fields, where the burn area can be tilled, fertilized, and crops can be successfully grown the next season. In wetlands, residues of light oils that remain mostly on the surface degrade quickly, within months to a year (Michel *et al.*, 2002). However, crude oils and residues can persist for long periods of time in wetland soils. In follow-up studies of *in-situ* burns of crude oil spills in wetlands conducted between 2 and 11 years after the spill/burn, Mendelssohn *et al.*, (1995) found elevated oil concentrations (relative to background) in the surface soils at five of six sites.

In some cases, it may be necessary to re-visit the site to determine if the residual oil is affecting habitat recovery and if additional action is required to speed recovery. This approach has been used at Arctic spills during winter, re-visiting the site during and after the thaw to conduct removal of any remobilized oil.

Relative Toxicity of Burn Residues On Land

The toxic effects of burn residues can be related to both physical and chemical effects. Crusts and thicker residues can physically smother the flora and fauna, preventing the regrowth from surviving roots. The impacts of heavy accumulations of weathered oil and burn residues are not expected to be very different, except that burn residues can be very sticky or very dense and less likely to be removed by natural processes such as rainfall or tidal flushing.

The chemical toxicity effects from soluble components of oil residues in sediments vary by oil type and amount. Low concentrations of oil may even stimulate plant growth. In greenhouse experiments, salt marsh plants could grow normally in soils containing up to 400,000 parts per million (ppm) weathered crude oil (Lin and Mendelsohn (1998) and 228,000 ppm No. 2 fuel oil (Lin *et al.*, 2002). Burn residues are likely to have less chemical toxicity than weathered oil because of their highly weathered initial condition and lower bioavailability of weathered, thick residues.

Environmental Concerns of Burn Residues from On Land ISB

The key concerns of burn residues on land are how they affect vegetative recovery and soil function. There will also be concerns about impacts to wildlife from contact with sticky residues. Studies of wildlife use of prescribed burn sites show that some species of birds are attracted to burned wetlands (Vogl, 1973), and deer and other herbivores would be attracted by increased access or new growth. Special care may be needed to initially keep out wildlife that might be attracted to burn areas where the residues are still sticky. Experience at oil spills has indicated that crude oils and heavy refined products coated on vegetation tends to harden up and no longer stick to fur and feathers after 3-4 weeks. There are no reports on how long it takes sticky residues to do the same.



Oil residue on shallow pond.

The key concern of residues from burns on small waterbodies such as ponds is whether a significant amount of residue will sink. Sunken residue can smother benthic resources, affect fish spawning habitat, degrade water quality, and become a chronic source of re-mobilized oil if part of the residue is liquid. It may be possible to rapidly recover burn residues immediately after a spill, before they cool and start sinking. Recovery of sunken residues, even in small areas, will be difficult because of their high viscosity.

Section V—ISB Case Histories and Lessons Learned

Spills where ISB was used as a response method are described in this section. The emphasis is on the effectiveness of the burn and the amount and nature of the oil residue. A majority of the burn cases are following oil spills from pipelines; only one of the case histories is the result of a planned on-water burning.

Case Study No. 1—Trans-Alaska Pipeline, Alaska, February 1978

The spill resulted from sabotage to the pipeline. The ground was frozen solid and snow retarded the oil's spread. Dikes were constructed to prevent additional spreading. Free oil was collected by vacuum truck and re-injected into the pipeline. Oily debris was transported to a recovery station. After 60 days of cleanup activities, road restrictions went into effect with the spring thaw. Vacuuming operations had to be terminated. The diked area (800 ft long and 15 ft wide), containing about 500 bbls of oil, was burned 63 days after the spill.

The oil ignited readily, and the 1.9 acres burned for two hours, then continued in pockets. Spot burning was conducted for another week. Very little melting of ice occurred. The frozen tundra thawed to a depth of several inches. The area that had thawed was disked and reburnt, and the entire spill zone was fertilized. Oil residues formed a light sheen in a ponded area that was recovered by skimmers the first summer. There was 50 percent revegetation after the first growing season (summarized from Buhite, 1979).

Case Study No. 1:	Trans-Alaska Pipeline, Fairbanks, Alaska
Spill Date:	15 February 1978
Oil Type:	Prudhoe Bay crude oil (API gravity = 29°)
Spilled Volume:	16,000 bbls (672,000 gallons)
Burned Volume:	500 bbls (21,000 gallons)
Habitat:	Ponded tundra

Case Study No. 2—Marathon Pipeline, Illinois, January 1995

The spill impacted 3,750 ft² of wet and muddy bean stubble field and 10,560 ft² of drainage ditch. The oil in the ditch (1 bbl) was recovered by vacuum and sorbents; the oil in the field, which was too muddy to work in, was burned on the day of the spill. Normal cultivation was resumed the following spring (summarized from May and Wolfe, 1997).

Case Study No. 2:	Marathon Pipeline, Cisne, Illinois
Spill Date:	14 January 1995
Oil Type:	Illinois crude oil
Spilled Volume:	3 bbl (126 gallons)
Burned Volume:	2 bbl (84 gallons)
Habitat:	Agricultural land and drainage ditch.

Case Study 3—Mosquito Bay, Louisiana, April 2001



Figure 1. Mosquito Bay – 1 hour after first burn ended.

This release occurred from a condensate pipeline located on Point au Fer Island, Louisiana. The release site was in the interior of a marsh island. The vegetation trapped the bulk of the condensate (a very light oil that was almost like diesel fuel). Manual removal was attempted for a week and was causing considerable damage to the vegetation from foot and airboat traffic. Two areas were burned 6 and 7 days after the spill. At the time of the burn, oil had penetrated up to 8 inches (20 cm) into the marsh soils via crab burrows and root cavities. Free oil was up to 1.5 inches (4 cm) thick, pooled on the water surface and in burrows, though there were extensive



Figure 3A and 3B. Mosquito Bay .
A - Heavily oiled vegetation (*Spartina patens*) immediately before the 12 April 2001 burn, starting to turn yellow after being in contact with the condensate for 6 days.

Case Study No. 3:	Mosquito Bay, Louisiana
Spill Date:	5 April 2001
Oil Type:	Condensate
Spilled Volume:	> 1,000 bbl (> 42,000 gallons)
Burned Volume:	500 bbl (> 21,000 gallons)
Habitat:	Salt and brackish marsh, intertidal



Figure 2. No burn residue on surface; free unburned oil in burrows.

areas where the oil thickness was on the order of 1 mm. Although 12 acres were oiled, 98 acres of marsh were burned before the fire went out. Approximately 90-95 percent of the surface oil was estimated to have burned. Oil remaining after the burn occurred as free oil that had not burned but remained pooled in the sediments and burrows (summarized from Michel *et al.*, 2002).

Case Study 4—Ruffy Brook, Minnesota, April 2001



Figure 4. Oblique aerial photograph of the Ruffy Brook spill site, taken on 17 July 2001, one year post burn, showing the position of the pipeline right-of way (dashed line), the release location (star), and the nature of the burn site. The approximate area of the burn is outlined.

The oil was spilled from a pipeline break in the middle of the ponded wetland and spread over 3 acres of a mix of open water, willows, and grasses. The entire spill area was burned the day of the release, and lasted three hours. The fire went out quickly when the edge of the oil was reached. Touch-up burning was conducted for three days. Approximately 80 percent of the oil was burned.



Figure 6. Photograph showing the nature of the tarry residue that was manually removed within three days after the burn; it was picked up in sheets.

Case Study No. 4:	Ruffy Brook, Minnesota
Spill Date:	5 April 2001
Oil Type:	Bow River crude oil (API = 21°)
Spilled Volume:	> 50 bbl (> 2,100 gallons)
Burned Volume:	> 50 bbl (> 2,100 gallons)
Habitat:	Ponded wetland with water depths of 1-3 ft.



Figure 5. The ponded wetland contaminated with medium crude oil discharged from the 34-inch pipeline at the Ruffy Brook spill site.

There was a significant amount of burn residue that was up to 0.5 inches thick. The residue was tar-like and could be picked up in sheets or “globs”. None of the burn residue was observed to have sunk. One year later, only a few droplets of oil could be found throughout the burn area (summarized from Michel *et al.*, 2002).

Case Study 5—Prince William Sound, Alaska, March 1989

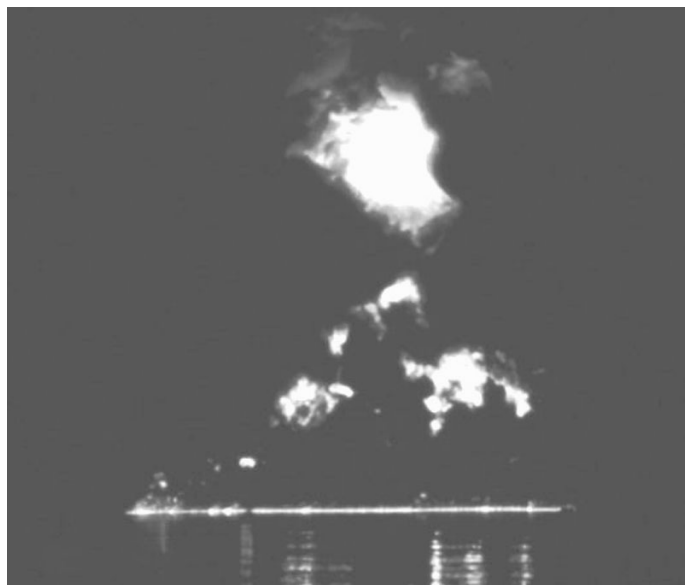


Figure 7 Exxon Valdez test burn.

Case Study No. 5:	Exxon Valdez Test Burn, Prince William Sound, Alaska
Spill Date:	24 March 1989
Oil Type:	Prudhoe Bay crude oil (API = 29°)
Spilled Volume:	257,000 bbls (10,800,000 gallons)
Burned Volume:	350-700 bbls (15,000-30,000 gallons)
Habitat:	Open water

A test burn was conducted on 25 March, the day after the initial grounding and oil release from the Exxon Valdez tanker. A fire boom was used to collect oil for about half an hour. Right after dark, the oil in the boom was ignited with a small plastic bag of gelled gasoline that was floated into the contained oil. The oil burned for about 1 hour. The seas were calm with only a light breeze. Responders collected about 300 gallons (7 bbls) of burn residue of a taffy-like consistency, representing 1-2 percent of the original oil volume. The floating residue collected against the boom and was about 4-5 inches thick. Further burning was not conducted because strong winds on the third day of the spill emulsified the oil and spread it over large areas (summarized from Allen, 1990).

Case Study—NOBE, Newfoundland, Canada, August 1993

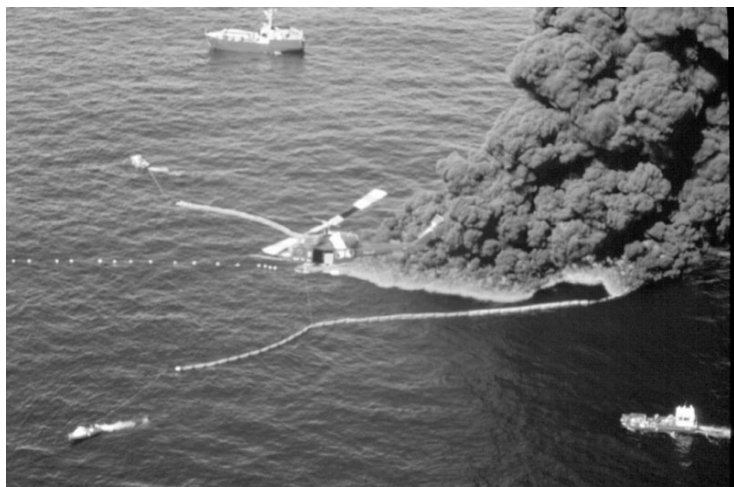


Figure 8. NOBE experimental burn.

An international, multi-sponsor test burn was conducted in 1993 offshore of St. Johns, Newfoundland known as the Newfoundland Offshore Burn Experiment or NOBE. The experiment verified that *in-situ* burning operations can be safely and effectively carried out with burn efficiencies exceeding 90%, resolved many of the uncertainties regarding air contamination, and confirmed the overall viability of *in-situ* burning as a response tool. There were two experimental open-water burns where fresh oil was released into fire-resistant boom and ignited with a Helitorch (Figure 8). The main objective of the experiment was to study air emissions under realistic, full-scale field conditions. The burn residue floated and looked like highly weathered oil. Chemical analysis of the residue showed loss of 40-50 percent of the original compounds (summarized from Fingas *et al.*, 1994). The test burn also showed that there was no significant increase in surface water temperatures during the burn. The burning layer is assumed to not remain over a given water surface long enough to change the temperature because ambient-temperature seawater is continually being supplied below the oil layer as the boom is towed (summarized from Fingas *et al.*, 1994).

Case Study No. 6:	Newfoundland Offshore Burn Experiment, Newfoundland, Canada
Spill Date:	12 August 1993
Oil Type:	Crude oil (API = 36°)
Spilled Volume:	Two releases totaling 485 bbls (20,400 gallons)
Burned Volume:	All the above



A- Residue Recovery.



B – Residue Examination.

Figure 9 A & B. NOBE Burn.

Section VI—Air Quality Issues—Fate of Burn Residue in the Air

Understanding the Problem

Responders in the United States are required to continuously monitor the smoke plume's behavior during all *in-situ* burns. In most large-scale burns, not enough air is drawn into the fire for complete combustion of the oil being burned. Since the burn continues under incomplete or “starved combustion” conditions, it produces a thick, dense, black plume of smoke composed of partially burned byproducts in particulate and gaseous form (AKDEC *et al.*, 2001). These airborne combustion by-products are essentially burn residues that enter the atmosphere. The airborne residues from an *in-situ* burn generate the greatest concern for downwind human populations and natural resources.

Most of the oil in the *in-situ* burn will be converted to carbon dioxide and water. The smoke plume contains gases and particulates that may have toxic effects on humans. Within the plume, there are several compounds that are of concern: particulate matter (soot composed primarily of elemental (“black”) carbon); gases such as carbon dioxide, carbon monoxide, nitrogen oxides, sulfur oxides, and volatile organic hydrocarbons. The typical breakdown of *in-situ* burning by-products of crude oil is as follows (modified from Ferek *et al.*, 1997):

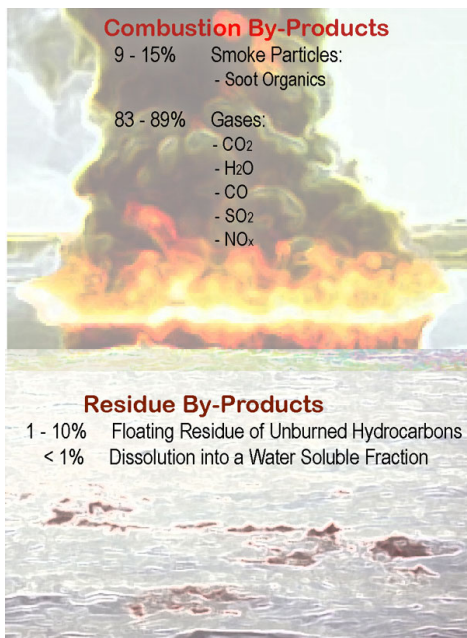


Figure 10. Typical composition of crude oil and combustion products produced from an *in-situ* burn (modified from Ferek *et al.*, 1997).

- 9%-15% Particulate matter
- 83%-89% Gases (including water vapor)
- 1-10% Floating Residue
- <1% Water soluble fraction

While the gases may be of higher abundance, they are of less concern than the soot (particulate matter) that is emitted. The black smoke consists of particles of solid materials (dusts, soot, fumes) or liquid material (mists, fogs, sprays) that remain suspended in the air long enough to potentially be inhaled by response personnel or the general public. Inhaled, they can cause respiratory problems, although the duration of exposure and particle concentration are important in determining effects. It usually takes a high concentration (several milligrams of particulates per cubic meter of air) to cause respiratory problems. In general, data from previous ISB research has shown that particulate concentrations in the plume are the primary concern to public health in the areas greater than one to two miles downwind of the burn location (not including response personnel). The gases created during the burn typically dissipate to



ISB plume during NOBE, August 1993.

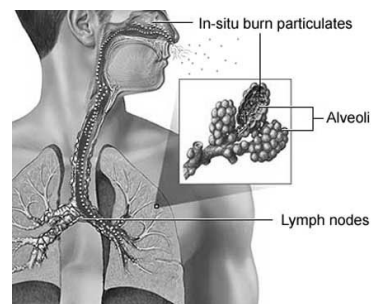
background levels within one to two miles downwind (Barnea, 1995).

Outcome of Air Residue

Particulate size plays a crucial role in determining how long the airborne burn residue will be suspended in the air. Larger particulates (tens of mm in diameter) would precipitate (settle or rain out) rather quickly close to the burn site. Smaller particulates (ranging from a fraction of a mm to several mm in diameter) tend to stay suspended in the air for a longer period of time and can be carried over long distances by the prevailing winds. Particulates small enough to be inhaled (particulate matter, 10 microns or smaller [PM-10]) may also remain suspended in the air for long periods of time. Due to plume dynamics, the concentration of PM-10s will decrease as the plume rises and spreads, and only those particulates that remain near the ground (where people are), will threaten the population downwind. However, public exposure to these plume components will be minimized, unless the smoke plume is transported at ground level.

Winds and **ATMOSPHERIC STABILITY** are, therefore, the two most important meteorological factors in effectively determining the smoke plume trajectory and likely population impacts (Figures 11 and 12). Smoke trajectories usually include forecasts of **TRANSPORT WINDS** and **MIXING HEIGHTS**. Local winds are also important considerations in all smoke plume trajectories. Local winds often become the transport winds, especially if winds above the fire are light, or at night when radiational cooling causes a surface-based inversion to form in the boundary layer, resulting in very low mixing heights. Local winds can also cause residual smoke to move to lower elevations overnight.

In-situ burns are typically limited to wind speeds of less than 15 to 20 knots. With stronger wind speeds, the smoke plume may become transported laterally at a much lower atmospheric level than if the plume had been allowed to travel to greater heights in reduced wind conditions (Ferek *et al.*, 1997). Also, ignition may not be achievable with wind speeds above 20 knots.



Inhalation of *in-situ* burn PM-10 particulates can travel deep into the lungs. (Picture modified from A.D.A.M. online).

Atmospheric Stability is the measure of the tendency for air mixing vertically within the atmosphere and determines the volume of air through which the smoke plume will mix and therefore, its concentration in the atmosphere.

Transport Winds are defined as the mean wind speed and direction of all winds within the atmospheric mixing layer.

The **Mixing Height** is defined as the height above the surface through which relatively vigorous mixing will take place vertically due to convection.

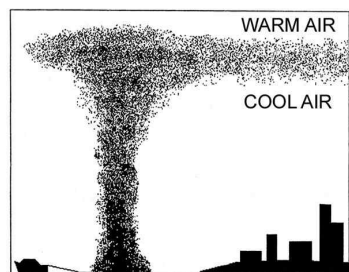


Figure 11. Typical smoke plume dispersion.

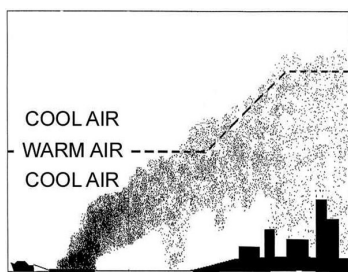


Figure 12. Possible smoke plume dispersion with inversion.

If an ISB is conducted during a temperature inversion (Figure 12), the plume may become trapped in the lower atmosphere resulting in a greater potential exposure of the downwind populations (Ferek *et al.*, 1997). Normally, warm air will rise through cooler air, since it has a lower density (Figure 11). But a temperature inversion is a stable feature – a condition in which the temperature of the atmosphere increases with altitude in contrast to the normal decrease with altitude. When temperature inversion occurs, cold air underlies warmer air at higher altitudes (Figure 12). During a temperature inversion, air pollution released into the atmosphere's lowest layer is trapped there and can be removed only by strong horizontal winds. Because high-pressure systems often combine temperature inversion conditions and low wind speeds, their long residency over an industrial area usually results in episodes of severe smog. Thus, inversions may trap pollutants emitted at the surface (including *in-situ* burn smoke plumes).

Because of the variability and potential impacts to downwind populations, local air quality experts and meteorologists should be involved in the modeling and assessment of the decision to burn.

Exposures to Airborne Residue

Particulate Matter

In the 1993 experimental *in-situ* burn off the coast of Newfoundland, monitoring efforts showed that the level of respirable PM-10 and smaller particulates varied within the smoke plume. At ground level, the PM-10 concentrations did not exceed the 150 mg/m³ levels (the one hour average exposure concentration recommended by the National Response Team [NRT, 1995]) because the hot smoke rose and did not mix downward, even at distances approaching 25 miles (40 km) or more from the burn site.

Within the smoke plume, several high concentrations (greater than 150 mg/m³) were detected as far as 10 miles downwind from the burn site, while in other places the plume had lower particulate concentrations. Additionally, the monitoring efforts determined that the PM-10 concentrations beneath the plume, 150-200 feet (46-61 m) above the surface, did not exceed background levels of 30 to 40 mg/m³ (Ferek et al, 1997).

Gases

The smoke emitted from oil combustion contains gases (and particulates) that may have toxic effects, much like exhaust emissions from motor vehicles or smoke from wood stoves. As mentioned earlier, toxic gases such as carbon monoxide (CO), sulfur dioxide (SO₂) and nitrogen dioxide (NO₂) as well as PAHs are emitted from an *in-situ* burn, but in very small concentrations. The following list summarizes the potential toxic effects from exposure to the gas emissions during an ISB:

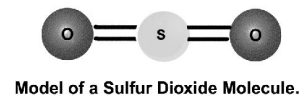
More on Particulate Matter

Particulate matter (PM-10) at the 10-micron level is a major concern for human health because these particulates are inhalable and can lodge deep into the lungs. Recently, EPA has established exposure standards for smaller, fine particles (PM-2.5) -- which travel deeper into the lungs than the PM-10 particulates and have been linked to premature deaths, chronic bronchitis and aggravated asthma.

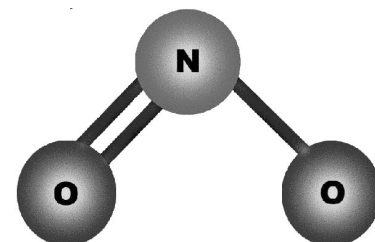
A significant quantity of the fine particulates come from the combustion of fuel by power plants and diesel trucks and buses, among others. Early episodes of extreme pollution by fine particles - the most famous of which occurred in Donora, Pennsylvania and London in the 1930's, 40's, and 50's and killed thousands of people. From:

<http://www.epa.gov/oar/primer/>.

- **Sulfur Dioxide (SO₂)** is a gas formed when sulfur in the oil oxidizes during the combustion process. This gas is toxic and irritates the eyes and respiratory tract by forming sulfuric acid on these moist surfaces (Scorecard online, 2003). Average SO₂ levels recorded in experimental burn smoke plumes have been in proportion to the sulfur content of the fuel. The SO₂ levels recorded in the plume 325-660 ft (100-200 m) and further downwind of the burn location are expected to be well below the level of concern for the general population (Fingas *et al.*, 1993).

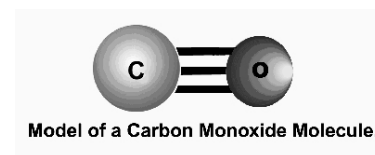


- **Nitrogen Dioxide (NO₂)** is another gaseous by-product of oil combustion. Like SO₂, it is reactive, toxic, and a strong irritant to the eyes and respiratory tract (Scorecard online, 2003). The effects of short-term exposure are still unclear, but continued or frequent exposure to concentrations that are typically much higher than normally found in the ambient air may cause increased incidences of acute respiratory illness in children. Short-term exposure (for example, less than three hours) to high NO₂ concentrations may lead to changes in airway responsiveness and lung function in adults with pre-existing respiratory illnesses and in children. Long-term exposure to NO₂ may lead to increased susceptibility to respiratory infection and may cause changes in the lungs.



NO₂ is less soluble than SO₂ and therefore may reach the deep portions of the lungs. Sampling indicated that the concentration of nitrogen dioxide in the plume several miles downwind of the burn does not exceed several parts per billion (Barnea, 1995). Therefore, it is not expected to pose a threat to the general public more than 2-3 miles (2-5 km) from a burn site.

- **Carbon Monoxide (CO)** is a common by-product of incomplete combustion. The primary toxic concern of CO is an acute effect and stems from its high affinity to the hemoglobin molecule in human red blood cells. The CO chemically displaces oxygen from the hemoglobin and causes oxygen deprivation in the cells of the body (EHC online). In experimental burns, the average level of CO in the smoke plume over the duration of the burns (15 to 30 minutes) was found to be 1 to 5 ppm 500 feet (150 m) downwind (Fingas *et al.*, 1993), well below the standards for 8-hour exposure given in Table 2.



- **Polycyclic aromatic hydrocarbons (PAHs)** have very low vapor pressures and are not very flammable (compared to other compounds found in crude oils). PAHs are found in the unburned oil as well as the smoke plume. Some PAHs are known or suspected carcinogens. Target organs may include the skin (from chronic skin contact with oils) or the lungs from inhalation of aerosols (Scorecard online, 2003). Based on data from NOBE and previous burns, most PAHs are consumed in the fire, and their concentration in the oil residue may be higher than in the smoke plume (Fingas and Punt, 2000).

One lab study measured the PAH content of smoke from several types of crude oil (Benner *et al.*, 1990), and found total PAH concentrations to be miniscule. For smoke collected from larger scale test burns, PAHs have generally been found to be in even less abundance per unit of smoke mass than indicated by the lab study (Fingas *et al.*, 1993).

- **Volatile Organic Compounds (VOCs)** readily evaporate and are released naturally from surface slicks and during an *in-situ* burn. Some VOCs are suspected carcinogens (Scorecard online, 2003). Determining the VOC concentration in smoke plumes and from surface slicks has been the focus of many studies. The levels of VOCs are relatively low in burns relative to evaporating surface slicks and appear to be well below the human health levels of concern (Fingas and Punt, 2000).
- **Carbon Dioxide** is found in increased concentrations in the vicinity of a burn. Fingas and Punt (2000) report that the recorded CO₂ levels near an ISB are still well below levels of health concerns.

The US Environmental Protection Agency's Office of National Ambient Air Quality Standards (NAAQS) has developed a list of air quality thresholds for smoke plume components (Table 2). However, sensitive individuals may develop respiratory problems at levels much lower than those listed.

REMEMBER:

The potential health hazards experienced by nearby response personnel conducting the burn will be different from those for the general public at a substantial distance away.

ISB & Health and Safety Issues

One of the main concerns surrounding ISB is the potential impact to the health and welfare of the responders, the general public and environmental resources that could be directly affected by exposure to the smoke plume. Determining the level of concern for exposure to particulates is not simple. Table 3 outlines the potential health hazards of *in-situ* burning as identified by the USEPAs National

Table 2. Air Quality Standards (taken from AKDEC et al., 2001).

Contaminant (unit)	Averaging Periods				
	Annual	24-hour	8-hour	3-hour	1-hour
National Ambient Air Quality Standards					
PM _{2.5} (µg/m ³)	15	65	—	—	—
PM ₁₀ (µg/m ³)	50	150	—	—	—
CO (mg/m ³)	—	—	10	—	40
SO ₂ (µg/m ³)	80	365	—	1,300	—
NO ₂ (µg/m ³)	100	—	—	—	—
OSHA Permissible Exposure Limits					
Total Particulates (mg/ m ³)	—	—	15	—	—
Respirable particulates (mg/ m ³)	—	—	5	—	—
CO (ppm)	—	—	50	—	—
SO ₂ (ppm)	—	—	5	—	—
NO ₂ (ppm)	—	—	5	—	—
CO ₂ (ppm)	—	—	10,000	—	—
PAH (mg/ m ³)	—	—	0.2	—	—
Benzene (in VOC) (ppm)	—	—	1	—	—

Table 3. Potential Health Effects From ISB Smoke Plume Exposure Based on Pollution and Air Quality Standards. (Adapted from AKDEC et al., 2001).

Air Quality Level (Public Notification Level)	Pollutant Levels					Health Effect Descriptor*
	PM10 (24-hour) (ug/m ³)	SO ₂ (24-hour) (ug/m ³)	CO (8-hour) ppm	O ₃ (1-hour) ppm	NO ₂ (1-hour) ppm	
Significant Harm	600	2,620	50	0.6	2.0	Hazardous
Emergency	500	2,100	40	0.5	1.6	
Warning	420	1,600	30	0.4	1.2	Very Unhealthy
Alert	350	800	15	0.2	0.6	
NAAQS	150	365	9	0.12	NR	Unhealthy
50% or NAAQS	50	80	4.5	0.06	NR	Moderate
	0	0	0	0	NR	Good

NR – not reported

* Location of breakpoints for descriptors are close approximations of the actual health effect values.

Are the NAAQS standards applicable for ISB?

The Clean Air Act and its Amendments, require EPA to set **National Ambient Air Quality Standards (NAAQS)** for pollutants considered harmful to public health and the environment. Exposure to these pollutants is associated with numerous effects on human health, including increased respiratory symptoms, hospitalization for heart or lung diseases, and even premature death. The EPA Office of Air Quality Planning and Standards (OAQPS) has set National Ambient Air Quality Standards for six principal pollutants called criteria pollutants:

- carbon monoxide [CO],
- nitrogen dioxide [NO₂],
- ozone [O₃],
- lead [pb],
- particulate matter [PM] at the 10 micron and 2.5 micron size, and
- sulfur dioxide (SO₂).

The standards were developed to monitor/protect worker health relative to continuous or long-term exposures from industry and at the work place. The existing standards (Table 2 above) report exposure limits based on annual means or averaged over 24-hours for continuous sources from industry. For each of these pollutants, EPA tracks two kinds of air pollution trends: air concentrations based on actual measurements of pollutant concentrations in the ambient (outside) air at selected monitoring sites throughout the country, and emissions based on engineering estimates of the total tons of pollutants released into the air each year. Despite the progress made in the last 30 years, millions of people live in counties with monitor data showing unhealthy air for one or more of the six common pollutants (from <http://www.epa.gov/air/urbanair/6poll.html>.)

Are these exposure levels consistent for an ISB that will most likely occur over a very short period of time (hours to possibly several days)? At present, there are no answers to this question. Decision-makers will continue to use the health standards that have been established to date as the baseline for their health and safety planning.

Ambient Air Quality Standards (NAAQS) and the Occupational Safety and Health Act (OSHA).

Based on the information in Table 3, an individual exposed to a PM-10 level of 600 micrograms per m³ over a 24-hour period is considered to have had a hazardous exposure from the smoke plume and may exhibit some of the health effects listed on the General Health Column. Keep in mind that the exposure periods used in these standards vary, and that some (24-hours) are longer than those used in occupational safety and health standards (e.g., eight hours) because the public may be exposed to ambient PM-10 throughout the day and night -- not just at a workplace. *In-situ* burning is likely to occur over a short period of time - hours, perhaps with multiple burns over a day or two. Therefore, information in Table 3 should be interpreted based on the duration of exposure. The potential effects may also vary from person to person.

The following sections identify the specific health and safety issues associated with exposure to the air residue for response personnel and the general public.

Response Personnel

Response personnel work close to the burn and may be exposed to high levels of gases and particulates that would require them to use personal protective equipment. All responders working in and

around the burn should be fully trained to conduct the operation safely. Monitoring of the responders' work environment should be conducted as needed. Occupational standards such as OSHA's **PERMISSIBLE EXPOSURE LIMITS** (PEL) are applicable to this group of typically healthy adults.

Exposure limits, personal protective equipment and other exposure-mitigating operating practices need to be incorporated into a site-specific health and safety plan.

General Public

The public is not likely to be exposed to sustained concentrations of the airborne residue. As the smoke plume extends, the quantities of many of the gases downwind will quickly dissipate to acceptable exposure levels. With acceptable burn conditions (no temperature inversion and moderate wind speed), the public exposure to smoke particulates from the burn should be minimal.

The general public may include sensitive individuals such as the very young and very old, pregnant women and people with pulmonary or cardiovascular diseases, and the tolerance of these subpopulations to particulates must be assumed to be significantly lower than that of the responders. Protecting the general public can be achieved by minimizing their exposure through notifications and warnings to shelter-in-place and conducting the burn only when conditions are favorable to ensure that their exposure to particulates from the burn is below the level of concern. Monitoring downwind air quality is done to provide the decision-maker with information on when it is necessary to extinguish the burn in order to protect the public.

Air Modeling for an *In-situ* Burn

Operational requirements for an ISB are specifically designed to limit the potential exposure of the public to the components of the smoke plume. With effective planning, a burn can be stopped if the plume contacts or threatens to contact the ground in a populated area.

One way to minimize the exposure from a burn to the general public is to use a numerical model such as the National Institute of Standards and Technology (NIST) ALOFT-FT (A Large Outdoor Fire plume Trajectory – Flat Terrain) computer-based model. The model predicts downwind distribution of smoke particulate and combustion products from large outdoor fires. ALOFT-FT was developed to aid in the planning process for the intentional burning of crude oils spills on water. The program may also be useful in predicting the smoke plume trajectory from other large outdoor fires particularly liquid pool fires. ALOFT-FT can be run on a Windows-based personal computer, and requires as input data wind speed and

OSHA defines a **Permissible Exposure Limit** (PEL) as a **TIME WEIGHTED AVERAGE (TWA)** concentration that must not be exceeded during any 8-hour work shift of a 40-hour work week.

The **Time Weighted Average (TWA)** is the average amount of a substance you can be exposed to over an eight-hour day.

variability, atmospheric temperature, number of fires and heat release rate. The ALOFT-FT model is available from <http://flame.cfr.nist.gov/fire/aloft/aloft.html> and is for smoke plumes forming over flat terrain. Future releases will incorporate complex terrain features.

There are other models commercially available that were designed for typical industrial sources, like smokestacks, that are much smaller in terms of energy output than an oil fire. These models use relatively simple correlations to describe a smoke plume. This includes (taken from McGrattan, 1998):

- The ISCST3 (Industrial Source Complex, Short Term) model was developed to predict the travel of short-term (hours, days), short-range (1 km to 10 km) concentrations of pollutants from industrial sources.
- The CTDMPLUS (Complex Terrain Dispersion Model PLus algorithms for Unstable Situations) model was designed to consider more complex terrain.
- The Offshore and Coastal Dispersion (OCD) model was created to assess the impact of offshore emissions on the coastal environment's air quality.
- Earth Tech, Inc's. CALPUFF model, adopted by US EPA, tracks the "puffs" of pollutants through a changing atmosphere.

These models could be used to estimate the dispersion of combustion products from *in-situ* burning. The smoke plume trajectory models are used to provide the federal and state on-scene coordinators with a "best estimate" on the likely fate of the smoke plume. This trajectory information helps determine whether or not an ISB operation would provide value in terms of the cleanup operations, as well as determine the potential impact on the general public. In the US, the Federal On-Scene Coordinator (FOSC) or SOSC may authorize a trial *in-situ* burn to confirm anticipated plume drift direction and dispersion distances downwind before authorizing the full-scale proposed burn***.

*****NOTE:** Of the **UNIFIED COMMAND (UC)**, only the FOSC can authorize a trial ISB in offshore waters.

SMART and Monitoring

In the United States, when the decision to conduct an *in-situ* burn is made, additional concerns regarding the possible effects of the particulates in the smoke plume on the general public downwind that need to be addressed. Special Monitoring of Applied Response Technologies (SMART) was developed by a multi-agency group in the US to address these concerns and assist the Unified Command in determining whether or not to continue, or terminate an ISB. SMART is a monitoring program developed to collect real-time data using portable, rugged, and easy-to-use instruments during *in-situ*

The SMART Perspective...

The examples/procedures for SMART are taken from the formalized processes developed in the US for ISB. They are presented in detail for specific use for responders in the US and for general knowledge for responders elsewhere in the world.

burning operations. The SMART Guidance document (2001) recommends deploying one or more monitoring teams downwind of the burn (a minimum of three teams during large-scale burns), at various locations where effects due to exposure to the smoke plume could be realized (e.g., population centers). Actual monitoring locations should be located in areas where the smoke plume could potentially affect the public or other environmentally sensitive areas. (Available from: www.response.restoration.noaa.gov.)

Whether or not monitoring is required depends on the predicted trajectory of the smoke plume and whether it will reach population centers and exceed safe levels of smoke particulates at ground level.

If impacts to humans are not anticipated, monitoring is not required.

Once the decision to conduct an ISB is made, the team(s) begins collecting background air quality data prior to initiation of the burn. After the burn begins, the team(s) continues collecting data on particulate concentration trends, recording them both manually at fixed intervals and automatically in the data logger. This information is then forwarded to the FOSC to allow them to address critical questions, such as: Are particulates concentration trends at sensitive locations exceeding the level of concern?

The following are the highlights for SMART (summarized from the SMART Guidance document):

- SMART is designed for monitoring *in-situ* burning of oil spills in both coastal and inland zones for public health protection, not worker health and safety.
- It is important for the FOSC to agree on the monitoring objectives and goals early on in the incident.
- Monitoring teams should be contacted as soon as burning is considered a viable response option.
- The FOSC must determine and clearly define what conditions would justify termination of the burn.
- Monitoring locations should be flexible and determined for the incident-specific conditions and issues of concern. In general, one team is deployed at the upwind edge of a sensitive location and a second team is deployed at the downwind end.
- Visual observations (monitoring) are conducted continuously while the burn is operational.
- Monitoring teams remain at their assigned locations, moving only to improve sampling capabilities.
- When addressing particulate monitoring for *in-situ* burning, the overall concentration trend, rather than individual

readings, should be used to decide whether to continue or terminate the burn. For SMART operations, the time-weighted average (TWA over one hour) generated by the particulate monitors should be used to determine the trend.

- The National Response Team (NRT) (1995) recommends that an *in-situ* burn not take place if the air quality in the region already exceeds the NAAQS listed in Table 2 and if burning the oil will add to the particulate exposure concentration.
- Quality assurance and control should be applied to the data at all levels.
- All data are properly archived, presentable, and accessible for the benefit of future monitoring operations.

Section VII—Burn Residue Issues Summarized

One response method for removing oil spilled on water or on land is burning the oil *in-situ*. Depending on the type of oil, the amount of time the oil has undergone weathering, and wind conditions, an *in-situ* burn can be upwards of 90% effective in removing the spilled oil.

This booklet examines the potential concerns to human populations and wildlife and other natural resources from the by-products of an *in-situ* burn. The by-products from a burn can include the solid residue that remains on the ground or on the water surface following the burn or the burn residue that enters the atmosphere as a component of the smoke plume.

The solid burn residue that remains after the fire extinguishes is a concern for humans and natural resources through direct (topical) contact or coating by the residue, through ingestion of the residue, and by smothering natural resources that become covered by the residue. Based on limited tests and the chemical composition of the burn residues, the solid burn residue is expected to yield little or no chemical toxicity.

The airborne burn residue is most notable through the generation of large quantities of black smoke. An *in-situ* burn smoke plume contains particulates (soot or carbon black), a variety of gases, and other volatiles. Of particular concern to human health are the particulates of the 10 micrometer size or smaller (PM-10). These particulates can be drawn deeply into the lungs and potentially cause respiratory problems in sensitive populations. The likely exposure of downwind populations needs to be addressed by the decision-

makers when contemplating a burn. There are several smoke plume trajectory models available for assisting decision-makers in determining the possible impacts to downwind populations from and *in-situ* burn.

The SMART monitoring protocols were developed to collect real-time data using portable, rugged, and easy-to-use instruments during *in-situ* burning operations. With effective planning, a burn can be stopped if the plume contacts or threatens to contact the ground in a populated area.

In-situ burning can be an effective and environmentally safe way to remove oil from the water, land, or ice/snow surfaces.

Section VIII—Other ISB Information

List of Acronyms

AKDEC.....	Alaska Department of Environmental Conservation
ALOFT-FT.....	A Large Outdoor Fire Plume Trajectory – Flat Terrain
API.....	American Petroleum Institute
bbbl.....	barrel
cm.....	centimeter
CO.....	carbon monoxide
CO ₂	carbon dioxide
CTDMPLUS.....	Complex Terrain Dispersion Model Plus algorithms for Unstable Situations
EPA or USEPA.....	US Environmental Protection Agency
FOSC.....	Federal On-Scene Coordinator
ft.....	feet
g.....	grams
H ₂ O.....	water
hr.....	hour
IFO.....	intermediate fuel oil
ISB.....	<i>In-situ</i> Burn(ing)
ISCST3.....	Industrial Short Complex, Short Term model
km.....	kilometer
m.....	meter
mg.....	milligram
mm.....	millimeter
NAAQS.....	National Ambient Air Quality Standards
NIST.....	National Institute of Standards and Technology
NOAA.....	National Oceanic and Atmospheric Administration
NOBE.....	Newfoundland Offshore Burn Experiment
NO ₂	nitrogen dioxide
NRT.....	National Response Team
O ₃	ozone
OAQPS.....	Office of Air Quality Planning and Standards

OCD Offshore and Coastal Dispersion model
OSHA..... Occupational Safety and Health Administration
PAH..... Polycyclic Aromatic Hydrocarbons
PEL Permissible Exposure Limit
PM-2.5 Particulate matter, 2.5 micrometer size
PM-10 Particulate matter, 10 micrometer size
ppmparts per million
RP Responsible Party
RRT..... Regional Response Team
SMART..... Special Monitoring of Applied Response Technologies
SO₂sulfur dioxide
SOSC..... State On-Scene Coordinator
TWA Time Weighted Average
UC..... Unified Command
µg micrograms
USCG..... U.S. Coast Guard
VOC Volatile Organic Compounds

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