In Situ Burning: A Decision Maker's Guide

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Purpose of Report

This report is intended to describe the use of and requirements for in situ burning (ISB) as an effective response technology for oil spills on land (including wetlands), on water, or in ice and snow. It was developed to serve as a reference for oil spill response policy makers and decision makers (government, industry, and other stakeholders). This report discusses requirements for ISB and includes a summary of oil chemistry, behavior, and weathering, which are important factors when making decisions to use ISB. Further, it allows decision makers to better understand the anticipated benefits and limitations to be considered when using this technology for an oil spill.

ISB has been used less frequently than other techniques such as booms and skimmers or oiled soil removal. Consequently, familiarity with the pros and cons of ISB might be limited. Extensive practical and operational experience has been gained from ISB efforts to the Deepwater Horizon oil spill response in 2010 and continues with the ongoing research and development efforts for responding in the Arctic. These lessons learned have been incorporated into this document in an effort to capture and share this expanding knowledge base.

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Executive Summary

The objective of this document is to provide a decision maker with information necessary to assess the use of controlled in situ burning (ISB) as a primary response option for oil spills on land, on water, and in ice/snow conditions. ISB is one of the most efficient ways to eliminate spilled oil under the right conditions. Using ISB, a high percentage of even large volumes of encountered oil can be removed quickly.

ISB has been extensively researched and has been used operationally since the late 1950s for spills of oil on land. ISB has been often used as a response procedure for small to medium on-land incidents in the United States, so there is a good understanding of conditions under which on-land ISB is feasible and effective. More recently it gained operational confidence and public notice for on-water responses during the more than 400 individual burns conducted in response to the Deepwater Horizon oil spill. ISB is well suited to cold weather conditions and can be done even in the presence of ice (on land or at sea). Cold slows the rate of weathering, so the window of opportunity for ISB can lengthen. Sea ice reduces wave activity (breaking waves), slows spreading (which keeps the oil thick enough to burn), and reduces the emulsification process.

Major benefits and reasons to consider ISB are its:

- **High efficiency**—an ISB can be up to 98% effective in removing encountered oil from the environment (dependent on oil type, extent of weathering, and oil thickness);
- **Versatility**—ISB can be used **on water** (fresh or salt water, rivers, streams, oceans), **on land** (terrestrial or riparian habitat, wetlands/marshes, other shorelines), and **in ice/snow** environments (including the Arctic);
- **High elimination rates**—most burns are completed within hours after ignition;
- **Minimal equipment and personnel needs**—personnel are needed for collection and containment of the oil to a thickness that will allow for ignition and sustainment of the burn; and
- **Waste stream reduction**—with high burn efficiencies, the need for waste recovery, removal, storage, transport, and disposal is removed or minimized.

The combustion plume contains most burn by-products that are released to the atmosphere:

- 85 to 95% of the total burned oil becomes carbon dioxide and water;
- 5 to 15% that is not burned efficiently is converted into particulates (soot); and
- A few percent is converted into combustion by-products.

Any remaining incomplete combustion product (burn residue) is usually less than 15% of the total volume burned.

The principles for using ISB, including containment, ignition, and controlling the spilled oil, are well established. There is an extensive history of use, research, and testing in the United States and internationally. The basic principle is to collect and/or thicken an oil slick to greater than 2 mm (0.08 in.) and provide an ignition source to heat the hydrocarbon vapors from the slick surface to ignite a burn. Most oils will burn if a slick is thick enough and if sufficient vapors are present to initiate and sustain combustion.

Decision makers should understand and consider the following when considering ISB:

- Spilled oil properties and the effects of weathering on its behavior;
- Operational requirements and limitations;
- Health and safety of response personnel and the public;
- Environmental effects—wildlife, habitats, etc.

When considering the human health and environmental trade-offs for ISB, the benefits often far outweigh any potential negative consequences. In review of the available information on spills where ISB was used, there were no instances where the response community determined burning was the wrong response option.

In the United States, multi-state Regional Response Teams (RRTs) and state or local governments can pre-approve burn zones within their jurisdiction. These organizations jointly develop planning guidance for the use of ISB for the federal and state decision makers on the requirements for ISB use within the region. The RRTs can establish pre-authorization areas such as:

- Pre-approved zones—areas that do not require RRT consultation;
- Case-by-case zones—areas that require RRT approval; and
- Restricted or exclusion zones—areas where ISB is not allowed.

As there is generally a short window of opportunity when a slick is capable of sustaining a burn, pre-authorization zones allow quicker, informed decisions.

Short-term, localized air quality should be considered relative to approved burn plans. For ISB planning purposes, the most significant National Ambient Air Quality Standards (NAAQS) are the primary NAAQS for particulate matter. Concerns for human health typically only exist for responders directly exposed to the visible plume. Monitoring for potential health effects from atmospheric pollutants generated from burning oil is recommended for the workers in the immediate area of ISB operations and, if there are receptors at risk, for several miles downwind of a burn site.

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Acronyms and Abbreviations

ABSORB .... Alaskan Beaufort Sea Oil Spill Response Body
ACS .... Alaska Clean Seas
AMOP .... Arctic and Marine Oilspill Program
API .... American Petroleum Institute
BSEE .... Bureau of Safety and Environmental Enforcement
CAA .... Clean Air Act
CDC .... Centers for Disease Control and Prevention
CERCLA .... Comprehensive Environmental Response, Compensation, and Liability Act
CFR .... *Code of Federal Regulation*
CTEH .... Center for Toxicology and Environmental Health, LLC
CWA .... Clean Water Act
DOC .... United States Department of Commerce
DOD .... United States Department of Defense
DOE .... United States Department of Energy
DOI .... United States Department of Interior
EPA .... United States Environmental Protection Agency
ESA .... Endangered Species Act
FOSC .... Federal On-scene Coordinator
HAZWOPER .... Hazardous Waste Operations and Emergency Response
IFO .... Intermediate Fuel Oil
IOSC .... International Oil Spill Conference
ISB .... In Situ Burning
JIP .... Joint Industry Project
LEPC .... Local Emergency Planning Committee
LOSCO .... Louisiana Oil Spill Coordinator's Office
MMS .... Minerals Management Service
MOU .... Memorandum of Understanding
NAAQS .... National Ambient Air Quality Standards
NCP .... National Oil and Hazardous Substances Pollution Contingency Plan
NEBA .... Net Environmental Benefit Analysis
NHPA .... National Historic Preservation Act of 1966
NIOSH .... National Institute of Occupational Safety and Health
NIST .... National Institute of Standards and Technology
NMFS .... National Marine Fisheries Service
NOAA .... National Oceanic and Atmospheric Administration
NOBE .... Newfoundland Offshore Burn Experiment
NO_x .... Nitrogen Oxides

NRC .... National Research Council
NRDA .... Natural Resource Damage Assessment
NRT .... U.S. National Response Team
OPA 90 .... Oil Pollution Act of 1990
OSC .... On-scene Coordinator
OSHA .... Occupational Safety and Health Administration
PAH .... Polycyclic Aromatic Hydrocarbon
PEL .... Permissible Exposure Limit
PM .... Particulate Matter
PPE .... Personal Protective Equipment
RCRA .... Resource Conservation and Recovery Act
RRT .... Regional Response Team
SHPO .... State Historic Preservation Officer
SIP .... State Implementation Plan
SMART .... Special Monitoring of Applied Response Technologies
SOSC .... State On-scene Coordinator
SO_x .... Sulfur Oxides
THPO .... Tribal Historic Preservation Officer
TPH .... Total Petroleum Hydrocarbon
UC .... Unified Command
USCG .... United States Coast Guard
USFWS .... United States Fish and Wildlife Service
USGS .... United States Geological Survey
VOC .... Volatile Organic Compound

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Section I: Introduction

The primary goal of an oil spill response is to limit exposure time and subsequent effects from spilled oil on natural and economic resources. Preferred response technologies are those that will result in the best outcome for the environment while minimizing possible adverse effects from the cleanup efforts. The objective of this document is to provide a decision maker with information necessary to assess the use of controlled in situ burning (ISB) as a primary response option for oil spills on land, on water, and in ice/snow conditions.

The main categories of response technologies used in the United States (U.S.) include:

1. Manual and mechanical removal of oil from shorelines and land;
2. Mechanical containment, recovery, and removal on water using booms, skimmers, etc.;
3. Application of dispersants;
4. Controlled (in situ) burning;
5. Treatment with specialized agents such as solidifiers and shoreline cleaning agents; and
6. Natural recovery with monitoring for possible future action.

This document focuses specifically on ISB for oil spill response.

Figure 1—Bayou Sorrel burn, 2013. Source: USCG.

I.1 Controlled In Situ Burning

In situ burning is a response technology that removes spilled oil from a land, snow, ice, or water surface by combustion of hydrocarbon vapors and that yields predominantly CO_2 and water to the atmosphere. ASTM International (2014) defines controlled in situ burning as "burning when the combustion can be started and stopped by human intervention." The combustion by-products (particulates, gases, water, etc.) are released to the atmosphere, with the possibility of some unburned oil or incompletely burned oil residue remaining at the conclusion of a burn.

One of the greatest benefits from ISB is that a burn can rapidly reduce the volume of spilled oil and minimize or eliminate the need to collect, store, transport, and dispose of recovered oil and oily wastes. Each of these actions has associated environmental and human health risks. ISB also has the potential to significantly reduce the duration of cleanup operations. In certain instances, ISB might provide the only means of quickly and safely eliminating large amounts of oil.

ISB has been extensively researched and has been used operationally for spills since the late 1950s as a response technology for spills of oil on land. More recently it gained operational confidence and public notice for on-water responses during the more than 400 individual burns conducted in response to the Deepwater Horizon oil spill. Research on the use of ISB in snow and ice has increased in the last decade as efforts to drill in more remote areas like the Arctic are being considered.

I.2 Document Organization

Key factors to determine the appropriateness of ISB are the feasibility of using ISB under existing spill conditions and safety and health considerations. This report addresses these factors for ISB **on land**, [1] **on water**, [2] and **in ice/snow** [3] and is organized around decision-making considerations for ISB:

- **Section II—In Situ Burning**: the benefits and applicability of ISB;
- **Section III—ISB Decision-making**: local, state, and federal role in the decision-making process;
- **Section IV—Influence of Oil Properties and Weathering**: how oil properties and weathering affect the feasibility of ISB over time;
- **Section V—Oil Combustion and Burn Residues:** the atmospheric by-products and burn residue that result from ISB;
- **Section VI—Human Health and Safety**: the possible health hazards of ISB on response personnel and the general public;
- **Section VII—Effects on Wildlife and the Environment:** the potential effects of ISB from the combustion plume and any burn residue;
- **Appendix A—ISB Case Histories and Lessons Learned:** case studies in which ISB was used as a response technology.

[1] **On land** includes a wide range of habitats, such as salt marshes, wetlands, ponds, grasslands, timberlands, and open fields.

[2] **On water** is defined as spills of oil on the ocean, coastal waters, estuaries, bays, freshwater lakes, rivers, and streams.

[3] **On ice/snow** refers to climates where winter conditions are cold enough to freeze; this includes Arctic-like environments with sea ice and cold temperatures that can exist for all or part of the year and can include spills on water and on land but with the additional environmental and logistical benefits and challenges of dealing with the presence of ice and snow.

Section II: In Situ Burning

II.1 How an In Situ Burn Works

To initiate a burn, sufficient quantities of hydrocarbon vapors are needed in the air above a slick to support combustion. An ignition source can either directly ignite those vapors or heat spilled oil to a temperature at which sufficient vapors to ignite are generated. Once a slick is ignited, hot air rising above the burn will draw air from the sides toward the burn (**Figure 2**). This induced air flow can also draw surrounding oil toward the burn, thereby feeding it with more vapors.

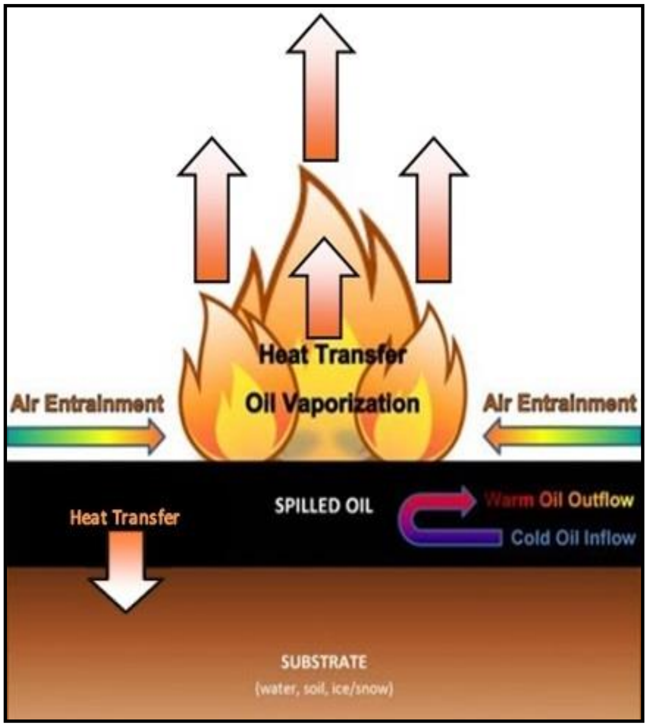

Figure 2—Key oil and heat transfer processes during ISB. Source: Modified from Fritt-Rasmussen (2010).

The key factor that defines whether or not an oil will burn is slick thickness. Slick thickness has two roles:

- Source of hydrocarbon vapors; and
- Retains heat to help vaporization to sustain a burn.

If a slick is thick enough, it insulates the slick by reducing heat loss to underlying media (i.e., water, soil, ice/snow) and keeps the slick surface at a high enough temperature to continue to vaporize. As a slick thins during combustion, its insulating capacity declines and more heat is lost to the underlying substrate. Eventually, the oil temperature will drop, the concentration of vapors will become insufficient to sustain a burn, and it will extinguish. As long as heat transfer to surrounding media is minimized by maintaining sufficient slick thickness, an oil slick will be capable of sustaining a burn.

II.2 Benefits of ISB

The goal of any response is to limit the effect of the spill on nearby communities and responders as well natural and economic resources. Some of the benefits and reasons to consider ISB are its:

- **High efficiency**—an ISB can be up to 98% effective in removing encountered oil from the environment (dependent on oil type, extent of weathering, and oil thickness);

- **Versatility**—ISB can be used **on land** (terrestrial or riparian habitat, wetlands/marshes, other shorelines), **on water** (fresh or salt water, rivers, streams, oceans), and **in ice/snow** environments (including the Arctic);

- **High elimination rates**—most burns are completed within hours after ignition. Once underway, burns proceed quickly. Oil removal rates are a function of the fire size (its diameter), slick thickness, oil type and any emulsification, and environmental conditions at the time of the burn. Larger fires have higher removal rates than smaller fires. Emulsified oils will burn at a slower rate, almost proportional to their water content, until the water content becomes too high; >50%. Empirical observations and experimental data indicate a range of removals (**Table 1**).

Table 1—ISB Elimination Rates

Oil Type	Removal Rate Ranges (mm/min) and (in/min)	
Gasolines	• 4–4.5	• 0.16–0.18
Diesels	• 3.5–4	• 0.14–0.16
Heavy Fuel Oils	• 2–2.2	• 0.08–0.09
Crude Oils	• 3–3.5	• 0.12–0.14

A typical removal rate of about 0.07 gal/min/ft^2 equates to about 4,350 bbl of oil an hour per acre;

- **Minimal equipment and personnel needs**—less equipment and fewer personnel are needed for collection and containment of oil for ignition and burning than for either mechanical recovery or dispersant use on water or for manual and mechanical recovery on land or shorelines; and

- **Waste stream reduction—**with high burn efficiencies, the need for waste recovery, removal, storage, transport, and disposal is removed or minimized.

Table 2 summarizes some of the advantages and disadvantages to be considered when deciding whether to use ISB in response to an oil spill.

Table 2—Advantages and Disadvantages of ISB [4]

Advantages	Disadvantages
• High-efficiency oil removal rates from water, land, or ice surface • Less equipment and less labor-intensive than other response options • Can be conducted at night • Can be applied in remote areas where other methods cannot be used because of distances and lack of infrastructure • Prevents or minimizes impacts to the environment and other resources at risk • Does not release toxic components of oil into the water column • Significant reduction in oil and oily waste requiring storage, treatment, and/or disposal	• Oil must be a minimum thickness to ignite and burn • Residue or unburned oil might need to be recovered. Sunken residue could be thick enough to smother/coat benthic organisms and habitats. • Visible smoke plume • Public concern about burn emissions to the air and into the water. Sensitive individuals can be vulnerable to combustion by-products. • Might not be appropriate in close proximity to populated areas; might require evacuation in sparsely populated areas • Risk of fire spreading to other combustible materials

[4] Modified from Fingas & Punt (2000).

II.3 When to Consider Using ISB

II.3.1 On Land

It is preferable to quickly remove spilled oil to limit its spread and reduce its potential impact to sensitive sites. ISB can remove encountered oil in hours, whereas manual or mechanical recovery can take days to months. Weather conditions and seasonal considerations become important in certain circumstances. For example:

- Forecast rain could flush oil from a spill site into sensitive areas and/or thin slicks such that they become un-ignitable.

- Temporary snow and ice containment structures are expected to fail during a predicted thaw.

These kinds of spill conditions trigger the need to rapidly remove as much oil as possible. Consider using ISB on land for the following spill conditions (Mendelssohn et al., 1995; Dahlin et al., 1999; Michel et al., 2002):

- Access to a spill site is limited, making it difficult for responders and equipment to arrive on scene. Surrounding terrain (e.g., steep canyons, extensive wetlands) can either restrict access or can be too soft to support foot or vehicular traffic without causing damage (e.g., wet tundra, salt marshes, peat bogs). ISB is logistically simpler than mechanical or manual recovery with associated recovered oil handling, storage, and disposal.

- Options for transportation and disposal (temporary and/or permanent) of oily wastes are limited. During both manual and mechanical cleanup operations, large volumes of oily wastes can be generated. The remoteness of a site from approved disposal facilities is an important factor in the decision to burn. Another consideration is weight restrictions on roads. For example, cleanup of a spill along the Trans-Alaska Pipeline changed from mechanical recovery to ISB after weight limitations were placed on the road to the site with the arrival of the spring thaw (Buhite, 1979).

- Other response options are ineffective or might cause additional damage to vegetation, the substrate, and other natural resources. Because cleanup activities such as the construction of access routes, vehicle traffic, foot traffic, or the diversion of water flow can cause unintended environmental effects, it might be advisable to use a less intrusive response option like ISB.

- If oil is spilled in wetlands. ISB is considered a primary response procedure for incidents where oil is spilled in wetlands.

II.3.2 On Water

Consider using ISB for the following on-water spill conditions:

- It is preferable to quickly remove large quantities of spilled oil to limit its spread or potential impact to sensitive sites. Burning can remove large volumes of encountered oil quickly. For example:

  - A 500-ft-long (152-m-long) fire-resistant boom containing 18,000 gal (68.1 m^3) of spilled oil is estimated to burn in 10 minutes. Whereas recovery rates by skimmer and vacuum systems after the oil is contained are on the order of 200–300 gal/min (0.8–1.1 m^3/min) for a time estimate of 72 minutes.

- Oil recovery is limited by skimming, storage, and recovered oil handling capabilities. On-water mechanical recovery requires skimming systems and logistical support (e.g., boats, booms, skimmers, pumps, storage tanks, support barges, crews for operations and support, fuel for vessels and trucks, etc.). It might not be possible to deploy such systems and provide logistical support to remote sites in a timely manner.

- Even under ideal conditions, most skimmers collect more water than oil, necessitating storage for large amounts of oily liquid. Collected oily liquid has to be transferred from the skimmer vessel to a storage tank or barge. The turnaround time for recovered oil and oily waste to be offloaded and a skimmer returned to active operations can be hours.

- Skimmers are rarely operated at night because crews need to see the slicks or be directed to slicks by observers in aircraft. These operational constraints limit the quantity of oil that can be recovered in a 24-hour period.

- The release is continuous from a source. On water, ISB is considered a primary response technology for incidents with a continuous release source (e.g., a well blowout or a leaking tanker).

II.3.3 In Ice/Snow

Consider using ISB in oiled ice/snow for the following spill conditions:

- **A spill occurs in snow**. Oiled snow can be plowed into piles and burned on the ground or on ice. Alternately, oiled snow can be collected by front-end loaders, loaded into dump trucks, and hauled to a burn pit (ACS, 2006).

  - Oiled snow containing up to 70% snow burns readily (Buist, 2007).

  - Snow and oil mixtures with as little as 3 to 4% oil have been piled into hollow cones and ignited, removing up to 90% of the oil, even two weeks after being spilled (Allen & Nelson, 1981).

  - For higher snow content mixtures (i.e., lower oil content), the use of accelerants or promoters, such as diesel fuel or gelled gasoline, might be necessary to start the burn.

Figure 3—Burning oiled snow in volcano-shaped piles. Source: Alaska Clean Seas.

- **Oil is trapped/contained in ice**. ISB is considered a primary response option when oil is trapped/contained in ice. The presence of ice can increase the window-of-opportunity for ISB by reducing the spreading, weathering, and emulsification of spilled oil.

- **A spill occurs in ice-infested waters**. Mechanical recovery can be either ineffective, too hazardous, or access to surface waters for dispersant spraying is limited. Spilled oil can pool on top of solid ice. Pools of spilled oil encapsulated in ice can rise to the ice surface in spring as oil migrates up from within or below the ice through brine channels.

  - Dickins et al. (2008) demonstrated that ISB can be up to 95% effective even 63 days after initial oil release under ice, when a 660 gal (2.5 m^3) spill was burned in field tests leaving a 0.4-in.-thick (1-mm-thick) residue.

- Significant quantities of melt water can be generated allowing oil to migrate upwards and combine with other pools of oil on the ice surface. Dickins et al. (2008) demonstrated that ground penetrating radar could detect oil films as thin as 1–3 cm under 65 cm of ice. Therefore, individual pockets of oil under ice could be located, tracked, and targeted for burning during spring thaw. When the oil is encapsulated in ice, the ice can be removed and treated by melting and then burning or oil recovery.

II.4 Physical Conditions for Successful ISB

Physical conditions such as wind speed, wave height (for on-water spills), slick thickness, and weathering state of an oil can limit the feasibility of ISB. Physical considerations for ISB are summarized in **Table 3**.

Table 3—Physical Conditions for Successful ISB [5]

Operational Conditions	• Fresh oil is easier to burn • Maximum towing speed for fire boom on water is < approximately 0.6 mph (0.5 knots) • Means of fire control is available
Environmental and Location Conditions	• Wind speeds <21 mph (18 knots) for ignition for ISB on water [a] • Wind speeds <12 mph (10.5 knots) for ignition for ISB on land [b] • Wind speeds <40 mph (35 knots) to sustain a burn • A Beaufort sea state of <3 (4 ft or 1.2 m) for ISB on water • Ice cover <30% or >70% for ISB on water • Un-vegetated land or land where vegetation is not actively growing [c] • Saturated soils [d] • Wetlands where 1–3.9 in. (2.5–10 cm) of water covers the roots [e] • Wetlands that will not be flooded immediately following the burn
Notes: [a] A. Allen (Pers. Comm., 18 December 2012). [b] API (TR 1251, 2015). [c] Mendelssohn et al. (1995). [d] Reardon et al. (2015). [e] Bryner et al. (2003); Lin et al. (2002).	

II.4.1 Evaporation and Emulsions

In general, fresh oil is easier to ignite and burn than oil that has been weathered and lost much of its more volatile hydrocarbons. Evaporation can remove most of the volatile components, making burning of collected oil difficult or unachievable beyond the first 12 to 24 hours. Colder temperatures slow evaporation rates. The longer oil remains on water, the greater chance for water-in-oil mixtures (emulsions) to form, which can greatly reduce the possibility of a successful burn.

II.4.2 Slick Thickness

Studies have shown that most oils will burn if a slick is thick enough. In general, slicks must be at least 2 to 3 mm (0.08 to 0.1 in.) thick to sustain ignition (Buist et al., 1996, 1998; Bech et al., 1992, 1993). Once a slick has thinned to approximately 1 mm (0.04 in.), much of the heat generated by burning can be lost to the underlying substrate (water, sediment, or ice/snow), resulting in insufficient heat to vaporize hydrocarbons, extinguishing the burn (ASTM, 2014). Although there have been cases on land in which thinner slicks have been ignited (Fingas & Punt, 2000), the use of containment, whether booms on water or natural and man-

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[5] Modified from Fingas and Punt (2000).

made barriers on land or in snow/ice, is generally necessary to thicken spilled oil to allow ignition and to sustain combustion.

- For spills in wetlands, where there is a layer of water underneath a slick, the minimum thickness rules discussed above for spills on water usually apply.
- Often oil is naturally contained by wet soil or vegetation, or concentrated in open water areas in wind rows.
- For spills that spread over relatively flat terrain, temporary dikes can be constructed to contain and isolate oil for burning.

II.4.3 Wind Speed

Recommended surface wind speeds for ignition are between 0–18 knots [0 to 21 miles per hour (mph)]. Once oil vapors are ignited, high wind speeds can extinguish a burn. ASTM (2014) recommends that burns be conducted with ambient wind speeds <20 knots (23 mph) for ISB on water. API Field Guides (2015) say burning can be sustained in winds up to 35 knots (40 mph) on land and on water.

II.4.4 Wave Height for On-water Burns

For on-water response, the presence of wave action can limit burning. Greater wave heights or steep waves that lessen boom conformance and make oil containment difficult can result in splash over or boom failure. Higher wave heights can also increase emulsification of a slick, which can limit the success of a burn. Allen et al. (2011) state that swell and wave heights should not exceed 4 ft (1.2 m) for an effective burn.

II.4.5 Ice Cover Ranges for On-water Burns

In open water circumstances to approximately 30% ice cover, an oil's spread and movement will not be greatly affected by ice, so open water ISB techniques are possible. In circumstances with 30% to 70% ice cover, ice will restrict movement of a slick, but will not completely contain the oil. However, deployment and towing of boom in this ice cover range would be difficult. In 70% to solid ice cover, the closely packed ice helps contain oil by serving as a natural barrier. If oil is restricted by the ice and kept thick enough, an effective burn can be possible.

The combination of cold temperatures and reduced wave energy due to the presence of ice and snow on water results in a slowed rate of weathering and an extended window of opportunity (Sørstrøm et al., 2010). Factors such as time of the year and how the ice was formed, will give the ice different characteristics and hazards that can influence the weathering of spilled oil. For more information on the effects of weathering in snow and ice, refer to Potter et al. (2012).

II.5 Equipment Requirements for ISB

There are two main requirements for ISB: containment or herding mechanisms to collect the oil thick enough to provide sufficient vapors for burning, and a heat source (igniters) to heat oil to its ignition temperature.

II.5.1 Containment

Spilled oil can spread rapidly into slicks too thin to provide enough vapors to ignite. Therefore, containment is generally a necessary step to achieve a slick thick enough to allow ignition and to sustain combustion.

- **On land**, oil containment can be achieved through the construction of earthen dikes and underflow dams, the use of lined trenches and pits, natural barriers or ditches, or the enhancement of natural barriers.

- **On water**,
  - Boom is used to collect and concentrate the oil for burning. There are three types of fire-resistant boom (ASTM, 2013):
    - Fence-type boom constructed of refractory fabric and using steel and glass floats,
    - Ceramic and stainless steel boom constructed with a solid core flotation,
    - Water-cooled, inflatable boom.

    See API Technical Report 1252 (2015) for more details. A key performance factor is how well a boom conforms to waves and/or swells, which is directly influenced by sea state. Some operational and environmental considerations are presented in ASTM (2014).
  - Herding agents are chemicals applied to surface water along the perimeter of a slick. These agents alter surface tension of surrounding water and act to "herd" an oil slick into a smaller area, thickening the slick by consolidating the oil.

    Herding agents do not require a boundary to push against and will work on open water (Buist and Nedwed, 2011). They work best in warm or temperate waters; however, they have proven effective with light- to medium-weight oils in colder temperatures, where they reduce spreading and work between ice pieces to increase oil thickness for burning. Buist et al. (2007) found herding agents are effective in light wind and swell conditions, but not very effective in short, steep-sided waves with ice.
- **In snow/ice**,
  - Oil mixed with snow has been successfully burned. Snow with 70% oil content will successfully sustain a burn. Igniters are used for oiled snow when ignition alone is not effective. After piling the oiled snow, gravity will natural concentrate the oil, and burns are possible when using an igniter.
  - When oil is trapped under ice, it can be exposed for collection and combustion when the oil's location is known. This can be accomplished by digging trenches and pits at the ice surface and augured holes to the water beneath ice to allow oil to rise and fill those temporary containment areas. Two other techniques include:
    - Cutting slots in the ice downstream of the source to intercept the ice as it moves with the currents;
    - Inducing the flow of oil toward the slots with air, water, or propeller-generated currents.

  These techniques direct oil to the surface for ignition and burning.
  - In areas with heavy ice concentrations, the ice itself can provide natural containment, limit the spread of oil, and help keep it at combustible thicknesses. At very high ice concentrations, especially with the presence of slush ice, it is often difficult to sustain an efficient burn.
  - In waters with low ice concentrations, fire-resistant containment boom is deployed in a manner similar to methods employed for open water ISB. Such containment can, however, collect ice along with the oil, reducing the available surface area of oil for combustion and affecting boom function. As ice concentrations increase, the ice can provide sufficient containment of oil without the need for fire-resistant boom.

II.5.2 Slick Ignition

Most ignition systems can be used for oil spills on land, on water, and in snow and ice conditions. For open-water burns or where necessary for safety reasons, ignition is conducted from a vessel or a helicopter. Commonly used ignition devices include propane or butane torches, gelled fuel with an attached flare, diesel-soaked rags or sorbents, helicopter-slung gelled fuel (helitorch), and road flares. Research is underway to expand the options for ignition devices from aerial platforms. Each type of ignition device should be: 1) capable of supplying a reliable heat source to produce oil vapors from a slick to ignite the oil; and 2) safe to use, simple to operate, and have long shelf-life (Fingas & Punt, 2000; ExxonMobil, 2014).

Section III: ISB Decision-making

Decision makers and natural resource trustees were asked what types of information would be requested to assess the benefits from using ISB. Their collective replies provide a view into the wide variety of information desired for decision-making and risk communications. There were three basic types of information desired:

1. Burn planning, logistics, and execution.
   - Does ISB have a >50% chance of success?
   - Where is the burn planned?
   - What is the volume of the burn and how long will it last?
   - How much oil is expected to be removed?
   - Can we maintain fire control?
   - Will the burn be effective?
   - Can the public be adequately notified and the burn still be conducted effectively?
   - What post-burn cleanup might be necessary?
2. Decision-making and natural resource management.
   - What populations/sensitive populations are located downwind?
   - What endangered species are adjacent?
   - What are the potential impacts to these resources from the burn?
   - Is the planned burn to be within an air basin [6] that has a "non-attainment" area for PM_{10} or for some other air pollutant?
   - If burns are planned on water, what are the water body uses?
   - What other government organizations or agencies should participate in decision-making?
3. Contrast in response outcomes beween ISB and not burning.
   - What oil type is planned to be burned?
   - What are the fate and transport forecasts for the spilled oil if we do not burn?
   - What are the fate and transport forecasts for combustion by-products?
   - Might there be combustion by-products of concern, in particular any carcinogens?
   - What effect would burning have on habitat recovery, versus other response strategies?

NOTE:

An example checklist for ISB on water was developed by the state of Alaska and could be used as a template for developing a checklist for the concerns of decision-makers. Available from http://alaskarrt.org/. Additional checklists are available in API Technical Reports 1251 and 1252 (2015).

[6] Air basins are areas that generally have similar meteorological and geographic conditions and in which air quality is regulated.

The spill location and volume most often determine which local, state, and/or federal regulations will apply and which agencies could be involved in an incident response. Response to spills within the U.S. will be influenced by a variety of U.S. federal laws. Key among them are:

- Clean Water Act (CWA) as amended by the Oil Pollution Act of 1990 (OPA 90);
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act of 1986;
- Clean Air Act (CAA);
- Resource Conservation and Recovery Act (RCRA).

Some of these laws contain guidance or requirements that apply to contingency planning (**Table 4**).

Table 4—Main Contingency Planning Guidance and Requirements

Authorities	Key Applicable Laws and Governing Bodies
Federal Authorities	• CWA, OPA 90, CERCLA, CAA, RCRA
Regional Planning	• Regional Response Team, Pertinent area committee
Regional Federal Planning Lead	• U.S. Coast Guard, U.S. EPA
State Planning Lead	• State environmental response agencies
Local Planning Lead	• Local emergency planning committees

III.1 Local and State Level Decision-making

For burns of small oil spills on land and on waters not subject to federal jurisdiction, fire department staff and other local emergency responders might be the only responders. Burns of larger oil spills to land and to waters not subject to federal jurisdiction are expected to be handled first by local officials who would likely quickly request additional emergency response resources from within their state.

It is highly unlikely that local jurisdictions would have any regulations or guidance on the conduct of ISB. Regulations or guidance could be available at the state level and are available at the multi-state, regional level via the U.S. Regional Response Teams (RRTs). Because the network of response experts is collegial and the number of ISB experts is not large, the assistance from ISB experts in state or federal agencies can be requested even if not required.

Over the past 20+ years the RRTs have developed regional guidance for response to a wide variety of hazards and emergencies within the U.S. and its territories (**Figure 4**). Many of the 10 RRTs have prepared guidance for burning of oil spills and on designation of burn pre-approval (or pre-authorization) zones that were published in the mid-1990s. Most of the ISB guidance and any pre-approved zones are for spills to coastal waters rather than for spills on land or non-navigable waters.

For consistency of approach across states within an RRT, it is anticipated that RRT guidance and direction would be requested for inland burns to land and non-navigable waters. RRT member-agency specialists and other technical and scientific resources could be available to states within a given region. The RRT network could help address unique spill circumstances. Local and state agency jurisdiction might also be specified in Regional Contingency Plans and in Area Contingency Plans for particular circumstances or locations.

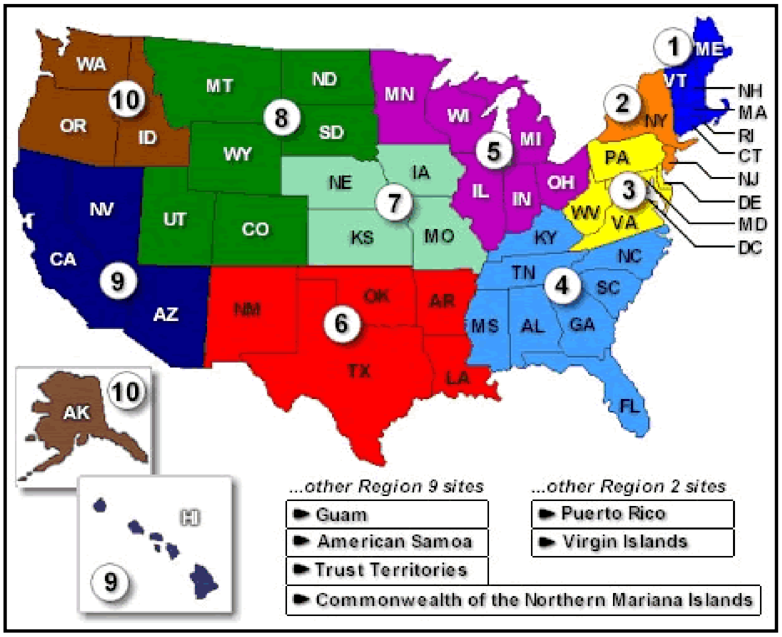

Figure 4—Map of Regional Response Team districts. Source: EPA.

III.1.1 Regional Response Team (RRT)

RRTs have decision-making authority within designated federal districts in the United States (**Figure 4**). Under the NCP, RRTs have the responsibility to evaluate and plan for use of spill response technologies, including ISB. RRTs provide guidance to Area Committees and their two principle components are:

- Standing Teams whose role is to establish pre-spill policy and to assist the FOSC and Area Committees; and
- The Incident-specific Teams whose role is determined by the operational requirements for each specific response.

The RRTs are co-chaired by representatives from the EPA and USCG and they are designed to support an FOSC with agency resources during a response.

III.1.2 Pre-authorization Planning

The Standing RRT develops pre-authorization policies and guidance for the use of ISB in their Region [on water, on land, and in ice/snow (where applicable)] in advance of an incident. These pre-authorization plans specify when and where ISB can and cannot be used within the Region in areas under federal response authority and what monitoring and documentation requirements are necessary. The status of the RRT pre-authorizations for ISB in the U.S. is provided in regional documents accessible from the National Response Team (NRT) website (https://www.nrt.org/Site/Regionmap.aspx). [7] The information includes the status of pre-approval (i.e., pre-authorization, case-by-case approval, non-approval); the conditions and zones where pre-authorizations exist; and the status of monitoring and consultation under Section 7 of the Endangered Species Act.

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[7] The pre-authorization status for a particular region is available from https://www.nrt.org/Site/Regionmap.aspx by linking to a specific RRT and reviewing the ISB planning documents established for that region.

As pre-approval agreements are drafted at the local area and regional levels, some variations in terminology have developed in the agreements themselves and/or in the supporting literature. In this document we have employed the following terms associated with pre-authorization status:

- Pre-authorized—areas where the FOSC is pre-authorized to use ISB;
- Case-by-case—areas where the FOSC must consult with appropriate agencies on the RRT [e.g., EPA, Department of Commerce (DOC)/National Oceanic and Atmospheric Administration (NOAA), DOI, and the affected states] to determine whether ISB use is appropriate;
- Additional or Special Consideration Consultation—areas where specific localized requirements are to be met in order for the FOSC to be given RRT concurrence to burn; or
- Exclusion or Restricted—areas where ISB is not to be used.

Many RRTs have established pre-authorization protocols to assist FOSCs to determine if ISB is a viable oil spill response option for their area of responsibility and under what conditions.

III.1.3 Developing the Burn Plan (State and Federal)

Even within pre-authorized areas, it is highly recommended that a burn plan be prepared. At a minimum, the burn plan can be as simple as completing the documentation provided in the regional guidance and should ensure the safety of the responder personnel. If ISB is selected as a response option, the FOSC will determine whether additional plans or provisions for responder or public health and safety are needed, and what approach should be taken for burn monitoring. Regardless of the level of detail in a burn plan used, the FOSC makes every reasonable effort to continuously evaluate the decision to burn and allow RRT agencies and the affected states the opportunity for comment.

A burn plan can evolve over time as the incident-specific conditions change and the requirements for the burn are adjusted accordingly. The FOSC has the authority to stop a burn at any time. The FOSC may receive formal requests to discontinue a burn from the RRT member agencies; these requests might be immediate grounds for discontinuance of burn operations and could entail additional discussions between the Responsible Party, FOSC, and incident-specific RRT members.

NOTE:

For more information on the federal ISB policies and requirements for each Region, go to https://www.nrt.org/Site/Regionmap.aspx and access the RRT Regional Home Page of interest and locate their regional contingency planning documents.

III.2 Net Environmental Benefit Analysis (NEBA)

The goal of every response is to minimize the overall impact from the release on natural and economic resources. NEBA is a planning process of considering advantages and disadvantages of different spill response options (against the baseline of no response) to arrive at a spill response decision resulting in the lowest overall environmental and socioeconomic impacts.

A spill response will likely involve some combination of response options. There are no response methods that are completely effective or risk-free. A NEBA compares the environmental and socio-economic outcomes of various spill scenarios using the possible response techniques against a baseline of “no response.” The results are then used in contingency planning and during a response to inform decision-makers as to those options with the least negative effects.

RRTs use the NEBA process to evaluate likely effects from an oil spill to determine which response option or combination of options will limit the spilled oil’s overall effect on the potentially impacted resources and the environment and which response option will increase the likely impacts to these same resources. For U.S. oil spill response, all levels of government, industry, and other stakeholders (e.g., members of the RRT, the natural resource trustees, state and local agencies, non-governmental organizations, etc.) come together to actively participate in the development of a consensus-based evaluation of the various response options, including ISB, to address their regional decision-making needs for responding to an oil spill, prior to an incident.

The decision to use ISB or other response options during an incident involves choosing the lower net risk, i.e., decreasing the expected risks to wildlife on the water surface, along shorelines, inland habitats, or in and around ice while increasing the potential risk to organisms in the water column or in the air.

III.3 Federal Level Decision-making

The National Oil and Hazardous Substance Pollution Contingency Plan (NCP) provides the "playbook" for oil spill response in the U.S. It defines a National Response System (NRS), a mechanism for coordinating response actions by all levels of government in support of the Federal On-scene Coordinator (FOSC) and is divided into national, regional and area levels. The NRS is composed of the National Response Team (NRT), Regional Response Teams (RRTs), the FOSC, Area Committees (ACs), special teams, and related support entities. The basic framework for the response management structure is a unified command system that brings together the functions of the federal government, the state government, and the responsible party to achieve an effective and efficient response, where the FOSC retains authority.

There are nuances to jurisdiction and authorities which can make each spill response different. Enforcement authority is pre-designated; typically, inland spill events are assigned to EPA and coastal and navigable water events to the USCG. [8]

More precise border definitions are described in EPA and USCG agreements and are identified in federal regional contingency plans. Spills originating in inland waters could be transported to coastal waters and ecosystems, particularly if the spill occurs in water systems near the coast (Ramseur, 2012), so it is possible that response leadership could shift in such cases. Further, the U.S. federal government shares jurisdiction over its territorial seas [within 0–12 nautical miles (nm) of shore] with coastal states. After the Deepwater Horizon incident and reorganization of the Minerals Management Service, a Memorandum of Agreement between USCG and the new Bureau of Safety and Environmental Enforcement (BSEE) clarified response jurisdictions for offshore energy and mineral operations between the two agencies (BSEE and USCG, 2012).

Under the NCP, RRTs have responsibility to evaluate and plan, in advance, for use of ISB as one of the available and legal response options. Most RRTs have prepared ISB guidance focused on offshore areas. Based on many anecdotal reports, ISB is believed to be widely used in inland and upland areas of the U.S. for predominately small spills reflecting the familiarity of firefighters and emergency response personnel with burning. For on-water spills, when ISB is a desired option, please seek pertinent RRT's guidance for a specific location (see https://www.nrt.org/Site/Regionmap.aspx).

RRT guidance will be used by NOAA Scientific Support Coordinators and by On-scene Coordinators (OSCs) to assess benefits of ISB relative to spill circumstances and to set plans for conduct of a burn(s) deemed appropriate to protect public health, welfare, and the environment.

III.3.1 Federal On-scene Coordinators (FOSCs)

Federal On-scene Coordinator (FOSC) is a designation in the United States for an individual who:

- Is responsible for providing access to federal resources and technical assistance; and
- Coordinates all federal containment, removal, and disposal efforts and resources during an oil or hazmat incident.

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[8] The Department of Defense (DOD) and the Department of Energy (DOE) provide FOSCs for hazardous substance pollution incidents at their facilities or under their jurisdiction.

The FOSC is charged with directing response efforts and coordinating other efforts at the scene of a discharge or release in accordance with Area Contingency or other pertinent plans for lands and waters under their specific jurisdictions (**Figure 5**).

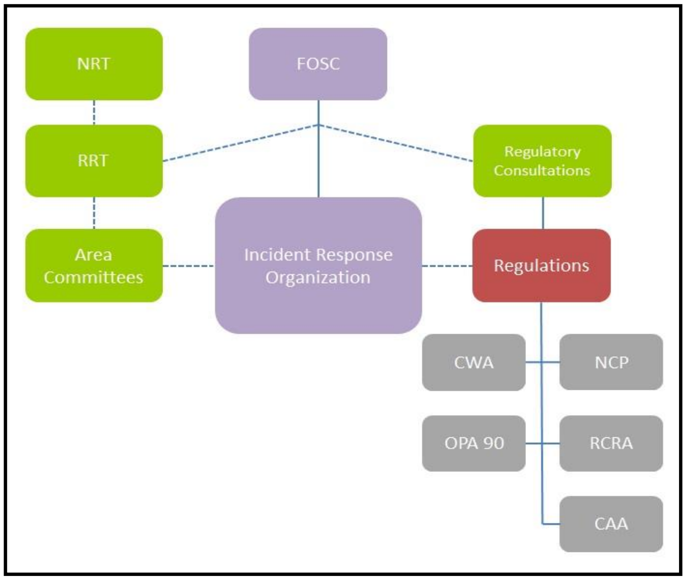

Figure 5—Generic U.S. spill response structure showing major regulatory components.

III.3.2 Decision-making Role of an FOSC

The decision to use ISB on a discharge of oil that has or potentially threatens waters of the U.S. rests with the FOSC. The primary question is whether ISB is appropriate for incident-specific conditions. If ISB is appropriate, then:

- Does the FOSC have pre-authorization approval authority to conduct a burn in the location being considered?
- If not, are incident-specific RRT notifications and consultations required? What other notifications are necessary?

An FOSC is to notify the incident-specific RRT of the operational use of ISB. The timing of notification varies based on RRT pre-authorization conditions, and might be a courtesy notification.

III.4 Federal Laws and Regulations

The primary U.S. regulations dictating the responsibility for cleanup and removal of spilled oil include: the Clean Water Act; the National Oil and Hazardous Substances Pollution Contingency Plan; the Oil Pollution Act of 1990; the Resource Conservation and Recovery Act; and the Occupational Safety and Health Administration's (OSHA's) Hazardous Waste Operations and Emergency Response standard. A brief summary of how each law or regulation can affect the use of ISB is provided below.

III.4.1 Clean Water Act (CWA)

The CWA establishes the basic structure for regulating discharges of pollutants into the waters of the U.S. and assigning quality standards for surface waters. Section 311 of the CWA addresses pollution from oil and hazardous substance releases, providing the EPA and the USCG with the authority to establish a program for preventing, preparing for, and responding to oil spills or hazardous substances that reach or might reach surface waters, including inland waters.

EPA shares jurisdiction over oil and hazardous substances with the USCG. A Memorandum of Understanding (MOU) between the two agencies allocates enforcement authority for inland spill events to EPA and for coastal and navigable water events to the USCG.

III.4.2 National Oil and Hazardous Substances Pollution Contingency Plan (NCP)

The NCP provides the federal government with an organizational structure and procedures to help prepare for and respond to discharges of oil and releases of hazardous substances, pollutants, and contaminants (40 *CFR* Part 300). The NCP [9] is intended to provide for an efficient, coordinated, and effective response to a discharge or release, including requirements for:

- Activation of the national response organization;
- Development of federal, state, and area contingency plans;
- Procedures for involving states and responsible parties in response activities;
- Listing of federal trustees for natural resources; and
- National procedures for the use of dispersants and other chemicals.

III.4.3 Oil Pollution Act of 1990 (OPA 90)

OPA 90 amended the CWA and initiated additional requirements related to prevention, preparedness, and response for the transport and storage of oil in the U.S. [10] It created a comprehensive prevention, response, liability, and compensation regime to deal with vessel- and facility-caused oil pollution to U.S. navigable waters.

III.4.4 Resource Conservation and Recovery Act (RCRA)

RCRA is the primary federal law governing disposal of solid and hazardous waste. RCRA can apply to ISB when the oil to be burned or any resultant ISB residue is defined as "hazardous waste." The regulations generally exempt oil spill responders from hazardous waste management requirements during response to a spill. EPA has issued RCRA Subtitle C regulations [11] that specify, among other things, what is considered hazardous waste under RCRA, how such waste is to be managed, and documentation requirements.

State and local waste management laws also might apply. Additionally, RCRA regulations might apply to disposal or other actions taken after a response is over. [12]

III.4.5 Clean Air Act (CAA)

The CAA is the primary federal law designed to protect and improve air quality. [13] The CAA regulations are implemented primarily by each state and their localities through state Implementation Plans (SIPs). The CAA restricts emissions of hazardous air pollutants and seeks to regulate atmospheric visibility (degradation of which can temporarily result from ISB), acid rain, noise pollution, and stratospheric ozone depletion. The main program of significance for ISB is the establishment and enforcement of ambient air quality standards for certain pollutants.

When ISB is considered for a response, the smoke produced might pose a threat to public health due to its effect on air quality; therefore, response efforts utilizing ISB require additional review and evaluation of a burn's potential effects on compliance with the National Ambient Air Quality Standards under the Clean Air Act.

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[9] For more information, access the NCP at: http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr300_main_02.tpl.

[10] For more information, access OPA 90 at: http://www.law.cornell.edu/uscode/text/33/chapter-40.

[11] For more information, access the RCRA regulations at: http://www.epw.senate.gov/rcra.pdf.

[12] For an analysis of how the RCRA regulations apply to the use of ISB for oil spill response, refer to the 1996 NRT Science and Technology Committee's Applicability of RCRA Hazardous Waste Management Regulations to the *In Situ* Burning of Oil Spills report, available from: http://www.nrt.org/production/nrt/nrtweb.nsf/AllAttachmentsByTitle/A-74rcrahazapril96/$File/rcra%20haz%20april%2096.pdf?OpenElement.

[13] For more information, access the CAA regulations at: https://www.gpo.gov/fdsys/pkg/USCODE-2008-title42/pdf/USCODE-2008-title42-chap85.pdf.

III.4.5.1 National Ambient Air Quality Standards (NAAQS)

The CAA requires EPA to set NAAQS (40 *CFR* Part 50) for pollutants judged harmful to public health and the environment. [14] The CAA identified two types of NAAQS:

- **Primary Standards** that protect the public health; and
- **Secondary Standards** that protect the public welfare. [15]

EPA has established NAAQS (**Table 5**) for six principal pollutants, which are called "criteria" pollutants. Four of those criteria pollutants may apply to considerations of ISB:

- Carbon Monoxide (CO);
- Nitrogen Dioxide (NO_2);
- Particulate matter (PM) ≤2.5 micrometers (μm) in diameter (also known as $PM_{2.5}$), and ≤10 μm in diameter (PM_{10}); and
- Sulfur Dioxide (SO_2) (EPA, 2012c).

An ISB generates black smoke composed primarily of PM and gases (Ferek et al., 1997). For ISB planning purposes, the most significant NAAQS are the primary NAAQS for PM. For more information on the components of an ISB plume and their effects on human health and safety, refer to Section VI—Human Health and Safety in this document.

III.5 Specialty Consultations

Emergency consultations might be necessary to determine what is required for:

- Addressing air quality concerns;
- Threatened and endangered species and essential fish habitats; and
- Special resources in a spill area protected under the National Historic Preservation Act.

There are many individuals who could be consulted to ensure potential impacts or exposures are documented and addressed as a result of the operational requirements. This includes, but is not limited to:

- Department of Interior (DOI) U.S. Fish and Wildlife Service (USFWS) and/or NOAA National Marine Fisheries Service (NMFS) [16]—to address the potential affects from the burn on threatened and/or endangered species and/or their critical habitats.
- DOI historic preservation specialists and State Historic Preservation Officers (SHPOs)/Tribal Historic Preservation Officers (THPOs)—to address any impacts or affects to historic properties and archaeological sites/tribal historic resources.

The requirements of these specialty consultations are summarized below.

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[14] For more information, access the NAAQS online from: http://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr50_main_02.tpl.

[15] From the EPA Air and Radiation: National Ambient Air Quality Standards (NAAQS) webpage. Accessed on 8/15/2012 from: http://www.epa.gov/air/criteria.html.

[16] Other federal landowners (e.g., DOD installations, National Park Service, etc.) are designated as resource trustees for on their lands and might need to be included in this consultation.

Table 5—NAAQS for Common Combustion Products [a]

Pollutant		Standards	Average Time	Level	Form
Carbon Monoxide (CO)		Primary	8 hour	9 ppm	Not to be exceeded more than once per year
			1 hour	35 ppm	
Nitrogen Dioxide (NO_2)		Primary	1 hour	100 ppb	98th percentile, averaged over 3 years
		Primary & secondary	Annual	53 ppb	Annual Mean
Particulate Matter	**$PM_{2.5}$**	Primary	Annual	12 µg/m^3	Annual mean, averaged over 3 years
		Secondary	Annual	15 µg/m^3	Annual mean, averaged over 3 years
		Primary & secondary	24 hour	35 µg/m^3	98th percentile, averaged over 3 years
	PM_{10}	Primary & secondary	24 hour	150 µg/m^3	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide (SO_2)		Primary	1 hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		Secondary	3 hour	0.5 ppm	Not to be exceeded more than once per year

Notes:

Units of ppm/ppb are most appropriate for gases; µg/m^3 is more appropriate for particulate and fumes.

[a] From the EPA Air and Radiation: National Ambient Air Quality Standards (NAAQS) webpage (https://www.epa.gov/criteria-air-pollutants/naaqs-table).

III.5.1 Air Quality Approval Consultation

Under federally-directed response actions, state air programs are consulted prior to conduct of an ISB (on waters or lands within a state). Coordination and consultation for burns conducted under local and state authorities are detailed in their respective planning documents.

State and local officials provide guidance to an RRT on how State Implementation Programs (SIPs) for air quality might influence execution of ISB (if at all). Because smoke has a greater ability to migrate than an oil slick itself, careful consideration of potential air quality impacts on neighboring states, regions, and countries is important. In most instances, air quality impacts are very limited in duration relative to leaving the oil in place. Local and state officials can clarify under what emergency or other conditions ISB may or may not be conducted. This clarification can help an RRT to identify relevant regulations quickly and early and help ensure a consistent approach across an RRT region.

III.5.2 Endangered Species Act (ESA)

During an incident, response decision-making might affect protected organisms or habitats covered under the Endangered Species Act. As a component of their pre-spill planning requirements, the Standing RRT initiates a consultation with the natural resource trustees [e.g., U.S. Fish and Wildlife Service (USFWS) for fresh water species and wildlife and the National Marine Fisheries Service (NMFS) for protected marine and anadromous species] when developing response policies for the region. Under Section 7 of the ESA, the Standing RRT determines whether a response option (e.g., ISB) is likely to:

- Adversely affect listed species or designated critical habitat;
- Jeopardize the continued existence of species that are proposed for listing; or
- Adversely modify proposed critical habitat.

Any potential effects that individual response technologies might yield are addressed to the extent practicable within the resulting response planning documents for the region. The USFWS and NMFS have developed the Endangered Species Consultation Handbook: Procedures for Conducting Consultation and Conference Activities under Section 7 of the Endangered Species Act. [17]

III.5.2.1 Endangered Species Act Emergency Consultation

For ISB operations, an ESA Section 7 Emergency Consultation should be conducted with the USFWS and the NOAA NMFS as soon as practicable to:

- Confirm the presence of threatened and endangered species in the burn area or in the plume coverage area or otherwise at risk from ISB operations, fire, or smoke.
- Ensure measures (often referred to as best management practices) are taken to prevent risk to any wildlife, especially endangered or threatened species. Examples of potential best management practices include:
    - Moving the location of the burn to an area where listed species are not present;
    - Temporary employment of hazing techniques, if effective; and
    - Physical removal of listed species individuals under the authority of the trustee agency.

If the risk to endangered or threatened species cannot be eliminated or reduced sufficiently, the burn should be re-evaluated for applicability.

[17] This handbook is available from: http://www.fws.gov/endangered/esa-library/index.html#consultations.

III.5.3 National Historic Preservation Act of 1966 (NHPA) Consultation

The National Historic Preservation Act Section 106 requires Federal agencies to account for effects of their undertakings on historic properties and to provide the Advisory Council on Historic Preservation (ACHP) with a "reasonable opportunity to comment." [18] Federal agencies are also required to consult on effects of their undertakings on historic properties with State Historic Preservation Officers (SHPOs), Tribal Historic Preservation Officers (THPOs), Indian tribes (including Alaska Natives), and Native Hawaiian Organizations (NHO). In some cases, burn plans and operations are adjusted to account for the proximity of historic properties. For example, burn planning and execution were influenced by proximity of an historic bridge from the first U.S. transcontinental railroad). In many instances, there are official listings of protected, historic properties. There have also been cases where culturally or archeologically important sites are purposely not listed by tribes.

For an ISB, a Section 106 consultation under the NHPA is required if a response could affect historic properties. [19] A Section 106 consultation:

- Requires historic properties be considered during a federal undertaking, i.e., when federal funds are used or an action is directed or permitted by a federal agency.
- Requires consultation with State Historic Preservation Office (SHPO), tribes, and other interested parties to ensure their concerns are considered.

The FOSC must identify the appropriate SHPO/Tribal Historic Preservation Office (THPO) and notify them of the potential *undertaking* that might occur from the response operation, including:

- Oil spill response activities—confirm the presence of historic properties in the burn area or in the plume coverage area or otherwise at risk from ISB operations, fire, smoke, or the response efforts associated with an ISB;
- Ensure measures are taken to prevent risk to any historic properties, archeological sites, etc., from an ISB or the response efforts associated with an ISB;
- Natural Resource Damage Assessment (NRDA) Activities; and
- Restoration and Recovery Activities.

III.6 Basic ISB Decision-making

The basic steps in ISB decision-making are not complex (**Figure 6**). With the understanding that trained responders are available and have equipment ready,

1. Is ISB a desired response option for a given incident (i.e., will mechanical recovery and/or dispersant application suffice for that incident)?
2. Are incident conditions such that safe conduct of a burn is feasible?
3. What are the predicted levels of particulate matter that could expose sensitive populations and can they be controlled?

[18] http://www.nps.gov/tribes/National_Section_106.htm.

[19] Under the NHPA, historic properties are properties that are eligible for inclusion in the National Register of Historic Places. Such properties include districts, sites, buildings, structures, and objects significant in American history, architecture, archeology, engineering, and culture.

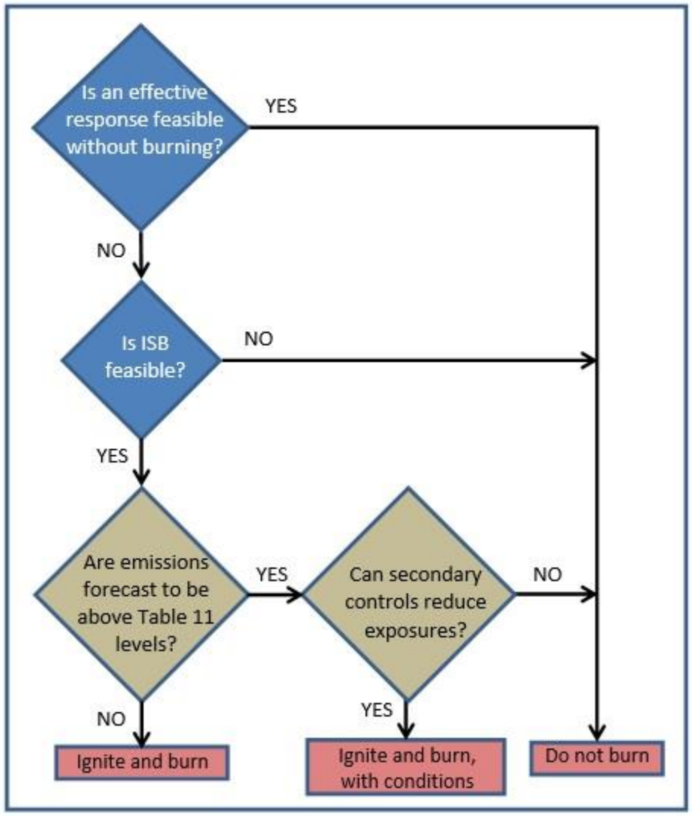

Figure 6—Simple ISB decision-making flowchart. Source: Modified from Alaska Clean Seas and Alaska Dept. of Environmental Conservation (1995).

Section IV: Influence of Oil Properties and Weathering

Oil is a complex and highly variable mixture of thousands of compounds. Even oil extracted from the same well can vary in component mixtures over time (Lewis and Aurand, 1997). Crude oil, the unprocessed oil that is recovered from an underground reservoir, is composed primarily of hydrocarbons, asphaltenes, and waxes (NRC, 1999, 2003), and to a smaller extent, compounds containing trace metals.

IV.1 Oil Groups and General Behavior

Petroleum hydrocarbons (oils) are classified into five groups based on their specific gravity and persistence in the environment (Group 1, Group 2, Group 3, Group 4, and Group 5). For spill response spills, knowledge of oil behavior is important for decision making. If the specific gravity [20] of an oil is less than the specific gravity of a receiving water [freshwater = 1.00 at 4°C (39 °F); seawater = 1.03 at 4 °C (39 °F)], it will float (**Table 6**).

IV.2 Transport and Weathering Effects on Oil

Decision makers need an understanding of spilled oil and its behavior to understand the likely ISB effectiveness. Once oil has been spilled, it then is subjected to nine transport and weathering processes, which are listed alphabetically below: advection, dissolution, emulsification, evaporation, microbial degradation (i.e., biodegradation), natural dispersion, oxidation, sedimentation, and spreading (**Figure 7**). Many of these processes are applicable to spills on land or on ice/snow.

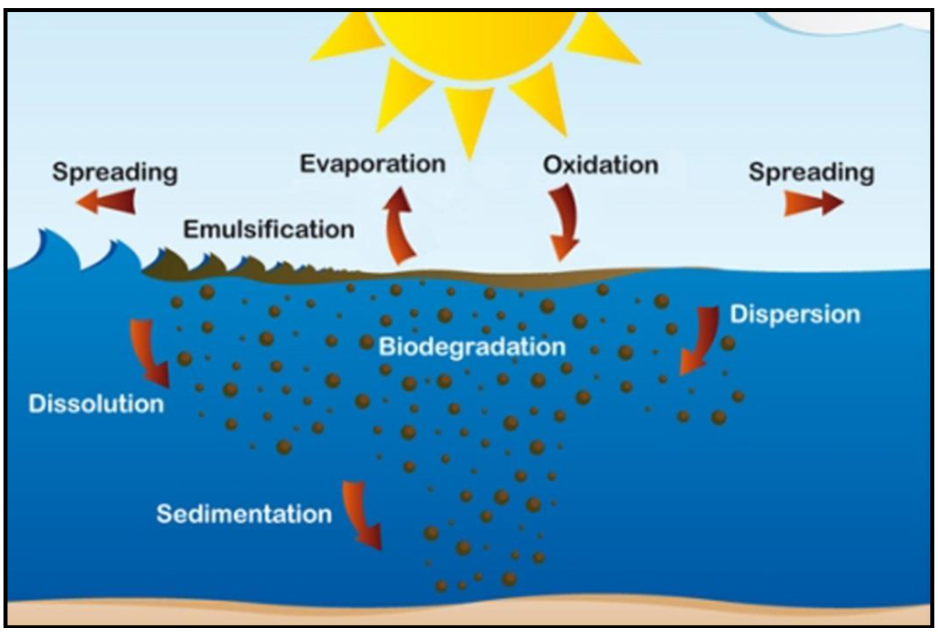

Figure 7—Illustration of spilled oil on water transport and weathering processes. Source: ITOPF.

[20] API gravity is a property that is often reported and can be used to indicate an oil's characteristics and whether or not it will float. API = (141.5/specific gravity) – 131.5. An API of 10 is equal to a specific gravity of 1.00; API of 45 is equal to a specific gravity of 0.80.

Table 6—Oil Groups and General Behaviors [21]

Group	Behaviors
Group 1: Gasoline products—ISB Not Recommended for Safety Reasons	• Specific gravity is <0.80; API gravity >45 • Very volatile and highly flammable • Evaporate and dissolve rapidly (in a matter of hours) • Narrow cut fraction with no residues • Low viscosity; spreads rapidly into thin sheens • Will penetrate substrates but are not sticky • High acute toxicity to animals and plants
Group 2: Diesel-like Products and Light Crude Oils—Candidate for ISB	• Specific gravity range of 0.80–0.85; API gravity range of 35–45 • Moderately volatile and soluble • Refined products can evaporate to no residue • Crude oils can leave residue after evaporation is complete • Low to moderate viscosity; spreads rapidly into thin slicks • Are more bioavailable than lighter oils (in part because they persist longer), so are more likely to affect animals in water and sediments
Group 3: Medium Crude Oils and Intermediate Products—Candidate for ISB	• Specific gravity range of 0.85–0.95; API gravity range of 17.5–35 • Moderately volatile • For crude oils, up to one-third will evaporate in the first 24 hours • Moderate to high viscosity; will spread into thick slicks • Are more bioavailable than lighter oils (because they persist longer), so are more likely to affect animals in water and sediments
Group 4: Heavy Crude Oils and Residual Products—Might be a Candidate for ISB	• Specific gravity range of 0.95–1.00; API gravity range of 10–17.5 • Very little product loss by evaporation or dissolution • Very viscous to semi-solid; might require heating during transport • Can form stable emulsions and become even more viscous • Tend to break into tar balls quickly • Low acute toxicity to water-column biota • Penetration into substrates will be limited at first, but can increase over time • Can cause long-term effects via smothering or coating, or as residues in the water column and sediments
Group 5: Sinking Oils—Not a Candidate for ISB on Water or Ice	• Specific gravity >1.00; API gravity <10 • Very little product loss by evaporation or dissolution • Very viscous to semi-solid; might require heating during transport or blended with a diluent that can evaporate if spilled into the environment • Low acute toxicity to water-column biota • Penetration into substrates will be limited at first, but can increase over time • Can cause long-term effects via smothering or coating, and as residues in sediments

[21] Modified from API (2001), Table 1.

Depending on the receiving environment (on water, on land, or on ice), a spill will be subject to different transport and weathering processes. The rate and extent of these processes will vary by oil type, air/water temperatures, wind, type of substrate, and wave conditions (for on-water spills). Refer to **Table 7** for a review of the relative impact of these weathering and transport processes on ISB for generic oils spilled on water, on land, or on ice/snow. These processes are presented in order of timeframe of action, from immediate to long term.

- On water—Of the major weathering and behavior effects, spreading, advection, evaporation, and emulsification directly influence slick ignition and burning on water.
- On land—Oil weathering processes that directly affect ISB on land include spreading, evaporation, dissolution, and microbial degradation.
- On ice/snow—Oil weathering processes that directly affect ISB on ice/snow include spreading, evaporation, dissolution, and microbial degradation.

Table 7—Oil Weathering and Transport Processes and their Timeframe of Action

Process	Mechanism of Action	Timeframe of Action
Natural Dispersion (Transport)	Wave energy or turbulence cause a slick to break up into small oil droplets (whole oil) that become mixed into the water column	Immediate (hours to days)
Spreading (Transport)	Movement of oil horizontally (in all directions) by gravitational forces	Immediate (hours to days)
Evaporation (Weathering)	Transfer of components of oil into the atmosphere	Immediate (hours to days; can continue in reduced capacity as long as oil is present)
Dissolution (Weathering)	Light-weight water-soluble components of oil dissolve into the surrounding water	Immediate (hours to weeks)
Advection (Transport)	Movement of oil by water currents, tidal action, wind-induced surface movement	Immediate to long term (as long as oil is present on water)
Sedimentation (Weathering)	Transferral of oil from a water surface and water column to the seafloor or shoreline; oil can attach to suspended solids in a water column and sink, or oil stranded on shore can become mixed with shoreline sediments and sink to the sea floor	Immediate to long term (hours to years; as long as oil is present on water)
Emulsification (Weathering)	Water droplets are suspended into oil through physical mixing (wave action)	Immediate to long term (days to years; as long as oil is present on water; most emulsification occurs within the first week of oil being spilled)
Photo-oxidation (Weathering)	Components of oil are chemically transformed by a photo-chemical reaction (sunlight) to produce new compounds that tend to be more water soluble than parent compounds	Moderate to long term (days to months)
Microbial Degradation (Biodegradation) **(Weathering)**	Naturally occurring micro-organisms consume petroleum hydrocarbons as food source, essentially removing oil from the environment	Moderate to long term (days to years)

Table 8 summarizes the relative impact of these weathering and transport processes for ISB for generic oils spilled on water, on land, and in snow and ice. The rate and extent of these processes will vary by oil type, air/water temperatures, wind, type of substrate, and wave conditions (on-water spills).

Table 8—Oil Weathering and Transport Processes and Their Influence on ISB

Process	On Water	On Land	In Ice/Snow	Relative Influence on ISB
Advection	Transport process of water currents that affects location of spilled oil; can result in increased or decreased shoreline effects	Not a transport process for on-land spills	Presence of ice and snow tends to limit transport of spilled oil. Oil under ice remains with ice in most cases.	Significant process for moving water and in snow/ice ISB. Affects transport of spilled oil.
Dissolution	Weathering process that affects soluble components from the slick into a water column; a minor process that has limited effect on ISB	Depending on soil permeability and oil type/viscosity, spilled oil could reach groundwater	A minor process that has little potential to affect ISB	A minor process that has limited effect on ISB
Emulsification	Weathering process that affects ignition and burn sustainability	Not a weathering process for on-land spills	Not prevalent in on-water ice environments since ice minimizes mixing action of waves	Affects ignition and burn sustainability
Evaporation	Weathering process that affects ignition and burn sustainability	Affects ignition and burn sustainability	Ice and snow minimize evaporation rates; can greatly extend window of opportunity months	Significant process for on water, on land, and in snow/ice ISB. Affects ignition and burn sustainability.
Microbial Degradation	Weathering process that results in consumption of spilled oil; this process typically initiates after periods of ISB viability	Weathering process that results in consumption of spilled oil; this process typically initiates after periods of ISB viability	Cold slows degradation rates and can greatly extend window of opportunity for months	Weathering process that becomes significant over long periods of time, typically initiates after periods of ISB viability
Natural Dispersion	Weathering process that removes soil from water surface, thereby decreasing volume of oil available to be burned; often a minimal process that has limited effect on medium and heavy oils	Not a weathering process for on-land spills	Not prevalent in ice environments on water as ice minimizes the mixing action of surface waves; natural dispersion will have little-to-no effect on ISB	Minimal process for on water and in snow/ice ISB
Photo-oxidation	Minor weathering process	Minor weathering process	Minor weathering process	Minor process for on water, on land, and in snow/ice ISB. This weathering process typically initiates beyond ISB viability.

Table 8—Oil Weathering and Transport Processes and Their Influence on ISB (Continued)

Process	On Water	On Land	In Ice/Snow	Relative Influence on ISB
Sedimentation	Weathering process that removes oil from water surface, decreases volume of oil on water surface available for ISB	Not a weathering process for on-land spills	Removes oil from water surface, decreases volume of oil available for ISB. Not a process for spills in snow and ice on land.	Can be a significant process for on water and in snow/ice ISB. Spill location dependent.
Spreading	Transport process that affects oil slick thickness by gravitational spreading; impacts ignition and burn sustainability	Transport process that affects oil slick thickness by gravitational spreading oil will seek to flow downhill and collect in thicker slicks in low places; decreases viability of ISB when the oil penetrates into soils	Transport process that affects oil slick thickness by gravitational spreading. Minimizes movement of oil; spreads more slowly and forms thicker slicks; increases viability of ISB.	Significant process for on water, on land, and in snow/ice ISB. Affects ignition and burn sustainability.

Major weathering and behavior effects are discussed below. The remaining weathering processes are either insignificant or do not occur during the period when ISB is considered as an effective response option.

IV.2.1 Advection

Advection is a transport process. Advection only occurs with spills on water where surface slicks are conveyed away from the site of a spill by water currents and wind-induced surface movements, including tides and river currents. It can be a factor in slick transport after oil is mixed or contained within ice on water and then moves with the ice. Advection greatly influences the location of a slick over time and can transport oil away from or towards land, sensitive resources, or population centers. Advection is not a factor on land.

IV.2.2 Emulsification

An emulsion is formed when two liquids combine, resulting in one liquid being suspended within the other. During water-in-oil emulsification of spilled oil, water is incorporated into oil in the form of microscopic droplets, usually through wave action. Emulsification tends to increase the total volume of oil, often two to four times its original volume. Emulsions formed from a spill on water are known as "mousse." Water-in-oil emulsions are highly viscous and weathering of emulsified oil is greatly reduced, making the emulsion more persistent. When the water content of a slick reaches 25 to 50%, depending on oil type, ignition and burning can become very difficult without the use of promoters or accelerators.

Emulsification and water content are important weathering processes in determining if ISB is feasible for spills on water. Emulsification is not a process for spills on land. It can become a factor when oil is spilled in water with pack ice if wave action is strong.

IV.2.3 Evaporation

Evaporation is the preferential transfer of light- and medium-weight volatile oil components from the liquid to vapor phase. During the first 24 to 48 hours after a spill, evaporation is the single most important weathering process in removing oil from a water surface. The amount of evaporation and the speed at which it occurs depend upon the volatility of the oil. Oil with a large percentage of light and volatile compounds will evaporate more than an oil with a larger percentage of heavier compounds. For example, spills of gasoline can achieve 100% evaporation whereas crude oils might only lose 20 to 35% of their total volume.

Evaporation increases the viscosity of oil as light- and medium-weight components are released to the atmosphere. Highly evaporated oils are difficult to ignite and burn because the remaining hydrocarbons do not readily sustain burning. Since combustion is a gas-phase process whereby volatile components are mixed with air to form combustible mixtures that are ignited, the loss of volatile hydrocarbons means the remaining oil components must be heated more than previously to obtain a combustible mixture that can be sustained.

The biggest weathering factor on land is related to the oil's exposure to the elements and overall thickness of the slick. If spilled oil has collected in low spots, it will be thicker than would normally be found for the same spill on water; therefore, evaporation is minimized. Additionally, oil spilled on land can be more sheltered from wind and solar radiation by vegetation and surface topography, which in turn can decrease the amount of evaporation. Reduction in evaporation can increase the success and window of opportunity for ISB because ignition and burn sustainment is enhanced.

In general, evaporation of oil spilled on ice or snow is slower than on water because of colder temperatures, formation of thicker slicks, and shelter from wind by the ice/snow. Spills covered with snow have an even slower evaporation rate. Snow acts as an absorbent and greatly slows evaporation rates, which can extend the window for burning by months.

IV.2.4 Spreading

Spreading is the movement by gravitational forces of a slick horizontally in all directions on the surface of water, land, snow, or ice. Spreading is controlled by the oil's viscosity, which is a measure of a fluid's resistance to flow. Low viscosity oils (Groups 1 and 2), such as diesel, tend to spread very quickly and form thin slicks, whereas high viscosity oils (Groups 4 and 5) such as a No. 6 fuel oil tend to spread more slowly and form thicker slicks. Spreading is typically a dominant weathering process in the initial stages of a spill. It is a key factor in the effectiveness of ISB because the thickness of an oil slick is critical to its ignitability.

On land, spilled oil will accumulate in low points and can form thick pools in depressions, holes, low spots, etc. Should a spill occur where a slope exists, oil will flow downhill by the most expedient means. Compared to spills on water, spreading on land generally results in thicker slicks that are more conducive for ISB. However, low-viscosity oils can quickly penetrate loose or porous sediments or flow into burrows and root cavities, which can directly affect the efficiency of an ISB because the volume of oil on the surface that would provide vapors for ignition is reduced. Experience has shown that burning does not remove oil that has penetrated below the sediment surface.

On ice/snow, the rate of spreading is controlled by an oil's viscosity, the amount of water surface present, wind, and the permeability and surface roughness of snow and ice. Oils tend to be more viscous at cold temperatures, so they spread more slowly and form thicker slicks. If the ambient temperature of surrounding water approaches the pour point of a spilled oil (the temperature below which the oil will not flow), spreading will cease. Oil spilled onto a snow pack will flow down through the snow to the ice layer, and then slowly undergo spreading, moving outwards under the snow.

Pack ice slows spreading on water by forming physical barriers. Spreading is controlled by the surface roughness of ice. Oil spilled on an ice surface can be completely contained as a thick pool, if the ice contours act to naturally contain the oil. Even smooth first-year ice has considerable surface roughness. As a result, slicks on ice in water tend to be much thicker and orders of magnitude smaller in diameter than equivalent slicks on water only. If ice is covered with a layer of snow, the snow can absorb spilled oil, further reducing spreading.

Section V: Oil Combustion and Burn Residues

Burning converts oil vapors into their primary, gaseous combustion by-products—water and carbon dioxide—plus a small percentage of other unburned or residual by-products, including soot, gases and any remaining burn residue (**Figure 8**) (Fingas, 2011; Ferek et al., 1997; NRT, 1992). This section describes the nature of these combustion by-products and residues and how they are expected to behave.

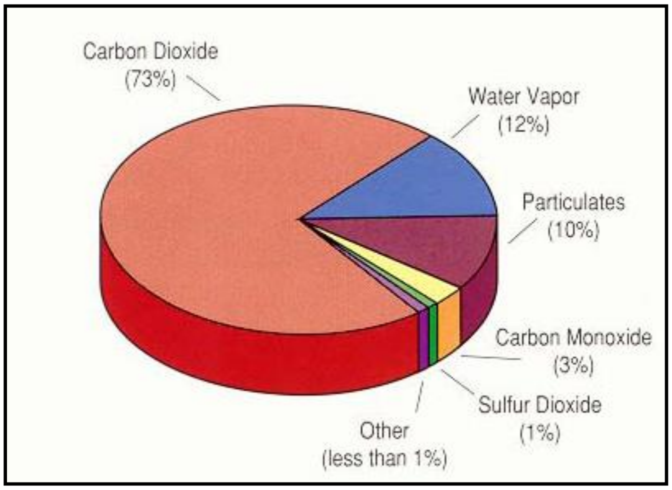

Figure 8—Typical composition of crude oil and combustion by-products produced from an on-water ISB.
Source: Modified from Ferek et al. (1997).

V.1 Combustion By-products

Combustion by-products produced during a burn include soot particulates and gases released as part of a smoke plume. Dark smoke in the burn plume can be of aesthetic concern to some and a health concern to nearby human populations or ecologically sensitive areas and resources. Since most soot precipitation occurs near a fire, adjacent locations are more likely to be exposed to soot. Additional information on health standards is in Section VI—Human Health and Safety.

V.1.1 Smoke Particulates

All ISBs produce particulate matter (PM or soot) that is transported into the air by turbulence and updrafts. PM yields range from 1 to 15% depending on oil type (Fingas, 2011; ACS, 2006; Ferek et al., 1997). The particulate matter generated during an ISB is composed primarily of black carbon. Some particles are large enough to be seen. Others are so small that they are only be detectable with an electron microscope. Larger particles usually remain in the air for a few minutes to hours and will settle near the source. Smaller particles ($\leq$10 µm) can remain aloft from several days to weeks and can be spread by winds over wide areas or long distances from the original source (Middlebrook et al., 2012). Particulates are generally removed from the atmosphere either by wet precipitation or when they contact other surfaces. Only the smallest particles (e.g., $PM_{2.5}$) tend to remain aloft for long periods. As distance from a burn site increases, the concentration of components in a burn plume decreases as dilution continues with distance.

V.1.2 Gases

There are many gaseous combustion by-products generated during an ISB, including carbon dioxide, water vapor, carbon monoxide, sulfur oxides, nitrogen oxides, and volatile organic compounds. Research has shown that these by-products are of little concern to downwind populations under most weather conditions. Gases emitted during ISB generally do not provide a threat to human health and safety except in the direct vicinity of a burn. The concentrations of gases in a smoke plume can exceed levels of concern at the burn origin, but are quickly diluted below levels of concern within very short distances.

The gaseous by-products of concern are summarized below (NIOSH/OSHA, 2010; Ferek et al., 1997; Stevens et al., 1993):

- Carbon dioxide (CO_2) is the primary gaseous by-product from ISB. Normal atmospheric CO_2 levels have been measured at over 380 ppm. Near an ISB, the concentration has been measured to be 500 ppm, which is not a health threat to human populations. Observations during the many large and extended duration Kuwait oil fires estimated that 95 percent of the oil burned was converted to CO_2 and water vapor (Olsen et al., 1995).

- Sulfur oxides (SO_2 and SO_3, collectively labeled SO_x) are formed when hydrogen sulfide or sulfur in the oil oxidize during combustion. These gases can irritate the eyes and respiratory tract by forming sulfuric acid on moist surfaces.

  The average ambient SO_2 concentration in the continental U.S. typically ranges from 1–12 ppb, depending on location and vicinity to combustion sources. The concentration of SO_x in a smoke plume depends on sulfur content of the oil. Average SO_2 levels measured in experimental burns have been <2 ppm in the plume by distances 100–200 m (109–218 yd) downwind (Fingas et al., 1993). Several miles further downwind, SO_2 concentrations are expected to be far below the level of concern for the general population (<0.5 ppm for a 3-hour exposure period).

- Nitrogen oxides (NO and NO_2, collectively labeled NOx) are by-products of oil combustion in air. NOx reacts with ammonia, moisture, and other compounds to form small particles. Like SOx, NOx can be an irritant to the eyes and respiratory tract.

  Sampling results indicate concentrations of NO_2 in a plume several miles downwind of a burn do not exceed several parts per billion, far below the 1-hour exposure maximum of 100 ppb identified by the EPA (Ferek et al., 1992). Therefore, NO_2 is not expected to pose a threat to the general public when 1 or more miles downwind of a burn.

- Carbon monoxide (CO) is a common by-product of incomplete combustion. The toxicity of CO is acute and can chemically displace oxygen from blood and cause oxygen deprivation in cells.

  Normal background CO concentrations in the atmosphere range from 50–150 ppb. In short experimental burns (15 to 30 minutes), the average concentration of CO in smoke plumes was found to be 1 to 5 ppm at a distance 150 m (164 yd) downwind (Fingas et al., 1993). This concentration range is 1 to 2 orders of magnitude below levels of concern.

- Volatile organic compounds (VOCs) are carbon-based compounds that combine with other elements such as hydrogen, oxygen, sulfur, nitrogen or metals, which can be present in combustion by-products. The chemical composition of VOCs will vary based on the original composition of an oil, weather conditions during a burn, and completeness of combustion.

  VOCs, when combined with nitrogen oxides, can react to form ground-level ozone (smog). VOC measurements from several test burns revealed high levels immediately downwind; however, even higher readings for VOCs were associated with spilled oil prior to the burn (ASTM, 2014).

V.1.3 Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are formed from incomplete combustion of fossil fuels and wood products. All crude oils contain PAHs. PAHs can be adsorbed onto particulates in smoke, thus providing an exposure pathway by inhalation. Some PAHs combust and form gases. With incomplete combustion, some will remain in burn residue or adhere to soot.

PAHs were found in barely detectable concentrations in smoke from the Kuwaiti oil fires, indicating very effective combustion (Olsen et al., 1995; Ferek et al., 1992). Low levels of PAHs were detected in plumes of experimental oil burns, at levels <0.01 ppm (Fingas et al., 1994). In each case, the quantity of PAHs in the smoke plume was found to be significantly lower than in the original oil (ASTM, 2014).

V.2 Burn Residue and Unburned Oil

ASTM (2014) defines burn residue as "the material, excluding airborne emissions, remaining after the oil stops burning." Residue tends to be missing the lighter petroleum components of an oil (which reduces its acute toxicity), yet it contains relatively elevated concentrations of heavier compounds, including PAHs, compared to the original oil.

Burn residues have been described as:

- A semi-solid, tar-like layer similar to the skin on a poorly sealed can of latex paint; [22]
- Tarry lumps; [23]
- Stiff, taffy-like residue (**Figure 9**) that could be collected easily; [24] and
- Texture similar to peanut brittle. [25]

The amount of burn residue remaining reflects the completeness of a burn. Estimates of burn efficiency range up to 90+% depending on oil type, slick thickness, and spill circumstances. Therefore, burn residue amounts can be expected to be about 10% or less of the original encountered oil volume.

Interest in, and subsequent recovery of, burn residue is dependent on location of burn residue (surface, floating, sinking, sunk), spill circumstances (practicality and safety of recovery operations), spatial cover (density of residue), and estimate of effects from leaving residue in place. During a response, recovered burn residue enters the process established for handing, treatment, storage, and disposal of recovered oil and oily waste management for that incident. For some spill circumstances, burn residue can be broken into fragments and tilled into soil to promote degradation. There is also the potential for recovered burn residue to be beneficially re-used (e.g., road beds).

Figure 9—Taffy-like burn residue. Source: A. Allen.

[22] Description by Buist (1998) from several laboratory experiments burning a thin slick of crude oil; Buist also reported residues from burning diesel remained liquid.

[23] From observations of three experimental burns of a medium crude oil (Fingas et al., 1994).

[24] From a test burn of 15,000–30,000 gal of North Slope crude oil from the *Exxon Valdez*, resulting in 300 gal of burn residue (Allen, 1990).

[25] After burning emulsified North Slope crude in outdoor pits (Buist et al.,1994).

V.2.1 Burn Residues and Unburned Oil on Land

Burning of oil spilled on land occurs more often than on water. Thus, there is more information on burn residue behavior on land. On land, as used here, includes a wide range of habitats, such as grasslands, forests, salt marshes, wetlands, ponds, and open fields. Spills on land tend to have thicker slicks since there is less spreading compared to spills on water and thereby result in thicker residues. **Table 9** summarizes the likely behavior of burn residues on land from different oil types (Scholz et al., 2004).

Lighter oils can penetrate the soil surface, leaving some amount of unburned liquid oil (Lin et al., 2002; Michel et al., 2002). Even medium crude oils can penetrate into highly porous sediments. The 1979 pipeline release of crude oil onto a glacial outwash plain in Bemidji, Minnesota resulted in groundwater contamination (USGS, 2011).

Burns of oil on the ground will behave differently depending on the physical aspects of the site. If the ground is dry and permeable, fresh oil can soak in and require the construction of trenches and ditches to collect oil prior to burning. If ground is water-saturated or frozen, there is little risk of spilled oil penetration into the ground.

Table 9—Behavior of Burn Residues for Different Types of Oil for On-land Burns [26]

Oil Type	Behavior on Land
Diesel-like products and light crude oils Diesel, No. 2 fuel oil, Light concentrate, West Texas crude oil	• Burn residue is mostly unburned oil that will penetrate into the ground, root cavities, and burrows with small amount of soot particles that often are enriched in heavier PAHs • Remains liquid; able to be recovered with sorbents and flushing
Medium crude oil and intermediate products South Louisiana crude oil, IFO 180, Lube oils	• Burn residue can form pockets of liquid oil, solid or semi-solid surface crusts or sheets, or present as heavy, sticky coating on sediments • Liquid oil can be flushed. Semi-solid and solid residues are typically recovered manually • Remaining residues are tilled and fertilized in appropriate habitats
Heavy crude oils and residual products Venezuela crude, San Joaquin crude, No. 6 fuel oil	• Difficult to burn; often have to add a lighter oil to initiate the burn • Leaves heavy, sticky residue that is a mix of unburned oil and semi-solid burn residue, requiring extensive cleanup • Remaining residues are tilled and fertilized in appropriate habitats

Of particular interest to the spill response community have been those freshwater wetlands containing highly organic soils, which have been regarded as poor candidates for ISB due to the potential for fire heat effects and assumptions of prolonged recovery times. Wetlands with highly organic soils include bogs, fens, and frozen soils of alpine or boreal wetlands. The effects of fire on wetlands are highly reflective of the height of the water table and soil saturation. For example:

- Regardless of fire intensity, when a water table is high, depth of soil heating or burning is low. Conversely, when a water table is low, soil heating or burning can go deeper.

- Frozen soils of alpine or boreal wetlands limit fire effects; melting conditions with high water saturation will also restrict fire effects.

[26] Scholz et al. (2004).

A detailed analysis of the effect of wildfires and prescribed fires on wetlands is provided in Reardon et al. (2005).

Oil degradation rates in peat, with its low oxygen concentrations and acidic conditions, can be very slow. Studies of a crude oil spill in a peat bog in Canada found high levels of lightly weathered oil to depths of more than 40 cm (15.7 in.) after 15 years (Blenkinsopp et al., 1996). Because peat is easily compressed, manual cleanup could cause more damage to a marsh/bog. Therefore, burning is often a preferred response technique, especially in remote areas.

Figure 10—Photographs of a burn in a peat wetland. Left: Initial burn on 5 July 2002. Right: The "thicker" burn residue and remaining oil. Note the re-sprouting of vegetation within days. Source: Minnesota Pollution Control Agency.

V.2.2 Burn Residues on Water

Combustion on water ceases when the burning oil slick thins to approximately 1 mm (0.04 in.) for light and intermediate refined oils and light crude oils (**Figure 11**). For thicker oil slicks and heavier oils, burn residue is expected to be 3–5 mm (0.1–0.2 in.) in thickness. For emulsified oil slicks, residue thickness can be thicker (Buist et al., 1998). Burn residues often are very chemically and physically different from the original oil. In general, burn residue will be more viscous and dense than the original oil (Li et al., 1992; Evans et al., 1986). Floating residue can be recovered manually with sorbents, nets, or other equipment.

Figure 11—Example of burn residue from an on-water burn. Source: S. Schraeder/USCG.

Several small-scale laboratory experiments determined (SL Ross, 2002; Buist et al., 1997; Trudel et al., 1996):

- Of 100 international crude oils, half of the burn residues would float and half would sink in seawater. About 60% of crude oil residues would likely sink in fresh water.
- In many experiments, hot residues initially floated, then began to sink after cooling. Typical burn residues cool within 30 minutes.

A strong correlation was observed between the density of burn residue and the density of its original oil (SL Ross, 2002). This correlation suggests that medium and light crude oils, condensates, and light and intermediate refined products are likely to produce floating residues, while heavy crude oil and heavy, refined products are likely to produce sinking residues.

Based on empirical observations and laboratory data, a few guide points have been offered on thickness of sinking burn residues (NRT, 2000):

- For unemulsified crude oil slicks up to 10–20 mm (0.4–0.8 in.) thick, residue will be ~1 mm (~0.04 in.).
- Thicker slicks result in thicker residues; residues can be up to 3–6 mm (0.1–0.2 in.).
- Emulsified oils can result in much thicker residues.
- For light/medium refined products, residue will be ~1 mm (~0.04 in.) regardless of slick thickness.

Because there have been so few on-water burns until the Deepwater Horizon incident, there is little information about sinking burn residues. Burn residue behavior is expected to mimic that of tar balls, so interest in tar balls (naturally occurring from seeps or as result of a spill) has increased.

Decision makers should evaluate the benefits derived from rapid removal of oil from a water surface by burning versus the potential effects from generation of burn residue that can sink or become neutrally buoyant in a water column. There might be sufficient value gained by removal of oil by ISB that generation of residue is acceptable and/or for which assignment of response resources to residue recovery operations are justifiable.

V.2.3 Burn Residues on Ice and in Snow

Much of the early research for ISB on ice was on landfast ice, in melt pools, and on oils mixed in snow (Buist, 2007).

- ISB is often a preferred response option to remove oil pools on ice. Oil spills on land fast ice and in melt pools tend to be thicker and naturally contained and can be effectively burned. Winds can drive oil to a downwind ice edge [thicknesses of 10 mm (0.4 in.) have been reported] resulting in very high ISB efficiencies in removing encountered oil from an ice surface.
- 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 snow melts, oil is released onto a pool of water where it can be ignited by the heat of the burn. Oil mixed in snow does not form an emulsion since there is no mixing energy or liquid water, and evaporation rates are reduced. Burns of oil-contaminated snow can be very efficient, producing less residue.
- Any burn residue not recovered from a burn on ice or in snow is likely to undergo minimal additional weathering. Residue remaining on ice over water can move with ice, sink, or become encapsulated during ice growth periods.

Based on small-scale experiments, SL Ross (2003) offered two rules of thumb for the amount of residue from burning thin slicks in broken ice:

- Residue thickness after a burn in broken ice in calm conditions is about 1.5 mm (0.06 in.).
- Residue thickness after a burn in brash or frazil ice with waves is slightly greater, at about 2 mm (0.08 in.).

Assuming a minimum thickness of 3 mm (0.12 in.) for ignition of weathered oil in ice, removal efficiencies of thin slicks would be 50% in calm conditions and 33% in wave conditions, compared to 67% on open water (Buist, 2007).

Section VI: Human Health and Safety

ISB is an efficient process for removing oil from the environment. Particulates, and other combustion by-products in a smoke plume, rise and are transported by winds. Larger particulates will fall by gravity sooner that smaller ones. Particulates can be sent to the ground or water surface during precipitation (e.g., rain, snow).

Decision makers need to be cognizant of, and account for, the health and safety of both response workers and the populations potentially affected by a smoke plume from ISB. These concerns should be weighed against the potential health and safety impacts from the spilled oil itself. **Table 10** provides information on the likely concentration range of combustion by-products in the air at a burn and one kilometer from a burn.

VI.1 Human Health and Safety—ISB Workers

The U.S. Occupational Safety and Health Administration (OSHA) developed specific requirements for training oil and hazardous materials spill responders under the Hazardous Waste Operations and Emergency Response (HAZWOPER) standard. These requirements apply to responder personnel participating in a burn (OSHA, 2001). OSHA is responsible for assuring safe working conditions for response personnel, and would include the potential exposure to combustion particulates from a burn. The NCP specifies the types of actions to be taken by a Responsible Party for responder health and safety.

VI.1.1 Occupational Exposure Monitoring

For an ISB, the issue of greatest health and safety concern is exposure of ISB response personnel to $PM_{2.5}$ components in a burn plume. While direct exposure to $PM_{2.5}$ in a smoke plume from a burn can impact human health, it is generally long-term exposures over months to years that adversely affect health. Short-term exposure to high concentrations during a burn can aggravate symptoms in sensitive individuals with existing heart or respiratory ailments.

The NIOSH/OSHA (2010) conducted occupational and medical health hazard monitoring of ISB teams conducting operational burns for the Deepwater Horizon response. NIOSH conducted personal breathing zone and area air sampling on the vessels used for towing fire boom and onboard the smaller, more-maneuverable, rigid-hulled boats used to ignite burns. Sampling was conducted for "VOCs, aldehydes, CO, H_2S, benzene, soluble fraction of total particulate matter, diesel exhaust, and mercury" (King and Gibbons, 2011). Their health hazard evaluation found exposures were either below detectable concentrations or well below applicable occupational exposure limits, with one exception. The exception was a peak concentration of 220 ppm for CO measured on one of the ignition boats. King and Gibbons (2011) attribute this reading to exhaust from the gasoline-powered engines.

NOTE:

Many of the chemical parameters in monitoring programs could be emitted by numerous sources, including motor vehicles such as boats and airplanes. Therefore, sampling results alone cannot determine with certainty where VOCs originated.

Table 10—Decision-making Endpoints for Airborne Emissions from Burning of Oil

Component of Concern		Health Standards [a] (Averaging Period)	Range at the Burn Site	Range One Kilometer Downwind
Smoke Particulates	$PM_{2.5}$	• 35 $\mu g/m^3$ (24 hr EPA NAAQS)	0.0–2.4 $\mu g/m^3$ [b] (from diesel)	No data identified for ISB
	PM_{10}	• 150 $\mu g/m^3$ (24 hr EPA NAAQS)	850 $\mu g/m^3$ [c]	86 $\mu g/m^3$ [d]
PAHs		• 0.2 mg/m^3 (OSHA PEL) [e]	0.0–13.1 $\mu g/m^3$ [b]	No data identified for ISB
Gases & Vapors	CO_2	• 35 ppm (24 hr EPA NAAQS) • 5,000 ppm (OSHA PEL)	26–543 ppm [f]	<32 ppm [g]
	SO_2	• 75 ppb (1 hr EPA NAAQS) • 500 ppb (3 hr EPA NAAQS) • 5 ppm (OSHA PEL) • 0.25 ppm (ACGIH STEL)	2,000 ppb [h]	< 1.2 ppm [h]
	NO_2	• 100 ppb (1 hr EPA NAAQS) • 53 ppb (Annual EPA NAAQS) • 5,000 ppb (OSHA PEL)	0.1–0.6 average ppb [i]	0.1 ppb [i]
	CO	• 35 ppm (1 hr EPA NAAQS) • 9 ppm (8 hr EPA NAAQS) • 50 ppm (8 hr OSHA PEL)	139–145 average ppb [i]	139–140 ppb [i]
	VOCs [j]	• 100 mg/m^3 (approx. 12 ppm) (ACGIH TLV)	2.6–8.3 average ppb [i]	1.3–1.6 ppb [i]

Notes:

Units of ppm/ppb are most appropriate for gases, and $\mu g/m^3$ is more appropriate for particulates and fumes.

[a] From the EPA Air and Radiation: National Ambient Air Quality Standards (NAAQS) webpage (http://www.epa.gov/air/criteria.html).

[b] As reported by Fingas & Punt (2000) for Environment Canada.

[c] As reported by Buist et al. (1999).

[d] As reported by Fingas et al. (1994).

[e] While the Occupational Safety and Health Administration (OSHA) has not established an occupational exposure standard for PAHs, there is an exposure limit for volatiles from coal tar pitch that covers the PAHs anthracene, benzo(a)pyrene, phenanthrene, acridine, chrysene, and pyrene. The current air standard for coal tar pitch volatiles in the workplace is 0.2 milligram/cubic meter (mg/m^3) based on an 8-hour time-weighted average (TWA) permissible exposure limit (PEL) for the benzene-soluble fraction of coal tar pitch volatiles.

[f] As reported by Fingas (2011).

[g] As reported by Fingas et al. (1994).

[h] Note that the level of SO_2 is dependent on the amount of sulfur in the oil. SO_2 levels are typically very low. Detection tubes can be used to perform real-time sampling. Buist et al. (1999).

[i] Data reported from Middlebrook et al. (2012) for the Deepwater Horizon response, especially Table S2.

[j] The ACGIH Threshold Limit Value (TLV) provided is for diesel fuel (inhalable fraction and vapors). There are no established limits in U.S. for VOCs, crude oil or total hydrocarbons. Fingas et al. (1994) notes that the VOCs emitted from crude oil exceed those emitted from burned oil.

VI.1.2 Control of Occupational Exposures

Combustion by-products from the many ISBs in the Gulf of Mexico in 2010 were not found in high concentrations at the distances the boats maintained from the smoke plumes. This observation is a reflection of the rapid transport of by-products in rising smoke plumes, which were well above responders' work locations. As a result, NIOSH/OSHA (2010) developed recommendations for ISB operations, which are summarized below.

VI.1.2.1 Dermal Contact

In general, minimal opportunities for dermal contact with oil should occur with appropriate personal protective equipment (PPE) and procedures in place for ISB responders. NIOSH/OSHA (2010) identified activities with greater opportunity for dermal exposures during on-water ISB including: handling oil-coated ropes used to tow boom; contacting surface oil from splashes while traveling at high speeds on the ridged hulled assist boats; and performing maintenance on fire booms after burns.

VI.1.2.2 Personal Protective Equipment (PPE)

ISB protocol dictates the use of appropriate PPE (not limited to flame-resistant coveralls and leather gloves) be worn by personnel conducting oil burn ignitions. PPE should be worn during every ignition as in safety operations protocols (NIOSH/OSHA, 2010). These protocols are location-dependent; e.g.:

- Response personnel close to a burn can be exposed to levels of gases and particulates that would require them to use additional PPE.
- NIOSH/OSHA (2010) reported that during the Deepwater Horizon ISB, the continuous use of respirators was not warranted. However, responders were cautioned to be aware of sudden or unexpected shifts in winds or other conditions that could result in direct exposure to smoke plume and necessitate the use of respiratory protection.
- Cold weather conditions can require additional levels of PPE.

VI.1.2.3 Operational Safety Requirements

While no overexposures attributable to ISB operations during Deepwater Horizon were identified, NIOSH/OSHA (2010) investigators recommend future ISBs be conducted with vessels positioned upwind at an adequate distance away from burns. For fire safety reasons, vessels are recommended to remain as far away from a fire as possible, per their site safety plan. Every effort should be made to keep responders out of a smoke plume and to move them as quickly as possible when conditions changed. Additionally, particulates can impede visibility and could pose a safety hazard to operators of ships, aircraft, and motor vehicles in the immediate vicinity of a fire. Hazards from ISB include heat, exposure to products of combustion, and, rarely, flash fire. The ISB site safety plan should address all anticipated hazards, plus whether or not air monitoring is needed, and if so how it will be conducted.

VI.2 Human Health and Safety—General Public

Public exposure to smoke particulates from a burn is not expected to occur unless a smoke plume drops in altitude down to very near ground level. Exposure and possible health effects from an ISB plume are greatest at a burn site and directly in a plume's path. The exposure and likely health effects rapidly diminish as the plume travels away from a burn location and should be quite low with smaller burns (**Figure 12**).

Figure 12—Burning oil from a pipeline spill in a trench. Source: David Fritz.

Whether or not air monitoring is appropriate for protection of public health depends on the scale of the burn, on predicted trajectory of the smoke plume, and whether smoke particulates are forecast to reach ground level near population centers. There are increasing amounts of data indicating minimal health impacts from inhalation of oil particulates from ISB on humans. Based on data from the Newfoundland Offshore Burn Experiment (Fingas et al., 1994; Bowes, 1994), previous burns (Fingas et al., 1993; Evans et al., 1992), the Kuwaiti oil fires (Ferek et al., 1992; Stevens et al., 1993), and Deepwater Horizon ISB (NIOSH/OSHA, 2010; Middlebrook et al., 2012), particulates in a smoke plume remain the only agent of concern beyond distances past 1–2 kilometer downwind. Gases and other combustion by-products created in a burn settle out or dissipate to levels near background (ASTM, 2014).

During periods of local atmospheric inversion or high winds, a smoke plume can become trapped in lower altitudes, resulting in increased concentrations of combustion by-products closer to ground level (Ferek et al., 1997). These increased concentrations can potentially expose individuals (responders or public) who are in the path of the smoke plume (Spektor, 1998). This potential has only a temporary effect on downwind air quality and should be considered against long term impacts to the environment from spilled oil when not burned.

Inhalation of volatile compounds and particulates is the major pathway for airborne ISB by-product exposure to the general public. Sensitive individuals include very young and very old, pregnant women, and those with pulmonary or cardiovascular diseases. Their tolerance to particulates and volatile compounds can be significantly lower than responders. Protecting the general public can be achieved by conducting a burn when wind and atmospheric conditions are favorable, such that their exposure to particulates would be below levels of concern, or by temporary evacuations.

In general, accepted practice is that an ISB should be avoided within 1 km upwind of either an ecologically sensitive or a heavily populated area, depending on meteorological conditions. According to ASTM, "No emissions greater than one fourth of the 2008 human health exposure limits have been detected at ground level further than 1 km from an oil fire" (ASTM, 2014).

VI.2.1 Air Quality Considerations

The most recent experience with offshore burns and detailed operational monitoring was during the 2010 Deepwater Horizon incident. During the Deepwater Horizon oil spill response, EPA conducted air monitoring for human health effects beginning April 28, 2010 through July 27, 2010. They sampled air for vapors that can evaporate from the water/oil mixture in the Gulf of Mexico as well as for particulate matter that might have resulted from the smoke generated by the controlled burns. EPA tracked the levels of particulate matter, VOCs (including specifically, benzene, ethylbenzene, toluene, and xylene, which can cause health problems at elevated concentrations), H_2S, and PAHs. Similarly, the National Oceanic and Atmosphere Administration (NOAA) led a study to measure the atmospheric plume for hydrocarbons from the evaporating oil that reacted with nitrogen oxides in the atmosphere to create ozone pollution. BP conducted air monitoring for crude oil vapors from numerous locations from Galveston, TX to Apalachee Bay, FL (CTEH, 2010). The objective was to ascertain levels of particulates in air (2.5 µm and smaller), VOCs, H_2S, SO_2, and benzene resulting from the spill and ISB. CTEH collected a total of 454,698 readings in communities until September 4, 2010 (Millner, 2012).

In general, based on monitoring data collected from the offshore spill and ISB during Deepwater Horizon response:

- Concentrations of benzene, ethylbenzene, toluene, and xylene in air were similar to or lower than those observed in longer duration samples from on shore and were below the levels of health concern.
- Over the course of the spill, the total mass of organic particles formed from evaporating surface oil was about 10 times bigger than the mass of soot from controlled burns (Middlebrook et al., 2012).
- The monitoring data did not exceed any state or federal air quality standards for PAH compounds during the Deepwater Horizon spill response.
- Monitoring data for particulate matter, VOCs, and H_2S were found to be below EPA's levels of concern based on federal standards (LDEQ, 2010).

VI.2.1.1 Modeling of ISB Plumes

One way to estimate the potential exposure from a burn plume or particulates 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. [27] The model is used to predict the downwind distribution of smoke particulate and combustion products and was developed to aid in the planning process for the intentional burning of crude oils spills on water.

For any federal response, the Interagency Modeling and Atmospheric Assessment Center (IMAAC) will likely provide modeling support using HYSPLIT. [28] IMAAC coordinates and disseminates atmospheric dispersion modeling and hazard prediction results. These can be used during actual or potential incidents or for exercises involving hazardous material releases. Through plume modeling results analysis, IMAAC can provide predictions of hazards associated with atmospheric releases (e.g., ISB plumes) to aid in the decision-making process to protect the public and the environment.

[27] The ALOFT-FT model is available from http://www.nist.gov/el/fire_protection/buildings/aloft-ft.cfm and is for smoke plumes forming over flat and more complex terrain features. The program can also be useful in predicting the smoke plume trajectory from other large outdoor fires, particularly liquid pool fires. ALOFT-FT requires as input data for wind speed and variability, atmospheric temperature, number of fires, fuel parameters, and emissions factors.

[28] HYSPLIT is the Hybrid Single Particle Lagrangian Integrated Trajectory Model. It is designed to support a wide range of simulations related to atmospheric transport and dispersion of pollutants and hazardous materials, plus their deposition to the surface. The model calculation method is a hybrid between the Lagrangian approach, which uses a moving frame of reference for the advection and diffusion calculations as air parcels move from their initial location, and the Eulerian approach, which uses a fixed three-dimensional grid as a frame of reference to compute the pollutant air concentrations.

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.

These models can be used to estimate the dispersion of combustion by-products from ISB. 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 the potential impact on the general public. In the U.S., the FOSC or SOSC can authorize a trial burn to confirm anticipated plume drift direction and dispersion distances downwind before authorizing the full-scale proposed burn.

VI.2.1.2 SMART Monitoring of ISB Plumes

The Special Monitoring for Alternative Response Technologies (SMART) protocol was developed by USCG, NOAA, EPA, CDC, and MMS (2006) as a way to monitor and evaluate the operational effectiveness of response technologies like dispersants and ISB. SMART establishes a monitoring system for the rapid collection and reporting of real-time, scientifically-based information in order to assist the Unified Command (UC) with decision-making during ISB.

If monitoring is appropriate, then a SMART ISB team(s) collects background air quality data prior to initiation of a burn. After a burn begins, team(s) continues collecting data on particulate concentration trends. This information is forwarded to the FOSC/UC and used with meteorological forecast data to determine whether or not to continue with a burn or if alterations in burn operations are needed.

As a follow-up to the monitoring experience during Deepwater Horizon, the U.S. NRT Science and Technology Subcommittee for SMART protocols has been developing modifications for improvement. Those interested should watch for announcement of revised SMART protocols.

Section VII: Effects on Wildlife and the Environment

This section summarizes possible effects on wildlife and habitats during and after ISB. The key concerns are impacts from exposure to smoke plumes and combustion gases and toxicity/effects of burn residues. In addition, information on impacts to habitats following ISB on land is summarized. A source of information on inland and upland burn is API (1999).

VII.1 Potential Effects from Exposure to Smoke Plumes and Gases

The approximate levels of concern for mammals, birds, reptiles, and other land animals to smoke and gases from ISB have not been determined. Effects from exposure to ISB gas by-products are likely to be similar to those experienced by humans. As seen in Section VI.2, monitoring data collected during previous burns indicates that the potential for overexposure to combustion by-products is limited.

VII.2 Potential Effects from Fire

For a spill in wet sites, the water layer provides two forms of protection to plant species. First, it provides an insulating layer to protect a plant's root system from heat and can prevent organic soils from igniting. Experiments with potted fresh and salt water marsh grasses showed 2.5–10 cm of water protected roots from heat stress (Bryner et al., 2003; Lin et al., 2002). Secondly, water prevents oil from soaking into soil and limits exposures. From burns in oiled wetlands, the empirical rule of thumb is that a layer of water is preferred, yet saturated soils can also provide protection.

One lesson from inland ISB and prescribed burns is that a burn should not take place in a wetland that is forecast to be flooded immediately following the burn. If a site is flooded immediately following a burn then oxygen in waterlogged soils could become greatly reduced and limit a plant's recovery potential. Consider timing of a burn and the relative benefit of oil removal pre-flood, versus the potential for further habitat oiling as flood waters transport spilled oil.

Studies of spill sites have shown ISB is less damaging to vegetation when it is not actively growing (Mendelssohn et al., 1995). During the growing season, plants have used their underground food reserves to produce leaves, branches, seeds, etc. If the aboveground vegetation is removed by burning, then plants might not have enough energy to produce new vegetation and food stores for regrowth.

Grasses are much more fire tolerant than woody vegetation (e.g., shrubs and trees), although some woody species are also fire tolerant (e.g., have thick bark, re-sprout quickly after fire). Even if not killed outright by fire, trees generally take a long time to recover because of their slow growth rates compared to faster growing shrubs and grasses. Michel & Rutherford (2013) reviewed 33 spills where ISB was used in wetlands and concluded vegetation would recover within 5 years, and more likely within 1–2 growing seasons.

Before use of ISB on water, consider if area is proximal to bird flocks, sea turtles, marine mammals, etc. ISB on land should also consider the presence of concentrations of fauna of concern, such as bird nesting colonies or threatened/endangered species.

VII.3 Potential Effects of Burn Residues

For burns on land and in snow/ice, thicker residues can have physical effects, such as preventing regrowth from surviving plant roots. Burn residues can be sticky or very dense and less likely to be removed by natural processes such as rainfall or tidal flushing. If a burn site is accessible, efforts should be made to recover as much residue on the surface as possible.

VII.3.1 Low Toxicity 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.

Studies of the aquatic toxicity of burn residues were conducted as part of the 1993 Newfoundland Offshore Burn Experiment (NOBE) in Canada using laboratory-generated burn samples and field water samples. Daykin et al. (1994) found:

- There were no significant differences in the concentrations of petroleum hydrocarbons below burned and unburned slicks. Concentrations were extremely low (less than 0.15 ppb total PAHs and 4–8 ppb TPH (total petroleum hydrocarbon).

- Acute toxicity tests with water samples from under both burned and unburned slicks using echinoderm sperm cell and larvae, marine bivalve larvae, and inland silversides showed very low levels of acute toxicity. No significant differences in acute toxicity were observed between water collected under burned and unburned slicks.

Laboratory-generated burns represented "worst-case exposures" because of the lack of dilution, yet still resulted in low acute toxicity. Blenkinsopp et al. (1997) evaluated the aquatic acute toxicity of samples from the NOBE burn using a different sample preparation method in which the burn residue was stirred in water for 48 hours to generate a water-accommodated fraction (WAF) for different oil loadings. The WAF was used in toxicity tests for three-spine stickleback, rainbow trout, and gametes of sea urchins. Results from toxicity tests indicate the WAFs were nontoxic to the species tested. The authors concluded that ISB does not generate a burn residue that is more toxic than un-burned, weathered oil. Similarly, in Australia, crude oil burn residues created in the laboratory showed no acute toxicity to amphipods and a very low sub-lethal effect (burying behavior) to marine snails (Gulec and Holdway, 1999).

Measurements from field and laboratory test burns under open water conditions show burning does not: 1) accelerate the release of oil components or combustion by-products to the water column or 2) increase acute toxicity levels (Daykin et al., 1994; Ferek et al., 1997). Water quality and aquatic toxicity after a burn are expected to be the same as before the burn.

VII.3.2 Contact Hazards

The risk to 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 surface oil since unburned oil can spread over larger areas. Sticky burn residues that float may foul feathers of birds and fur of marine and terrestrial mammals (e.g., seals, otters). Contact with oil may 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, lighter crude oils and diesel did produce sticky burn residues.

VII.3.3 Ingestion Hazards

Currently, there is no data on effects to birds from ingesting burn residue, as would occur during preening. It is likely that burn residue ingestion would result in similar effects as from ingestion of weathered oils (Leighton, 1995). The spatial extent of an unburned slick provides a larger area for potential contact than a burned slick with just residue remaining.

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

In their report, "Oil and Sea Turtles," NOAA (2010) suggested ISB near sea turtle habitats could be of concern because they might try to eat submerged oil residues. During the Deepwater Horizon ISBs, observers were used to assure that sea turtles were not where burns occurred; no sea turtles were observed in the areas where burns were conducted (Mabile, 2012).

VII.3.4 Hazards from Sinking Burn Residues

Most burns have been conducted on land or along saturated shores of small water bodies. Depending on the oil type and whether sufficient quantities of residue sink and remain, residues could smother or coat animals that live on and in the bottom of a water body. Generally, the amount of residue expected from intentional burning of oil at on water is very small and this residue should spread over large areas of the bottom. Residues of small burns can yield very localized physical impacts. However, if a large amount of oil is to be burned in a shallow area with slow currents or low flushing rates, then potential for residue accumulation on the bottom to affect benthic resources increases. In South Korea, approximately 2,000 tonnes (1,466 bbl) of heavy oil spilled when a vessel went aground. A burn of one slick was conducted and its residue was reported to have sunk, affecting nearby caged crabs (Moller, 1992).

Oils typically float on water because they are less dense. When oils adsorb particles or weather and become denser than water, it is possible for them to become neutrally buoyant and float subsurface in a water column or to eventually sink. Because of the chemically inert nature of burn residue, its environmental impact is believed to be mostly due to physical smothering effects (NRT, 2000).

A famous example of a marine spill with sinking burn residue is the M/T Haven in 1991 off the coast of Italy. The 3-day fire of the M/T Haven's cargo of heavy crude was a consequence of the incident not an ISB, and it was estimated that 70% of the cargo burned. Sand in the near shore zone was thought to be one cause of sinking oil, of which some warmed in summer, refloated, and stranded on nearby beaches. Surveys of adjacent sea bottom indicated a "concentration" of sunken burn residue that was cohesive, tarry, and located in an area southwest of the spill. Trawling recovered about 200 tonnes (146 bbl) of sunken oil (Moller, 1992). Fouling of fishing nets and smothering of sea grass beds was observed (Martinelli et al. 1995). However, far more inert than the original heavy oil, this sinking oil indicated negligible contamination in water column based on chemical analysis.

VII.4 Habitat Recovery Following ISB

An on-land ISB is operationally preferred when the location is mostly unvegetated, such as dirt roads, ditches, dry streambeds, and idle cropland. There have been several spills in crop lands during winter when the fields were bare or had stubble from the previous year's crop. Complete mechanical removal of oil would require removing a significant amount of soil. In these cases, burning was used instead to remove as much oil as possible; then the fields were tilled and fertilized. Natural biodegradation completed the oil removal process. The land was farmed normally the next season (Dahlin et al., 1999).

Habitat effects and recovery rates following ISB vary by habitat and season (Dahlin et al., 1999). At one end of the recovery spectrum are low-oxygen, acidic peat habitats in sub-Arctic and Arctic regions where weathering rates are extremely slow (decadal), particularly where oil concentrations are high and oil penetrated into peat. At the other end of the recovery spectrum are agricultural fields, where burn areas are typically tilled, fertilized, and crops are successfully grown the next season. **Figure 13** illustrates plant regrowth after a large inland burn. **Figure 14** shows the post-burn potential for rapid vegetation recovery, even when some pockets of free oil remain.

Figure 13—Plant regrowth following a burn. Source: Minnesota Pollution Control Agency

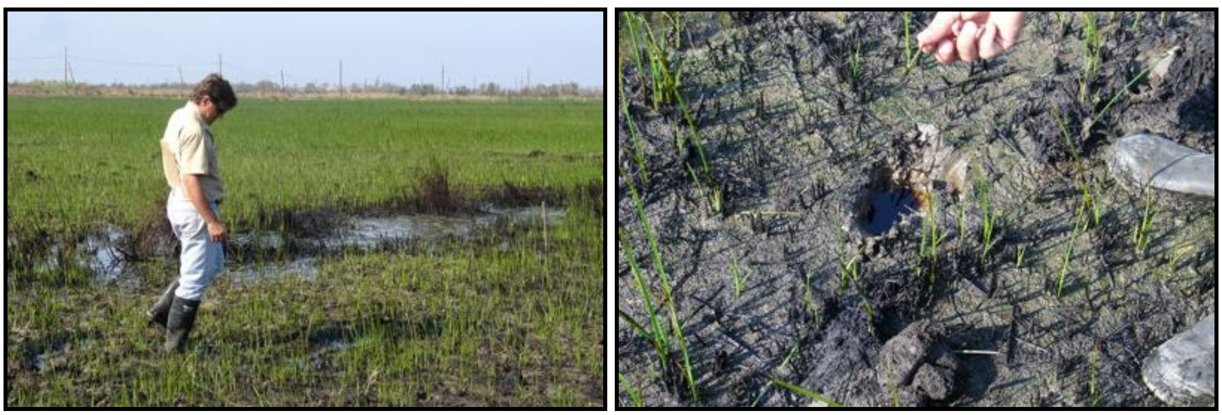

Figure 14—Photographs of a burn site in November 2005 showing the rapid vegetation re-growth within 3 weeks after a burn. Source: NOAA.

Section VIII: Summary

ISB is a response technology that removes spilled oil from a land, snow, ice, or water surface by combustion of hydrocarbon vapors and that yields predominantly CO_2 and water vapor to the atmosphere. Combustion by-products (particulates, gases, water, etc.) are released to the atmosphere, with the possibility of some unburned oil or incompletely burned oil residue remaining at the conclusion of a burn. The goal of any response is to limit the effect of the spill on natural and economic resources. Some of the benefits and reasons to consider ISB are its:

- High efficiency;
- Versatility—on land, on water, and in ice/snow;
- High elimination rates;
- Minimal equipment and personnel needs; and
- Waste stream reduction.

To initiate a burn, sufficient quantities of hydrocarbon vapors are needed in the air above a slick to support combustion. The key factor that defines whether or not an oil will burn is slick thickness. Slick thickness has two roles: 1) a source of hydrocarbon vapors and 2) retention of heat to help vaporization of petroleum hydrocarbons to sustain a burn. An ignition source can either directly ignite those vapors or heat spilled oil to a temperature at which sufficient vapors to ignite are generated. Once a slick is ignited, hot air rising above the burn will draw in air. This induced air flow can draw in surrounding oil to feed the burn with more vapors.

Spill location and volume most often determine which local, state, and/or federal regulations will apply and which agencies could be involved in an incident response.

  - Contingency planners should examine the locations for their spill risks and check state agency jurisdiction assignments for spill response.

Regulations and/or guidance could be available at the state level and are available at the multi-state, regional level via the RRTs and their RCPs. Many RRTs have prepared guidance for ISB and on designation of burn pre-approval zones, most of which apply to spills to coastal waters rather than to spills on land or to non-navigable waters.

The main federal regulations dictating the responsibility for cleanup and removal of spilled oil include: the Clean Water Act; the National Oil and Hazardous Substances Pollution Contingency Plan; the Oil Pollution Act of 1990; the Resource Conservation and Recovery Act; and the Occupational Safety and Health Administration's (OSHA's) Hazardous Waste Operations and Emergency Response standard. OPA 90 Section 4201 amended the CWA [Section 311(c)] to provide options to either: 1) perform response and cleanup immediately (by "federalizing" an incident); 2) monitor the efforts of a spiller; or 3) direct a spiller's cleanup.

The decision to use ISB on an oil spill that has or potentially threatens waters of the U.S. rests with the FOSC. The primary question is whether ISB is appropriate for incident-specific conditions. If yes, then:

- Does the FOSC have pre-authorization approval authority to conduct a burn in the location being considered?
- If not, then are incident-specific RRT notifications and consultations required? What other notifications are necessary?

An FOSC is to notify the incident-specific RRT of the operational use of ISB. The timing of notification varies based on RRT pre-authorization conditions, and might be a courtesy notification. In regions with either case-by-case approval zones or for areas that have special consideration and/or consultation requirements, the

FOSC is to request and obtain concurrence from the incident-specific RRT prior to burn approval.

For some spills, emergency consultations might be necessary to determine how to address:

- Air quality concerns;
- Threatened and endangered species and essential fish habitats; and
- Special resources in a spill area protected under Section 106 of the National Historic Preservation Act.

Information is provided on oil properties and weathering processes as they can influence the fate and behavior of spilled oil, its ignitability, ability to sustain a burn, and the time window of opportunity for burning. Information on combustion byproducts, burn residues, and unburned oil are provided as they can influence a decision to burn or burn execution.

U.S. health standards for smoke particulates plus PAHs, gases, and vapors in a smoke plume are described. Forecasted concentrations from modeling results can influence a decision to burn or burn execution based on responder health concerns. The issue of greatest concern is exposure of ISB response personnel to $PM_{2.5}$ components in a burn plume. While direct exposure to $PM_{2.5}$ in a smoke plume from a burn can impact human health, it is generally long-term exposures over months to years that adversely affect health.

Public exposure to smoke particulates from a burn is not expected to occur unless a plume drops in altitude to near ground level near the burn site. There are increasing amounts of data indicating minimal human health impacts from inhalation of particulates from an ISB smoke plume. Whether or not air monitoring is appropriate for protection of public health depends on the scale of a burn, predicted trajectory of the smoke plume, and whether particulates are forecast to reach ground level near population centers.

Recovery from a spill and burn varies by habitat type, circumstances of a spill, and the season of a spill and burn. Water saturated soils or standing water provide insulation against soil heating effects from ISB on land. Understanding habitat sensitivity will assist in burn planning and execution. Some spills can be burned a second time to remove even more oil.

Burn residue is more viscous, less toxic, and far more chemically inert than the original oil. Information on residue composition, potential effects to wildlife and the environment are summarized. Residue amounts are anticipated to be <10% of the original oil volume. A localized amount of burn residue can influence post-burn recovery or treatment operations. Recovery and treatment of residues from ISB on land is easier than from ISB on water.

This document is intended to improve the understanding of ISB and the process for decision-making. Delays in decision-making extend the time for oil weathering (negatively influencing ignitability) and for habitat and wildlife exposure (negatively influencing degree of impact and recovery). Pre-planning and timely decision-making improve the likelihood that ISB will be effective and limit the subsequent effects from spilled oil on natural and economic resources.

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Appendix A

ISB Case Histories and Lessons Learned

Case histories in which ISB was used as a countermeasure are described in this section. The emphasis is on the effectiveness of the burn, the amount and nature of oil residue produced, the impacts of the burn, and lessons learned.

A.1 Case Studies of In Situ Burning on Land

ISB on land can be conducted on a wide range of habitats, from ditches, to agricultural fields, to wetlands. Representative ISB case studies for spills on land are summarized below.

1. Chiltipin Creek, Texas—1992.
2. Refugio County, Texas—1997.
3. Pipelines, Illinois—1994 to 1995.
4. Pipeline, Utah—2000.
5. Tank Farm, Louisiana—2005.

A.1.1 Chiltipin Creek, Texas, 1992

Spill Date: 7 January 1992

Oil Type: South Texas Light crude oil (API = 37)

Spilled Volume: 2,950 bbl (124,000 gal)

Burned Volume: 1,150 bbl (48,000 gal)

Habitat: High-elevation salt marsh

Oil spilled from an underground Exxon pipeline, affecting 25 acres (10.1 hectares) of a high marsh dominated by salt grass, salt wort, and shore grass. The ground was saturated from days of rain and site access was difficult. Responders used vacuum trucks to recover oil for 4 days.

The oil continued to spread below the dense vegetation and the forecast was for more rain, so it was feared oil would reach the Aransas River, about 460 m (503 yd) from the slick's leading edge. Oil in the marsh was 1–3 mm (0.04–0.1 in.) thick. After ignition with mineral spirits, the fire burned for 21 hours, removing 80–85% of the oil. Three remaining pools of oil were burned the next day. Burn residue was described as an asphaltic, taffy-like material that was very sticky. Cleanup workers, working on planks in the marsh, used sorbents to recover the residue over the next 15 days (summarized from Gonzalez & Lugo, 1995).

Researchers monitored recovery for 5 years. They studied vegetation, fiddler crab population, animals in small ponds, bird use, and sediment contamination. After 2 years, vegetation cover was back, yet most of it was salt grass, a pioneering species, rather than the normal mix of species indicative of a healthy marsh. Five years later, about 20% of the burned marsh was bare, compared to 4% for a reference marsh. The researchers concluded: 1) the dead vegetation was from burn intensity and/or oil penetrating into roots and 2) the burn probably allowed a more rapid recovery when compared to mechanical or "monitoring" approaches (summarized from Tunnell et al., 1997; Hyde et al., 1999).

Figure A.1—Photos from Chiltipin Creek. Left: During the burn January 1992.
Right: One year later in January 1993. Source: Texas General Land Office.

A.1.2 Refugio County, Texas, 1997

Spill Date: 12 May 1997

Oil Type: Refugio Light and Giddings Stream crude oils (probably API = 41)

Spilled Volume: 500–1,000 bbl (21,000–42,000 gal)

Burned Volume: Not determined

Habitat: Brackish wetland used for cattle grazing

Oil was spilled from an underground pipeline and spread down slope via numerous cattle paths into a wetland with brackish marsh species that was used to graze cattle. Although trenches were dug near the leak to intercept the oil, the slick continued to spread into the wetland, eventually affecting 11 acres (4.4 hectares). Because the slick could not be contained, the remaining oil was burned. A layer of water 10–15 cm (3.9–5.9 in) deep covered the ground. Fire officials ignited the oil, which burned intensely over 5–6 acres (2–2.4 hectares) for 4 hours. Oil removal by the burn was estimated to be 90%. After the burn, standing water remained only in the deeper tracks. Oil in fringe areas was burned the next day. Many crayfish in the burned area were killed, but many also survived. The landowner did not allow follow-up studies (summarized from Clark and Martin, 1999).

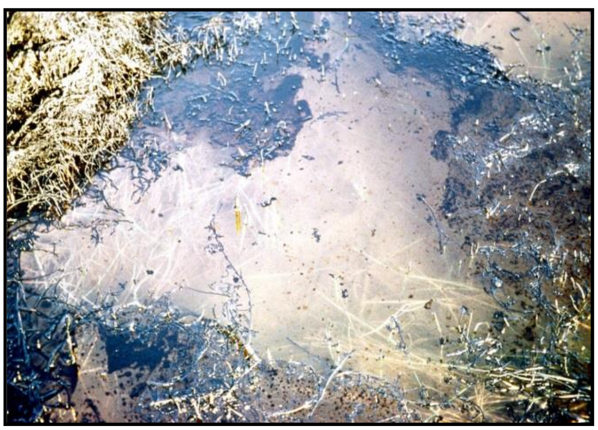

Figure A.2—Photos from Refugio County Texas wetland burn.
Left: Minor amounts of burn residue remained after the ISB. Right: Inspecting the site the morning after the burn. Photo credit: Texas General Land Office.

A.1.3 Pipelines, Illinois, 1995

Spill Date: Multiple spills in 1994 and 1995

Oil Type: Illinois crude oil (API not specified but likely >30)

Spilled Volume: 0.5–10 bbl (20–420 gal)

Burned Volume: 0.5–3 bbl (20–126 gal)

Habitat: Cultivated fields and adjacent sloughs, ditches, and roads

All releases were from pipeline ruptures. In most cases, free oil was removed using vacuum trucks and sorbents. The decision to burn the remaining oil was based on the following types of conditions: forecast of heavy rain that would spread the oil into larger or more sensitive areas; muddy conditions that limited vehicular access; oil trapped in crop stubble/vegetation; and remaining oil inaccessible in a slough. There was no information on the type of igniter used or duration of the burns. No air monitoring was conducted, and no problems were reported. At the sites located in cultivated fields, sometimes the burned area was fertilized and tilled; other sites underwent normal cultivation the next year. Sediment sampling conducted 7 months to 2.5 years post-spill showed elevated concentrations of total petroleum hydrocarbons, diesel-range organics, with concentrations up to 10,000 ppm. May and Wolfe (1997) concluded that, for small spills in rural areas, the following factors influence the decision to conduct a controlled burn: spill volume, surrounding terrain, weather conditions, accessibility of the oil, public health and safety, and proper permission. They also noted the importance of remedial treatment of the burned area post-burn to improve re-vegetation (summarized from May and Wolfe, 1997; Dahlin et al., 1999).

A.1.4 Pipeline, Corrine, Utah, 2000

Spill Date: 21 January 2000

Oil Type: Diesel

Spilled Volume: ~100 bbl (>4,200 gal)

Burned Volume: >500 bbl (>21,000 gal)

Habitat: Wetlands bordered by salt/mud flats, snow, and ice cover

A Chevron diesel pipeline leak occurred in a remote area north of Great Salt Lake and spread into a ponded wetland and a salt flat. Total affected area was 38.2 acres (15.5 hectares). It took about 4 weeks to secure federal agency burn approval due to required classification of PAH distribution in impacted sediment and preparation of detailed surveys and post-burn sampling work plans, during which time there were multiple freeze and thaw periods. The oil became trapped in and under ice and penetrated into sediments. One objective was to reduce the potential threat to migratory and resident birds. The first burn was on 10 March using a Helitorch for ignition. While most oil burned, oil in ice-covered areas did not completely burn. A second burn was conducted on 27 April with a propane torch as an igniter.

The RRT set a soil cleanup target of 20 ppm Total PAHs and requested tilling to speed biodegradation. In September 2000, 6.8 acres (2.7 hectares) of salt flat were fertilized and tilled. Dryer, more saline areas appeared to recover more slowly than wetter areas. Almost 1 year later, some spots were still above the cleanup target, so 3.4 acres (1.4 hectares) were re-tilled.

Some lessons learned included:

- Snow and ice can both help (keep from spreading) and hinder (cover oiled areas) an ISB.
- Burning is effective in removing surface oil, but not oil that penetrated into sediments.
- It is important to evaluate need for additional burns at thaw.

In summary, the burn would have been more effective in diesel removal, reduced soil penetration, and any impacts to vegetation if conducted sooner (Michel et al., 2002; Williams et al., 2003).

Figure A.3—Photographs of MP 68 spill site. Left: Immediately after the burn (March 2000). Right: July 2001. Note good recovery of vegetation along the edges of ponded area. Source: Chevron and J. Michel.

A.1.5 Tank Farm, Louisiana, 2005

Spill Date: 30 August 2005

Oil Type: South Louisiana crude oil (API = 33.8)

Spilled Volume: 100–200 bbl (4,200–8,400 gal)

Burned Volume: 100–200 bbl (4,200–8,400 gal)

Habitat: High intermediate marsh

As a result of Hurricane Katrina, a release occurred from a Chevron tank farm on a bank of the Mississippi River near Empire, Louisiana. An estimated 33,900 bbl (5,390 m^3) were spilled into secondary containment and a retention pond. Delineation indicated ~28 acres (11.3 hectares) of oiled marsh. Vegetation included salt meadow cord grass, bulrush, and salt grass. RRT approval to burn was received on 11 October and burns were conducted 6 weeks after the release. The decision was based on: site remoteness, human population were not at risk, difficult site access for manual or mechanical oil removal that could cause habitat damage, and standing water levels of 12–25 cm (4.7–9.8 in.) were more than adequate to protect roots. No air quality monitoring was required by the RRT because of remoteness and logistical challenges after Katrina. Cleanup workers were offsite during burns. Oil was ignited with a hand-held propane torch. The first burn lasted about 2 hours and spread about 30 m (33 yd) beyond one fire break. The next day, multiple burns were conducted. In all, 27 acres (11 hectares) were burned (summarized from Merten et al., 2008). Some free oil remained, mainly in crab burrows, which was recovered using sorbents.

A vegetation monitoring program was implemented (Baustian et al., 2010). Plant biomass and species composition returned to control levels within 9 months. Plant productivity recovered within one growing season. Total PAH and total alkane levels varied, yet were relatively low and generally decreased over time. Quick recovery was attributed to low organic content of marsh soils, high water level that limited oil penetration, relatively low oil loading, and lack of physical habitat changes.

Figure A.4—Aerial photographs of the Empire burn site. Left: 13 October 2005, immediately after the burns. Right: 16 March 2006, 5 months post-burn. Source: NOAA.

A.2 Case Studies of In Situ Burning on Water

Representative ISB case studies for spills on water are summarized below.

1. Prince William Sound, Alaska test burn—1989.
2. Offshore Burn Experiment, Newfoundland, Canada—1993.
3. North Sea Open Ocean Test Burn, United Kingdom—1996.
4. Deepwater Horizon Operational Burning, Gulf of Mexico—2010.

A.2.1 Prince William Sound, Alaska Test Burn, 1989

Spill Date: 24 March 1989

Oil Type: North Slope crude oil (API = 29)

Spilled Volume: 257,000 bbl (10.8 million gal)

Burned Volume: 350–700 bbl (15,000–30,000 gal)

Habitat: On water

A test burn was conducted during the evening of the second day of the Exxon Valdez spill, when ~15,000–30,000 gal (56.8–113.5 m^3) of crude oil had been collected by towing 140 m (153 yd) of fire boom in a U configuration. This test burn was the first time fire-resistant boom was used at a spill (Allen, 1990). The oil was ignited with gelled gasoline in a plastic baggie that was lit and allowed to float back into the oil contained within a fire-resistant boom. A helitorch was available; however, a hand-held igniter was used because it got dark before the test burn was finally approved.

Under calm sea conditions, the burn lasted 1 hour and 15 minutes. The area of burning oil was controlled by adjusting the speed of the towing vessels. Upon completion of the burn, there was an area of approximately 100 ft^2 (9.3 m^2) of burn residue concentrated within the apex of the boom. The residue had a taffy-like consistency with an average thickness of 10–12 cm (3.9–4.7 in.). The volume of residue, estimated at about 300 gal (1.1 m^3), represented 1–2% of the original volume of oil collected, a burn efficiency of approximately 98%. Burning was not conducted the following day because of delays in securing additional regulatory approval and the development of a storm with seas approaching 2 to 2.5 m (6.5–8.2 ft) in height within Prince William Sound by late afternoon. During the days after the storm, emulsified oil in excess of 60 to 70% water-in-oil had spread over large areas making ignition impossible (summarized from Allen, 1990).

Figure A.5—Night-time test burn of North Slope crude oil showing flames and reflected light on rising combustion plume. Source: A. Allen.

A.2.2 Offshore Burn Experiment, Newfoundland, Canada, 1993

Spill Date: 12 August 1993

Oil Type: Crude oil (API = 36°)

Spilled Volume: Two releases totaling 485 bbl (20,400 gal)

Burned Volume: All the above

Habitat: On water

The 1993 Newfoundland Offshore Burn Experiment (NOBE) was the largest scale open-water experiment to date. There were two experimental open-water burns where fresh crude oil was released into fire-resistant boom and ignited with a helitorch. The main objective was to study air emissions under realistic, full-scale field conditions. About 15% of the oil was released as smoke (the "smoke yield"). The smoke plume rose rapidly and remained more than a 1,000 m (1,094 yd) above the sea. Air emissions measured at sea level at a distance greater than about 150 m (164 yd) from the fire were below occupational health exposure levels. Very little emissions were detected at sea level beyond 500 m (547 yd) distance. Pollutants were measured at lower levels in this offshore burn than in previous laboratory tests. Both burns produced residues that revealed burn efficiencies of approximately 99% (summarized from Fingas et al., 1994).

Figure A.6—NOBE test burn, showing oil that has been released directly into a fire boom toward the end of a burn. Source: J. Smith.

A.2.3 North Sea Open Ocean Test Burn, United Kingdom, 1996

Spill Date: 11–12 June 1996

Oil Type: Larkwhistle Farm; Specific gravity = 0.8376 (API = 37.4)

Spilled Volume: 60,000 liters (~378 bbl or 15,900 gal)

Burned Volume: Burn 1 = 5,300 to 7,400 liters + Burn 2 = 7,280 to 10,160 liters

Habitat: On water

Two open-water test burns were conducted by Oil Spill Response Limited in the North Sea approximately 75 km northeast off the coast of Lowestoft, England. The purpose of these trials was to advance operational experience for conducting ISB and to test two differing ignition systems: a hand-held ignition system and a helitorch using an emulsion-breaking ignition mix (this mixture of heavy fuel oils, gasoline, a demulsifier, and gelling powder was designed to increase the effectiveness of ignition of stable water-in-oil emulsions). Air monitoring was conducted during both burns to assess worker exposure to the ISB by comparing measurements for particulate matter, combustion gases, VOCs, and metals against known occupational exposure standards.

The first burn, involving the release of 95 bbl (15.1 m^3) of fresh Larkwhistle oil, resulted in a 20-minute burn after being successfully ignited using a hand-held incendiary device. Researchers estimated that 36–50% of the test volume had been consumed (the rest escaped containment). At the completion of the burn, it was estimated that 1 bbl (0.2 m^3) of burn residue remained, approximately 2–3% of the original oil volume.

The second ISB used 113 bbl (18 m^3) of Larkwhistle emulsified oil (25% by volume water content) that had undergone 12 hours of evaporation. This second burn lasted approximately 22 minutes after ignition using the helitorch with an emulsion-breaking ignition mix. During the emulsified oil burn, researchers estimated that 2 bbl (0.3 m^3) of "thick taffy-like residue" remained. The residue was approximately 3–4% of the total volume. The burn efficiency was estimated to be higher, at 56–76% of the volume released (summarized from Thornborough, 1997).

Figure A.7—North Sea burns, 1996. Source: A. Allen.

A.2.4 Deepwater Horizon Operational Burning, Gulf of Mexico, 2010

Spill Date: April–July 2010

Oil Type: South Louisiana crude, Mississippi Canyon 252 (API = 37)

Spilled Volume: 4.9 million bbl (205 million gal)

Burned Volume: 220,000–310,000 bbl (9.24–13.02 million gal)

Habitat: On water

Open-water ISB was conducted on an unprecedented scale during the Deepwater Horizon oil spill response. From April to July 2010, 411 burns were completed. ISB Task Forces consisted of 3–4 burn teams: each team had 2 shrimp boats to tow fire boom, 2–3 larger vessels for Command, Safety/Fire Control, and Boom Supply/Repair, plus multiple small boats for ignition. Turtle and wildlife observers onboard burn vessels in July reported no sea turtles in or near fire boom when aboard. Hand-held igniters had gelled diesel in 1-gal (3.8-liter) plastic bottles with a float and road flare. Fire boom types included water-cooled, ceramic/stainless steel, inflatable and solid-core, plus high-temperature, ceramic/steel fence booms. Air quality monitoring at and near burn sites reported no injuries or illnesses from burn operations.

Burns were optimized by spotting teams, which made multiple sorties per day to direct towing vessels. One of the longest burns was 11 hours and 48 minutes. Oil removal was estimated from burn area and duration using an empirical elimination rate of 0.05–0.07 gal/ft^2/min (2–2.8 liters/m^2/min). A conservative estimate of about 5% of the total oil spilled (as reported by NOAA) was burned.

Lessons learned included the value of trained aerial surveillance/spotting personnel, good communications, plus tracking and documentation systems because of the many response operations being conducted simultaneously. Local vessel operators, familiar with conditions in the area, were also of great value (summarized from Allen et al., 2011).

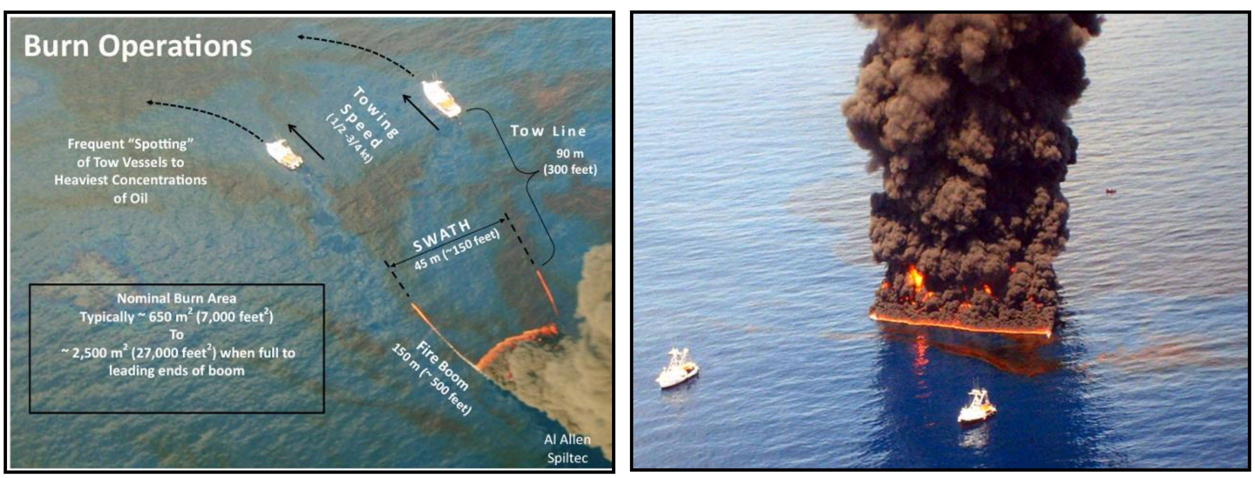

Figure A.8—Deepwater Horizon oil spill in situ burns.
Left: Typical fire boom configuration. Right: Feeding emulsified oil into an ongoing full-area burn.
Source: A. Allen.

A.3 Research & Case Studies of In Situ Burning in Snow and Ice Conditions

ISB is an important response option for oil spills in snow and ice conditions. Research has shown it can be successfully used under a wide range of sea ice concentrations. The following summaries highlight most of the medium- to large-scale experimental crude oil spill burns conducted on water, on land, and in ice, regardless of latitude. Additional information on burns in ice and snow is available in Buist et al. (2013).

1. Trans-Alaska Pipeline, Alaska—1978.

2. Oil Burn Pits, Prudhoe Bay Alaska—1979 to 1981.

3. Brunswick Naval Air Station, Maine—1993.

4. Svalbard Experimental Spill, Norway—2006.

5. Barents Sea Experimental Burns, Norway—2008 to 2009.

A.3.1 Trans-Alaska Pipeline, Alaska

Spill Date: 15 February 1978

Oil Type: Prudhoe Bay crude oil (API gravity = 29)

Spilled Volume: 16,000 bbl (672,000 gal)

Burned Volume: 500 bbl (21,000 gal)

Habitat: Ponded tundra

The spill resulted from sabotage to the pipeline. The ground was frozen and snow retarded the oil's spread and weathering. Dikes were constructed with sand bags 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 [240 m long and 4.5 m wide (262 yd long and 5 yd wide)], containing about 500 bbl (79.5 m^3) of oil, was burned 63 days after the spill. The oil ignited readily, and the 1.9 acres (0.8 hectares) burned for 2 hours, then continued in pockets. In a small area of ponded water varying in depth from several centimeters to 1 m (1.1 yd), as the water heated during the burn, small globs of oil were freed from the ground, floated to the surface, and ignited. Spot burning was conducted for another week. Very little melting of ice occurred. The frozen tundra thawed to a depth of several centimeters (about an inch). This area was diked and reburned, 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% re-vegetation after the first growing season (summarized from Buhite, 1979).

A.3.2 Oil Burn Pits, Prudhoe Bay Alaska, 1979–1981

Research Date: Winter 1979–1980; winter 1980–1981

Oil Type: North Slope Crude

Spilled Volume: Unknown

Burned Volume: Unknown

Habitat: Beaufort Sea on water, in ice and snow

In 1979, the petroleum industry formed an oil spill response organization called the Alaska Beaufort Sea Oil Spill Response Body (ABSORB) to develop oil spill response capabilities in the Arctic as a result of the drilling efforts in the Beaufort Sea (Hillman and Shafer, 1983). During the winters of 1979–1980 and 1980–1981, ABSORB conducted a series of studies on the behavior of oil spilled in the Beaufort Sea. During these tests it was determined that oil spilled on or beneath ice does not move from the spill site as it is bound into the ice matrix. Once ice melt begins, oil travels vertically through brine channels that form in the ice. The burn tests were considered a success as these burns were efficient and were able to remove the oil from the ice surface (summarized from Allen and Lukin, 1983a, 1983b, 1984 and MMS, 1984).

Figure A.9—Photographs of burns on ice. The image on the left shows a helitorch with gelled fuel used to ignite the test oil. The image on the right shows a test burn underway in open slot cut out of sea ice. Source: A. Allen.

A.3.3 Brunswick Naval Air Station, Brunswick, Maine, 1993

Spill Date: 26 March 1993

Oil Type: JP-5 aviation fuel

Spilled Volume: 1,512 bbl (63,500 gal)

Burned Volume: 500 bbl (21,000 gal)

Habitat: Freshwater pond and adjacent wetlands

Oil was spilled from a pipeline valve at a newly constructed tank farm. The oil was naturally contained in the pond by extensive ice and about 1 m of snow. Approximately two-thirds of the oil was recovered by vacuum trucks over a week’s time. The rest of the oil could not be accessed, so it was burned 8 days after the spill. The oil burned for 5 hours. Smaller burns were conducted over the next 2 days. Approximately 11 bbl of oil remained after the burn (98% burned). There was no burn residue, only unburned oil.

Studies of the vegetation, fish, birds, mammals, benthic community, water quality, and sediment quality were conducted the following summer. The results showed normal species abundance and distribution. Sediment samples showed elevated oil levels in a low flow area of a connected stream, but none in the burned areas (summarized from Eufemia, 1994).

Figure A.10—Photographs of the Brunswick Naval Air Station burn. Left: Burning of aviation fuel in open water areas. Right: Burning of oil in slots cut into the ice. Source: S. Lehmann, NOAA.

A.3.4 Svalbard Experimental Spill, Norway 2006

Research Date: March 2006

Oil Type: Statfjord crude oil (API gravity = 37.8)

Spilled Volume: 21.4 bbl (900 gal)

Burned Volume: 15.7 bbl (660 gal)

Habitat: Ice

The project was designed to study three topics: 1) test commercially available radar and acoustics systems in detecting oil spilled under ice; 2) document the weathering processes governing oil behavior in ice; and 3) evaluate the effectiveness of ISB as an oil removal strategy. Oil was injected under 60–70 cm of first-year ice and contained within an area of 100 m^2 (119.6 yd^2) by a skirt inserted through the ice. The burn occurred on 30 April, when the oil had surfaced into the melt pool. About 27% of the oil was lost to evaporation since first released. The burn lasted for 11 minutes. The oil thickness was 3.5 cm (1.3 in.) prior to the burn and 1 mm (0.04 in.) post-burn, so the burn rate was 3.1 mm/min (0.12 in./min) and the burn efficiency was 96%. The residue was easily recovered (summarized from Dickins et al., 2008).

A.3.5 Barents Sea Experimental Burns, Norway

Research Date: 2008 and 2009

Oil Type: Heidrun crude oil, fresh

Spilled Volume: 2008—5 bbl; 2009—4 bbl

Burned Volume: 96%; 5,280 liters (33 bbl or 1,400 gal)

Habitat: On water, very open pack ice

The objective of the program was to improve the capabilities of efficiently managing oil spills in ice-covered waters by improving knowledge about how oils behave and how they respond to traditional response technologies when there is ice present, as well as extending the operability of existing equipment. The ISB studies spanned a range of volumes and sites:

- Burning-cell studies to collect data to improve the SINTEF Oil Weathering Model, including ignitability based on oil properties and weathering patterns;
- Meso-scale studies [300–600 liters (79.2–158.5 gal)] were conducted in basins to characterize weathering patterns for five oil types (varying in asphaltene and wax content, as well as pour point) at three ice covers (0, 50, and 90%). The ignitability and burning effectiveness of weathered oils was measured.
    - In 90% ice cover, water uptake was lower due to reduced mixing energy, which extends the window of opportunity for burning. This trend did not occur for oils that formed very stable emulsions.
    - In 50% ice cover, the properties of emulsified oil became important; emulsions that were stabilized by waxes were more easily broken by heat and ignited over longer periods than oils with a higher asphaltene content which formed more stable emulsions; and
- Large-scale field studies [up to 2,000 liters (528 gal)] in the Barents Sea:
    - Testing of two fire booms demonstrated they could be towed and contain oil in low (trace to 3/10ths) of broken/drift ice cover. The collected oil was burned at 89–98% efficiency, with the lower rate under conditions with smaller ice pieces, more slush ice, and higher waves.
    - Testing showed that oil in very open pack ice that had spread too thin to burn could be thickened using a chemical herding agent, and then burned at 90% efficiency.
    - Burning of 525 bbl (83.5 m^3) of oil in ice 12 hours after release at 95% efficiency.

All of the publications for this program are available at: http://www/sintef/no/Projectweb/JIP-Oil-in-Ice/Publications/. ISB topics are covered in reports #5, 6, 19, 20, 26, 27, and 34.

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