
The Science, Technology, and Effects of Controlled Burning of Oil Spills at Sea

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LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS

Term	Abbreviation or Symbol
Alaska Clean Seas	ACS
Arctic and Marine Oilspill Program	AMOP
American Petroleum Institute	API
Benzene-toluene-ethylbenzene-xylene	BTEX
Benzo(a)pyrene	BaP
Captain of the Port	COTP
Conceptual site model	CSM
Defence Research Establishment at Valcartier	DREV
Equilibrium Flash Vaporization	EFV
Environmental Protection Agency (U.S.)	EPA
Environmental Protection Service (Canada)	EPS
Federal Aviation Administration	FAA
Food and Drug Administration	FDA
Federal On-Scene Coordinator	FOSC
Hazardous Waste Operations and Emergency Response	HAZWOPER
Hazard Index	HI
Hazard Quotient	HQ
Integrated Risk Information Systems (EPA)	IRIS
Minerals Management Service	MMS
Marine Safety Office	MSO
Marine Spill Response Corporation	MSRC
National Academy of Sciences	NAS
National Contingency Plan	NCP
National Institute of Standards and Technology (U.S.)	NIST
National Oceanic and Atmospheric Administration	NOAA
Newfoundland Offshore Burning Experiment	NOBE
National Research Council	NRC
National Response Team	NRT
Oil and Hazardous Material Simulated Test Tank	OHMSETT
Office of Hazardous Materials Transportation	OHMT
Oil Pollution Act	OPA
Occupational Safety and Health Administration	OSHA

Term	Abbreviation or Symbol
Oil Spill Intelligence Report . . . . .	.OSIR
Polynuclear (or polycyclic) aromatic hydrocarbons	PAHs
Polychlorinated biphenyls	PCBs
Particulate matter . . . . .	.PM
Regional Response Team . . . . .	.RRT
Reference Doses . . . . .	.RfDs
Slope Factors . . . . .	.SFs
State On-Scene Coordinator	SOSC
Scientific Support Coordinators . . . . .	.SSCS
Short-Term Exposure Limit . . . . .	.STEL
Total petroleum hydrocarbons . . . . .	.TPH
Threshold Limit Value . . . . .	.TLV
U.S. Coast Guard . . . . .	.USCG
Visual Flight Rules . . . . .	.VFR
Volatile organic compoundsVOCs
Volatile organic hydrocarbonsVOHs
Warren Spring LaboratoryWSL

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The Science, Technology, and Effects of Controlled Burning of Oil Spills at Sea

Abstract

The study serves to summarize and evaluate the state of knowledge in the area of in-situ burning as a countermeasures technique for oil spills at sea. All technological aspects of in-situ burning are covered in detail as are the potential impacts of the technique on the environment and on human health and safety. A literature review of relevant scientific studies and experiments is presented in terms of the key physical and chemical processes involved in in-situ burning and the factors that control the ignitability and combustibility of oil spills on water. The technologies available for in-situ burning, including igniters, fire-proof booms, floating burners, and additives such as ignition and burn promoters and smoke suppressors, are discussed and presented in terms of their historical development, technical specifications, and advantages and disadvantages. Operational considerations are presented for implementing an effective and safe burn of spilled oil at sea. Included are a checklist of critical items that must be considered before burning is attempted and a flowchart to work through the burn/no-burn decision. The study presents a literature review on the subject of human health and safety and a detailed risk evaluation of the acceptability of in-situ burning as an at-sea countermeasures technique. The evaluation describes the chief pathways by which humans could be exposed to the chemicals produced from an in-situ burn operation, identifies "chemicals of concern" and their concentrations for adverse health effects, and estimates the carcinogenic and non-carcinogenic risks associated with exposure to those chemicals. A similar analysis is conducted with respect to ecological risks. The analyses show that risks are generally low, although people between 1200 to 2500 m of the burn site could be exposed to concentrations of particulate matter in the smoke plume that exceed U.S. or state ambient air quality standards by a factor of about 2. Simulated "worst-case" exposure conditions for particulate matter in the smoke plume exceed air quality standards to a distance of 4.5 km to 5.0 km from the burn site. The study ends with recommendations for future work and a comprehensive bibliography on the subject.

1.0 Introduction

1.1 Objective

The objective of this study is to provide a comprehensive report on the role of burning technology as a response option for the control, removal and mitigation of major marine oil spills. All aspects of in-situ burning technology are addressed except the problem of oil spilled under or on a complete ice cover (e.g., winter spills in the arctic offshore) and burning or incineration techniques used for dealing with the products of a shoreline cleanup program.

The intent of the document is to assist users in (1) the preparation of contingency and implementation plans for combustion of spilled oil and (2) the application of this technology in the field. It is also to document and evaluate all knowledge and experience on the subject, to identify important missing information, and to recommend research to obtain the lacking information. The basic idea is to advance the practicality and safe employment of this promising spill-control technology.

1.2 Recent Interest in In-Situ Burning

In-situ burning is a countermeasures technique that has rarely been used on marine oil spills, but there is high interest in the method at this time. One reason for the interest is that in-situ burning compares favorably to the methods of physical recovery and dispersant-use, the two techniques in common usage today in most parts of the world. In North America chemical dispersants are seldom used, so physical recovery remains the main option for treating marine oil spills. However, mechanical recovery operations for large spills are acknowledged to be expensive, labor-intensive and complex. For example, each oil recovery system usually involves two or more ocean-going ships, thousands of meters of boom, large pumping equipment, temporary storage vessels, and transfer and disposal systems. Worse, recovery systems are slow in skimming oil because of intrinsic limitations related to skimmer-pumping rates and temporary-storage capacity.

The skimming time could be reduced by increasing the number of recovery and storage systems that respond to spills, but each complete recovery system, as stated, involves several ocean-going vessels, much heavy-duty equipment, and many highly trained responders, and there are severe cost limitations to having many such systems available on a stand-by basis, ready to reach spills within hours.

It is obvious, then, that any spill response method that encounters and removes surface oil more quickly than do skimming systems should be carefully evaluated. One such method may be chemical dispersion. Dispersants can be applied on surface slicks via aircraft spraying systems that fly at speeds up to 200 knots and that create a dispersant-spray swath of up to 50 meters. Physical recovery systems can operate with similar swath widths but are generally restricted to vessel speeds less than one knot (because of slick breakup and entrainment losses that occur beyond 1 knot). Therefore, dispersant systems can encounter or treat marine spills at rates that are many times greater than skimming systems. There are other operational advantages of dispersant-use over physical recovery, but there are also major roadblocks to the extensive use of dispersants in North America; these relate to concerns over the ecological consequences of using such chemicals and questions regarding the effectiveness of present-day products on weathered spills.

Considering the apparent shortcomings of existing spill response methods it is not surprising that there is great interest in the concept of in-situ burning. The technique is simple, is implemented quickly, and removes surface oil at a very high rate.

The method of in-situ burning is not new, having been researched and used for a variety of oil spills since the early 1970s. In general, the technique has proved effective for oil spills in ice conditions and has been used successfully to remove oil spills in ice-covered waters resulting from storage tank and ship accidents in Alaska, Canada and Scandinavia.

Although there have been numerous incidents of vessel oil spills that inadvertently caught fire, the intentional ignition of oil slicks on open water has only been seriously considered since the development of fire-proof oil containment boom beginning in the early 1980s.

Added interest in in-situ burning of spills on water has also developed as a result of research in the mid-1980s that suggested that large spills on water might be ignited via aerially-deployed igniters and successfully burned without the use of containment boom. The theory is that, if ignited soon enough, thick slicks of burning oil should remain thick enough for burning because of the herding action of the strong air currents drawn into the burning slick zone to feed the fire. If future research confirms this, it will dramatically increase the potential for in-situ burning as a practical response tool. This is because the method does not require the transportation of equipment and vessels to the spill site and the mechanical booming of the surface oil; both are slow processes that place severe limits on spill cleanup capability, as is the case for physical recovery techniques.

1.3 Incentives and Disincentives for In-Situ Burning

Incentives

There are several incentives for the use of in-situ burning as an oil spill countermeasures tool. (Details supporting the following statements are presented in subsequent chapters of the report.)

Simple Logistics: In-situ burning of thick, fresh slicks can be initiated very quickly by igniting the oil with devices as simple as an oil-soaked sorbent pad. The use of towed fire containment boom to capture, thicken and isolate a portion of a spill, followed by ignition is far less complex than the operations involved in recovery, transfer, storage, treatment and disposal. If the small quantities of residue from an efficient burn require collection, the viscous, taffy-like material can be collected and stored in open-top containers for further treatment and disposal.

High Elimination Rates: The burning rate of thick (1 cm or more), large (3-m diameter or more) slicks of relatively fresh oil has been measured to be in the range of 3 mm/minute. Thus, removal rates of 10,000 barrels/hr (1600 m³/hr) can be achieved with a fire area of only about 10,000 m² or a circle of about 100 m in diameter.

High Efficiency of Burn: The volume of oil eliminated depends on the original thickness of oil, which is commonly burned to a thickness ranging from 1 to 10 millimeters depending on the type of oil burning. Burning oil layers of about 100 millimeters or more can thus result in an efficiency of removal of 90 to 99 percent.

Versatility: In-situ burning can be used on fresh water or salt water; on lakes, streams, and oceans; onshore; or on wetlands/marshes with only a few centimeters of water. Burning can be used on calm water and in sea conditions approaching a Beaufort scale wind force of 4 to 5. The burning of spilled oil can be used under tropical and arctic conditions, and is particularly effective in ice conditions.

Cost: Based on comparable spill events and volume control rates, the cost of controlled burning is likely to be substantially less than that of physical recovery.

Disincentives

Despite the strong incentives for considering in-situ burning as a primary countermeasures method, there remains stiff resistance to the approach. There are two major concerns: first, the fear of causing secondary fires that threaten human life, property and natural resources; and, second, the potential environmental and human-health effects of the by-products of burning, primarily the smoke.

Flashback and Secondary Fires: If oil on water is at a temperature near or above its flash point, ignition of the oil will result in very rapid spreading of the flame. In cases where a large amount of volatile oil is spilled, a cloud of vapors can collect near the source in calm wind conditions and may represent a major explosion hazard. In such cases, care must be taken to isolate the portion of the slick to be burned from other areas of the slick.

It is understandable that tanker owners and personnel have serious reservations about in-situ burning of oil spills: fires are one of the greatest fears that exist in the tanker industry (and in the offshore oil and gas industry) and major training efforts are dedicated to fire prevention. To propose the use of fire near a tanker or offshore facility is inconceivable to many people in the maritime industry.

Combustion Byproducts: In-situ burning of oil slicks on water can be described as "starved combustion" in which not enough air (oxygen) is drawn into the fire to burn the fuel completely to carbon dioxide and water vapor. As a result, in-situ burning produces a large, dense, black plume of smoke rising from the fire. At low wind speeds and in stable atmospheric conditions the plume can rise several hundreds of meters into the air before levelling off. The plume is slowly dispersed by wind and is usually visible within a few kilometers of the burn site. Laboratory and field tests have indicated that the soot produced is about 5-15% of the mass of oil burned. The soot particles are generally composed of elemental carbon with about a 10% organic (or unburned hydrocarbon) content. Soot from very large burns can also contain unburned droplets of oil. One class of constituents of the soot that is of particular concern is polynuclear aromatic hydrocarbons (PAHs), certain of which have been documented to be carcinogenic.

1.4 Summary of Key Issues

The effect that smoke from burning oil spills might have on the environment and on human health is a great concern in the U.S. The concern is so great that even well-researched proposals for in-situ burning experiments in the field involving relatively small amounts of oil have been rejected by environmental regulators.

Proponents of burning believe that the method shows great promise as a primary response technique and that the environmental trade-offs (burning vs. unburned oil spills) strongly favor burning in many scenarios. They further believe that the most important issues

relate to operational feasibility, and that well-designed field trials are necessary to answer many of these operational questions.

Opponents of in-situ burning do not view the issue in terms of environmental trade-offs. They rather cite specific reasons for proceeding cautiously before accepting and approving the method. These are:

1. a perception of inadequate research and demonstration efforts on the feasibility of successful ignition and combustion of oils (especially weathered and emulsified oils) in open waters and in diverse climates;
2. a fear of the potential hazards of the fire and combustion products to human life, property and natural resources;
3. a lack of adequate information on the environmental and human health implications of the smoke and residue generated by in-situ burning; and
4. a general lack of logistical and systems planning for the use of burning in spill contingency plans.

This study serves to summarize and evaluate the state of knowledge in all of these areas and allows both proponents and opponents of in-situ oil spill burning to work with the facts as we know them today and make decisions that are based on hard data and not opinions.

1.5 Report Outline

This report documents and evaluates important information on the subject of oil spill in-situ burning. It also provides operational and research ideas for advancing the practicality and safe use of the technique.

The report begins in **Chapter 2** with a summary of the fate, behavior and effects of untreated oil spills on water. The dual purpose of the chapter is to explain aspects of spill behavior that affect the ignition of burning of slicks on water, and to provide baseline information on the environmental and human-health effects of untreated oil spills against which the effects of burning can be compared.

Chapter 3 follows with a brief chronological review of in-situ burning at both accidental and experimental spills. This is to provide some historical context to the studies and technologies that are reviewed in the following two chapters.

Chapter 4 presents a treatise on the science of in-situ oil burning, including a detailed literature review of all relevant scientific studies and experiments on the subject. Excluded are studies related to environmental and human-health issues, which are reserved for Chapters 7 and 8. All the key physical and chemical processes involved in in-situ burning are discussed as well as the factors that control the ignitability and combustibility of oil spills on water. Also discussed in detail is how various oil spill processes, such as water-in-oil emulsification, affect the ignition and burning processes.

The next chapter (**Chapter 5**) deals with the technologies available for in-situ burning, including igniters, fire proof booms, floating burners and additives such as ignition and burn promoters and smoke suppressors. The chapter not only presents a brief history, a detailed description, and tabular data on existing or recommended systems but also discusses disused

systems that, for one reason or another, are no longer available or recommended. These disused systems are included not only for completeness but also to help future researchers avoid “re-inventing the wheel” in attempting to develop different and better systems than are available today.

Chapter 6 focuses on operational considerations in planning and implementing an effective and safe burn of spilled oil at sea. A checklist is also presented of critical items that should be considered before burning is attempted.

Chapters 7 and 8 discuss and evaluate the important subject of the environmental and human-health effects associated with in-situ burning. **Chapter 7** begins the analysis with a literature review. The review is necessarily short because there have been no studies that have attempted to measure directly the ecological or human health effects from oil-on-water burns. However, recent experiments with small amounts of oil have determined the chemical composition and environmental fate of burn products, and the results of these studies are provided in Chapter 7.

The results of the latter experiments figure prominently in **Chapter 8** where a detailed risk evaluation is conducted of the acceptability of in-situ burning. The evaluation first describes the chief pathways by which humans could be exposed to the chemicals produced during in-situ burning of an oil spill, identifies the “chemicals of concern” and their exposure thresholds or dosages for adverse health effects, and estimates carcinogenic and noncarcinogenic risks associated with exposures to those chemicals. A similar analysis is conducted with respect to ecological risks. The chapter concludes with a discussion of the “acceptability” of in-situ burning.

Chapter 9 presents information on regional approval and permitting processes for oil spill burning, and **Chapter 10** presents a proposed decision-making flow chart including both feasibility and acceptability factors.

The final chapter (**Chapter 11**) presents recommendations for future work to advance the practicality and safe use of in-situ burning to control marine oil spills. The report ends with a comprehensive bibliography on the subject.

1.6 Scope and Limitations of Study

The scope of the study is large in that it attempts to document and evaluate virtually all knowledge and experience on the subject of in-situ burning of oil spills. There are several limitations to the study, however, and these are presented below.

- The subject of the report is in-situ burning of oil spills, that is, the burning of marine oil spills “in place” while they are on the water surface. The problem of burning oil on a stricken vessel or the use of combustion or incineration techniques to deal with recovered oil or materials collected in a shoreline cleanup operation is not dealt with.

- Not addressed in the report is the use of in-situ burning to deal with oil spilled on, in or under a complete ice cover, such as might occur in the arctic marine environment in winter. Oil spills in such ice conditions were not considered to be a problem within the geographic areas of responsibility of the sponsor of the study, Marine Spill Response Corporation (MSRC). Although the scientific and operational issues related to in-situ burning of oil in ice are not addressed as specific subjects in this report, the following should be noted: oil spill burning was first investigated seriously in the Arctic (Canadian and U.S. Beaufort Sea); there is a large body of literature on the subject; current technologies (for example, igniters, fire-proof booms and portable burners) were first developed for arctic use; and in-situ burning techniques have been incorporated for some time in industry contingency plans in the Arctic. It has thus been impossible to avoid mentioning arctic-related work in this study although references have been restricted to arctic work that has had some relevance to the burning of oil spills in primarily ice-free environments.
- The formal results of the important in-situ burning experiments that took place off Newfoundland in August, 1993, were not available at the time of writing. However, some results have been described in informal presentations and these are mentioned in this report. Regarding the smoke-analysis aspects of the experiments, indications are that the results differ little from earlier experiments (at Mobile, Alabama) upon which the human-health risk evaluation in Chapter 8 of this report is based. In any case, this report should be updated as necessary after the results of the Newfoundland experiments are made available formally.
- Attempts are made in the report (Chapter 6) to provide operational advice on the safe and effective use of in-situ burning systems at actual spills. This advice must be accepted with caution because it is not based on actual spill response experience. This is because the operational experience with controlled burning in open water conditions is extremely limited: the method has only been used once, and then only on a trial basis, at the *Exxon Valdez* spill in 1989. Some of the advice provided in Chapter 6 can be accepted with confidence because it is based on experience with conventional spill containment operations; other advice on the spill types and conditions that allow for ignition and burning should also be realistic because it is based on extensive experience with small burns in the laboratory and the field. One weakness, however, relates to advice on response tactics and the coordination of in-situ burning with other response methods. Much of this advice has been provided on the basis of common sense and general spill response experience, and not on actual experience with in-situ burning, and hence must be viewed with a certain degree of scepticism. This situation will improve as in-situ burning techniques are used with some regularity at real spills.

- Current interest in in-situ burning by U.S. state and federal government agencies is high, and new regulations, guidelines or positions are being developed at the time of writing this report. Therefore, the information in Chapter 9, Survey of Regulatory Issues and Regulations, which was assembled at the beginning stages of the project and modified only slightly later, should not be accepted necessarily to represent current views. Interested parties should consult local regulatory bodies for more up-to-date information.
- In addition, formal results of burning experiments which took place in Prudhoe Bay, Alaska in September 1994 and the effects workshop at the Center for Disease Control in Atlanta, Georgia were not available at the time of writing.
- The subject of safety of spill workers and safety regulations have not been specifically addressed in this document.

2.0 Fate, Behavior and Effects of Unburned Oil Spills on Water: The Baseline Case

2.1 Introduction

This chapter has two main functions. The first is to describe the fate and behavior of oil spills at sea with particular reference to factors that affect the ignition and burning of slicks on water. This will help readers understand subsequent chapters that discuss the theory and practicabilities of in-situ burning. For example, where following chapters indicate that in-situ burning effectiveness decreases dramatically as oil spills emulsify, this chapter explains (briefly) the phenomenon of emulsification and the factors that influence the process.

The other purpose of the chapter is to describe the various environmental and human-health effects of unburned oil spills. This will serve as a baseline against which effects of in-situ burning can be compared, as is done in Chapters 7 and 8.

2.2 Petroleum Oil Characteristics

The fate, behavior and effects of a marine oil spill are strongly influenced by the chemical composition of the oil being spilled. It is thus important to understand the characteristics of petroleum oils, especially crude oil itself because crude oil is the main target for an in-situ spill burning operation. Much of the following brief description of petroleum oils has been abstracted from National Research Council (1985).

2.2.1 Crude Oil

The chemical composition of crude oils from different producing regions, and even from within a particular formation, can vary tremendously. Crude oils contain thousands of different chemical compounds. Hydrocarbons are the most abundant compounds in crude oils, accounting for up to 98% of the total composition. While carbon (80-87% by weight) and hydrogen (10-15%) are the main elements in petroleum, sulfur (0-10%), nitrogen (0-1%), and oxygen (0-5%) are important minor constituents. Crude oils also contain widely varying concentrations of trace metals such as V, Ni, Fe, Al, Na, Ca, Cu, and U. Vanadium and nickel, the most abundant metal constituents, can reach thousands of parts per million.

Table 2.1 presents three examples of the composition of crude oils. Petroleum hydrocarbons consist of alkanes, cycloalkanes, and aromatic compounds containing at least one benzene ring. The alkanes, or aliphatic hydrocarbons, consist of the fully saturated normal alkanes (also called paraffins) and branch alkanes (iso- and cyclo-alkanes). Aromatic hydrocarbons, usually less abundant than the saturated hydrocarbons, contain one or more aromatic (benzene) rings connected as fused rings (e.g., naphthalene) or lined rings (e.g., biphenyl). The polycyclic aromatics with more than 3 rings consist mainly of pyrene, chrysene, benzanthracene, benzopyrene, benzofluorene, benzofluoranthene, and perylene structures.

Petroleum contains a significant fraction (0-20%) of compounds called asphaltenes which are of higher molecular weight (1,000 to 10,000), and which consist of both

Table 2.1 Chemical Composition of Three Crude Oils

Characteristics or Component	Prudhoe Bay	South Louisiana	Kuwait
API Gravity	27.8	34.5	31.4
Sulfur (wt %)	0.94	0.25	2.44
Nitrogen (wt %)	0.23	0.69	0.14
Nickel (ppm, mg/kg)	10	2.2	7.7
20-205° C Boiling Point Fraction (wt %)			
Alkanes	12.5	8.8	16.2
Cycloalkanes	7.4	7.7	4.1
Aromatic Hydrocarbons	3.2	2.1	2.4
Above 205° C Boiling Point Fraction (wt %)			
n-Alkanes (C11-C32 plus)	5.8	5.2	4.7
Isoalkanes	---	14.0	13.2
Cycloalkanes	28.5	37.7	16.2
Aromatic Hydrocarbons	25.0	16.5	21.9

1. Table does not include polar compounds and asphaltenes

Source: World Health Organization. 1989.

hydrocarbon and nitrogen-sulfur-oxygen compounds. In oil spill situations, asphaltenes contribute significantly to the oil's tendency to form water-in-oil emulsion. Specifically, asphaltenes, in association with similar but lower molecular weight compounds called resins, are surface active agents (surfactants) which promote emulsification when crystallized out of solution following evaporation of light hydrocarbons from an oil slick (Bobra 1990, 1991).

The physical characteristics of crude oils that take on importance from a spill perspective are summarized as follows:

Volatility: Crude oils contain a large proportion of light, volatile hydrocarbons (up to about C₁₁₋₁₂) which quickly evaporate once exposed to the open environment.

Insolubility: Generally, crude oil is insoluble in water and less dense than water; hence, it floats on water. Some compounds, such as low molecular weight alkanes and aromatics, are soluble in water, but only slightly.

Spreadability: The surface tension of crude oil is such that virtually all petroleum oils spread on the surface of water. Exceptions are highly viscous oils and oils whose "pour point" (described later) is higher than environmental temperature.

Tendency to Emulsify: As noted, most crude oils contain natural surfactants (asphaltenes, resins) in sufficient concentration to cause an oil spill to emulsify at some stage during its time on the water surface.

2.2.2 Refined Products

Refined petroleum products introduced to the marine environment include gasoline, kerosene, jet fuels, fuel oils (No. 2, No. 4, No. 5, No. 6), and lubricating oils. Generally, refined products are not targets for an in-situ burning program because spills of heavier fuel oils are very difficult to ignite and to sustain combustion, and slicks of the lighter products such as gasoline are usually left alone to volatilize quickly to extinction. Only spills of middle distillates, from kerosene to the lighter fuel oils, may be reasonable candidates for burning, especially because of their tendency not to form water-in-oil emulsion (they do not contain asphaltenes and resins which have been removed during the refining process).

2.3 Fate and Behavior of Oil Spills

When oil is spilled at sea it is subject to several so-called weathering processes described schematically in Figure 2.1. The major processes that influence slick ignition and burning are drifting (advection), spreading, evaporation, natural dispersion of oil in water, and water-in-oil emulsification. These and the additional processes of dissolution, photolysis, and sedimentation influence the environmental and/or human-health effects of spills.

2.3.1 Drifting

Drifting or advection is the process of surface slicks moving away from the site of a spill by water currents. These currents usually combine residual current movement and wind-induced surface movements (whose velocities are about 3.5 percent of the wind velocity [Mackay 1984]). In nearshore marine waters, the movement of oil slicks is also affected by tidal currents, river outflows and longshore currents.

The importance of the advection process insofar as in-situ burning is concerned is simply that the process influences the location of slicks as a function of time and thus determines whether the oil can be burned at a safe distance from the spill source (say, a partially loaded tanker) or from land where people, property or other resources may be at risk.

2.3.2 Oil Spreading

The most notable feature of any marine oil spill is the surface spreading phenomenon. Spreading is a key process for in-situ burning because the thickness of an oil spill at any given time is determined by the spreading rate (and size) of the spill, and the ignitability and burnability of an oil spill is strongly dependent on the thickness of the spill. The "rule of thumb" is that an oil slick must be greater than 1 mm thick for ignition and burning of fresh crude oil to occur.

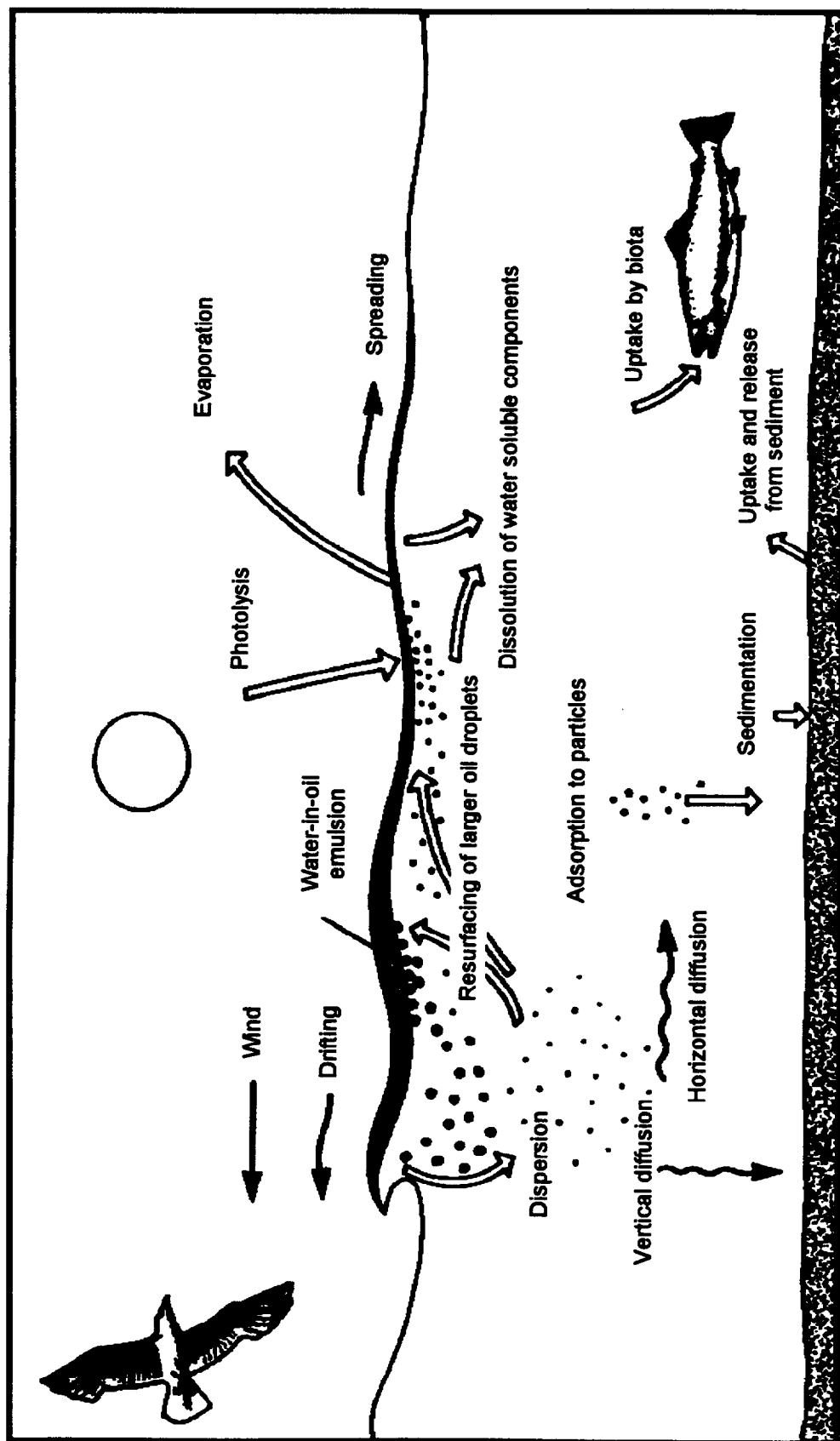


Figure 2.1 Oil spill processes (Source: IKU 1991)

Numerous models of oil spreading behavior and its dependence on oil properties and environmental conditions have been developed over the last three decades (e.g., Blokker 1964, Fay 1969, Mackay et al. 1980). All models relate the properties of the oil (density, viscosity and interfacial tension) to its spreading on calm water. Most models today also include an oceanic diffusion term to describe spreading behavior in more realistic sea conditions. In addition, the more recent models (e.g., S.L. Ross and D. Mackay 1988) use a modified version of the commonly-used Fay's equation (1969) that replaces water viscosity by oil viscosity. These models also take into account the influence of pour point in the spreading rate of the spill.

The generally fast rate of oil spreading is demonstrated in Figure 2.2, which is a version of a figure first developed in the late 1970s (Mackay *et al.* 1980) and used extensively in industry contingency plans in North America today. The figure can be used to show that for a spill of, say, 1000 m³ (6300 barrels) the total slick area reaches about 10 km² in one or two days of spreading, and this is equivalent to an average slick thickness of 0.1 mm. This might suggest that such spills cannot be ignited and burned because they are at least 10 times too thin (0.1 vs 1 mm) according to the above-mentioned rule-of-thumb.

The fact is, fortunately, that oil spills are now known to be comprised of thick patches (usually thicker than 1 mm) that contain most of the spill's volume (the rule-of-thumb is that 90 percent of an oil spill's volume is contained in 10 percent its area) and that these patches are surrounded by sheens (about 1 to 10 μ m or 0.001 to 0.01 mm). The areas noted in Figure 2.2 represent the total area of thick patches and sheen.

Although the phenomenon of thick/thin spreading is widely accepted today, and there is much remote sensing and photographic imagery to support the notion of slicks being comprised of thick and sheen portions, there is surprisingly little quantitative information available in the literature on the subject. Nonetheless, some very well documented actual and experimental spills have involved measurement of either thickness or volume/area (see Table 2.2) and these indeed show that oil spills at sea, even relatively small ones, do tend to stay relatively thick (> 1 mm) for reasonable periods of time. This is of great importance for in-situ burning of uncontained oil spills.

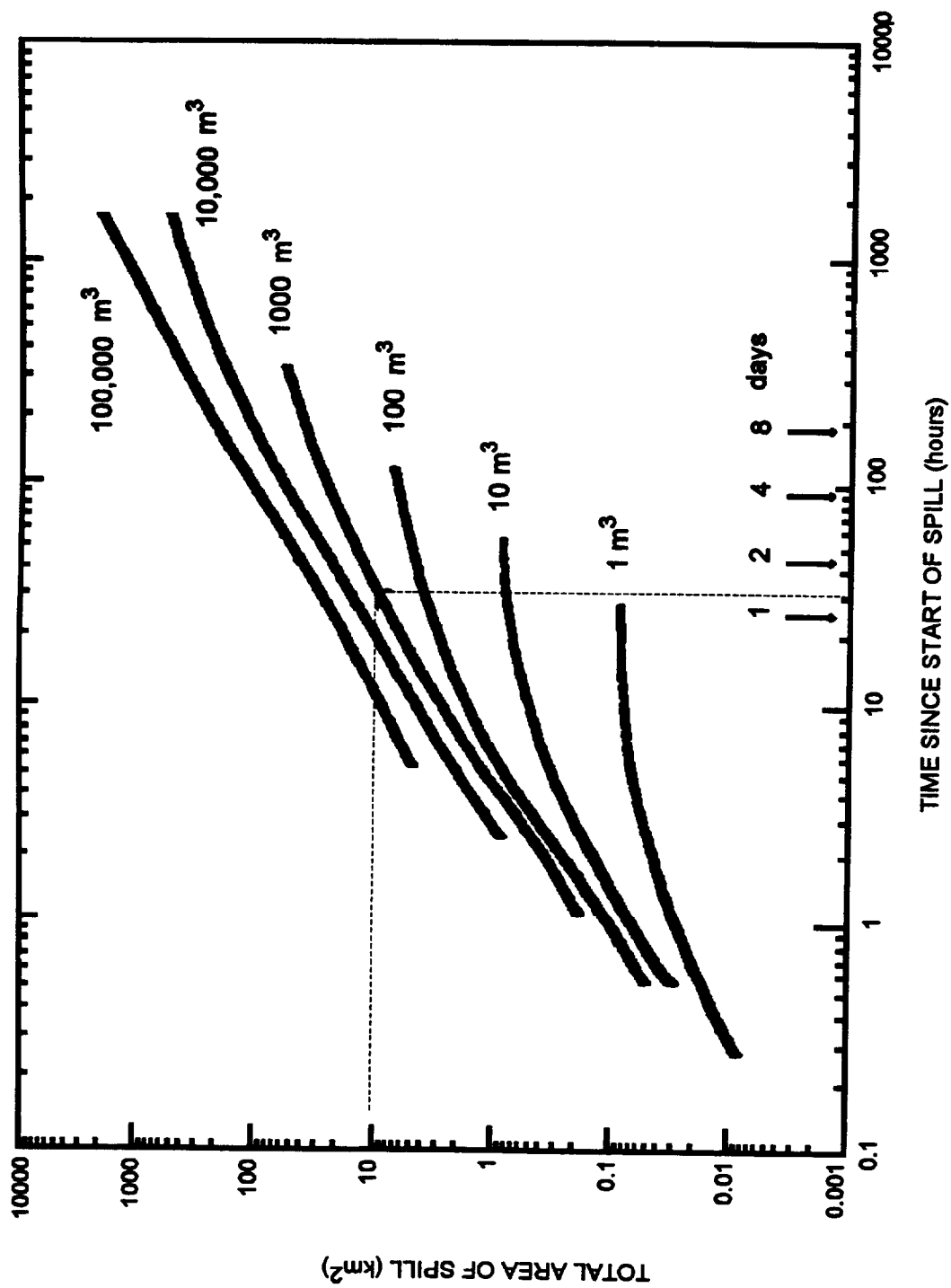


Figure 2.2 Total oil slick area vs. time (after MacKay et al. 1980)

Table 2.2 Thicknesses of Selected Crude Oil Spills

	Spill Volume (m ³)	Elapsed Time	Spill Area (m ²)			Thickness (mm)	
			Thick Portion	Thin Portion	Total	Thick Portion	Average
a. EXXON VALDEZ 1989	39700	7 hrs. 12 hrs.	- -	- -	2259400 2541800	- -	17.6 15.6
b. WSL, exptl. N. Atlantic, 1973	120	30 min. 1 hr.	- -	- -	146100 214600	- -	0.8 0.6
c. N. Sea, exptl., 1984	10	2 hrs.	4510	27690	32200	2.2	0.3
d. WSL, exptl. N. Atlantic 1992	12.5	1 hr. 2 hrs. 7 hrs.	880 2500 5000	92220 51300 93200	93100 53800 98200	13.2 4.8 2.3	0.1 0.2 0.1

REFERENCES

- a. The National Response Team 1989.
- b. Jeffrey 1973.
- c. Mackay and Chau 1986.
- d. Lunel and Lewis 1993.

2.3.3 Pour Point

The spreading relationships shown in Figure 2.2 do not apply to highly viscous oils and generally to oils that will not spread over the water surface. This category includes oils that have a pour point (i.e., the temperature below which the oil does not flow) that exceeds the ambient temperature. The pour point of an oil can be naturally high, or it may be increased by evaporative losses of some hydrocarbons during weathering.

It is not unusual for a crude oil to be relatively light (low density, high API gravity) and yet have an intrinsically high pour point. Spills of such oils are believed to be good candidates for in-situ burning because they cease to spread in the early stages of a spill, maintain a large thickness which is good for ignition and burning, and yet provide light components trapped in a rigid, waxy structure for easy and efficient combustion.

2.3.4 Evaporation

Evaporation is one of the most important processes that affect the properties and therefore the behavior of spilled oil. Because highly evaporated oils are difficult to ignite and burn it is important to have a good knowledge of evaporation rates and how evaporation affects the properties of the oil remaining on the surface.

Evaporation is one of the most intensively studied and predictable processes (Mackay 1984). It is known that the evaporation rate of an oil slick is controlled or affected by: (1) the temperature of the oil and the air; (2) the surface area of the oil in contact with air; (3) the thickness of the oil; (4) wind speed; and (5) the concentration and vapor pressure of the individual components of the oil. Although there have been many studies of oil evaporation rates, they have all followed a similar approach of determining an overall "mass transfer coefficient" as a function of environmental conditions (see for example, Nadeau and Mackay 1978 and Stiver and Mackay 1983). In these studies, the volume or mass fraction of oil evaporated is related to an exposure coefficient (combining time, oil volume and area, and the mass transfer coefficient to the atmosphere) and to the pressure-concentration behavior of the oil. The unique aspect of this approach is that it permits the results from a variety of laboratory evaporation experiments to be easily extrapolated to actual environmental conditions with a relatively high degree of confidence. Table 2.3 illustrates the results of this approach in predicting the evaporative loss from a 1 mm slick of crude oil as a function of sea state (Exxon 1983).

One potentially important route by which humans might be exposed to hydrocarbons during a spill would be via exposure to the plume of volatile hydrocarbons evaporating from a slick or from stranded oil. The low- to medium-molecular weight hydrocarbons evaporate from oil slicks rather quickly, as suggested in the above table. Once in the atmosphere, these hydrocarbons are transported by wind. Vapor concentrations in the gas plume are greatest near the spill site, but are lower at downwind locations through horizontal and vertical diffusion. Vapor concentrations at any point in the plume are a function of evaporation rate, wind speed and diffusion rates.

Table 2.3 Evaporative Oil Loss of Light and Medium Crude Oil Slicks as a Function of Sea State (after Nadeau and Mackay 1978)

SEA STATE	OIL LOSS (Percent)					
	Exposure Time = 6 h			Exposure Time = 24 h		
	5° C	15° C	25° C	5° C	15° C	25° C
LOW (0-1)	16	21	28	23	32	38
MEDIUM (2-3)	23	32	39	28	37	44
HIGH (4-6)	26	35	42	29	38	45

Assumptions: Slick Thickness = 1 mm
Oil Density = .836 g.cm⁻³

Evaporation rates and concentrations of hydrocarbon vapors over slicks are rarely measured during spills. However, as a worst-case scenario, the hydrocarbon concentrations of an airborne vapor plume were calculated in this study for a hypothetical large (8000 m³) tanker spill of condensate using a theoretical model based on work by Mackay *et al.* (1980). The results of this simulated spill scenario suggests that for a range of reasonable wind speeds (3 to 15 m/sec) and atmospheric conditions, the maximum total hydrocarbon concentrations in the plume 1000 m downwind from the slick would commonly range from 1000 to 10,000 ppm total hydrocarbons in air.

2.3.5 Emulsification

When most crude oils are spilled at sea, they tend to form water-in-oil emulsions (occasionally and improperly referred to as "mousse"). Emulsification occurs in the presence of mixing energy such as that provided by wave action. During emulsification, seawater is incorporated into the oil in the form of microscopic droplets. This water intake results in several undesirable changes to the oil. First, there is a significant increase in the bulk volume of the oil (usually up to a 4- or 5-fold increase), greatly increasing the amount of oily material that can contaminate shorelines and biological resources. Secondly, there is a marked increase in fluid viscosity. The much higher viscosities greatly inhibit the natural dispersion of oil. Of particular importance here is the fact that the presence of 50% to 85% water in the emulsion makes ignition and burning very difficult, if not impossible, without the use of special additives to break the emulsion and/or promote ignition.

The mechanisms and rates of oil emulsification are poorly understood. Through some mechanism, the mixing energy associated with waves causes small water droplets to become entrapped in the oil layer. It is likely (but not certain) that this process occurs in a manner similar to the natural dispersion of oil droplets into the water column, as both are mixing

phenomena that require wave action. The two processes are competitive. Emulsification tends to inhibit dispersion because the former increases oil viscosity, while the latter is negatively dependent on viscosity. Spills of some crude oils will start to form emulsion within a few minutes of environmental exposure, and to form a highly viscous and stable emulsion within hours. On the other hand, a few crude oils and most refined petroleum products do not emulsify. More research and testing is needed to determine emulsification rates more precisely.

2.3.6 Photo-oxidation

After a spill the surface oil is exposed to sunlight and is vulnerable to photo-oxidation. There is some evidence (Bobra 1992, Daling and Brandvik 1988) that the main effect of this from a spill behavior perspective is to make the oil more prone to water-in-oil emulsification. This happens because the photolysis leads to a strong increase in oxygen content at the expense of carbon content, resulting in the formation of additional surface-active components that promote emulsification tendency and stability.

2.3.7 Natural Dispersion and Dissolution

The dispersion and dissolution of oil into the water-column by natural forces is an important process controlling the long-term fate of oil slicks at sea. In conjunction with evaporation, this process reduces the volume of oil on the water surface, thereby influencing the potential extent of surface and shoreline contamination.

Dispersion and dissolution are physical processes by which oil and the more soluble lower molecular weight hydrocarbons move from the slick into the water-column. Oil droplets are dispersed from the slick into the water-column by surface currents and breaking waves. The larger of these droplets, which are buoyant, resurface quickly and rejoin the slick. The smaller droplets remain in suspension in the water-column. The lighter, more water-soluble hydrocarbons partition from these droplets into the water phase. Clouds of the entrained dissolved and particulate oils then spread horizontally and vertically by diffusion and other long range transport processes. Thus the oil concentrations in the water-column under the slick are the result of the competing processes of entrainment of oil into the water-column, which increases the concentration, and horizontal and vertical diffusion and transport of hydrocarbons which serves to decrease the oil concentration in the water-column.

Although natural dispersion is a poorly understood process, it is known that oil/water interfacial tension, oil viscosity, oil buoyancy and slick thickness each inversely affect the ability of a particular oil to disperse naturally. Sea state is also an important factor controlling the rate and amount of dispersion. Even light, non-viscous oils do not rapidly disperse under calm conditions. On the other hand, even the heaviest, emulsified oils can disperse over a period of time in heavy seas with frequent breaking waves.

The net flux rate of oil from a slick (small particles and dissolved hydrocarbons) into the water-column will vary greatly depending on the properties of the spilled oil and mixing energy (Delvigne 1985, 1987, Mackay *et al.* 1980), but simulations done for this study suggest that net entrainment rate of oil from a thick slick of Arabian medium crude oil into the water-column at average wind speeds (10 knots) would be of the order of 1 to 2 mg oil $\text{cm}^{-2} \text{hr}^{-1}$. In experimental spills, oil concentrations measured in the water beneath the slicks have ranged from several hundred ppb to as much as several ppm (McAuliffe *et al.* 1981,

Lichtenthaler and Daling 1985).

From the viewpoint of in-situ burning, natural dispersion is not a particularly key process except that oil is removed from the water surface that otherwise could be burned. One very likely problem with natural dispersion vis-a-vis burning is the phenomenon of "temporary dispersion". In this case, moderate-to-high sea states may break all or part of the surface slick into relatively large droplets and globules that are temporarily "dispersed" or submerged under the surface. This will indeed remove oil from the surface in terms of its availability for burning. Also, the heavy wave action might serve to splash water on and extinguish incipient fires.

2.3.8 Sedimentation

Some of the oil that becomes entrained into the water-column may become associated with suspended particulate matter which ultimately may settle to the seabed. The amount and concentrations of hydrocarbons that reach the seabed near a spill site appear to be a function of the amount of oil entrained into the water-column, the amount and nature of particulate matter suspended in the water-column, water depth, and the speed of subsurface water movements. Historically, seabed contamination has been observed in spills in shallower nearshore environments where suspended sediments loads are greater and settling times are less. In several historical spills that have occurred near to shore, levels of seabed contamination have been measured to be as great as several hundreds of ppm (S.L. Ross 1993). In deeper, offshore waters it is unlikely that significant levels of oil contamination would develop in seabed sediments near a spill site because of the low suspended sediment load and the long settling times due to the greater water depth.

Once seabed sediments have become contaminated with spilled oil, decontamination appears to require from several weeks to several years, with smaller lighter hydrocarbons being degraded more quickly than higher molecular weight molecules (S.L. Ross 1993).

2.4 Environmental and Human-Health Effects of Unburned Oil Spills

As discussed above, oil spilled on water forms a slick on the water's surface. With the passage of time, some oil evaporates into the atmosphere, some disperses into the water-column, and the rest spreads and moves on the sea surface and may ultimately strand on nearby shorelines. The overall environmental impact of a spill is a combination of the effects of the oil on the water surface, the oil on the shoreline, the oil entrained into the water-column and the hydrocarbons evaporated into the air.

In-situ burning removes surface oil by driving much of it into the atmosphere in the form of combustion gases and soot. In this way in-situ burning reduces the environmental threat posed by the oil slick, but only at the cost of increasing the environmental threat posed by the airborne plume. In both the burned and unburned cases, a weathered residue is left on the surface to pollute water-surface resources and shorelines. However, the amount of residual oil is much greater without burning, especially considering that most spills of crude emulsify quickly and increase in bulk several-fold if not burned or dispersed beforehand.

The problem for decision makers is to compare the effects of burning versus not-burning and choose the option that provides the greater net benefit to the environment.

The fate and effects of oil spills have been extensively reviewed in the past. The following are a few of the reviews: Clarke and MacLeod (1977); Jordan and Payne (1980); Lee (1980); Mackay (1981); National Research Council (NRC) (1985); Owens and Trudel (1985); Ross (1986); and S.L. Ross Environmental Research (1993). Most of the following text is based on these few reviews.

2.4.1 Environmental Effects

This is a brief summary of the potential effects of oil spills on living environmental resources and the exposure conditions causing these effects. The following are discussed in turn: 1) effects of oil slicks and oil stranded on shorelines; 2) effects of dispersed oil in the water-column and of sedimented oil; and 3) effects of the airborne plume of hydrocarbon vapor.

2.4.1.1 Oil Slicks and Oil Stranded on Shores

The most visible effects of oil spills are those caused by oil slicks at sea and oil stranded on shorelines. Slicks and stranded oil cause a variety of effects on natural resources and human-use environmental resources.

Oil slicks on the sea affect species that inhabit the sea surface or dive through the sea surface. These include marine birds, waders and marine mammals. Oil affects these animals either by physically disrupting the water-proofing of their plumage or pelage or through chemical toxicity to the organism if the oil is inhaled or ingested while preening. Effects are dose-dependent, although exposure or dosage may be difficult to quantify in some circumstances, and exposure thresholds may be difficult to determine precisely. Marine birds and certain mammals, such as sea otters, that for insulation depend solely on water-proof plumage or pelage, appear to be more sensitive to physical effects of oil than are mammals such as whales that rely on insulation properties of a thick layer of subcutaneous blubber. The degree of effects of any spill depend on spill size, oil persistence, and environmental conditions (winds) and the sensitivity and vulnerability of local resource populations.

In addition, oil slicks pose a significant risk to human activities such as commercial fishing and aquaculture. Slicks disrupt fishing activities by oiling fixed gear or by preventing fishermen from retrieving nets or catches through the oil-covered waters. As with the biological effects, the degree of impact depends on the sensitivity and vulnerability of the local fisheries, as well as on spill size, oil persistence, and environmental conditions.

Oil slicks generally dissipate quickly on the open sea, lasting only a matter of days or weeks, depending on the size of the spill, the type of oil spilled and the weather conditions. Recovery rates for resources affected by oil spills vary widely. The length of time required for populations of seabirds or marine mammals to recover from significant damage is long because of the low reproductive rates of these species. Disruptions of most marine fisheries by spills are short-lived, lasting only as long as the visible oil slicks are present.

Oil that becomes stranded on shorelines may have important and long-lasting effects on the natural biological communities and on the human-use potential of these shorelines. Biological resources may be affected by chemical toxicity or smothering. Oil affects the biological communities of all different shoreline types, but perhaps the most noteworthy effects are those involving vegetated shorelines such as marshes or mangroves. Spill effects are important here because the marshes and mangroves provide cover, substrate, and energy

for the biological communities that depend on them and, as a result, damage to plants may indirectly result in significant damage to other constituents of these communities. In addition, roots of shoreline vegetation provide stabilization of shoreline sediments, and loss of the plants and their root systems may lead to erosion of the shorelines and thus lead to longer-term consequences of spills. Effects on marsh plants and mangroves are dose dependent: light oiling may do limited damage causing only short-lived, sublethal effects, but heavy oiling or oiling with light oil with high aromatic content may cause death to mangrove trees and marsh plants and have long-lasting effects (years).

As with oil slicks at sea, effects of stranded oil depend on the level of oiling, the properties of the oil arriving at shorelines and the sensitivity of the shorelines. Persistence of the oil depends on the degree of exposure of the shore to wave action, oil type and the type of shoreline substrate. Recovery time for shoreline environments after the spilled oil has been removed may vary from months to many years depending on the nature of the community affected and the level of damage.

2.4.1.2 Water-Column and Seabed Effects

As described earlier, some oil from a slick becomes dispersed or dissolved in the water-column under the slick. Some of this entrained oil may ultimately associate with particulate matter and settle through the water-column to the seabed. Despite the vast number of laboratory studies that have found toxic effects of dispersed oil or oil-contaminated sediments, significant kills of fishes and other pelagic or benthic species have rarely been found at actual spills, even extremely large ones. Similarly, extensive contamination of seabed sediments and damage to seabed communities are uncommon phenomena during spills.

Although rare, extensive fish kills have nevertheless been observed during some oil spills. Fish kills or wide-spread sublethal effects have been observed in spills that have caused high levels of hydrocarbons in the upper water-column, such as very large spills or spills of lighter, higher-aromatic-content oil occurring in shallow or confined nearshore waters. For example a nearshore spill of a large quantity of No. 2 fuel oil (from the Barge *Florida*; Saunders *et al.* 1972), and a similar spill involving a mixture of fuels including aviation fuel (Gooding 1971) both resulted in extensive fish mortality. In most spills, however, major fish kills are not observed.

In offshore waters or open coastal waters under average wind conditions (8-15 knots), oil generally disperses into the water-column only slowly. This fact coupled with the fact that dispersed oil diffuses horizontally and vertically very quickly means that oil concentrations even in the upper 1 m of the water-column under an oil slick seldom exceed several hundred parts per billion or a few parts of total oil per million parts of water. This concentration is below the toxic threshold for most significant acute effects on marine organisms. Thus the threats to fish and other pelagic species from entrained oil is minor in most cases. In cases where fish populations are damaged because of exposure to high levels of hydrocarbons, recovery might require only a few years or less because the reproductive potential of fish is high.

Extensive seabed contamination was observed following the *Amoco Cadiz* oil spill with extensive evidence of sublethal effects on finfish and shellfish. More recently, contamination and sublethal effects on finfish were observed following the *Exxon Valdez* spill. In general, the risks to benthic communities from oil settling to the seabed are limited because: 1) oil is entrained into the seabed only very slowly; 2) only a portion of the

entrained oil becomes associated with large particles that will actually sink; and 3) sinking rates of suspended particles are very slow relative to the rates of spreading and diffusion. As a result, although some spilled oil may ultimately reach the seabed through sedimentation, offshore spills are unlikely to result in extensive local contamination of the seabed to a level (concentration) necessary to cause effects to benthic infauna and epifauna. On the other hand, when seabed sediments do indeed become heavily contaminated with hydrocarbons from spilled oil, contamination can be long-lasting, with some hydrocarbons persisting in measurable amounts in sediments for several years. However, once hydrocarbon concentrations return to background levels, benthic communities appear to recover as quickly as pelagic communities.

2.4.1.3 Airborne Oil and Hydrocarbons

As mentioned above, a considerable proportion of spilled hydrocarbons can be lost from a slick into the atmosphere through evaporation. Evaporating hydrocarbons form an invisible plume originating over the slick and setting downwind. However, no record exists of significant environmental effects having been caused by plumes of hydrocarbon fumes.

2.4.2 Human Health and Safety

There has been some concern in recent years about the human health implications of marine oil spills. This concern is founded in part on the known toxicity of hydrocarbons to humans (NRC 1985) and in part on reports of symptoms of acute hydrocarbon poisoning among individuals in the vicinity of spills. The present section summarizes the human health aspects of major oil spills as well as the safety aspects.

2.4.2.1 Oil Slicks and Oil Stranded on Shorelines

Oil slicks and oil stranded on shorelines pose a threat to human health through the potential for fire and through chemical toxicity resulting from dermal contact with oil. The risk of accidental fire is significant only in spills of lighter oils during the early stages of the spill while the oil is thick and fresh and will support combustion. The adverse effects of dermal contact with oil are well known; for example, in small animal studies prolonged dermal exposure to crude and refined products has resulted in dermal irritation, but with certain oils has led to dermal necrosis and systemic effects (NRC 1985). In historical spills, response workers have reported skin effects from dermal contact; for example, during the *Amoco Cadiz* spill, response workers reported skin irritation resulting from direct skin contact with oil (Menez *et al.* 1978). However, there have been no reports of systemic toxic effects or skin necrosis among spill response workers that can be attributed to skin contact with oil.

In view of the obviously limited risk to spill workers from direct dermal contact with oil, it is reasonable to assume that local residents would be at even less risk of toxic effects resulting from incidental contact with oil at sea or on shorelines.

2.4.2.2 Dissolved/Dispersed and Sedimented Oil

As discussed above, oil that becomes entrained into the water-column may occur in the form of dissolved hydrocarbons, dispersed oil droplets, or oil-contaminated seabed sediments. Humans might be exposed to this oil via two routes. The oil might be ingested directly if the contaminated waters are used for human consumption. More commonly, however, the oil poses a threat if the contaminated waters support stocks of fish, shellfish, or aquatic plants that are exploited for human consumption.

The threat to drinking water supplies is of concern in spills into fresh waters or in marine spills when seawater intakes for desalination plants are threatened (e.g., Ecopetrol pipeline spill, Columbia. Anonymous 1993). In either case, the potential for significant exposure to humans is difficult to assess since in most cases the threatened waters are processed prior to consumption. Threats are generally short-lived except in the case of very large spills, with extensive shoreline contamination such as the 1991 Arabian Gulf spill.

The contamination of exploited fish stocks with spilled hydrocarbons has been common in the past (Tidmarsh *et al.* 1986). Fish and shellfish may become contaminated via water-borne hydrocarbons or through hydrocarbon-contaminated seabed sediments. Aquatic organisms accumulate a broad spectrum of hydrocarbons and, although all hydrocarbons have potential health implications, the group of particular concern historically has been the polynuclear aromatic hydrocarbons (PAHs) some of which have been shown to be carcinogenic (e.g., benzo[a]pyrene) (NRC 1983).

Contamination of edible tissues of finfish and shellfish is a common consequence of spills. Contamination of offshore pelagic species by water-borne hydrocarbons appears to be far less important than that of benthic species contaminated via sediments in shallow, nearshore environments because the former phenomenon would be very short-lived, while the latter may persist for months or years, as long as significant levels of contaminants persist in the sediments. Contamination of certain invertebrates, such as bivalve molluscs, is regarded as being of greater significance than that of finfish because finfish are capable of rapidly metabolizing accumulated PAHs while bivalves lack this capability.

Unfortunately, the human health implications of contamination of edible fish with PAHs is difficult to assess because, as pointed out by Walker and Field (1993), as of the date of the *Exxon Valdez* oil spill in 1989, no guidelines for the human-health implications of PAH-contaminated fish were available. There apparently are still no safety standards for the levels of oil-derived PAH-contaminants in seafoods. However, as reported in Walker and Field (1993), in the case of the *Exxon Valdez* spill, a government panel concluded that the risks associated with consumption of finfish and shellfish contaminated with spill-related hydrocarbons were low.

2.4.2.3 Airborne Hydrocarbon Plume

In recent years concerns have been expressed about the potential human health effects of air-borne plumes of hydrocarbons generated by oil spills. Plumes are most commonly composed of hydrocarbon vapors, but under unique circumstances they may also contain concentrations of airborne oil droplets. Workers or local residents would be exposed to these airborne hydrocarbons primarily via inhalation or ingestion.

Historically, there are few documented cases of health effects caused by hydrocarbon vapor clouds generated by spills. Only one partially documented case of possible petroleum

intoxication is described in the literature involving the *Amoco Cadiz* spill. During the course of the spill, cleanup workers and local residents exhibited symptoms characteristic of hydrocarbon poisoning. Victims suffered prolonged exposure to clouds of hydrocarbon vapor that enveloped the coast of Brittany, as well as to clouds of airborne oil droplets caused by high pressure water washing of oiled shorelines. Some victims exhibited gross symptoms of hydrocarbon poisoning including dizziness, nausea, and abdominal pains, but clinical tests suggested that none had suffered systemic effects (Menez *et al.* 1978, cited in NAS 1985). Regrettably, there does not appear to be any systematically gathered data concerning the hydrocarbon exposure conditions of these workers or residents during this spill.

More recently during the *Braer* spill in the Shetland Islands in January, 1993, there was sufficient concern among the regional medical community for the health of the local inhabitants that a number of local residents were examined for indications of hydrocarbon toxicity. The results of these tests have yet to be published (Campbell 1993, Christie 1993).

The effects of acute and chronic exposure to hydrocarbon vapors by inhalation have long been recognized. Experimental studies have established that relatively brief exposures (30-60 minutes) to gasoline vapors produce eye, nose and throat irritation at concentrations of 500-1000 ppm; headache and numbness at slightly higher concentrations; and deep anaesthesia at 10,000 ppm (Poklis and Burkett 1977). Regulatory standards have been established for short-term and chronic exposure to hydrocarbon vapors and mists in the workplace. For example, the Threshold Limit Value for gasoline vapors is 375 ppm for brief exposures and 300 ppm for prolonged exposures (Table 2.4).

Unfortunately, there has been little documentation of the atmospheric hydrocarbon concentrations during major historical spills and those that have been identified are of little value for the present purposes (Dowty *et al.* 1981, Martec Ltd. 1984). As discussed above, in a simulated spill scenario, hydrocarbon concentrations in the vapor plume 1000 m downwind of a slick from a 8000 m³ spill of highly volatile condensate was estimated to be from 1000 to 10,000 ppm total hydrocarbons at ground level. Obviously, for smaller spills in-plume hydrocarbon concentrations would be considerably lower, but this worst-case analysis suggests that for large spills of lighter crudes and refined products, human health considerations might be significant. This subject merits further consideration.

In short, the toxic potential of petroleum hydrocarbon vapors is well-recognized. Toxic thresholds have been determined and industrial exposure standards have been established for vapors from a variety of petroleum hydrocarbon products. There are indications from accounts of actual spills that acute petroleum intoxication from airborne plumes may have occurred during historical spills. Unfortunately, there are few data available from these cases concerning concentrations of hydrocarbon vapors in the atmosphere over or around actual oil slicks. There are data from computer simulated spill scenarios that suggest that concentrations of vapors in airborne hydrocarbon plumes from condensate spills may exceed at least the industrial standards for maximum average for chronic exposure to gasoline vapors.

Table 2.4 Workplace Exposure Standards for Vapors of Oil and Petroleum-Derived Hydrocarbons (American Conference of Government Industrial Hygienists, 1993)

Contaminant	TLV ¹	STEL ²
Oil mist, mineral	5 mg/m ³	10 mg/m ³
Oil mist, mineral, severely refined	5 mg/m ³	No standard
Oil mist, mineral, mildly refined ³	0.2 mg/m ³	No standard
Gasoline	890 mg/m ³ (300 ppm)	1480 mg/m ³ (500 ppm)
Asphalt (petroleum fumes)	5 mg/m ³	No standard

Hydrocarbon Compounds

Benzene	32 mg/m ³ (10 ppm)	No standard
Napthalene	52 mg/m ³ (10 ppm)	79 mg/m ³ (15 ppm)
N-Hexane	176 mg/m ³ (50 ppm)	No standard
Ethylbenzene	434 mg/m ³ (100 ppm)	543 mg/m ³ (125 ppm)
Cyclohexane	1030 mg/m ³ (300 ppm)	No standard
Butane	1900 mg/m ³ (800 ppm)	No standard
Xylenes	434 mg/m ³ (100 ppm)	651 mg/m ³ (150 ppm)

- 1 Threshold Limit Value. Registered trademark by American Conference of Government Industrial Hygienists. Maximum average continuous exposure to chemical for 8-hour day, 5 days per week as in the workplace.
- 2 Short-Term Exposure Limit. Similar to TLV except that it is the maximum concentration for continuous exposure for up to 15 minutes no more than four times per day with minimum of one hour between exposures.
- 3 Oil mist, mineral, mildly refined, as cyclohexane-soluble particles containing PAHs.

2.4.3 Summary

The purpose of this review has been to summarize the more significant effects of oil spills under conditions of conventional response. This has been done in order to provide a baseline of environmental and human-health effects against which potential effects of in-situ burning could be compared.

Spills appear to pose a greater risk to living environmental resources than to human health and safety. The level of effects vary greatly from spill to spill depending on the volume and type of oil spilled and the circumstances of the spill. However, given a moderate-sized batch spill of medium crude oil in coastal zone waters under average summer weather conditions for the continental U.S., the following generalities hold for environmental effects of spills.

1. Untreated oil spills pose a threat to organisms that inhabit the sea surface, intertidal zone, and to a lesser extent the seabed and water-column in shallow nearshore waters. Spills also pose a risk to human activities such as fishing that depend on resource in these areas.
2. The greatest environmental damage results from the contact of wildlife (birds and mammals) by oil slicks and of habitat resources (marshes, mangroves) by oil stranded on shorelines.
3. Oil that becomes entrained into the water column poses only a moderate threat to natural resources because, in general, concentrations of oil in the water-column are low and very short-lived. On the other hand, significant mortalities to fishes have been reported under unique circumstances in which large volumes of lighter oils have been spilled in shallow nearshore areas or in confined areas with limited dilution potential.
4. Contamination of seabed sediments with the associated risks to benthic resources is rare in offshore spills, but in cases involving large, nearshore spills such as the *Amoco Cadiz*, significant levels of benthic contamination have resulted. In the *Amoco Cadiz* case, extensive contamination and biological damage did occur to populations of living benthic resources that persisted for months to years.
5. There is no recorded evidence of significant environmental effects caused by plumes of volatile gases generated by oil slicks. However, under unique circumstances, oil has been transported in the form of droplets (aerosols) and deposited on or ingested by terrestrial wildlife and domestic livestock.

Although the toxic potential of oil and petroleum hydrocarbons to humans is well documented, there are very few cases in which significant health or safety problems have resulted from spills. During spills, the groups at greatest risk from the spilled oil include the cleanup workers and the local residents. Their health risks from the spills are as follows.

1. Under all but exceptional circumstances, oil slicks or oil stranded on shorelines pose little health/safety risk except when the oil poses a significant fire risk within the first few hours immediately following the spill.
2. Historical evidence suggests that humans can suffer adverse effects from exposure to the airborne plumes of hydrocarbon vapors generated by oil slicks. Both cleanup workers and local residents might be at some risk of sublethal effects (nausea, dizziness) from the air-borne plume of volatile gases (and in certain circumstances airborne oil droplets) generated by a large slick, or a vapor cloud caused by high pressure

water or steam jets used to clean oil from shorelines.

3. The oil that becomes entrained into the water-column probably poses little threat to human health. However, in larger nearshore spills appreciable amounts of oil may accumulate in the sediments where they in turn pose a threat to contaminate exploited fishing resources for months or years following a spill. These may pose a health risk to humans ingesting the fishery products, but these risks are difficult to evaluate due to the lack of health standards for ingestion of hydrocarbon-contaminated food products.

2.5 References to Chapter 2

- American Conference of Government Industrial Hygienists. 1993. 1993-94 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Limits. American Conference of Government Industrial Hygienists, Cincinnati, OH. 124 pp.
- Anonymous. 1993. Columbian spill threatens water supply. Oil Spill Intelligence Report, XVI (34) pp. 4.
- Blokke, P.C. 1964. Spreading and evaporation of petroleum on water. Proceedings of the 4th International Harbour Conference, Antwerp, Belgium.
- Bobra, M. 1990. A Study of the formation of water-in-oil emulsions. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 87-117.
- Bobra, M. 1991. Water-in-oil Emulsification: A Physicochemical Study. Proceedings of the 1991 International Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 483-488.
- Bobra, M. 1992. Photolysis of Petroleum. Environment Canada Environmental Emergencies publication EE-131, Ottawa, Ontario K1A 0H3.
- Campbell, D.M. 1993. Shetland oil spill. Br. Med. J. 306:519.
- Christie, B. 1993. Shetland Oil spill prompts health checks on islanders. Br. Med. J. 306:230.
- Clark, R.C. and W.D. MacLeod. 1977. Impacts, transport mechanisms and observed concentration of petroleum in the marine environment. In D.C. Malins (ed). Effects of petroleum on arctic and subarctic marine environments and organisms. Vol. 1. Nature and fate of petroleum. Academic Press, Inc. New York, N.Y., pp. 91-223.
- Daling, P.S. and P.J. Brandvik. 1988. "A study of the formation and stability of water-in-oil emulsions". Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 153-170.
- Delvigne, G.A.L. 1985. Experiments on natural and chemical dispersion of oil in laboratory and field circumstances. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C.
- Delvigne, G.A.L. 1987. Droplet size distribution of naturally dispersed oil. In Kuiper, J. and W.J. Van den Brink (eds). Fate and Effects of Oil in Marine Ecosystems. Martinus Nijhoff Publ., Dordrecht, Netherlands, pp. 29-40.

- Dowty, B.J., J.W. Brown, F.N. Stone, J. Lake, and J.L. Lasetar. 1981. GC-MS analysis of volatile organics from atmospheres impacted by the *Amoco Cadiz* oil spill. In *Amoco Cadiz: Fates and Effects of the Oil Spill*. Proc. Int. Symp., Centre Oceanog. de Bretagne, Brest, France, 19-22 November 1979. Centre Nationale Pour Exploitation des Oceans. Paris, pp. 13-22.
- Exxon. 1983. Oil Spill Cleanup Manual; Volume II. Exxon Corporation.
- Gooding, R.M. 1971. Oil pollution on Wake Island from the Tankers R.C. Stones NOAA/NMF's Spec. Sci. Rep. (Fish): 636:12 pp.
- IKU (Institutt for kontinentalsokkelundersøkelser og petroleumsteknologi A/S). 1991. Characterization and prediction of the weathering properties of oils at sea — a manual for the oils investigated in the DIWO Project. DIWO-report no. 16.
- Jeffrey, P.G. 1973. Large-scale experiments on the spreading of oil at sea and its disappearance by natural factors. Proceedings of the 1973 Conference on Prevention and Control of Oil Spills, March 13-15, Washington, D.C. American Petroleum Institute, Washington, D.C. pp.469-474.
- Jordan, R.E. and J.R. Payne. 1980. Fate and weathering of petroleum spills in the marine environment. Ann Arbor Science Publ. Ann Arbor, MN.
- Lee, R.F. 1980. Processes affecting the fate of oil in the sea. In Geyer, R.A. (ed). *Marine Environmental Pollution 1 Hydrocarbons*. Elsevier. New York, N.Y., pp.337-351.
- Lichtenthaler, R.G. and P.S. Daling. 1985. Aerial application of dispersants — comparison of slick behavior of chemically treated vs non-treated slicks. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp.471-478.

- Lunel, T. and A. Lewis. 1993. Oil concentrations below a demulsifier treated slick. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp.955-972.
- Mackay, D., I.A. Buist, R. Mascarenhas, and S. Paterson. 1980. Oil spill processes and models. Department of Chemical Engineering, University of Toronto, Toronto, Ontario, Environmental Protection Service Publication No. EE-8.
- Mackay, D. 1981. Fate and behavior of oil spills. In J.B. Sprague *et al.* (eds). Oil and dispersants in Canadian seas. Environmental Protection Services, Ottawa, Canada., p.7-27.
- Mackay, D. 1984. The fate and behaviour of oil in cold climates. Department of Chemical Engineering and Applied Chemistry. Report to Environment Canada, Ottawa.
- Mackay, D. and A. Chau. 1986. The effectiveness of chemical dispersants: a discussion of laboratory and field test results. DOOS — seminar, November 10-12, 1986. Trondheim, Norway.
- Martec Ltd. 1984. Report on the environmental program associated with the blowout at Shell *et al.* Uniacke G-72. Unpublished report prepared for Shell Resources Canada Ltd., Dartmouth, Nova Scotia, Canada.
- McAuliffe, C.D., D.E. Fitzgerald, B.L. Steelman, J.P. Ray, W.R. Leek, and C.D. Barker. 1981. The 1979 southern California dispersant treated research oil spills. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp.269-282.
- Menez, J.R., F. Berthou, D. Picart, and C. Richie. 1978. Impacts of the oil spill (*Amoco Cadiz*) on human biology. Penn. Ar. Bed. 94:367-378.
- Nadeau, J.S. and D. Mackay. 1978. Evaporation rates of complex hydrocarbon mixtures under environmental conditions. Spill Technology Newsletter, Canadian Environmental Protection Service, Volume 3(2). p.42-55.
- National Research Council (U.S.). 1985. Oil in the Sea: Impacts, fate and effects. National Academy Press, Washington, D.C., 601 pp.
- National Research Council of Canada. 1983. Polycyclic aromatic hydrocarbons in the aquatic environment: Formation, sources fate and effects on aquatic biota. Associate Committee on Scientific Criteria for Environmental Quality, NRCC No. 18981, National Research Council of Canada, Ottawa, Canada.
- The National Response Team. 1989. The *Exxon Valdez* oil spill. A report to the President [United States] from S.K. Skinner, Secretary, Department of Transportation, and W.V. Reilly, Administrator, Environmental Protection Agency, 37 pp.

- Owens, E.H. and K. Trudel. 1985. Oil spill countermeasures for low-energy shorelines in Canada. Environment Canada, Report EE-73.
- Poklis, A. and C.D. Burkett. 1977. Gasoline sniffing: a review. *Clinical Toxicol.* II(1):35-41.
- Ross, S.L. 1985. An overview of physical and chemical processes in open water. In Duval, W.S. (ed). A review of the biological fate and effects of oil in cold marine environments. Unpubl. Rep. by ESL Environmental Sciences limited, S.L. Ross Environmental Research Ltd., and Arctic Laboratories Limited for Canada, Environmental Protection Service, Edmonton., pp.5-12.
- Saunders, H.L., J.F. Grassle and G.R. Hampson. 1972. The West Falmouth Oil Spill. I. Biology. Tech Rep. Woods Hole Oceanogr. Inst. (72-80): 48 pp.
- S.L. Ross Environmental Research Limited and D. Mackay Environmental Research Limited. 1988a. Laboratory studies of the behavior and fate of waxy crude oil spills. Environmental Studies Research Funds, Report 084, Ottawa.
- S.L. Ross Environmental Research Ltd. 1993. The risk of tainting in flatfish stocks during offshore oil spills. Environment Studies Research Funds Report No. 121. Calgary, 48 pp.
- Tidmarsh, W.G., R. Ernst, R. Ackman, and T. Farquharson. 1986. Tainting of fishery resources. Environmental Studies Research Funds No. 021.
- Walker, A.H. and L.J. Field. 1991. Subsistence fisheries and the *Exxon Valdez*: Human health concerns. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp.441-446.
- World Health Organization (WHO). 1989. IARC monographs on the evaluation of carcinogenic risks to humans. Occupational exposures in petroleum refining: Crude oil and major petroleum fuels. International Agency for Research on Cancer. Vol. 45. Lyon, France.

3.0 Chronology of In-Situ Burning at Experimental and Accidental Spills

3.1 Introduction

This chapter presents a chronology of the use of in-situ burning techniques at experimental and accidental spills. The purpose is to provide some historical context to the technological developments that have been made in the area. Although an ad-hoc approach was used in the past on actual spills, various promising results were achieved despite the lack of planning, and these results encouraged the R&D activity that led to the in-situ burning technologies that exist today.

The following historical review is intentionally brief; more detailed information on the various chemicals, equipment and techniques that have been used at both experimental and actual spills is presented in Chapter 5. The review begins with the presentation of a table that lists all relevant spills in chronological order, and then follows with a brief history of only the accidental spills. The experimental spills are discussed in detail in either Chapter 4 or Chapter 5.

3.2 Spills Involving In-Situ Burning

Table 3.1 lists the 40 or so spills that have provided the base of our knowledge on oil spill in-situ burning. Most detailed information has been derived from laboratory tests and the mesoscale tests noted in the table. Of the actual spills listed, only nine included the purposeful burning of oil on water, as opposed to oil accidentally burning.

3.3 Chronological History of Burning at Accidental Spills

The first recorded use of in-situ burning as a spill countermeasures technique was to remove oil spilled from a pipeline in the Mackenzie River at Norman Wells, N.W.T. in 1958. The oil was boomed with logs and successfully burned off (McLeod and McLeod 1972).

The next recorded use of in-situ burning was in response to the *Torrey Canyon* grounding in March 1967 off Lands End, U.K. The vessel's entire cargo of 100,000 tons of Kuwait crude was lost (Wardley-Smith 1971). After salvage operations failed, attempts were made to burn the oil in the vessel, on the sea and on beaches. Aerial bombardment was used to ignite and burn oil in the tanker and on the sea. Swift *et al.* (1968) report that over a three-day operation some 73,000 kg of high explosives, 45,000 L of aviation kerosene and 14,000 L of napalm were dropped on the ship to set the cargo afire. Estimates (Swift *et al.* 1968) place the amounts of oil burned in the ship as high as 40,000 to 50,000 tons.

Four attempts were made to ignite seemingly thick oil slicks on the sea near the *Torrey Canyon* using pyrotechnic devices containing sodium chlorate (Swift *et al.* 1968; Anonymous 1967) but these attempts were unsuccessful. It was concluded that, after the Kuwait crude had been on the water surface for only 40 minutes, wave action had emulsified it to such an extent that it would not ignite (Anonymous 1967).

Table 3.1 Summary of In-Situ Burning: Tests and Use on Spills*

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
1958	Pipeline spill in Mackenzie River	Spill was boomed with logs and burned.	Crude	Burn was successful
1967	Tanker accident (Torrey Canyon)	Attempts were made to burn oil on water with bombs, napalm and other materials.	100,000 tonnes of crude	40,000 to 50,000 tonnes of oil burned on ship.
1969	Holland	Series of experiments. Igniter Kontax tested.	Crude	Proved the possibility of burning slicks.
1969	Cargo ship <i>Eiwa</i> sank releasing oil in Gulf of Finland	Oil burned on shores and bays using paraffinic oil as primer.	15 tonnes of diesel fuel.	Burn was reported to be successful.
1969	Tanker <i>Raphael</i> went aground off Finland	Peat moss, fuel oil and petrol used.	60 tonnes of crude.	90% of oil was burned.
1970	Accident in Deception Bay, Quebec	Onshore spill reached intertidal ice. Oil pumped to ice surface and burned; some oil on ice, and contained by nearshore ice, burned.	1500 tonnes of diesel and gasoline spilled.	
1970	Tank farm accident in Quebec caused oil spill into sea ice.	Oil rags used as igniter. Oil pumped to surface first.	2000 tonnes of diesel fuel oil and gasoline.	Successful burn.
1970	Accident in Chedabucto Bay (Arrow)	Some isolated slicks were burned using Seabeads. Varsol also used as primer. Oil on shoreline was ignited and burned with napalm and a flame thrower.	Bunker C, approx. 16,000 tonnes.	Mixed results.
1970	Vessel collision in Tralhavet Bay, Sweden, March (Othello and Katalystia)	Spill was trapped in pack ice and a silica wicking agent (Cab-O-Sil St-2-0) was used to burn. Conditions precluded mechanical containment and recovery.	Between 52,000 and 90,000 tonnes of Bunker C spilled.	Good results reported.
1972	Diesel fuel spill in ice-choked river in Sweden	Sorbent product "Saneringsull" used as wicking agent.	600 tonnes of diesel fuel oil.	400 tonnes burned.
1973	Canada	Rimouski — experiment	Crude	Demonstrated high removal rates possible, >75%.
1974-75	Experimental spill, Balaena Bay, Canadian Beaufort Sea	Oil spilled under ice was burned in spring as it accumulated in melt pools on the ice surface.	45 tonnes of crude.	Highly successful burns; proved the use of burning for oil in ice.

* Compiled largely from Alaska Clean Seas (1991) and Fingas and Larocche (1990).

Table 3.1 Summary of In-Situ Burning: Tests and Use on Spills continued

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
1976	Tanker <i>Urquiola</i> went aground off Spain	Oil burned accidentally over 3-day period.	100,000 tonnes of light Arabian crude.	
1976	Accident in Lake Huron (<i>Imperial St. Clair</i>)	Oil became incorporated in ice, and numerous burns conducted as oil melted out of ice. Oily rags used as igniters.	Diesel and gasoline, 220 tonnes spilled.	80-95% of the oil burned.
1976	Tanker <i>Argo Merchant</i> went aground off Nantucket	Tullanox 500, primed with JP-4, used as igniter.	28,000 tonnes of No. 6 Fuel.	Not able to burn slicks on open water.
1976	Experiments in Canadian Arctic	Various tests on parameters controlling burning.	Crudes	
1977	Barge (<i>Bouchard #65</i>) accident in Buzzards Bay, Massachusetts	A pool of 950 liters in broken ice was ignited with Tullanox/JP-4 igniters dropped from helicopter	No. 2 fuel oil, 300 tonnes spilled.	15 tonnes burned.
1978	Experiment — Ontario, Canada	1 barrel — 5 m diameter x 1 cm	Alberta Crude Blend	Scientific studies of products from burn.
1979	Tank collision (<i>Atlantic Empress</i> and <i>Aegean Captain</i>) in Caribbean Sea	Two fully laden VLCC's collided leading to oil burning on water.	288,000 tonnes of crude	Virtually all oil burned.
1979	Accidental burn of grounded <i>Burmah Agate</i> , Galveston, Texas	Oil burned on the tanker and on water.	Nigerian crude and blend, 40,000 tonnes.	74% of oil burned.
1979-80	Experimental release	Oil release with air under first-year sea ice to simulate blowout under ice.	Prudhoe Bay crude, 20 m ³	
1980	Tests at Port Mellon, B.C.	Static test of Dome Petroleum's stainless steel fireproof boom with burning crude oil.	Redwater crude oil, 1.5 m ³	
1980	Canada	McKinley Bay — experiment	Crudes	Test of igniters; measured burn rates.
1980	Cargo vessel <i>Edgar Jourdain</i> went aground in NWT in ice conditions in September	Oil burned after ice melted.	50 tonnes of marine diesel fuel.	Successful burn.
1981	Tests at EPA OHMSETT test tank	Test of Dome Petroleum's boom with burning crude oil and waves in test tank (22 tests)	Circo 4X light oil and Murban crude.	
1981	Canada	McKinley Bay — experiment	Crudes	Noted difficulty in burning emulsions.

Table 3.1 Summary of In-Situ Burning: Tests and Use on Spills continued

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
1983	Storage tank leak into Warwick Lake, Ontario in January	Oil pumped to ice surface and burned over winter and following spring.	59 tonnes of diesel fuel oil.	85% burned.
1983	Tanker <i>Honan Jade</i> goes aground off South Korea	Uncontained 3-km diameter slick set afire; oil burned for 2 hours; residue sunk.	2000 tonnes of Arabian Heavy crude oil.	Successful intentional burn of large, uncontained spill.
1983	Tier 2 burn test in Prudhoe Bay test pit (Task 1)	Four tests conducted with uncontained oil spilled in broken ice conditions.	Circo 4X light oil and Murban crude.	55% — 73% of oil burned.
1983	Tier 2 burn tests in Prudhoe Bay test pit (Task 2)	Burning of oil inside fire containment boom in test pit (single burn and continuous burn); follow-up tests conducted in test tank.	Single burn: 34 gal. fresh, degassed Prudhoe Bay crude. Continuous burn: 1 hr @ 2.5 gpm.	72% — 88% of oil burned.
1984	Experiments at OHMSETT (New Jersey)	4 tests were run in EPA test tank.	Prudhoe Bay crude (fresh and weathered).	
1984	Canada	Series of experiments	several	Uncontained burning only possible in few conditions.
1985-1989	Various small-scale tests	National Institute of Standards and Technology tests to study combustion and smoke generation.	Alberta Sweet, Murban, Prudhoe Bay	Comprehensive analysis of physics and fate of burn products.
1986	Canada	Ottawa — experiment/analysis	various	Analysis shows PAH's about same in oil and residue.
1986	Experiments at OHMSETT (New Jersey)	Test in EPA test tank	Prudhoe Bay and Hibernia-A crudes	
1986	Experimental spills off Nova Scotia	Two spills each 1 m ³ ignited after several hours spreading in pack ice.	Alberta crude	
1986	ACS Deadhorse Helitorch tests	Tests of ignition of crude oil in test pans using a Helitorch	Fresh and weathered crude oil (20 L/pan)	
1986	Calgary, Alberta	25 tests in Jan. and Feb. at the Esso Research Ice Basin to test burning in ice leads (2 experiments in brash ice)	Aged Normal Wells crude	

Table 3.1 Summary of In-Situ Burning: Tests and Use on Spills continued

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
1988	Experimental spill off Spitsbergen	100 m of 3M Fire Boom used to contain slick, which was ignited with Helitorch	Statford crude, 2 m ³	
1988	St. Vincent's Bay, B.C. spill	Burning of spilled diesel on water; winter.	9 tonnes diesel spilled	
1989	Test burn in Prince William Sound during Exxon Valdez spill	150 m of 3M Fire Boom towed by 2 vessels to collect oil and contain it for burning; the oil had been floating on calm water for 30 to 40 hours before it was burned.	Prudhoe Bay crude, approx. 60 to 120 tonnes.	98% burn efficiency in fire boom collected oil. Residue of stiff, taffy-like oil.
1990	Rivers Inlet, B.C.	Fuel burned on water	Approx. 85 tonnes fuel	Efficient removal; noted need for experienced personnel.
1990	ACS test burns	Purpose was to test 3M Fire Boom for a 48-hour burn in a test tank.	Prudhoe Bay crude	
1990	Tanker accident (Mega Borg), Gulf of Mexico	Fire from series of onboard explosions on tanker	Palanc Angola crude, 15,000 tonnes	Estimated 51% burned and about 27% evaporated.
1990	Tanker accident (Haven), Gulf of Geneva, Italy	Fire from series of onboard explosions within 500 m of populated area.	Iranian heavy crude, 144,000 tonnes	3-day fire consumed most oil.
1991	Tanker accident (Aegean Sea), La Coruña, Spain	Fire from onboard explosions within 500 m of populated area.	Brent crude	24 hours burn — smoke led authorities to evacuate approximately 100 houses near harbor.
1991	Oil well blowout off Louisiana	Oil contained by conventional boom was ignited and burned; boom was destroyed.		
1991-1992	Test burns in Mobile, Alabama	Mesoscale tests in water-filled test tank with oil slicks up to 1.5 m in diameter inside fire containment boom. NIST	Louisiana crude	Comprehensive analysis of physics and chemistry of burning.
1993	Test burns off Newfoundland	Two burns of boomed oil, 29 m ³ and 48 m ³ .	Alberta Sweet Mix Blend crude oil	Detailed results on the fate and chemistry of the products of combustion.

Similarly, oil on the shores from the *Torrey Canyon* proved very difficult to ignite and burn. Some success was reported in burning unemulsified oil in pools between rocks (Swift *et al.* 1968). Flame throwers or flame-thrower fuel were used to ignite these pools and they burned nearly to completion. Emulsified oil could be burned on the beach, but only as long as the flamethrower was applied and remained in place. Water boiling out of the emulsion was observed during these tests. Combustion promoters such as "oxygen tiles", wood chips, and magnesium powder, were applied to the emulsified oil, but without success (Swift *et al.* 1968).

In December 1969 the cargo ship *Eiva* sank releasing 15,000 L of diesel fuel in the Gulf of Finland. Some of this oil was successfully burned on nearby shores and in bays using paraffinic oil as an igniter (Haaktela 1970). Six days later the tanker *Raphael* went aground west of Emäsoaloa, Finland releasing more than 60 tons of crude. Peat moss, fuel oil and petrol were used to remove more than 90% of the oil by burning (Coupal 1972, Haaktela 1970).

On February 4, 1970, the *Arrow* ran aground in Chedabucto Bay, Nova Scotia, and spilled most of its 16,000 ton cargo of Bunker C. SeaBeads were used successfully on isolated larger slicks (4.6 m diameter) and on some beaches to burn the oil. The slicks were primed with Varsol and ignited with a marking flare. Once ignited, the slicks tended to spread and had to be reignited several times to achieve a 50% reduction (Freiberger and Byers 1971, Battelle 1979). Part of the spill was burned by spilling two drums of fresh oil on it and igniting it with Kontax (Coupal 1972). Oil deposited onshore at Arichat, Nova Scotia was ignited with napalm and a flame thrower and reportedly burned well (Coupal 1972).

In March, 1970, the *Othello* collided with the *Katelsia* in Tvalhavet Bay near Stockholm, Sweden and spilled about 95,000 L of heavy fuel oil in broken ice. Early efforts by the Swedish Coast Guard to promote ignition of the oil with kerosene failed. Cab-O-Sil was applied by hand from small tugs to 0.3 to 0.6 m diameter pools of oil contained by ice and ignited with small amounts of primer. It is reported that this successfully removed the oil (Anonymous 1970, Freiberger and Byers 1971, Energetex 1979).

In June, 1970, a slush avalanche near Deception Bay, Quebec caused 1,940,000 L of diesel fuel and gasoline to spill from a shoreside tank farm onto and under the adjacent sea ice. Exposed pools of oil were ignited and burned using oily rags as igniters; oil trapped beneath the ice was pumped onto the surface and was subsequently burned (Ramsier *et al.* 1973).

In January, 1972, 600 tons of diesel fuel was accidentally discharged into the icy Ume River in Sweden. The oil spread downriver into a small lake. A particulate sorbent product "Saneringsull" was used as a wicking agent and about 400 tons of oil was burned over a period of a month from a mixture of oil, ice and snow on the lake (Jerbo 1973).

On the morning of May 12, 1976, the supertanker *Urquiola* went aground in the harbor at La Coruña, Spain, exploded and caught fire. Although not a case of intentional burning, this incident illustrates the high removal rates and efficiencies possible with in-situ burning. Approximately 70% of the 100,000 ton spill of light Arabian crude was consumed in the fire over a three-day period (Robertson *et al.* 1976, Gundlach *et al.* 1978).

On December 23, 1976, the oil product tanker *Imperial St. Clair* went aground near Parry Sound, Ontario, and spilled 260,000 L of gasoline and diesel. Throughout the following winter, as oil appeared on the ice surface it was periodically burned with oily rags. About 80 to 95% of the oil spilled was burned or evaporated. It was noted that it was difficult to burn the oil in very cold and windy conditions (Beckett 1979).

On December 27, 1976, the *Argo Merchant* went aground near Nantucket Island and spilled most of its cargo of 28,000 tons of No. 6 fuel oil. Part of the response by the U.S. Coast Guard involved attempts to burn the oil. One 30 m x 40 m x 15 cm thick slick was treated with Tullanox 500 (a wicking/insulating agent), primed with 200 L of JP-4 and ignited with JP-4-soaked cotton sheets set afire with a flare. About 95% of the Tullanox was blown off the treated slick by wind and the flames would not spread from the sheet to the primed slick. In another experiment boxes of Tullanox 500 charged with JP-4 fuel were dropped onto a slick from a helicopter and ignited with timed thermite grenades. The isolated boxes burned but the flames did not spread (Det norske Veritas 1979, Battelle 1979).

On January 28, 1977, 300,000 L of #2 fuel oil was spilled into the ice-covered Buzzards Bay, Massachusetts by the barge *Bouchard #65*. Boxes of Tullanox soaked with jet fuel were dropped from helicopters onto pools of oil in the broken ice. Delay-fused thermite grenades were used to ignite the boxes. The ensuing fires burned for 1½ to 2 hours and consumed 4000 to 8000 L of oil. The 38 to 46 km/hr (20 to 25 knot) winds drove the flames from pool to pool in areas where adjacent pools were nearby; in other areas the fires did not spread. Another series of burns was conducted at a later date. These burns were initiated by knotted rags soaked in diesel fuel. Some of these fires had flames 9 to 12 m high and lasted 40 to 50 minutes. Other pools were considered for burning but rejected due to concerns about nuisance effects of smoke to nearby residents and the possibility of the fire jumping ashore to beachfront properties. Overall, 15,000 L of oil was estimated to have been burned (Schrier and Ediam 1979, Ruby *et al.* 1978).

Beginning in the late 1970s, a concerted research effort was made to develop in-situ burning as a tool for oil spill response in arctic waters. As these ice-related studies were being conducted, three events in 1979 catalyzed world-wide interest in burning as a method for dealing with oil spills on water: the IXTOC-1 blowout in the Bay of Campeche, Mexico, the *Burmah Agate* spill in the U.S. Gulf of Mexico and the sinking of the *Atlantic Empress* off Trinidad. These spills illustrated again the potential for in-situ burning to remove large amounts of oil from the sea surface (e.g., for the *Burmah Agate* spill 186,000 bbl or 74% of the spilled oil was burned) and highlighted the need for fire resistant booms to contain burning oil (Kana *et al.* 1981). The *Atlantic Empress* incident, in which all the oil released from the 288,000 dwt tanker was consumed in fire, was a particularly dramatic illustration of the potential for in-situ burning to remove oil from the sea surface (Horn and Neal 1981).

These spills promoted a serious research effort into fire-resistant containment booms, a major review and experimental program in the U.S. on in-situ burning for open water spills, and a major effort to quantify the environmental consequences of in-situ burning.

In September, 1980, the cargo vessel *Edgar Jourdain* went aground off Hall Beach, N.W.T., and spilled 50,000 L of marine diesel fuel. Within a week the ice began to grow and froze the remaining oil into the ship. The following spring the remaining fuel was deliberately burned in the ship (Brander-Smith *et al.* 1990).

In 1983, near Prudhoe Bay, Alaska, a series of burns of uncontained crude oil among ice in a pit were conducted (Industry Task Group 1983, S.L. Ross 1983). The results of these burns (55% of a 140 L test spill, 85% of an 1100 L test spill and 73% of a 1200 L test spill) led to a research project to examine the concept of igniting uncontained spills on open water (S.L. Ross and Energetex 1986). The project culminated with uncontained burns of 960 to 1350 L of Prudhoe Bay crude on water in Alaska. Removal efficiencies of 72 to 88% were obtained for free-floating, burning slicks.

In January, 1983, about 59,000 L of diesel fuel leaked from a storage tank into Warwick Lake, Ontario. Over the ensuing winter and spring about 50,000 L of this was burned from snow, on ice and after being pumped from beneath ice (Burns 1988).

On February 28, 1983, the tanker *Honan Jade* went aground off Yosu, South Korea, losing 2000 tonnes of Arabian Heavy crude oil (Moller 1992). Some three hours after the spill, one of the cleanup contractors set fire to the main slick, which was circular in shape with a diameter of 3 kilometers. The fire burned with great intensity for about two hours before going out spontaneously and leaving a residue which sank nearby. The sunken oil affected the cultivation of crabs which were being reared in submerged cages (Moller 1992). Some attempts were made to recover the oil using trawls, but not with much success.

In March, 1989, the *Exxon Valdez* went aground on Bligh Reef in Prince William Sound, Alaska and released 41,000,000 L of crude oil. During the evening of the second day following the accident an estimated 57,000 to 144,000 L of slightly emulsified (20 to 30% water) North Slope crude were burned in-situ using 136 m of 3M Fire boom (Allen 1991). This was the first recorded incident of the use of fire-resistant boom at a major spill response. By the time additional burns were attempted, a storm had further emulsified the slick and rendered it unignitable (Exxon 1990).

In the Gulf of Mexico on June 8, 1990, the *Mega Borg* suffered an explosion during lightering operations and caught fire. By June 16 the fire had been extinguished and the oil leakage stopped. Surveys indicated that 15,000,000 L of oil had been lost; most of which burned near the tanker (OSIR, 3 January 1991), some of which formed large slicks and some 2,200,000 L of which was recovered by skimmers (Leveille 1991). The remaining cargo (144,000,000 L) was successfully lightered.

In November, 1990, a landslide at Rivers Inlet, B.C. resulted in a spill of some 85,000 L of fuels from a storage area into the adjacent water. Containment was partially effected by a log boom and boomsticks. Tidal currents were causing continued losses from the contained oil. In order to remove the oil from the aquatic environment, the boom was moved to provide separation between the tank farm, and the collected fuel and the contained slick was ignited using fuel soaked sorbent pads manually placed from small boats. The ensuing burn lasted some 30 minutes and was less than 23 m in diameter. It was estimated that no more than 10,000 L of fuel was burned (Robertson 1991).

In April, 1991, the tanker *Haven* caught fire and ultimately exploded and broke in three off the coast of Genoa, Italy. At the time it was carrying some 144,000 tons of heavy Iranian crude. The fire lasted three days and consumed most of the oil; this substantially reduced the oil spillage. This fire was intentionally allowed to burn to reduce pollution. Reports suggest an undefined amount of the oil/burn residue sank and covered areas of the sea floor and wreck with solid masses. Some of the viscous residue remained floating after the spill and caused severe problems for skimmers; thus the main response efforts became those of beach protection and shoreline cleanup (Jacobsson 1993, Turbini *et al.* 1993).

On the 29th of September, 1991 an oil well in a bay on the southern coast of Louisiana blew out and subsequently caught fire on October 1. At the time of the fire, conventional boom had been deployed; the contained oil was ignited by the burning well and burned, as did the boom. It was reported that fire resistant boom was subsequently deployed around the burning well, but was damaged by storm waves (OSIR, 8 October 1992). The well was intentionally allowed to continue burning during well-capping operations to minimize oil slick threats in a sensitive wetland area (OSIR, 15 October 1992).

Finally, two land spills occurred in 1992 and 1993 that involved in-situ burning as the primary response technique. The first involved a fuel truck spill in September 1992 in Alaska during which oil was burned out of snow (D'Atri and King 1993) and the second involved the successful removal of a 13 mm thick slick of JP5 from a marshy area. After vacuuming and pumping efforts had been exhausted, the remaining oil in the marsh was ignited with a lighter and sorbent pads. The burn lasted 45 minutes to an hour; the resulting smoke plume is said to have risen and started to dissipate before it reached inhabited areas (OSIR, April 8, 1993).

3.4 References to Chapter 3

- Allen, A.A. 1991. Controlled burning of crude oil on water following the grounding of the *Exxon Valdez*. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp.213-216.
- Anonymous. 1967. Chemicals vs. crude oil. *Chemical Week* 100(20):49.
- Anonymous. 1970. Oil for burning. *Marine Pollution Bulletin* 1(12):181; 1970.
- Battelle. 1979. Combustion: An oil spill mitigation tool. Report for U.S. Department of Energy, Contract No. EY-76-C-06-1830. U.S. Department of Energy, Washington, D.C.
- Beckett, C.J. 1979. The grounding of the *Imperial St. Clair* — a case history of contending with oil in ice. Proceedings of the 1979 Oil Spill Conference, March 19-22, New Orleans, Louisiana. American Petroleum Institute, Washington, D.C. pp.371-375.
- Brander-Smith, D., D.P. Therrien and J. Tobin. 1990. Protecting our waters. Public Review Panel on Tanker Safety and Marine Spills Response Capability. Final Report, September 1990. Minister of Supply and Services Canada 1990. Catalogue No. EN21-91/1990 E.
- Burns, R.C. 1988. Cleanup and containment of a diesel fuel spill to a sensitive water body at a remote site under extreme winter conditions. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp.209-220.
- Coupal, B. 1972. Use of peat moss in controlled combustion technique. Environment Canada, Ottawa, Ontario. Environment Canada Report No. EPS 4-EE-72-1, 32 p.
- D-Atri, B. and T. King. 1993. Flicking your Bic at twenty-five below (or: The Atigun Pass Diesel Spill project). Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp.669-678.

- Det norske Veritas. 1979. Tanker oil spill analysis study. Technical report for Canadian Marine Drilling Limited. Det norske Veritas Ship Division.
- Energetex Engineering. 1979. A review of oil slick combustion promoters. Environment Canada, Ottawa, Ontario. Environment Canada Report EPS-3-EC-79-8. 48 p.
- Exxon. 1990. Valdez oil spill technology. Exxon Production Research Company.
- Freiberger, A. and J.M. Byers. 1971. Burning agents for oil spill cleanup. Proceedings of the 1971 Conference on Prevention and Control of Oil Spills, June 15-17, Washington, D.C. American Petroleum Institute, Washington, D.C. pp.245-251.
- Gundlach, E.R. and M.O. Hayes. 1971. Vulnerability of coastal environments to oil spill impacts, Mar. Tech. Soc. J. 12 18-27.
- Haaktela, I. 1970. Oil spills off Finland. Marine Pollution Bulletin 1(1):19-20.
- Horn, S.A. and P. Neal. 1981. The *Atlantic Empress* sinking — a large spill without environmental disaster. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp.429-435.
- Industry Task Group. 1983. Oil spill response in the Arctic. Part 2. Field demonstrations in broken ice. Industry Task Force comprised of Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company, U.S.A., and Amoco Production Company, Anchorage, Alaska.
- Jacobsson, M. 1993. The *Rio Orinoco* and *the Haven* — Two major cases from a legal point of view. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp.663-666.
- Jerbo, A. 1973. Two types of oil spills in Swedish inland waters — Tests of new materials, ideas and methods. Proceedings of the 1973 Conference on Prevention and Control of Oil Spills, March 13-15, Washington, D.C. American Petroleum Institute, Washington, D.C. p. 559.
- Kana, T.E., E. Thompson, and R. Pavia. 1981. *Burmah Agate*: chronology and containment operations. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp.131-138.
- Leveille, T.P. 1991. The *Mega Borg* fire and oil spill: a case study. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp.273-278.
- McLeod, W.R. and D.L. McLeod. 1972. Measures to combat offshore Arctic oil spills. Offshore Technology Conference paper #1523 (2):14. pp.141-162.

- OSIR (Oil Spill Intelligence Report). Published weekly by Cutter Information Corp., 37 Broadway, Arlington, MA 02174-5539.
- Ramsier, R.O., G.S. Gantcheff, and L. Colby. 1973. Oil spill at Deception Bay, Hudson Strait. Scientific Series No. 29. Inland Waters Directorate. Water Resources Branch. Environment Canada, Ottawa.
- Robertson, I., J.R. McDonald, N.S. Robertson and L.B. Solsberg. 1976. The *Urquiola* Oil Spill, La Coruña, Spain. Spill Technology Newsletter, May-June 1976, Canadian Department of the Environment, Environmental Protection Service, Ottawa, Ontario.
- Robertson, I. 1991. Operational examples of in-situ burning: Lessons from the burning of two recent diesel spills on the B.C. coast. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 411-419.
- Ruby, C.H., L.G. Ward, I.A. Fischer, and P.J. Brown. 1978. Buzzards Bay oil spill — an arctic analogue. International Conference on Ports and Ocean Engineering under Arctic Conditions (POAC '77), 4th Conference, St. John's, Newfoundland, 1977, Volume 2.
- Schrier, E. and C. Eidam. 1979. Cleanup efficiency of a fuel oil spill in cold weather. Proceedings of the 1979 Oil Spill Conference, March 19-22, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp.419-427.
- S.L. Ross Environmental Research Ltd. 1983. A study of on-board self-help oil spill countermeasures for arctic tankers. Report to Environment Canada. Environment Canada, Ottawa, Ontario.
- S.L. Ross Environmental Research Ltd. and Energetex Engineering. 1986. Decision-making aids for igniting or extinguishing well blowouts to minimize environmental impacts. Environmental Studies Revolving Funds Report Number 051. 95 p.
- Swift, W.H., C.J. Touhill, and P.L. Peterson. 1968. Oil spillage control. Chemical Engineering Progress Symposium Series 65(97):265-273.
- Turbini, W., E. Fresi and F. Bambacigno. 1993. The *Haven* Incident: Lessons learned with particular reference to environmental damages. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp.179-183.
- Wardley-Smith, J. 1971. Oil pollution: causes and cures. Engineering 211(6):644-648.

4.0 The Science of In-Situ Burning

4.1 Steady-State Burning Fundamentals

In order to burn oil spilled on water three elements must be present: fuel, oxygen and a source of ignition. In addition, the oil must be heated to a temperature, called the fire point, at which sufficient hydrocarbons are vaporized to support combustion in the air above the slick. The key oil slick parameter that defines whether or not the oil will burn is slick thickness; if the oil is thick enough it acts as insulation and keeps the burning slick surface at a high temperature by reducing heat loss to the underlying water. As the slick thins, increasingly more heat passes through it; eventually enough heat is transferred through the slick to allow the oil temperature to drop below its fire point, at which time burning stops.

Figure 4.1 illustrates the heat and mass transfer processes that occur during the in-situ burning of an oil slick on water. The key process is radiative heat transfer from the flame back to the surface of the slick. This heat is partially used by vaporizing the liquid hydrocarbons which rise to mix with air above the slick and oxidize, or burn; the remainder transfers through the slick to the underlying water. Once ignited, a burning thick oil slick reaches a quasi-steady-state in which the vaporization rate sustains the necessary heat transfer back to the slick surface.

Maximum flame temperatures of 900°C to 950°C for crude oil burns on still water have been recorded by a number of researchers (Hägglund and Persson 1976, Evans *et al.* 1987, McAllister and Buist 1981, SINTEF and S.L. Ross 1993 and Koseki 1993). Koseki (1993) reports thermocouple readings of 1200 to 1400°C in a 17 m diameter fire. Just before the fire extinguishes, boiling water beneath the slick ejects oil droplets into the flame creating more intense burning; during this vigorous burning phase flame temperatures may jump by 150°C to 200°C (Evans *et al.* 1987, SINTEF and S.L. Ross 1993). Wind can also increase flame temperatures due to improved fuel/air mixing (Babrauskas 1988).

Several authors have studied the heat transfer processes that occur during in-situ burning and pool burning (pool burning refers to combustion of oil in pans or open-topped tanks with no water substrate). In 1981 Twardus and Brzustowski proposed a model in which the rate of combustion is controlled by radiative heat transfer to the fuel surface, the heats of vaporization and combustion of the subject oil, and heat conduction through the slick to the underlying water. The model shows the correct relationships and allows for the incorporation of wind speed into the heat transfer model. This model was modified (Brzustowski and Twardus 1982) to incorporate a radiative heat loss component through the slick.

Researchers at Battelle (Battelle 1979) conducted an in-depth review of in-situ combustion processes and, starting from the basic combustion model described above (Energetex 1978), performed an extensive review of pool fire heat transfer. Their premise was that for quasi-steady-state burning to proceed, the fraction of the heat radiated back to the fire must be greater than the sum of the heat of vaporization of the oil and the sensible heat required to warm the oil from ambient temperature to its boiling point. The key parameter to be determined was the fraction of the heat of combustion of the fuel transferred back to the fuel surface. There are three mechanisms by which heat can be transferred: conduction, convection and radiation. In turbulent fires conduction can be ignored, leaving the latter two. The Battelle study concluded that radiative heat transfer was the dominant heat transfer

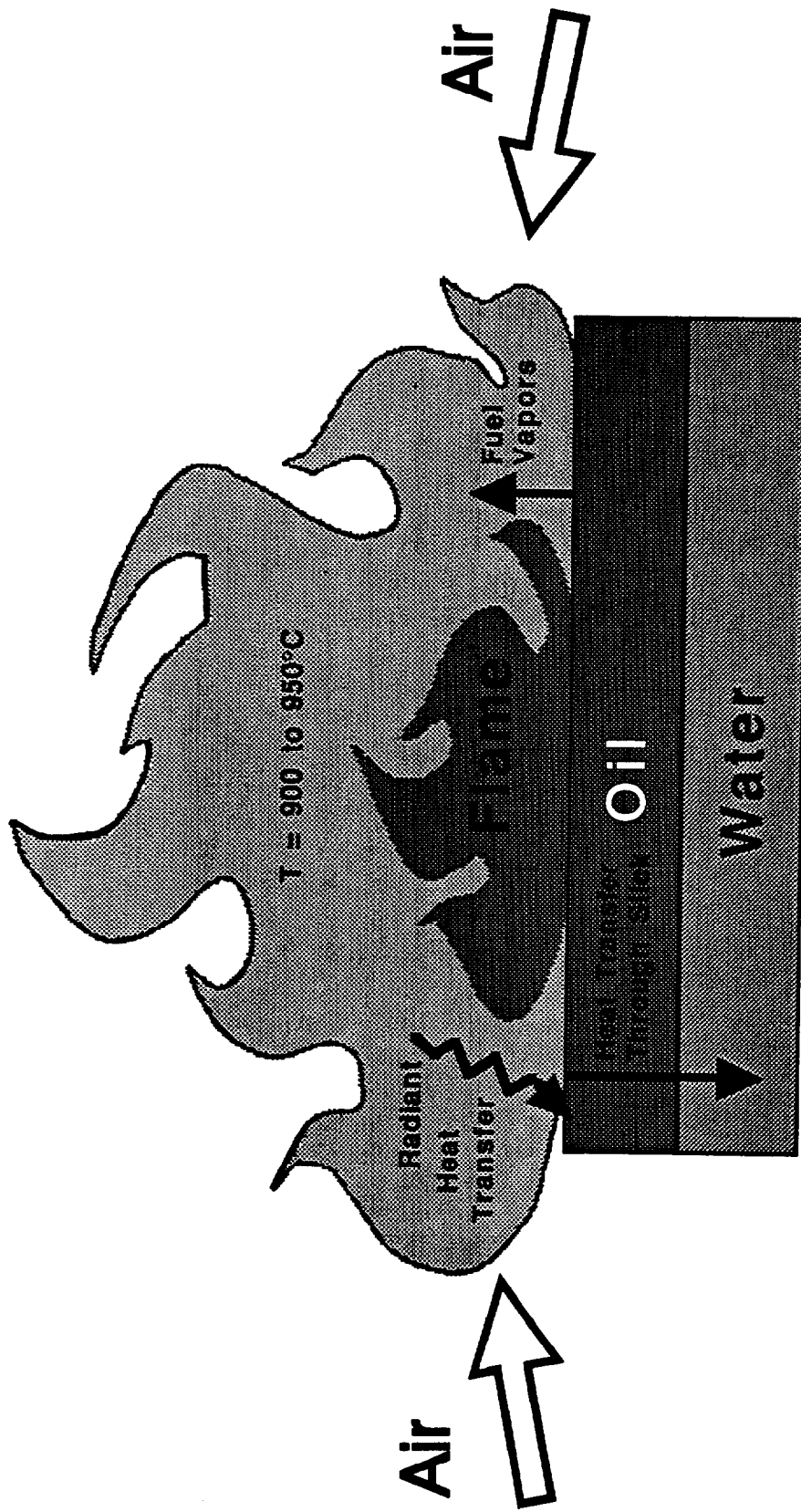


Figure 4.1 Key heat and mass transfer processes in in-situ burning

process for all but the smallest fires. This conclusion is supported by the data of Yumoto (1971) who reported that the radiative and convective contributions were equal for pool fires of gasoline with 0.6 m diameters but at 3 m diameter radiation was contribution 70% of the heat transferred back to the slick. Babrauskas (1988) also reports that burning pools of diameter greater than 0.2 m are dominated by radiation heat transfer.

Based on a review of laboratory data on radiation from pool fires of hydrocarbons Battelle (1979) concluded that about 2 to 3% of the heat of combustion of a liquid fuel is radiated back to the surface. Twardus and Brzustowski (1981) showed that theoretically the heat radiated back to the pool surface from a flame with a height equal to twice the pool diameter would be 2.2% of the heat of combustion of the fuel. This is in agreement with the Battelle conclusion.

Evans *et al.* (1988) measured the incident radiant energy flux at the center of a 1.2 m diameter burning slick of Alberta crude as 40 to 65 kW/m² and 18 kW/m² at the rim of the test pan with a burning rate of 1.6 mm/min (1.5 kg/min). They calculated that the heat required for vaporization was 6.7 kW/m² and the heat loss by conduction through the slick to the underlying water was 2.5 kW/m²; the remainder of the heat was likely reradiated or convected away. The measured total heat release rate for the burn during steady state was 1.25 MW or 1.1 MW/m² of pool surface. The fraction of heat released that was radiated back to the pool surface ranged from 0.016 at the rim to 0.036 to 0.05 at the center, in good general agreement with the Battelle conclusions. The higher than expected fraction may be related to the fact that this calculation used a measured total heat output instead of a heat of combustion calculation. Wakamiya *et al.* (1982) reported that, in 2 m diameter 50-mm thick test burns of six crude oils on water, just before the flames extinguished the fraction of the heat of combustion being radiated back to the slick was between 0.01 and 0.021.

Thus, only a small fraction of the heat generated by the vapor-phase combustion is returned to the slick to maintain the process; the vast majority of the heat is radiated and convected away.

The heat that is radiated back to the slick is used to vaporize liquid oil to provide fuel for combustion in the air above the slick. Extensive tests by Wakamiya *et al.* (1982) showed that the process by which the oil vaporizes is not a distillation (whereby the lightest, most volatile components are boiled off from the entire slick first followed by progressively heavier, less volatile components) but is similar to an Equilibrium Flash Vaporization (EFV) in which vapor of essentially constant composition over time is produced by a feed of oil of essentially constant composition. Three observations lend credence to the EFV theory of combustion: (1) the surface temperatures of burning oil slicks remain almost constant in the 200 to 300° range during steady state burning (Wakamiya *et al.* 1982, Evans *et al.* 1988, SINTEF and S.L. Ross 1993) (if burning were a distillation the surface temperature of the slick would steadily increase); (2) a steep temperature profile in the burning slick (Wakamiya *et al.* 1982, SINTEF and S.L. Ross 1993), indicating a poorly-mixed oil layer, as would result from EFV; and, (3) the presence of light ends in the oil residue remaining after a burn (i.e., Energetex 1977, Dome Petroleum 1981, Wakamiya *et al.* 1982) which would not be present if in-situ burning was a distillation process. It is believed that EFV occurs during in-situ burning because the hot flames and the insulating characteristics of the oil combine to create high heat inputs to the oil surface layer and high surface temperatures in a layer known as the "hot zone". This promotes near-complete vaporization of successive layers of the oil slick with minimal mixing and heat transfer to the underlying oil and/or water layers.

In summary, the steady state phase of in-situ burning is controlled by radiant heat transfer from the flames back to the surface of the burning slick; this heats and vaporizes a thin surface film of oil which subsequently burns in the air above the slick.

4.2 Steady-State Oil Removal Rates

The rate at which in-situ burning consumes oil is generally reported in units of thickness per unit time (mm/min is the most commonly used unit). The removal rate for in-situ oil fires is a function of fire size (or diameter), slick thickness, oil type and ambient environmental conditions.

Blinov and Khudiakov (1959) in the USSR studied pan fires of a range of petroleum products to determine the effects of fire diameter on oil removal rate. Their data, shown in Figure 4.2 shows an initial decrease in burn rate with increasing size, followed by a minimum at about a 10 cm pan diameter, then a subsequent increase to a constant rate of about 4 mm/min above a 2 m fire diameter (up to a maximum diameter of 22.9 m). Figure 4.3 shows data from in-situ burn tests involving fresh unemulsified thick (10 to 50 mm) slicks of crude oils on water superimposed on the graph of Blinov and Khudiakov (McAllister and Buist 1981, S.L. Ross and Energetex 1984, Wakamiya *et al.* 1982, Evans *et al.* 1992, S.L. Ross 1989, SINTEF and S.L. Ross 1993, Bech *et al.* 1992, Koseki and Mulholland 1991). It is clear that the data follow the same trend as that of Blinov and Khudiakov (1959). Koseki and Mulholland's (1991) curve (Figure 4.4) appears to reasonably correlate the data (considering the range of experimental conditions and crude oil types involved). One data set differs significantly from the curve: the 2 m diameter burn rates reported by Wakamiya *et al.* 1982 of 3 to 4.9 mm/min are somewhat higher than the correlation and other data (e.g., Evans *et al.* 1992 and Bech *et al.* 1992) which would suggest a 2 to 2.5 mm/min burn rate for this diameter.

Babrauskas (1988) gives the following equation to correlate the burning rate of hydrocarbon pool fires in the open with $D > 0.2$ m:

$$m'' = m''_{\infty} (1 - e^{-k\beta D}) \quad (4-1)$$

where

m''	=	burning rate [kg/m ² s or mm/min]
m''_{∞}	=	burning rate at infinite diameter [kg/m ² s or mm/min]
$k\beta$	=	constant for a given fuel [m ⁻¹]
D	=	pool diameter [m]

With an m''_{∞} of about 3.5 mm/min, as suggested by the data of Koseki and Mulholland (1991) and Evans *et al.* 1992 and 1993, an equation of the form:

$$m'' = 3.5 (1 - e^{-D}) \text{ [mm/min]} \quad (4-2)$$

approximates the data well, for $D > 0.2$ m as shown on Figure 4.3. For most large fires of unemulsified crude oil on water, the "rule-of-thumb" is that they burn at 3.5 mm/min.

Babrauskas (1988) notes that for very large pool diameters, greater than 5 or 10 m, a decrease in pool burning rate on the order of 20% can be observed. This is attributed to

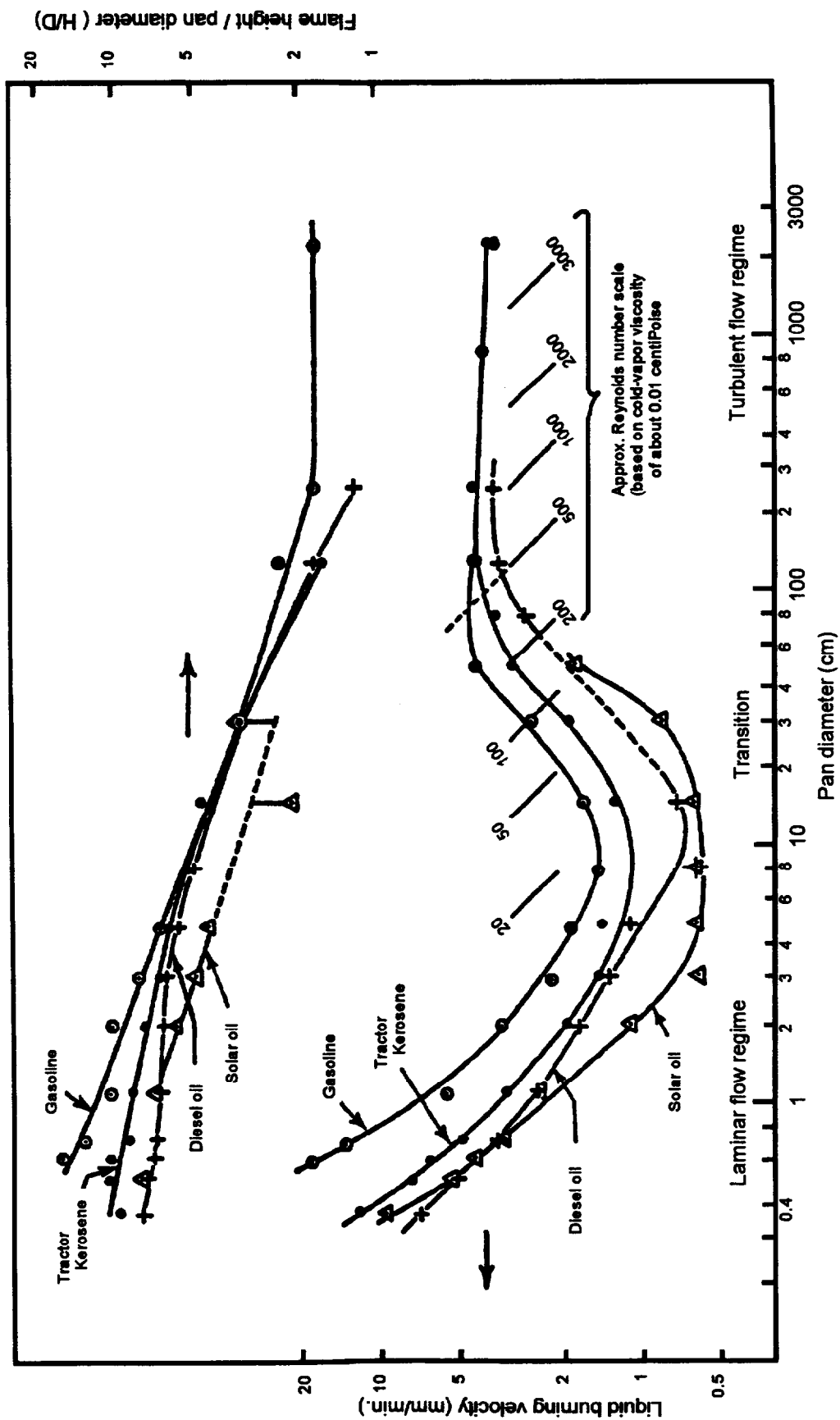


Figure 4.2 Burning data (from Blinov & Khudiakov 1959)

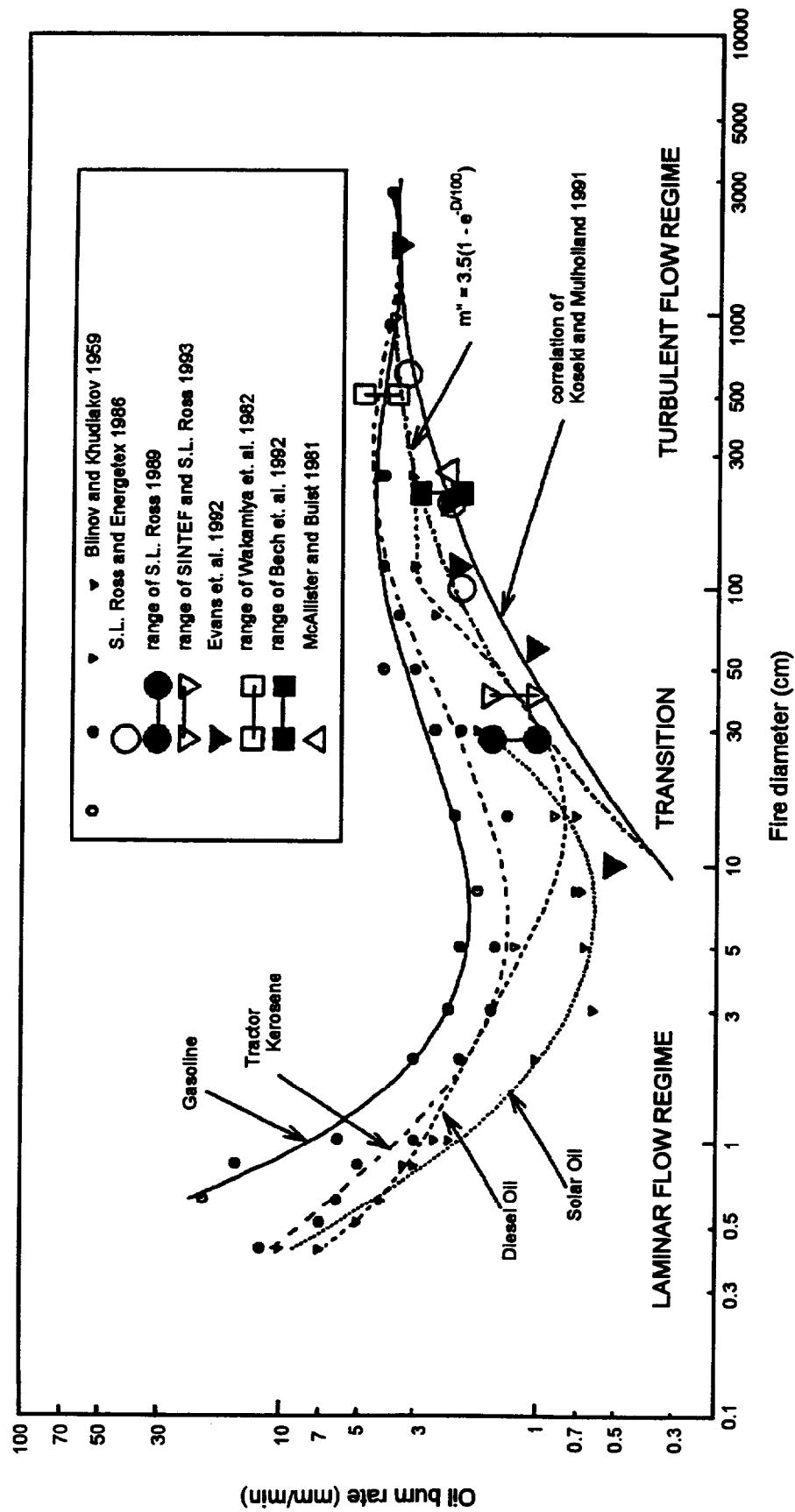


Figure 4.3 Burning rate vs. fire diameter - a comparison of data sets

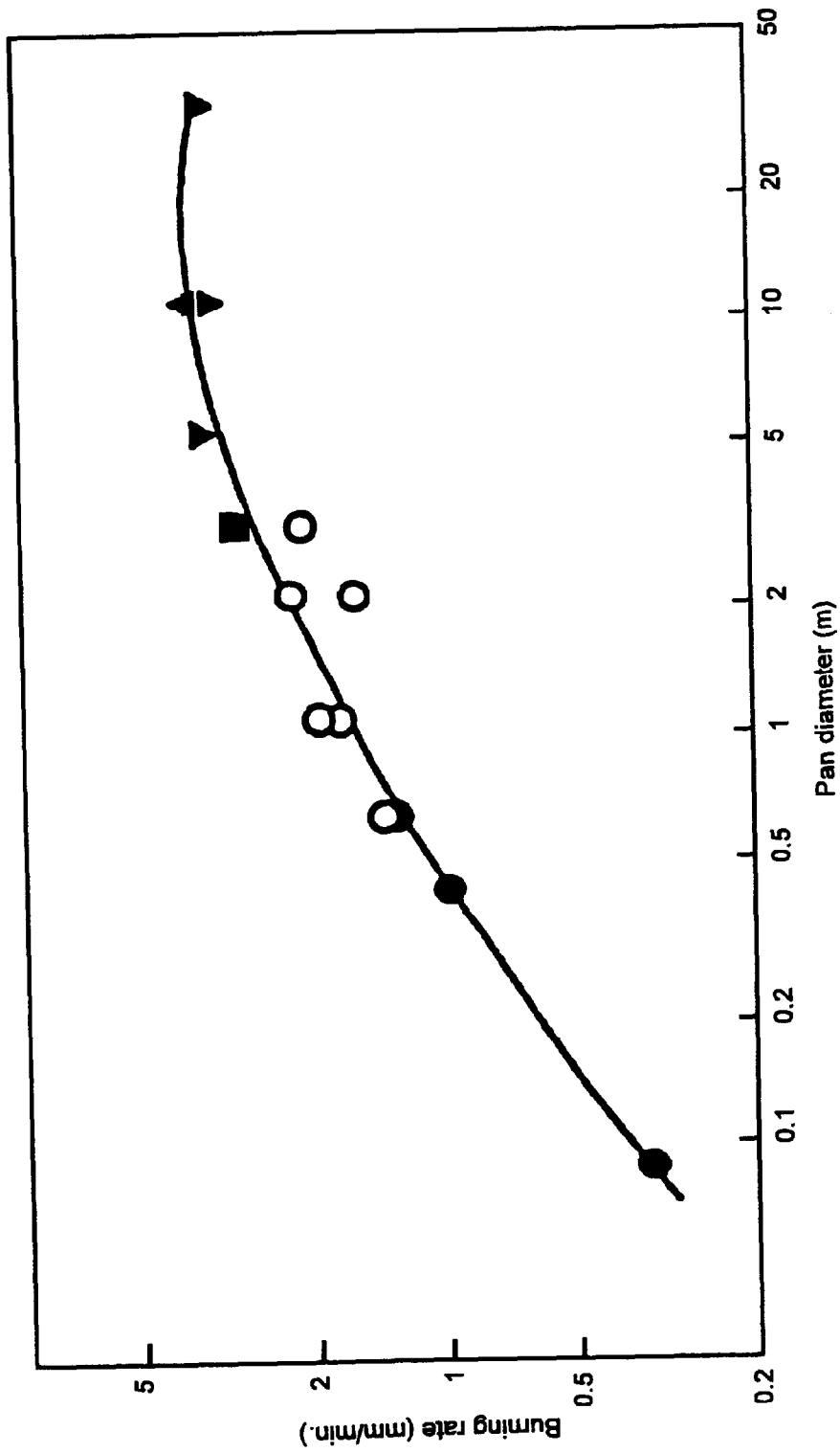


Figure 4.4. Relationship between burning rate and tank diameter
(from Koseki and Mulholland 1991)

poorer mixing, poorer combustion and a layer of cold smoke above the pool surface. The data of Walton *et al.* 1993 and, Koseki and Mulholland can be interpreted as indicating a slight reduction in burn rate with increasing diameter over 10 m; the reduction is much less than 20% and possibly within the experimental measurement error. Akita and Yumoto (1965) observed that the burning rate of a pool fire is a function of distance from the center of the fire. Their research indicated that pool fires burn fastest at the periphery and slowest at the center of the fire due to lack of air at the center. They postulate that this causes a radial flow of fuel from the center of the fire outwards.

Slick thickness also affects burn rates, with thicker slicks burning faster than thinner slicks. Data presented in S.L. Ross and Energetex (1986) show an increase in overall burning rate for constant fire diameter (1 or 2 m) with increasing slick thickness up to about 10 mm; above this the burn rate does not appear to be a function of slick thickness. Evans *et al.* (1988) present data that imply that the peak, or "vigorous", burning rate increases with thickness up to 10 mm, but an increase from 5 to 10 mm does not increase steady state burning rates for 0.6 and 1.2 m diameter fires (see below). S.L. Ross (1989) show that overall burning rate increases for small diameter fires (28 cm) with increasing slick thickness up to 10 mm. Analysis of mesoscale burn data presented in Evans *et al.* (1992) indicates that there is no increase in overall burn rate with thickness for slicks 18 to 90 mm thick and 6.9 to 17.2 m in diameter.

Review of the available data for slicks less than 10 mm thick indicates a slight decline in overall burn rate of about 10% with a decline in slick thickness from 10 mm to 5 mm and a 50% reduction with a decline to a 2 mm slick thickness. This suggests a relationship between initial slick thickness of the form:

$$m'' = m''_{\infty} (1 - e^{-cx}) \quad (4-3)$$

where

- m'' = average or overall burn rate at slick thickness x [kg/m²s or mm/min]
- m''_{∞} = burn rate at large (>10 mm) slick thickness [kg/m²s or mm/min]
- c = a constant [mm⁻¹]
- x = initial slick thickness [mm]

A value of $C = 0.35 \text{ mm}^{-1}$ gives the correct general shape of the curve.

Oil type and degree of oil weathering are also known to affect overall burning rate. Blinov and Khudiakov (1959) found that different petroleum products burn at different rates, at least in fires less than 2 m in diameter (see Figure 4.2). Babrauskas (1988) gives m''_{∞} data for a variety of petroleum products (see Table 4.1). Note that these are for pool fires rather than in-situ fires and thus would be somewhat lower than the overall in-situ burning rate, which includes the contribution of the vigorous burn phase. Wakamiya *et al.* (1982) found that overall burning rates for six crudes ranged from 3.0 to 4.9 mm/min. It is interesting to note that both data sets show no correlation between density (i.e., volatility) and burning rate. Obviously, flame temperature and smoke obscuration differences among fuels play a stronger role in determining burning rate than does fuel density. The only trend in the data sets is the tendency of residual fuel oils to burn at lower rates (2 mm/min) than either lighter products or crudes.

Table 4.1 Data for Large-Pool Burning Rate Estimates*

Material	Density (kg/m ³)	Δh_c (MJ/kg)	m''_{∞} (kg/m ² s)	m''_{∞} (mm/min)	$k\beta$ (m ⁻¹)
Petroleum Products					
benzene	740	44.7	0.048	3.9	3.6
gasoline	740	43.7	0.055	4.5	2.1
kerosene	820	43.2	0.039	2.9	3.5
JP-4	760	43.5	0.051	4.0	3.6
JP-5	810	43.0	0.054	4.0	1.6
transformer oil	760	46.4	**0.039	**3.0	**0.7
fuel oil, heavy	940-1000	39.7	0.035	2.1	1.7
crude oil	830-880	42.5-42.7	0.022-0.045	1.6-3.3	2.8

* Adapted from Babrauskas (1988)

** Estimate uncertain since only two data points available.

Evaporation of light ends from an oil has little effect on burning rates. Wakamiya *et al.* (1982), S.L. Ross (1989), and Evans *et al.* (1992), indicate that there is no effect of evaporation on overall burn rate. Bech *et al.* 1992 indicate a slight decrease in burn rate with increasing evaporation but note that environmental factors may be the cause of this. Preliminary results of SINTEF and S.L. Ross (1993) show no consistent dependence of burn rate on degree of weathering.

Environmental factors affect burning rates somewhat. Ambient temperature effects are generally small in magnitude. Wakamiya *et al.* (1982) indicated an average reduction in burning rate of 15% for an ambient temperature decline of 25°C for four crude oils. This is presumably related to a combination of increased sensible heat requirements for warming the slick and increased heat conduction through the slick. Hall (1973) reports similar reductions for pool fires of benzene and toluene. Evans *et al.* (1988) present data for 1.2 m diameter crude oil fires at temperatures of 5 to 28°C. Although the trend is far from clear, a 10% reduction in burn rate with a 23°C ambient temperature drop is indicated.

Wind also affects burning rate. Babrauskas (1988) gives the following expression, based on data from Blinov and Khudiakov (1959), for the relationship between pool fire

burning rate and wind speed, as a function of pool diameter:

$$m''_{\text{winds}}/m''_{\text{still}} = 1 + 0.15(u/D) \quad (4-4)$$

where

u = wind speed [m/s]
D = pool diameter [m]

This applies up to the blow-off velocity (the wind speed at which vapor is carried away faster than it can be replaced and the flame goes out), which can be as low as 5 m/s for some fuels. Evans *et al.* (1988) report an increase in the quiescent burning rate of a 1.2 m diameter fire of crude oil on water from 2.3 mm/min to 2.9 mm/min with a wind of 1 m/s and up to 4 mm/min with a 2.5 m/s wind. Evans *et al.* (1992) present data that indicate no effect of an increase from 1 to 5 m/s on 6.9 m to 17.2 m diameter crude oil fires on water; this is broadly consistent with equation 4-4. Both Allen (1986) and Bech *et al.* (1992 and 1993) report the maximum wind speed at which crude oil will burn is about 10 to 12 m/s.

The presence of wave action may also reduce burning rates, by increasing heat transfer to the underlying water. This effect has been noted by Tam and Purves (1980) in small spills (<5 L) in small (5 and 10 cm) waves. Buist and McAllister (1981) reported reduced burn times at constant tow speeds with increasing regular wave height from 0 to 0.4 m x 19 m (height x length) waves, but reported no decrease in visible combustion intensity. These tests involved burning 38 to 57L of crude oil in a fire proof boom at the OHMSETT test facility. Increased residue amounts were also reported, but not quantified, so the decreased burn times may be related to earlier extinction of the fire rather than to reduced burning rates. Bech *et al.* (1993) reported no effects of 40 cm x 4 m waves on the burning of 4 m³ of unemulsified crude oil in a 300 m² test pit but a considerable reduction in burn intensity for a 25% water emulsion in waves. The effect of waves on burn rate is thus unclear, and for thick, large slicks of unemulsified oil it may be negligible.

Buist and McAllister (1981) showed that the effects of currents on in-situ burning rates are negligible, up to a relative velocity between the slick and underlying water of up to 1 m/s (conventional containment equipment normally fails to contain oil at relative velocities of 0.35 to 0.5 m/s). Preliminary results from field trials in Norway (SINTEF and S.L. Ross 1993) support this conclusion.

In summary, wind speed and ambient temperatures can affect in-situ burn rates to some extent, currents do not seem to affect burning rates, and it is unclear whether or not wave action affects burning rates.

4.3 The Vigorous Burning Phase

As noted above, during oil slick burning the oil layer itself acts as insulation between the hot vapor/liquid interface and the oil/water interface. This is true while the slick is thick (>5 to 10 mm), but once the slick thins as burning progresses, the "hot zone" approaches the water surface and increasing amounts of heat are transferred into the water column. This process is illustrated in Figure 4.5. As the rate of heat transfer increases the temperature of the layer of water directly beneath the slick increases. Once the boiling point of the water is reached, the generated steam vigorously mixes the remaining oil layer and ejects oil droplets into the flames. This results in increased burn rate, flame height and radiative output

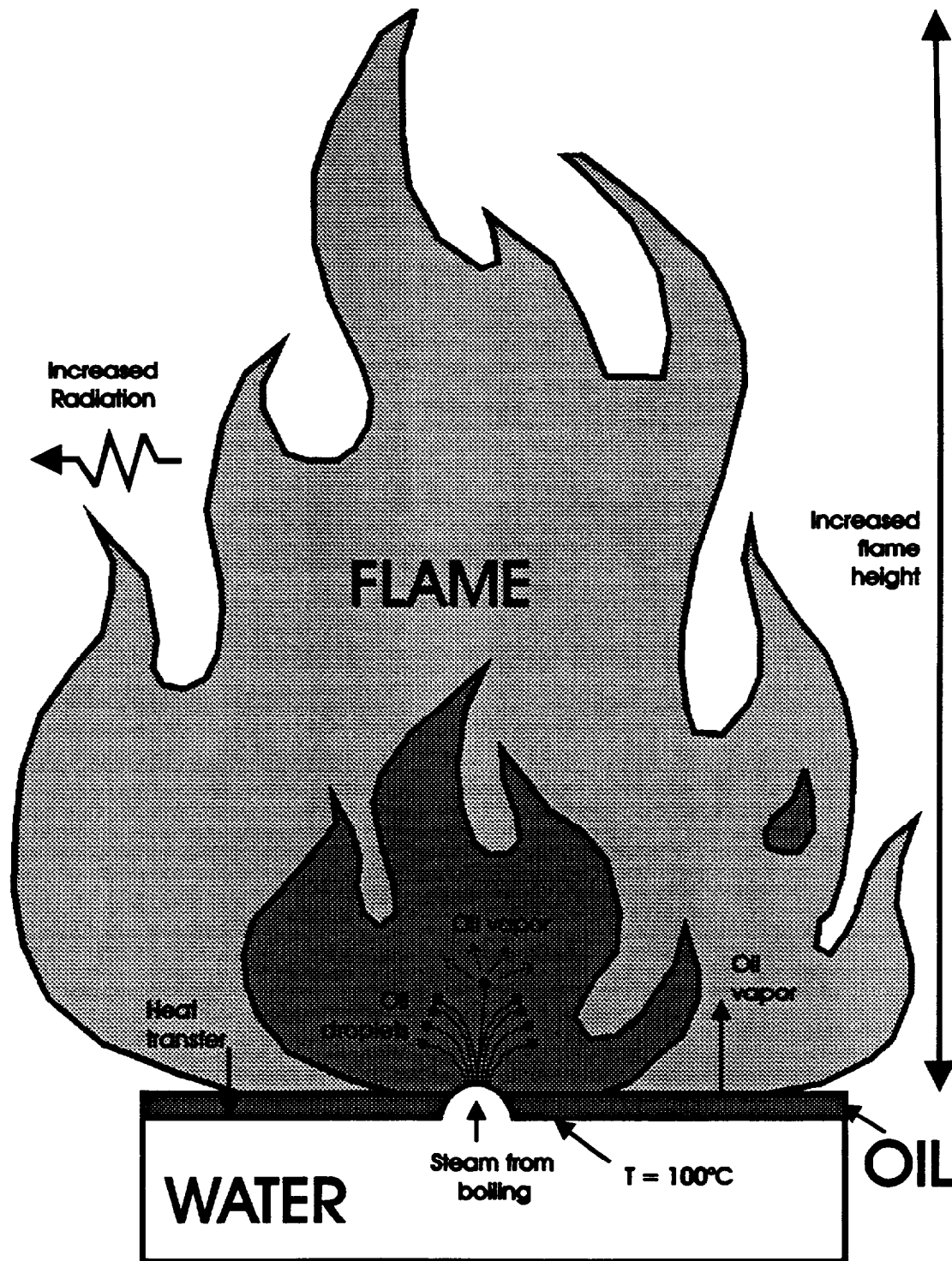


Figure 4.5 Development of the vigorous burning phase

(Energetex 1977, Wakamiya *et al.* 1982, Evans *et al.* 1988 and 1992). Evans *et al.* (1988 and 1992) have studied this end-phase of in-situ burning extensively and have shown that:

- burning rates increase by up to 400% during the vigorous burning phase, likely as a result of liquid oil droplets being ejected into the flames by the action of the underlying boiling water.
- the increase in burn rate during the vigorous burning phase appears to be an inverse function of fire size — the increase is a factor of two for a diameter of 0.6 m, a factor of 1.8 for a diameter of 2 m, and a factor of 1.3 at a diameter of 17 m.
- heat release rates and flame heights are consequently increased during the vigorous burning phase.
- for small fires up to 10 mm in initial thickness the duration of the vigorous burning phase is relatively unaffected by initial slick thickness, but the intensity of the vigorous burn phase increases with increasing slick thickness (see Figure 4.6); for larger fires up to 90 mm thick there seems to be a trend of an increased length of vigorous burn with increasing slick thickness (but not diameter). This would make sense as the depth of the "hot zone" in the thicker slicks would increase with time leading to a longer vigorous burning phase.

One effect of the vigorous burning phase that has been observed is foaming of the burning oil, followed by rapid extinguishing of the flames (S.L. Ross 1989, SINTEF and S.L. Ross 1993, Energetex 1980, Hall 1973). This appears to be a phenomenon related to oil type, with the presence of water in the burning oil a key contribution to foaming (S.L. Ross 1989, Energetex 1980, SINTEF and S.L. Ross 1993).

4.4 Oil Removal Efficiency and Residue Amounts

Oil removal efficiency, defined as the percentage of the original oil that was ignited that is remaining after the flame extinguishes, is primarily a function of three factors: the initial thickness of the slick; the thickness of the residue remaining after extinction; and, the coverage of the flame spreading. Other, secondary factors include environmental effects such as wind and current herding of slicks against barriers and temperature effects. Flame spreading is discussed in the succeeding section.

The dependence of burn efficiency on initial thickness is straightforward for the case of a fully ignited slick in a relatively quiescent environment:

$$\% \text{ removed} = (1 - x_r/x_o) 100\% \quad (4-5)$$

where

x_o = initial slick thickness [mm]

x_r = residue slick thickness [mm]

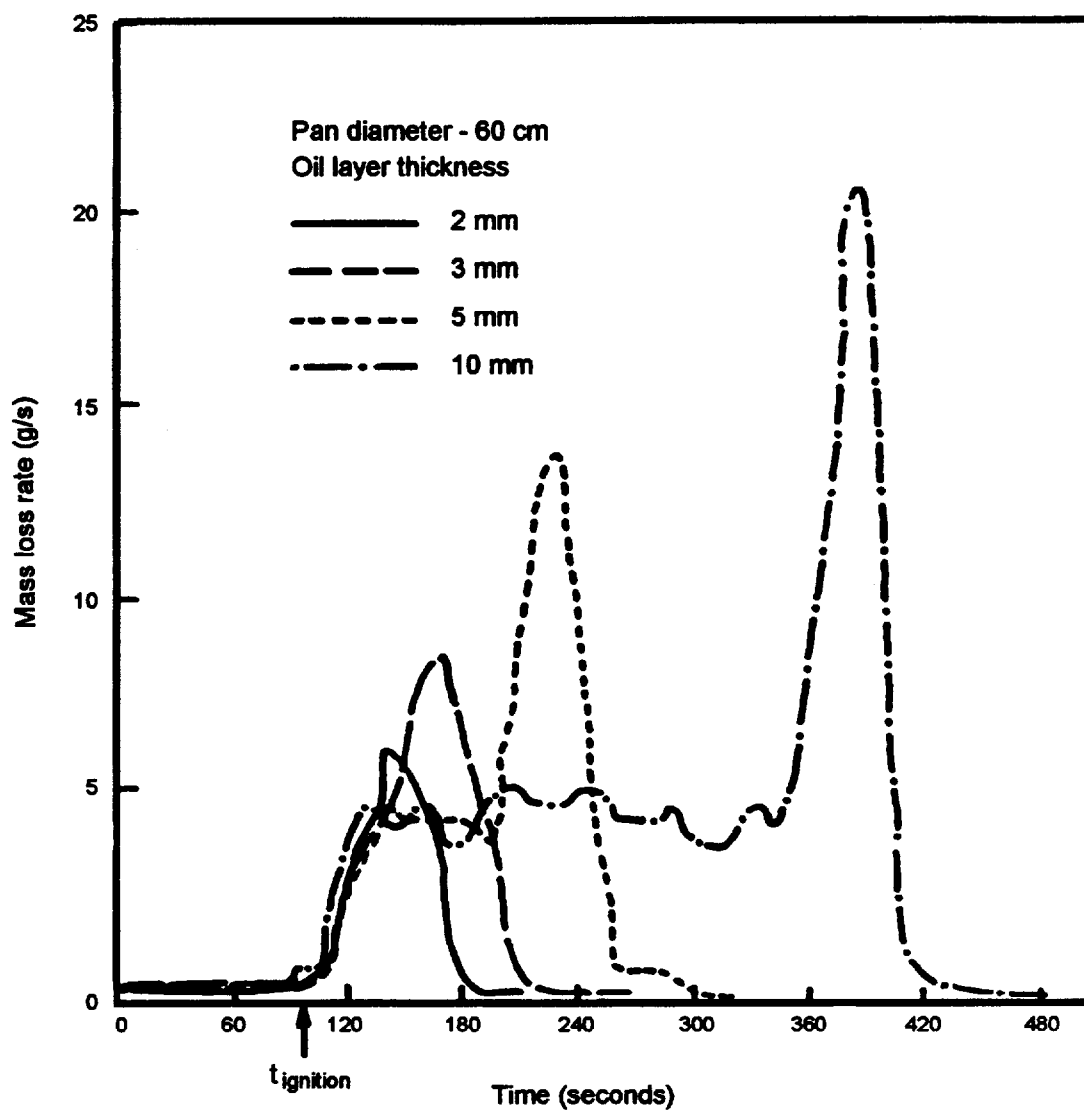


Figure 4.6 Effect of oil layer thickness on mass loss rate (fuel) for crude oil fires (from Evans et al. 1989)

For constant residue thickness, it is seen that the burn efficiency is simply dependent on the initial thickness of the slick.

Numerous investigations have studied the effects of various parameters on residue thickness and burn efficiency (e.g., Maybourn 1971, Energetex 1980, Wakamiya *et al.* 1982, S.L. Ross and Energetex 1986, Evans *et al.* 1986, 1987, 1988, 1992 and 1993, Smith and Diaz 1986 and 1987, Bech *et al.* 1992). The major results from these studies are discussed below.

Residue thickness is a weak function of initial thickness in quiescent burns. Up to an initial thickness of about 40 mm the residue thickness is approximately constant at 1 mm; for initial thicknesses greater than about 40 mm the residue thickness increases with increasing thickness. Data from S.L. Ross and Energetex (1986) (see Figure 4.7) show no clear correlation of increasing residue thickness with increasing initial thickness for 1 and 2 m diameter burns. The data of Evans *et al.* (1992) (Figure 4.7) indicate an increase in residue thickness with initial thickness for 7 m diameter fires. The data of Wakamiya *et al.* (1982) (2 m diameter, 50 mm initial thickness, average of 6 crudes) are also shown on Figure 4.7.

There may be a dependence of residue thickness on oil type. Energetex (1980) reports that the residue thicknesses for Bunker C fuel were 2 to 3 times greater (2 mm) than for equivalent burns of crude oils and diesels (0.5 to 0.8 mm). Wakamiya *et al.* (1982), however, reported no difference in residue thickness (5 mm) between crude oil and Bunker "C" for initially thick (50 mm) burns. S.L. Ross and Energetex (1986) report no observable difference between the residue thickness remaining after diesel and crude oil burns. The differences in the oils that cause differences in residue thickness may be overshadowed by the "hot zone" formation in initially thick, large fires.

Degree of evaporation does not seem to be a factor in unemulsified oil burn residue thickness (Energetex 1980, S.L. Ross 1989, Evans *et al.* 1992, Cabioc'h 1993) with the possible exception of the case of thin slicks of highly weathered oil (Bech *et al.* 1992).

Environmental factors also can affect the thickness, or amount, of residue remaining. The key factors for unemulsified oils are wind and currents. The action of these two forces is to continuously herd a slick against a barrier, thus thickening the oil as it burns down.

The phenomenon of "wind herding" is well known and the efficiency of wind to herd oil against a barrier has been extensively studied (Energetex 1981) and modelled (Energetex 1981, S.L. Ross and Energetex 1986). It is the phenomenon of a self-induced wind (that is drawn in by the combustion process and the rising column of hot gases) keeping an uncontained slick at burnable thicknesses that is the basis for the theory of "uncontained" in-situ burning (S.L. Ross and Energetex 1986). As little as a 2 m/s wind is capable of herding oil to thicknesses that will sustain combustion. The residue remaining after a burn against a barrier in winds 2 m/s or greater should be substantially less than in calm conditions, but, as wind speed increases the flames are bent further over and the heat radiated back to the fuel surface decreases. The interfacial tension of oil decreases with increasing temperature as does its viscosity, both of which lead to a greater tendency for the oil to spread. The interplay of these factors results in only a small increase in burn efficiency with increasing wind speed for small diameter burns (Figure 4.8).

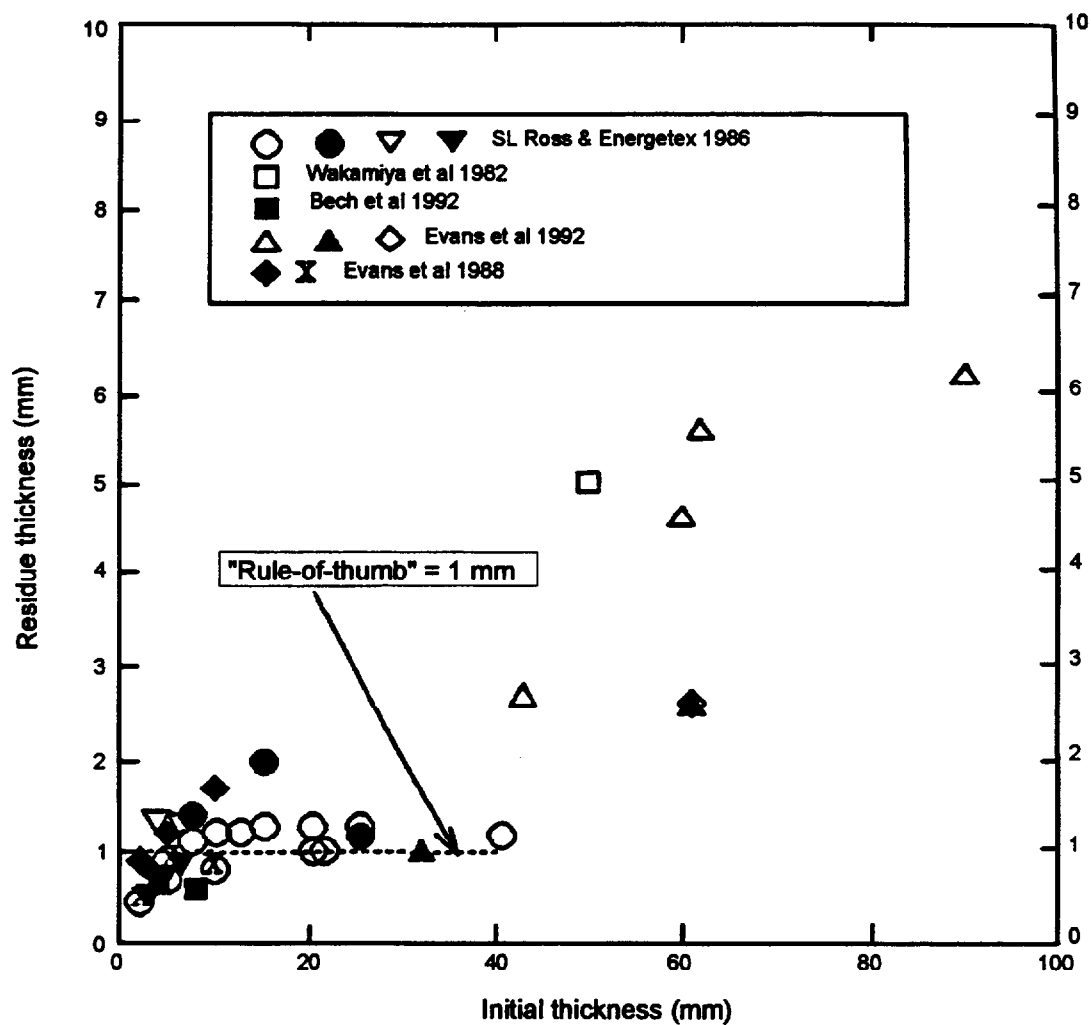


Figure 4.7 Residue thickness as a function of initial slick thickness

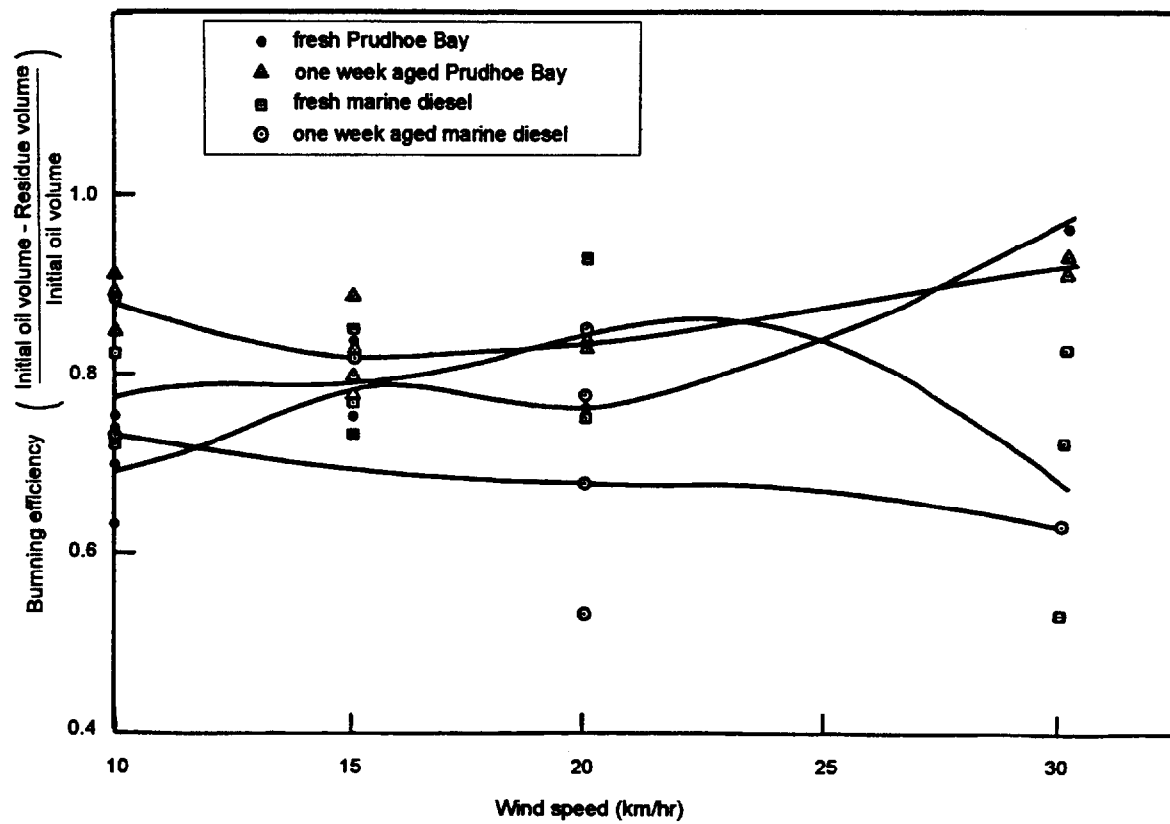


Figure 4.8 Removal efficiency vs. wind speed for 1m² burns (from Energetex 1981a)

The beneficial effects of wind herding for large fires, noted by many researchers, can be noticed during the extinction phase of a burn. As the flames die down after the vigorous burning stage, the oil cools and, as it is pushed by wind against the barrier and thickens, it re-ignites (if some flames are still present) or can be re-ignited. This process can result in extremely high burn efficiencies (Dome 1981, S.L. Ross and Energetex 1986, Evans *et al.* 1992).

Currents can also dramatically reduce the amount of residue remaining by herding oil against a barrier. Although this phenomenon has not been thoroughly researched, recent field trials (SINTEF and S.L. Ross 1993, OSIR August 18, 1993) suggest that burning against a barrier in currents can result in very low amounts of residue. The detrimental effects of currents on the amount of residue could include entrainment of residue beneath a floating barrier as the residue density and viscosity increase during the burn process (SINTEF and S.L. Ross 1993) and overwashing of the burning slick, causing extinction of the flames (Energetex 1981, SINTEF and S.L. Ross 1993).

Ambient temperature does not seem to affect the amount of residue remaining. Comparison by Wakamiya *et al.* (1982) of burn efficiency data from two test sites with a 25°C ambient temperature difference showed no difference. Similar results were obtained by Evans *et al.* (1988) over a 23°C temperature difference.

The effects of waves on residue remaining seem to be a function of the scale of the burn and the type of wave. Tam and Purves (1980) noted that steep, 5 cm waves resulted in a reduction in burn efficiency from 84% to 24% for 1 m diameter burns; steep, 10 cm waves further reduced the efficiency to 10%. Tests of a fire proof boom at OHMSETT with 38 L of oil in a 2 m diameter semi-circle showed increased residue amounts with increasing wave height (0.2 m x 19 m swell and 0.4 m x 19 m swell). Choppy waves extinguished burning slicks. Tests with a 13 m diameter slick of unemulsified crude oil in 40 cm x 3 to 4 m long regular waves (Bech *et al.* 1993) resulted in a 90% burn effectiveness (including the effects of wind herding). Presumably the detrimental effect of waves relates to increased heat transfer through the slick causing earlier slick cooling.

In summary, burn efficiency is a strong function of initial slick thickness; anything that serves to thicken or contain the burning oil results in improved burn efficiencies. Residue thickness, or amount, is the other factor that dictates burn efficiency. A good "rule-of-thumb" is that the residue is 1 mm thick for initial slick thicknesses of up to 40 mm; above this the residue thickness increases to about 6 mm for a 100 mm thick slick in quiescent conditions. The action of winds (from 2 to 12 m/s) and gentle currents (up to 0.4 m/s) can greatly reduce the amounts of residue remaining after a burn against an edge. The action of waves may be detrimental to burn efficiency, even to contained slicks, particularly if the waves are short, steep and choppy.

4.5 Oil Slick Ignition and Flame Spreading

4.5.1 Oil Slick Ignition

An important goal in in-situ burning of oil is to ignite the maximum possible area of the slick. Ignition involves heating of the slick to a temperature high enough that the liquid hydrocarbons are vaporizing fast enough to generate a concentration in the air layer above the slick that is great enough to support burning (the Lower Flammability Limit or Lean

Flammability Limit) then providing ignition energy to start burning. It should be noted that, as the temperature of the oil rises and its vaporization rate increases, the concentration of fuel vapors above the slick can exceed the Upper Flammability Limit or Rich Flammability Limit and the vapors will not burn until more air diffuses into the mixture. This may be a process that occurs in the center of large diameter fires. The temperature at which the slick produces vapors at a sufficient rate to catch fire is called the Flash Point. At a temperature (called the Fire Point) a few degrees above the Flash Point the oil is warm enough to supply vapors at a rate sufficient to support continuous burning (Kanury 1988). The ambient temperature of a slick and its Flash Point are extremely important considerations for in-situ burning from ignitability and safety perspectives.

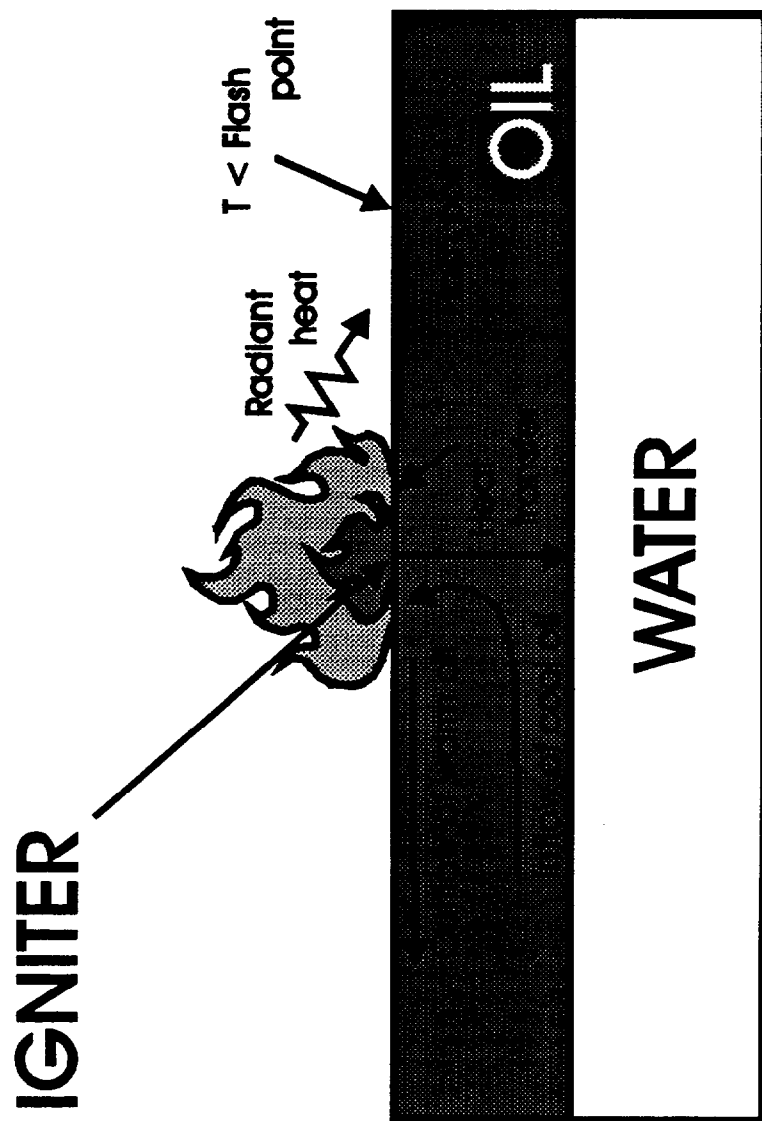
Ignition of an oil slick and subsequent flame spreading are strong functions of temperature of the slick. If the oil is at a temperature above its flash point, ignition is simple and flame propagation is rapid; otherwise ignition and flame spreading can be slow and difficult.

For an oil slick on water at a temperature below its flash point, the igniter must heat the slick to above its flash point. This problem involves two aspects: heat transfer through the slick and convective motion effects induced in the heated slick (Figure 4.9). When an oil slick on water at a sub-flash temperature is exposed to a radiant heat/ignition source initially, the surface of the slick is heated. As soon as this happens, the warm oil (with a lower air/oil interfacial tension than the colder, underlying oil) begins to flow horizontally away from the heat source. Its place is taken by colder fuel rising up from beneath in convection-induced, gravity-driven flow. It has been shown that this convective flow is decreased with increasing oil viscosity and decreasing bulk oil surface tension (Murad *et al.* 1970); thus, more viscous oils (all other factors being equal) are easier to ignite. In any case, as heat is flowing outward, it is also simultaneously conducted and convected vertically through the oil slick to the underlying water. If the slick is sufficiently thick to insulate itself and allow the surface layer to heat to its flash point, the slick will start to burn in the vicinity of the igniter.

Extensive experimentation with a variety of oil types, igniters and environmental conditions (Maybourn 1971, Energetex 1978 and 1980, Spiltec 1987, S.L. Ross 1989, Bech *et al.* 1993) has confirmed the following "rules-of-thumb" for the ignition of oils on water in relatively calm, quiescent conditions:

- the minimum ignitable thickness for fresh, volatile crude oil on water is about 1 mm;
- the minimum ignitable thickness for aged, unemulsified crude oil and diesel fuels is about 3 to 5 mm;
- the minimum ignitable thickness for residual fuel oils, such as Bunker "C" or No. 6 fuel oil, is about 10 mm; and,
- once 1 m² of burning slick has been established, ignition can be considered accomplished.

Note that although thick residual fuel oil slicks have been found to be ignitable, it is likely that efficient burning of a large spill of residual oil at sea will be extremely difficult



65 *Figure 4.9* Heat transfer and convective motion during slick ignition

unless promoters like diesel are first spread on its surface to enhance flame spreading.

Aside from oil type, several factors can affect the ignitability of oil slicks on water. The key parameters are: wind speed and igniter strength; secondary factors include ambient temperatures and waves. Emulsification of the oil affects ignitability but this is dealt with in a separate section.

The effects of wind speed on the ignitability of oil slicks has been studied both theoretically and experimentally. Murad *et al.* (1970) developed a physical model for the streamlines denoting the lean flammability limit over a flat pool of evaporating, combustible liquid at a temperature above its flash point in a laminar boundary layer of flowing air. They showed that the thickness of the ignitable layer of vapors over the fuel pool decreased with increasing wind speed. Wind speed also reduces the ignitability of oil slicks at sub-flash temperatures possibly by increasing convective heat and mass transfer at the oil/air interface. Energetex (1981) in tests with solid propellant igniters reported that, in an 8 m/s wind created by a fan adjacent to the slick (equivalent to an 11 m/s wind measured at a 10 m elevation) ignition of weathered crude and marine diesel slicks was not possible, even with slick thicknesses of 10 mm. For fresh crude oil a 2 mm slick was ignitable in a 3 m/s wind but not in an 8 m/s wind (11 m/s @ 10 m) the minimum ignitable thickness for fresh crude in an 8 m/s (11 m/s @ 10 m) wind was 5 mm. Spiltec (1987) reports that winds of 3 to 5 m/s did not affect slick ignition with small (60 to 120 ml) blobs of gelled gasoline; but, winds of 8 m/s required the use of 250 to 500 ml blobs to effect ignition. The maximum wind speed for successful ignition for large burns has been estimated as 10 to 12 m/s (Bech *et al.* 1993, Cabioc'h 1993).

The presence of waves can prevent the ignition of marginally ignitable slicks (Tam and Purves 1980, Energetex 1981, Bech *et al.* 1993). Energetex (1981) reports that the minimum ignitable thickness for one week aged Prudhoe Bay crude increased from about 3 mm in a 5 m/s wind to 10 mm with the application of 10 cm high waves.

Ambient temperature can also affect slick ignitability. If an oil slick is at a temperature above its flash point it will ignite rapidly and easily; oil slicks at sub-flash temperatures are more difficult to ignite. Ambient temperature has a greater effect on flame spreading velocity than on ignition, as discussed in the next section.

Various devices and techniques have been developed for the ignition of oil slicks on water; a detailed discussion of these is reserved for a section in the next chapter (5.2).

4.5.2 Flame Spreading

Flame spreading is a crucial aspect of effective in-situ burning; if the fire does not spread to cover a large part of the surface of a slick, the overall removal efficiency will be low. Flame spreading can be divided into two distinct categories: sub-flash and super-flash spreading with an intervening transition zone characterized by pulsating spread. The dependence of flame spreading velocity on liquid temperature is shown in Figure 4.10 (Akita 1972) for methanol. At temperatures above the fluid's flash point, the flame spreading is controlled by vapor phase effects. As the temperature rises from the flash point to the stoichiometric temperature (the liquid temperature required to produce vapor at a rate allowing combustion of stoichiometric amounts of fuel and oxygen) the flame spreading velocity increases from the laminar flame burning velocity at the lean flammability limit to a maximum that is on the order of the laminar flame burning velocity for a stoichiometric mixture of fuel vapor and air. For sub-flash fuel temperatures, the flame spreading velocity

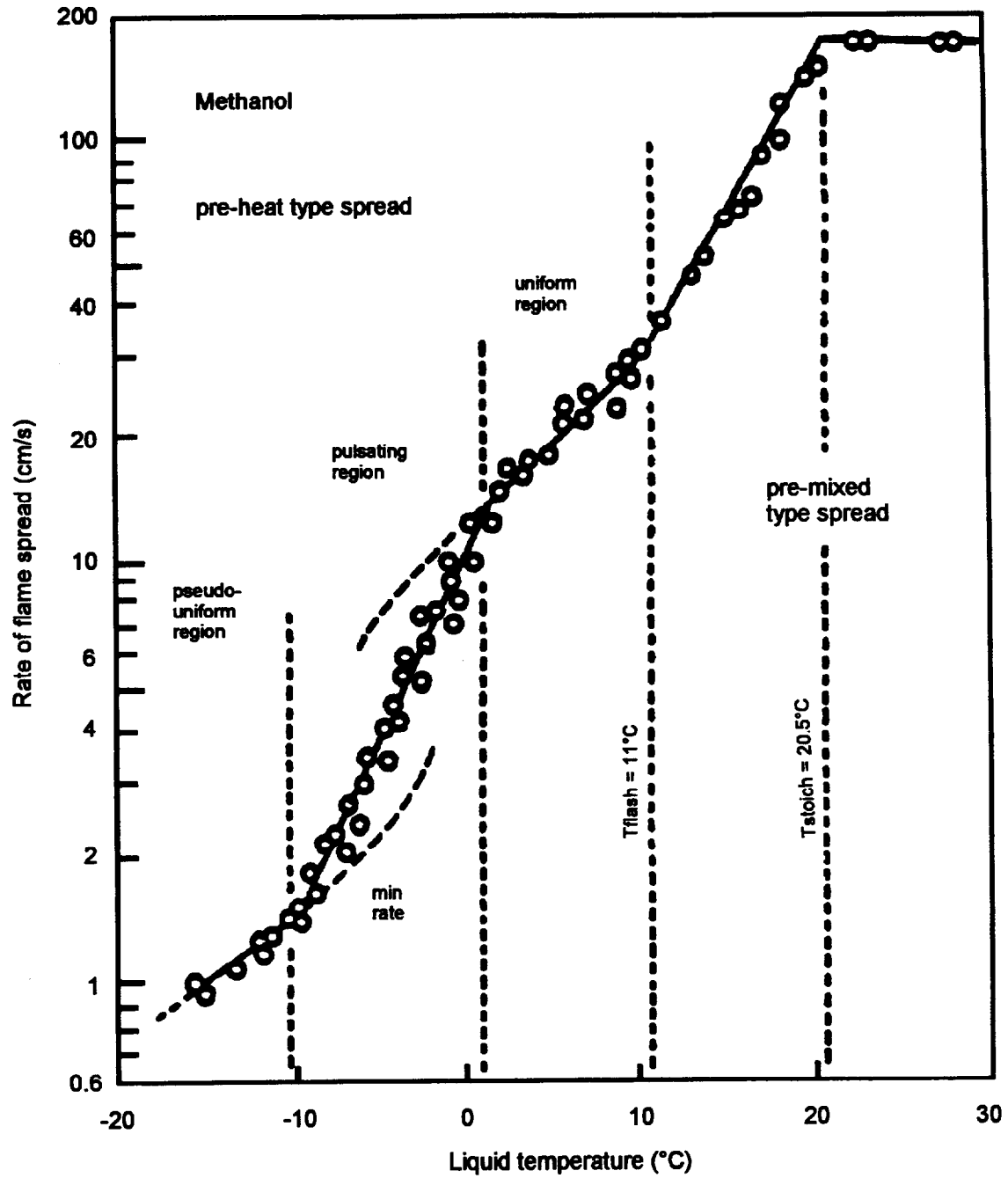


Figure 4.10 Relationship between the liquid temperature and the rate of plane flame spread of methanol in a vessel 2.6 cm wide and 1.0 cm deep.

seems to be controlled by liquid-phase heat and mass transfer phenomena. Starting at a temperature well below the flash point (say -20°C on Figure 4.10) the flame spreading is controlled by the rate at which the cold fuel in front of the flame is warmed by the advancing flame front. There are two mechanisms by which heat is conducted from the flame to the cold fuel: radiation and convective flow (Glassman *et al.* 1968, Sirignano 1970, Mackinven *et al.* 1970, Akita 1972). In the early stages of fire spreading over a sub-flash fuel on water, it is the convective flow process that dominates; for larger fires, the radiation of heat dominates (Mackinven *et al.* 1970). Figure 4.11 shows a schematic cross-section of an advancing flame that illustrates the processes involved for a quiescent sub-flash situation.

For small fires (and in the early stages of a larger fire), the fuel underneath the leading edge of the flame front is hotter than the unignited fuel; as such the hot fuel has a lower interfacial tension than the cold fuel and tends to flow forward over it (Mackinven *et al.* 1970, Glassman *et al.* 1968, Torrance *et al.* 1974). This is called the Marangoni effect. This interfacial tension flow outwards sets up a return flow of cold oil beneath the warm layer. As well, the combustion process itself sets up a bulk inward flow towards the fuel (Torrance and Mahajan 1974). Additional resistance to the interfacial flow is provided by viscous dissipation in the warm fuel layer itself (Glassman and Hansel 1968, Glassman *et al.* 1969). Figure 4.12 shows the dependence of flame velocity on fuel viscosity for a slick of kerosene at temperatures 40°C below its flash point (Glassman *et al.* 1969). It is interesting to note that the flow-dissipating effects of increased viscosity aid in ignition of oil slicks (discussed in the previous section), but detract from subsequent flame spreading. This may be an area for future igniter development research.

As the bulk temperature of the fuel approaches the flash point on Figure 4.10, the flame begins to pulsate. This pulsating region is characterized by a thin, blue "pre-mixed" flame travelling ahead of the yellow "diffusion" flame front (Figure 4.11). Akita (1972), Glassman and Hansel (1968), and Mackinven *et al.* (1978) state that for hydrocarbon fuels this pulsating flame relates to the difference between the flash and fire points of the fuel. As the oil surface in front of the flame front heats up to the flash point, the flame flashes forward, consumes the vapor and flashes back. A few degrees warmer and the fuel exceeds its fire point and continuous burning begins.

Many in-situ burning studies (e.g., Energetex 1977-1981, Evans *et al.* 1986, 1988, 1992, S.L. Ross 1989, SINTEF and S.L. Ross 1993) have measured flame spreading rates as the time for the flame to cover the entire surface of the slick and denoted this as ignition time. Their results indicate that, in quiescent conditions:

- as oil weathering increases, ignition time increases (i.e., the difference between ambient temperature and the oil's flash point increases, decreasing the flame spreading velocity);
- ignition times decrease with increasing slick thickness; and,
- for a constant thickness and flash point, increasing viscosity reduces flame spreading rates.

S.L. Ross and Energetex (1986) used a small wind tunnel to study flame spreading velocities and the effects of wind and ambient temperature. Their results for a fresh and weathered (unemulsified) crude and diesel fuel are shown on Figure 4.13.

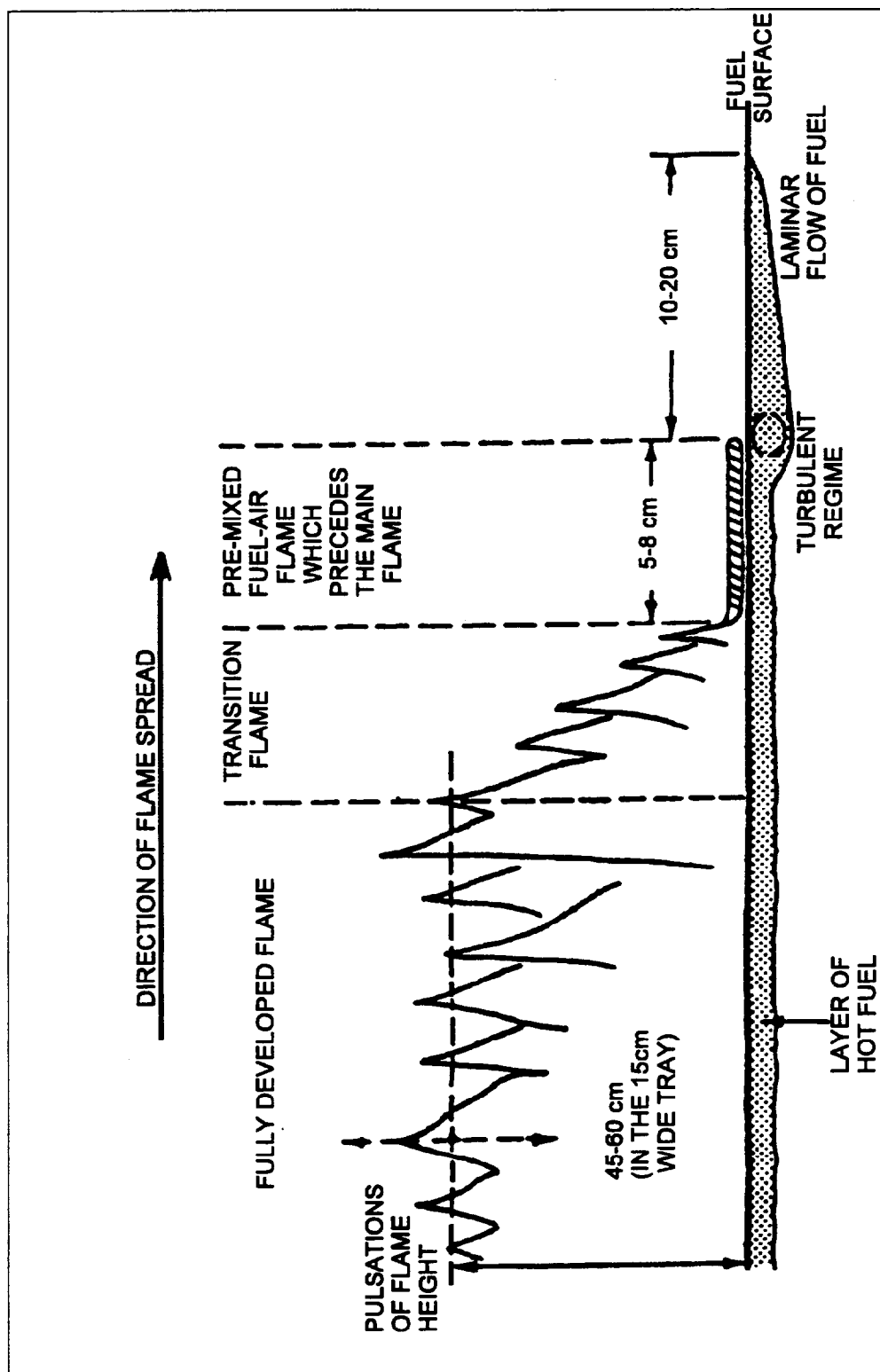


Figure 4.11 Schematic representation of the spreading flame

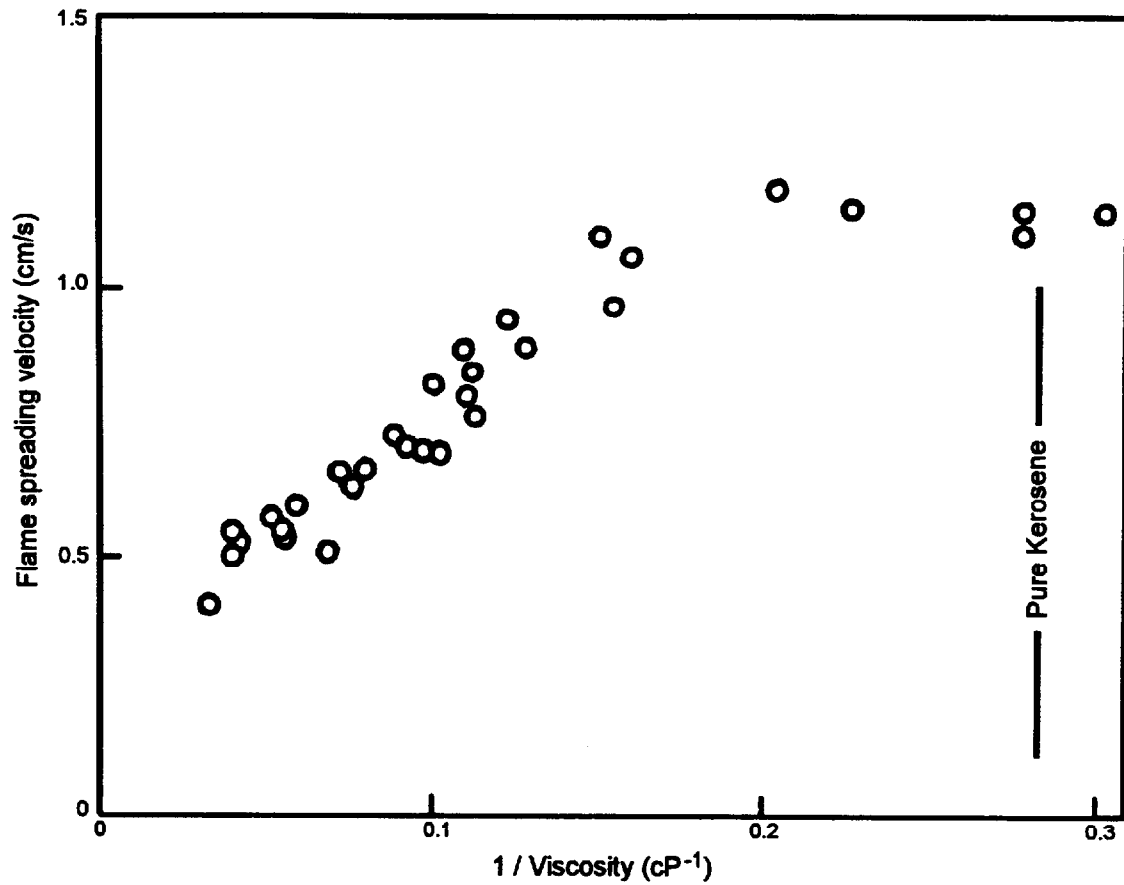


Figure 4.12 *The flame spreading rate across thickened kerosene surfaces at room temperature (21°C) as a function of viscosity. A 3.5 mm kerosene film floated on 7.0 mm of water. (from Glassman et al. 1969)*

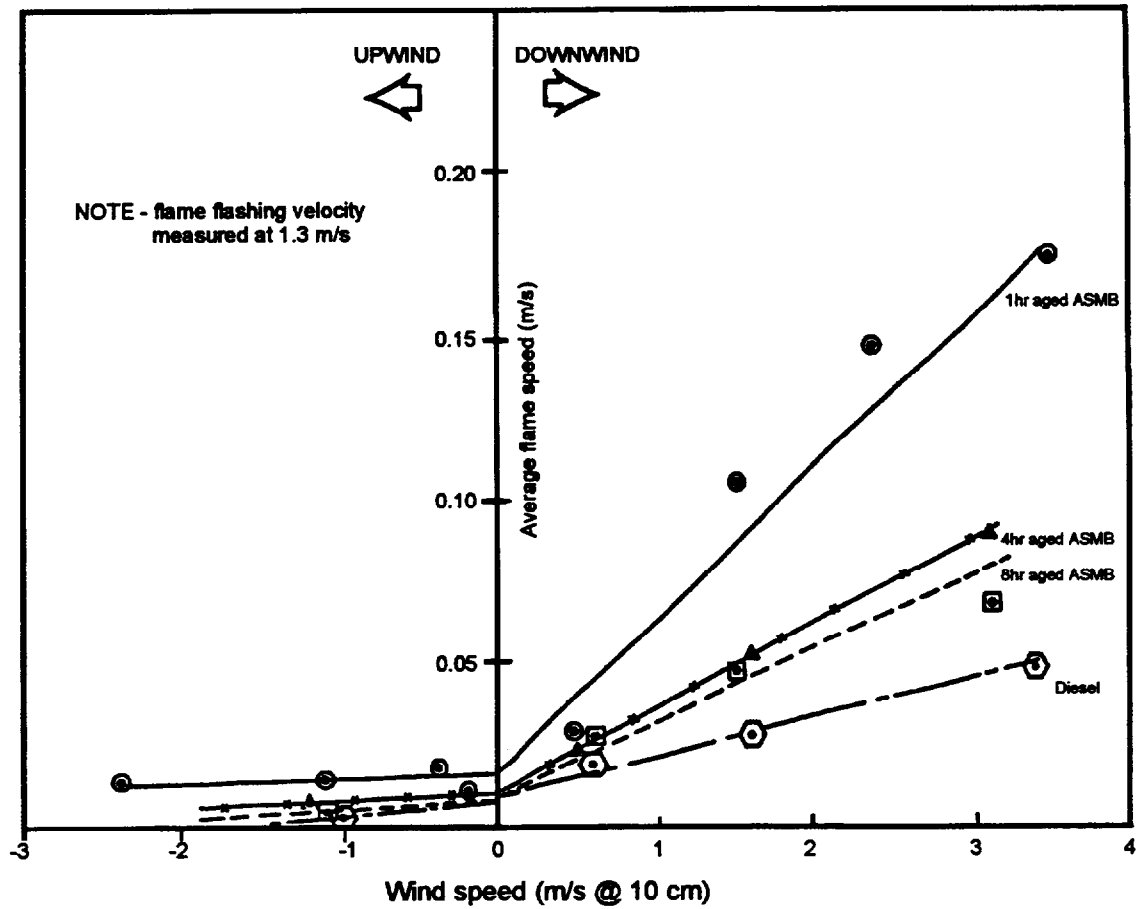


Figure 4.13 Flame spreading velocity

The data show that downwind spreading increases with increasing wind speed. This is likely due to the bending of the flame by the wind enhancing radiative heat transfer to the slick (Energetex 1981). The flame velocity is also dependent on oil volatility.

The data in Figure 4.13 show that flame spreading upwind is slow but measurable. This spreading must be due to surface-tension-driven flow as radiative heat transfer on the upwind side of the flame would be near zero. S.L. Ross and Energetex (1986) developed a simple model to reflect these effects on sub-flash flame spreading velocity. They based the oil volatility term on initial boiling point rather than flash point, because flash point results vary greatly with the method and apparatus employed (Murty 1988). The model is:

- for upwind flame spreading

$$U_{F,u} = 1.3 \exp (-7.88 ((T_B - T_A)/T_B)^{0.19}) \quad (4-6)$$

where the term 1.3 is the flame flashing velocity in quiescent conditions

- for downwind flame spreading

$$U_{F,d} = U_{F,u} + u \exp (-6.52 ((T_B - T_A)/T_B)^{0.23}) \quad (4-7)$$

where

$U_{F,u}; U_{F,d}$	=	upwind and downwind flame spreading velocities [m/s]
u	=	wind speed [m/s]
T_B	=	initial boiling point of oil (ASTM D87) [°K]
T_A	=	temperature of oil slick [°K]

Data from Smith and Diaz (1985) indicate an upwind flame spreading velocity of 0.04 m/s for fresh Prudhoe Bay crude and 0.025 m/s for weathered crude against 4 to 7 m/s winds. For crosswind flame spreading the upwind flame velocity is used. This is consistent with the observation that, in windy conditions, flames spread nearly straight downwind from an ignition point without much crosswind spread (e.g., Energetex 1981, Dome 1981). Data reported in Bech *et al.* 1992 for downwind flame spreading velocities over slicks of weathered crude oil show a trend in declining spreading velocity with increased weathering.

It has been observed numerous times that, although flame spreads slowly upwind or crosswind, the presence of a barrier or edge that provides a wind break can permit rapid upwind or cross-wind spreading.

The presence of currents and regular waves (or swell) does not seem to affect flame spreading for unemulsified oils, but choppy or steep waves have been noted to curtail flame spreading (Energetex 1981, Dome Petroleum 1980, Bech *et al.* 1993).

4.6 Flame Heights and External Radiation

Flames from in-situ burning of oil on water are characterized as diffusion flames (in which oxygen must diffuse into the combustion zone) with yellow or orange color and smoke production (as opposed to blue, premixed flames where the correct amount of oxygen is already present in the combustion zone). For the size range of interest for in-situ burning (>1 m diameter) the flames can be considered as turbulent. The starved (i.e., oxygen-poor) nature of in-situ combustion of large oil slicks results in the obscuration of the flames by the thick, black smoke produced. This often makes it difficult to estimate flame heights for these fires.

Furthermore, large pool-fire flames are known to oscillate in height at a predictable frequency. Evans *et al.* (1992) have correlated in-situ burning flame pulsation data for 2 to 17 m diameter crude oil fires on water with Pagni's (1991) equation:

$$f = 1.5/D^{1/2} \quad (4-8)$$

where

$$\begin{aligned} f &= \text{pulsation frequency [Hz]} \\ D &= \text{diameter of fire [m]} \end{aligned}$$

The results of Evans *et al.* (1992) indicate little effect of wind speed on pulsation frequency.

The best available data set on flame heights of large-diameter hydrocarbon fires is that of Blinov and Khudiakov (1959) shown in Figure 4.14. Also shown on Figure 4.14 are the data of Gostintsev *et al.* (1984); data from photographs contained in McAllister and Buist (1981), S.L. Ross and Energetex (1987), SINTEF and S.L. Ross 1993; estimates based on thermography from Koseki (1993) and reported flame heights from a test burn after the *Exxon Valdez* spill (Allen 1991). It should be noted that it is extremely difficult to visually estimate flame heights and particularly so from photography; it is likely that such flame height estimates are only accurate to within $\pm 50\%$. Another complicating factor is that all of the above-noted larger burns occurred outdoors in some wind, which will bend flames and affect flame heights.

McCaffrey (1988) recommends the following equation of Heskestad (1983) to estimate flame heights of pool fires:

$$\frac{H}{D} = 3.7 Q^{*0.4} - 1.02 \quad (4-9)$$

where

$$\begin{aligned} H &= \text{flame height [m]} \\ D &= \text{flame diameter [m]} \end{aligned}$$

and, for pool fires of hydrocarbons

$$Q^* = Q/(\rho_{\infty} C_p T_{\infty} g^{1/2} D^{5/2}) \quad (4-10)$$

where

$$\begin{aligned} Q^* &= \text{dimensionless heat release rate} \\ Q &= \text{heat release rate [kW]} \\ \rho_{\infty} &= \text{density of ambient air [kg/m}^3\text{]} \\ C_p &= \text{heat capacity of ambient air [kJ/kg}^\circ\text{K]} \\ T_{\infty} &= \text{absolute temperature of ambient air [}^\circ\text{K]} \\ g &= \text{acceleration of gravity [m/s}^2\text{]} \end{aligned}$$

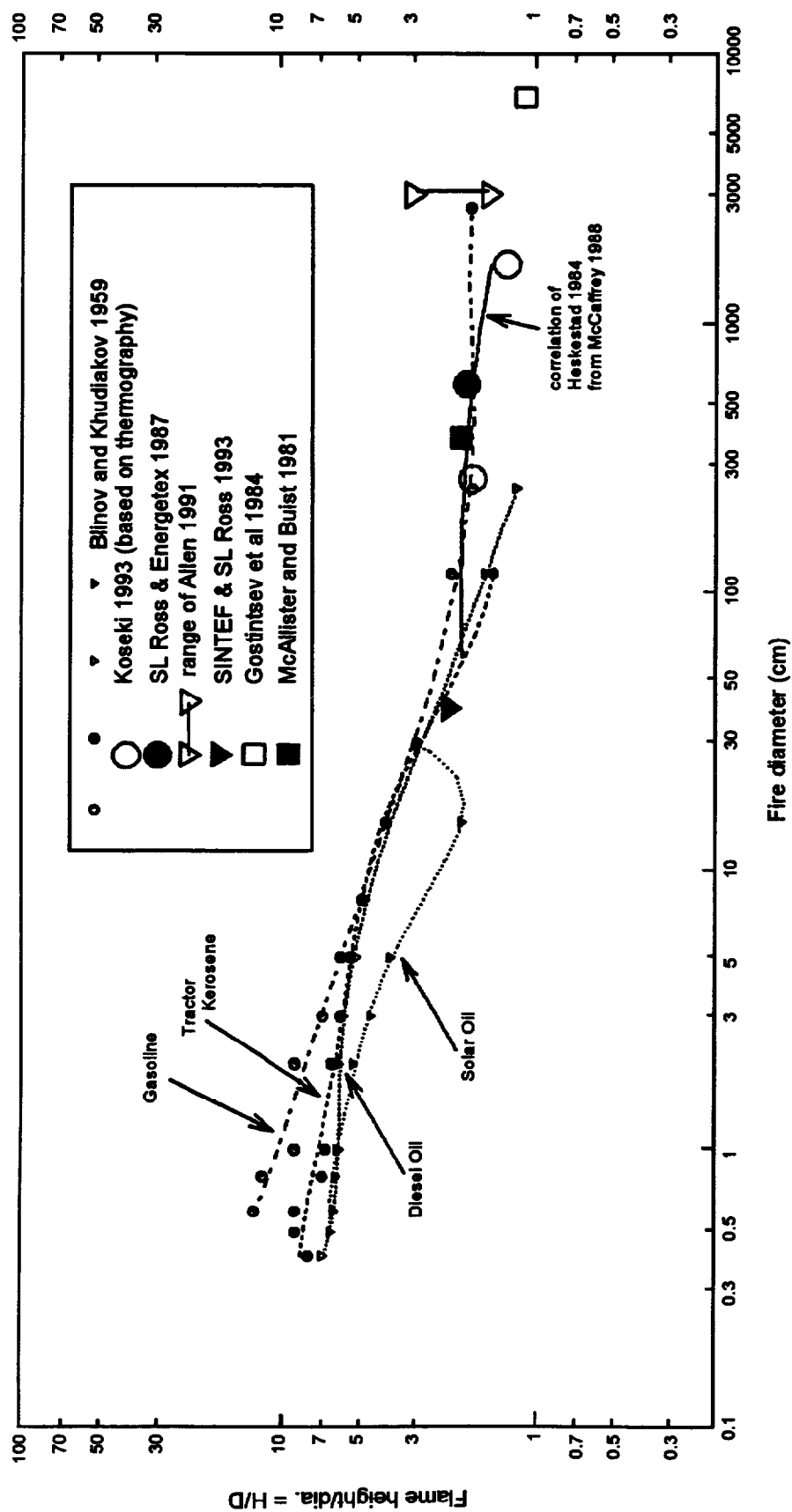


Figure 4.14 Flame height vs. fire diameter - a comparison of data sets

McCaffrey (1988) recommends the use of

$$Q^* = Q/(1110D^{5/2}) \quad (4-11)$$

where

$$Q = m\Delta H \quad (4-12)$$

where

m = mass burning rate [kg/s]

ΔH = net heat of combustion of fuel [kW/kg]

Data from Evans *et al.* (1992) and Walton *et al.* (1993) indicate the following dependence of Q (for steady state burning) on D for crude oil fires:

D(m)	Q (kW)	Q^*	H/D
0.6	180	0.58	1.96
2.0	4000	0.64	2.07
6.9	82,000	0.59	1.98
17.02	500,000	0.37	1.46

At smaller fire diameters, (0.6 to 7 m) H/D is almost constant at 2; this coincides with the “rule-of-thumb” that fire heights are twice the fire diameter. At greater fire diameters, the ratio declines, as predicted by equation 4-9 (see also Figure 4.14). The data of Gostintsev *et al.* 1984 indicates that the flame height to fire diameter ratio approaches one as the fire diameter approaches 100 m.

One characteristic of the vigorous burning phase is an apparent increase in flame height compared to steady state burning. Evans *et al.* (1992) and Walton *et al.* (1993) give the increase in heat release rate during vigorous burning. This increase, as a function of flame diameter, and the corresponding increase in flame height are shown below.

D[m]	Q_{vig}/Q_{ss}	H/D	% increase in height over steady state burning
0.6	1.95	2.865	47%
2.0	1.76	2.88	64%
12	1.25	2.21	77%
17	1.34	1.80	34%

As shown, the flame heights during vigorous burning can be expected to be greater than the steady state height. This is consistent with anecdotal reports of in-situ burns.

Wind is the predominant environmental factor that affects flames. Its primary effect is to deflect the flame from the vertical. Mudén and Croce (1988) give two correlations for

the effect of wind speed on flame length; Thomas's (1963) correlation for wood crib fires shows a dependence of wind speed to the -0.2 power and Moorhouse's (1982) correlation for pool fires shows a -0.044 power dependence. Thomas's (1963) correlation would indicate a 50% increase in flame height with an increase in wind from 1 to 10 m/s. Moorhouse's correlation would predict only a 10% change in flame length with a similar wind speed increase. These increases are within the accuracy of flame height measurements because of flame pulsation.

Brzustowski and Twardus (1981) use the dimensional equation of Pipkin and Sliepcevich (1964) to estimate flame deflection angle as a function of wind speed:

$$\tan\delta/(\cos\delta)^{1/2} = 7.72F_r \quad (4-14)$$

where

δ = deflection angle from vertical [degrees]

F_r = kinematic Froude number = u^2/gD

u = wind speed [m/s]

The solution to this equation is shown in Figure 4.15. For a 17 m diameter fire in a 4 m/s wind ($F_r = 0.096$) a flame deflection angle of 30° from vertical would be predicted; this is broadly consistent with the thermographs presented by Koseki for a crude oil fire under similar conditions. SINTEF and S.L. Ross (1993) report nearly horizontal flames for a 3 m x 1 m fire ($D = 2$ m) in a 10 m/s wind ($F_r = 5.0$); equation 4.15 predicts a deflection angle of about 70°. Mudén and Croce (1988) recommend the American Gas Association correlation for hydrocarbon pool fires, which for most larger crude oil burns can be written as:

$$\cos\delta = 1.1 D^{1/6}/u^{1/2} \text{ for } D \text{ in m and } u \text{ in m/s} \quad (4-15)$$

This equation predicts a deflection angle of 25° for a 17 m diameter fire in 4 m/s winds and a 70° deflection for a 2 m diameter burn in 10 m/s winds.

The amount of heat radiated by the flame and smoke to external surfaces is a function of a number of variables and its theoretical derivation can be very complex (e.g., Tien *et al.* 1988). Shokri and Beyler (1989) have developed a convenient engineering expression based on measured data for large pool fires. Their correlation, which is valid only for vertical targets at ground level is:

$$q'' = 15.4 (L/D)^{-1.59} \quad (4-16)$$

where

q'' = incident heat flux [kW/m²]

L = distance from pool center to target [m]

Figure 4.16 shows a comparison of this correlation with some experimental in-situ burning measurements; though far from perfect, the fit is acceptable for estimation purposes. The increase (almost a doubling) in radiation associated with the vigorous burning phase is apparent in the data of Wakamiya *et al.* 1982 as shown in Figure 4.16. It is also worthy to note that Koseki (1993) has measured a considerable decrease in heat flux from crude oil fires at large fire diameters; he postulates that this is due to increased flame radiation blockage by soot particles in larger fires.

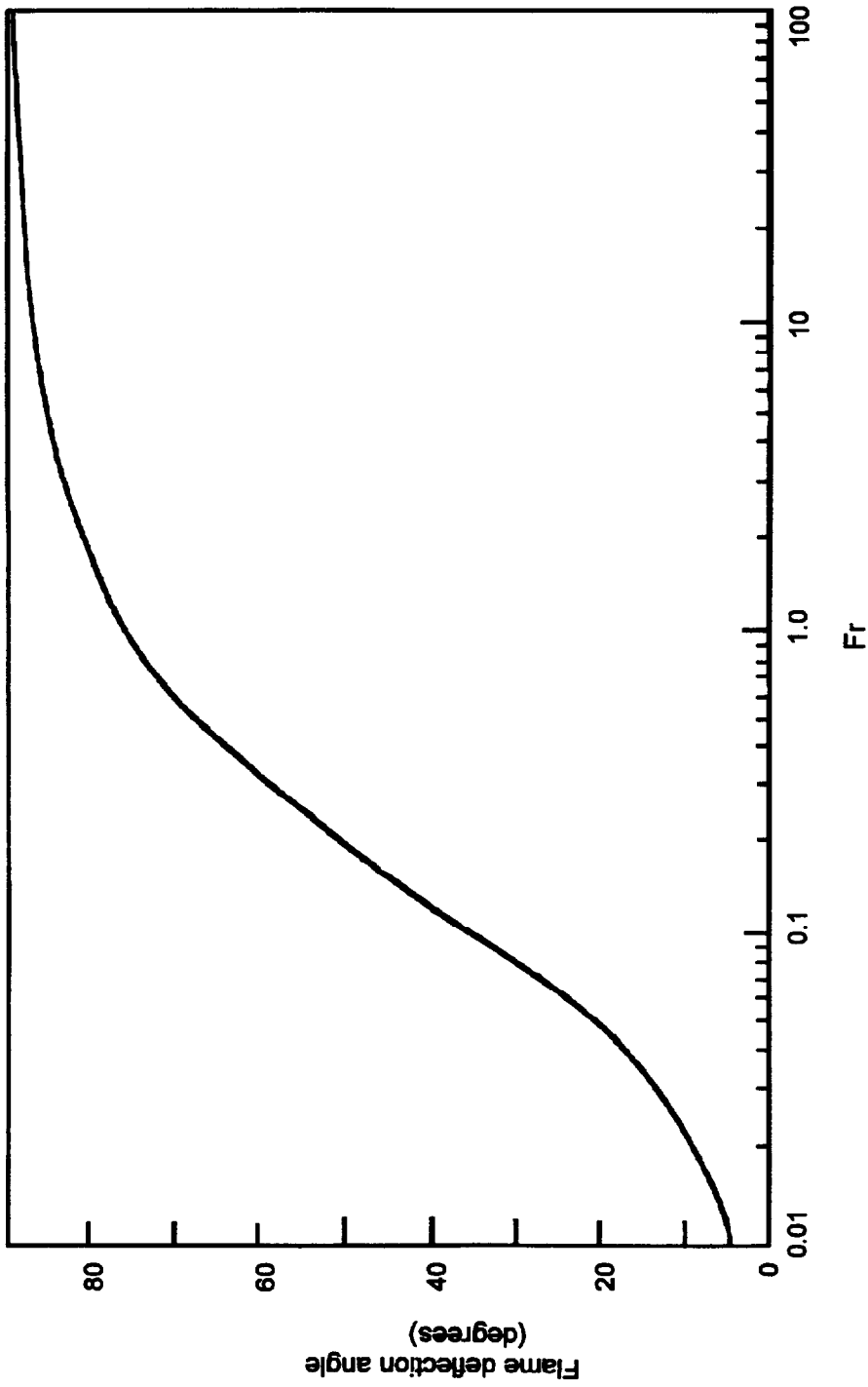


Figure 4.15 Flame deflection angle as a function of the kinematic Froude number, from Eq. 4-14 (from Brzustowski and Twardus 1981)

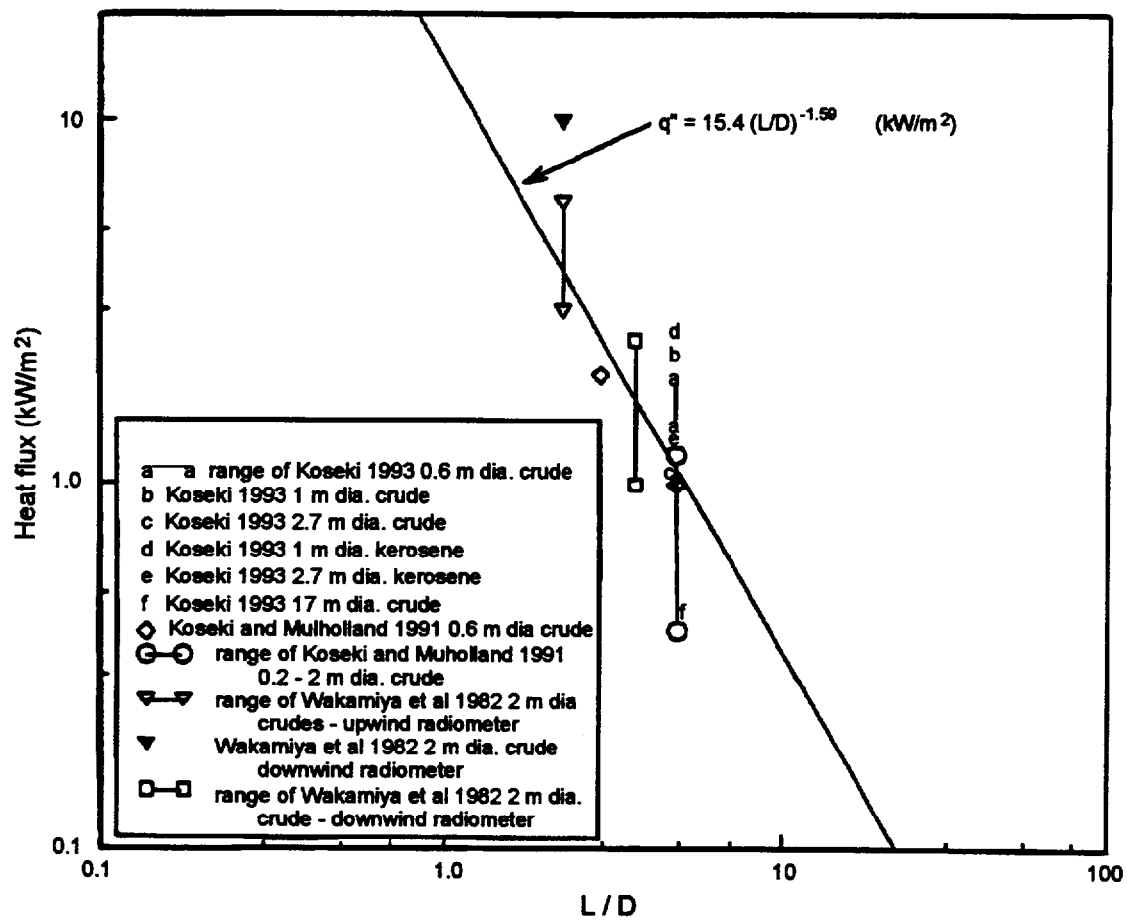


Figure 4.16 External heat flux from burning - comparison of Shokri and Beyler's (1981) correlation with in-situ burn data

4.7 Safe Distance from Oil Flame

Equation 4-16 above can be used to estimate the safe distance for response personnel to keep from the flame of a burning pool of oil. Figure 4.17 shows a number of data sets correlating heat flux from fires to exposure times for the uncovered skin of personnel. The limits for infinite exposure are in the range of 1.7 kW/m^2 (Muden and Croce 1988, Brzustowski and Sommer 1973, Atallah and Allen 1961). Substituting this into equation 4-16 above yields $L/D=4$. This means that the safe approach distance is 3.5 pool diameters from the edge of the fire. This is quite conservative as it does not take into account the effects of clothing and wind cooling on the safe heat flux. If personnel are exposed to bright sunlight in addition to fire radiation, the contribution of sunlight (1 kW/m^2) should be taken into account.

Closer approaches can be made to the edge of the fire for short periods of time. The table below summarizes the calculated safe approach distance (measured in fire diameters) to in-situ burns for various exposure times.

Calculated Safe Approach Distance to In-Situ Oil Fire

Exposure Time (min)	Safe Approach Distance for Personnel (fire diameters)
infinite	4
1/2 hour	3
5 minutes	2

Radiant heat fluxes necessary to cause charring and ignition of wood are on the order of 10 to 20 kW/m^2 ; these heat fluxes would be experienced within one diameter of the center of the fire (0.5 diameters from the edge).

4.8 Effects of Emulsification

Experiments on in-situ burning of emulsions have been conducted sporadically over the past 20 years (Maybourn 1971, Energetex 1980, Hossain and Mackay 1981, Energetex 1981, Dome 1982, S.L. Ross 1989). In the last few years, the research has intensified and become more focused (Bech *et al.* 1992 and 1993, Cabioc'h 1993, SINTEF and S.L. Ross 1993).

In-situ burning of water-in-oil emulsions involves several different processes compared to the burning of unemulsified oils. The key differences relate to the heat and mass transfer processes involved.

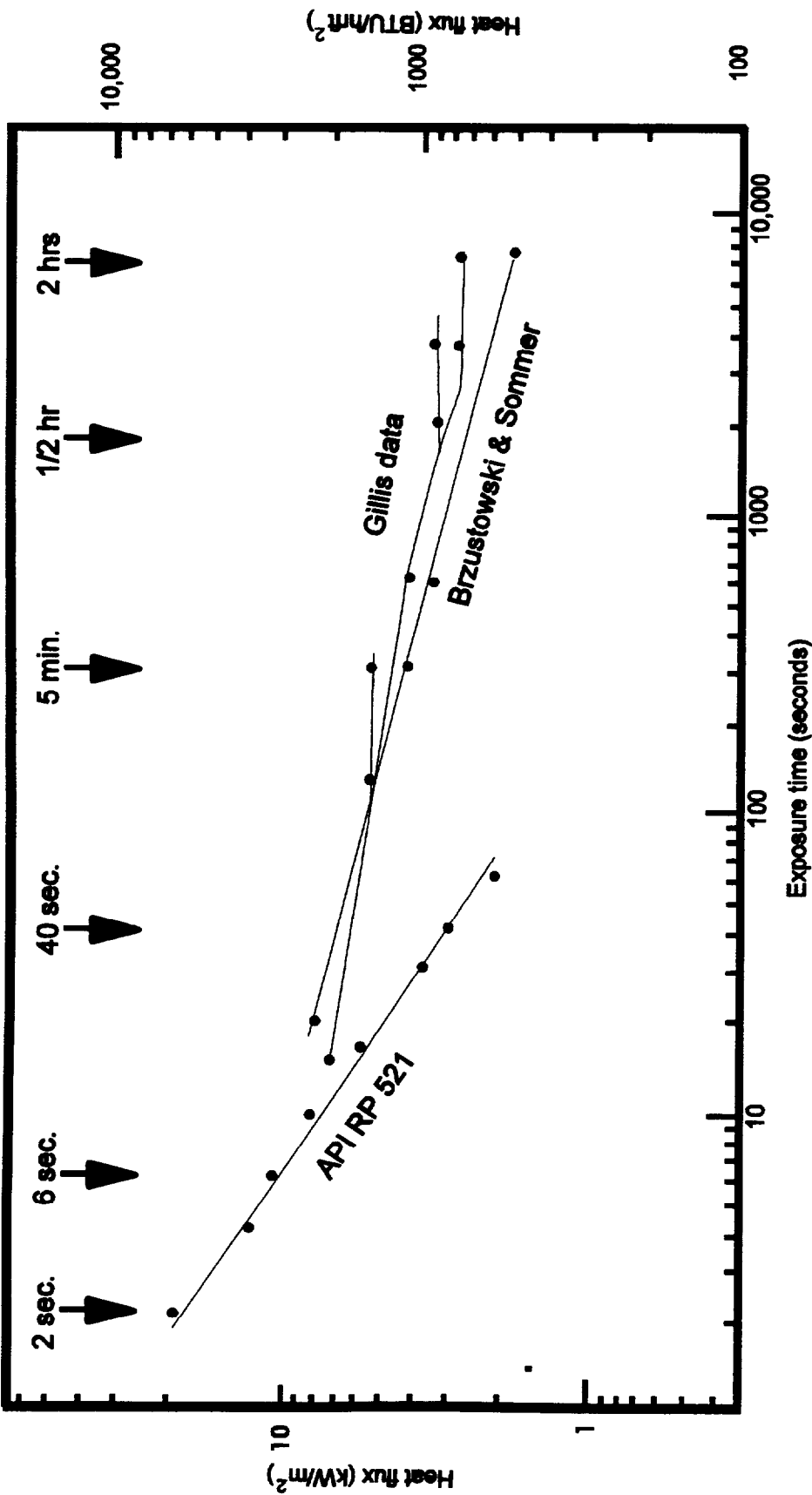


Figure 4.17 Allowable fluxes for personnel exposure
(adapted from Oenbring and Sifferman 1980)

It has been postulated (Bech *et al.* 1992 and 1993) that in-situ ignition and burning of emulsions involves a two-step process: breaking of the emulsion to form a layer of unemulsified oil laying on top of the emulsion slick; and subsequent combustion of this oil layer. Cabioc'h (1993) confirms this theory as do SINTEF and S.L. Ross (1993). Rate controlling processes for this model of emulsion burning may include: the rate of emulsion breaking; evaporation of emulsion water; and, heat conduction through the emulsion slick. It is clear that emulsion stability at elevated temperatures plays a key role in defining whether or not a particular emulsion slick is burnable.

The rate of oil removal by burning declines with increasing water content. Data from S.L. Ross (1989) indicates that an increase in water content from 0 to 25% by volume reduces oil burn rates by 1/3 to 1/2 for oils that form stable emulsions. Increasing the water content further to 50% by volume further reduces the oil removal rate by a total of 1/2 to 1 (i.e., no burning). The data of Energetex (1980), Bech *et al.* (1992) and Cabioc'h (1993) support this general trend. The decrease in burning rate with increasing water content is decreased further by evaporation of the oil. It should be noted that the in-situ burning of some oils that form emulsions does not appear to be as greatly affected as noted above. Some researchers believe that perhaps high wax content, low asphaltene content oils fall into this category (Energetex 1980, S.L. Ross 1989, SINTEF and S.L. Ross 1993). The reason that emulsions of these oils are more burnable may relate to their instability at elevated temperatures (below 100°C). It is theorized that although emulsions stable at elevated temperatures can only burn as fast as the emulsified water is evaporated, emulsions that break spontaneously at elevated temperatures can release water-free oil for burning, and thus allow burning to proceed at a faster rate.

Emulsification not only affects burn rates, as noted above, but also affects burn efficiencies. The results of S.L. Ross (1989), Bech *et al.* (1992), Bech *et al.* (1993) and Cabioc'h (1993) show that there is:

- little effect on oil removal efficiency (i.e., residue thickness) for water contents up to about 25% by volume;
- a noticeable decrease in burn efficiency with water contents above 25%, the decrease being more pronounced by weathering; and
- unburnable slicks of emulsion having water contents ranging from as low as 30 to 40% for extremely weathered oils forming stable emulsions to as high as 70% for less weathered oils forming less stable emulsions.

The burning of higher water content emulsions in-situ can involve vigorous burning (with its characteristic droplet production and more violent burning) throughout the entire burn as opposed to only just prior to extinction (Energetex 1980, S.L. Ross 1989). This, of course, relates to the superheating and boiling of emulsion water from within the slick. The vigorous stage of burning, just prior to extinction, also may be enhanced for emulsions; this may relate to enhanced heat transfer through an emulsion slick as opposed to a pure oil slick.

The residue thickness remaining after an emulsion burn increases with increasing water content, depending on the stability of the emulsion. The data of Energetex (1980) indicate little change in residue thickness for oils not forming very stable emulsions;

however, for oils that did form stable emulsions the residue was two to three times as thick as unemulsified slicks. The water content of the residue was not reported.

Often, when burning emulsions, extinction is initiated by foaming action of the burning slick (Energetex 1980, S.L. Ross 1989). The foaming is presumably associated with boiling of water, but its origin and contributing factors are unclear. It is not unusual for a burning emulsion slick to foam over one area of its surface while another is still burning; as the foam breaks, the extinguished surface is re-ignited by adjacent flames. This process can result in sudden and rapid flare-ups of flame near the end of an emulsion burn. Emulsion slick combustion, perhaps because of the more complex and likely delicate heat balance, seems to be more sensitive to environmental conditions than unemulsified slicks. Bech *et al.* (1993) report that regular wave action resulted in a considerable reduction in burn efficiency (from 80 to 50%) for a weathered, 25% water emulsion. Waves did not have a similar effect on an unemulsified slick of the same oil (removal efficiency = 90%). Energetex (1981) indicates that burning stable 50% water emulsions of weathered crudes were far more sensitive to wind effects than unemulsified oils.

The ignition of emulsions is more difficult than ignition of unemulsified oil; subsequent flame spreading over emulsion is also slower. Energetex (1980) indicates that the flash and fire points of water-in-oil emulsions increased with increasing water content. Figure 4.18 shows that the fire point of fresh oils that formed highly stable emulsions rises rapidly above 30% water; oils that form less stable emulsions have less dramatic increases. SINTEF and S.L. Ross (1993) observed this behavior and attributed it to breaking of the less stable emulsions with increasing temperature and mixing in the flash/fire point test apparatus. Smith and Diaz (1980) also observed an increase in flash point with emulsification. Many authors (Energetex 1980, Hossain and Mackay 1981, Dome 1982, S.L. Ross 1989, Bech *et al.* 1992, SINTEF and S.L. Ross 1993) have noted that ignition of emulsions in-situ becomes more difficult with increasing water content. Energetex (1980) noted that, for fresh-oil, stable emulsions with water contents in excess of 40%, a layer of fresh crude oil spread over the surface of the emulsion was necessary for successful ignition. In essence, the added crude oil was acting as a flame spread promoter. Other experience has shown ignition of emulsion slicks in ice melt pools could not be accomplished with gasoline-soaked sorbents; diesel-soaked sorbents were required, as was priming the slick with diesel (Dome 1982). S.L. Ross (1989) noted that, as water content increased, successively stronger ignition sources were required (5 cm square gasoline-soaked sorbent, then a 10 cm square gasoline-soaked sorbent pad and finally a 2 mm layer of fresh crude oil).

This trend was further explored by Bech *et al.* 1992 who ranked ignition sources in increasing order of strength as: gelled gasoline, gelled diesel, gelled crude oil. They postulated that the success of the stronger igniters rested with higher flame temperatures (and thus increased radiant heat). Cabioch (1993) concluded that gelled diesel was an effective igniter for emulsions. SINTEF and S.L. Ross (1993) also reported the strength of igniter fluid increasing as: gelled gasoline → gelled diesel → gelled crude → layers of fresh crude as a flame spread promoter. They noted that the addition of emulsion breaking chemicals and ferrocene (see later discussions of this chemical) to the gelled crude igniter improved its performance.

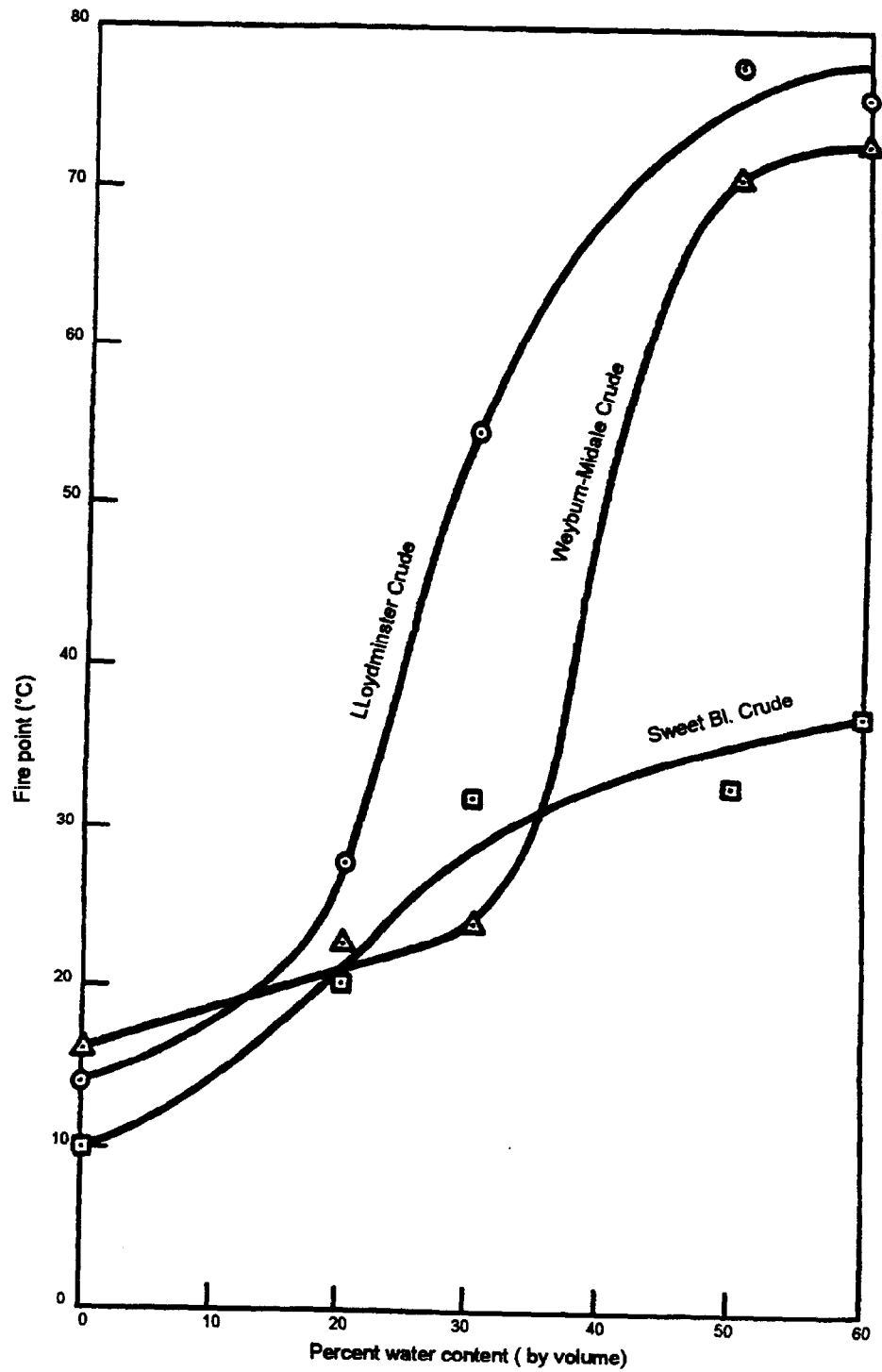


Figure 4.18 W/O emulsion fire points vs. water content (from Energetex 1980)

The maximum ignitable water content of an emulsion seems to be controlled by three factors:

- degree of weathering of the parent oil (more evaporated emulsions are more difficult to ignite);
- the stability of the emulsion at temperatures less than 100°C (SINTEF and S.L. Ross 1993 and Cabioc'h 1993 postulate that high asphaltene emulsions are more difficult to ignite); and,
- the strength of the igniter.

The maximum ignitable water content for oils has ranged from 10% to 70% by volume, depending on the above (Energetex 1980, S.L. Ross 1989, Cabioc'h 1993, SINTEF and S.L. Ross 1993).

Not only are water-in-oil emulsions more difficult to ignite, flame spreading over their surface is much slower. Energetex (1980 and 1981), Hossain and Mackay (1981), Smith and Diaz (1987), S.L. Ross (1989), Allen (1991), Bech *et al.* (1992), and SINTEF and S.L. Ross (1993) have all noted significant reductions in flame spreading velocities with increasing water content. This is likely due to a combination of the following factors:

- increased slick viscosity, slowing interfacial-tension-induced flow and flame spreading;
- increased heat transfer by conduction through the emulsified slick;
- increased flash/fire points of the emulsified slick; and
- delays due to the need to break the emulsion and form a layer of water-free oil for the flame to propagate across.

This latter factor is believed by SINTEF and S.L. Ross (1993) to be the controlling factor for higher water content, stable emulsions. Bech *et al.* 1993 have noted that flame spreading over emulsions is very sensitive to wave action; even regular, swell-type waves prevent ignition and flame spreading over heavily weathered, 25% water emulsions. Energetex (1981) concluded that flame spreading over emulsions is more sensitive to wind influences than unemulsified oils.

Flame heights for emulsion burns in quiescent conditions tend to be higher than for unemulsified oils (S.L. Ross 1989, SINTEF and S.L. Ross 1993); this is believed to be related to micro-explosions (Twardus and Brzustowski 1981) in the slick ejecting oil droplets into the flame (in a manner similar to the vigorous burning phase at the end of an in-situ burn of unemulsified oil on water). Although no data on radiant heat fluxes from emulsion fires could be found, anecdotal accounts exist of emulsion fires being "warmer" than unemulsified oils. This may be a result of suppressed soot production due to the presence of the water or due to increased flame heights (the rate of oil consumption for emulsions is less than that for unemulsified oil; thus an increased combustion rate cannot be a reason).

4.9 References to Chapter 4

- Akita, K. and T. Yumoto. 1965. Heat transfer in small pools and rates of burning of liquid methanol. Tenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 943-948.
- Akita, K. 1972. Some problems of flame spread along a liquid surface. Fourteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 1075-1083.
- Allen, A.A. 1986. Alaska Clean Seas survey and analysis of air-deployable igniters. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 353-373.
- Allen, A.A. 1991. Controlled burning of crude oil on water following the grounding of the *Exxon Valdez*. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 213-216.
- Atallah, S. and D.S. Allan. 1961. Safe separation distances from liquid fuel fires. *Fire Technology* 7(1):47-56.
- Babrauskas, V. 1988. Burning rates. *The SFPE Handbook of Fire Protection Engineering*. pp. 2.1-2.15.
- Battelle. 1979. Combustion: An oil spill mitigation tool. Report for U.S. Department of Energy, Contract No. EY-76-C-06-1830, U.S. Department of Energy, Washington, D.C.
- Bech, C., P. Sveum, and I.A. Buist. 1992. In situ burning of emulsions: The effects of varying water content and degree of evaporation. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 547-559.
- Bech, C., P. Sveum, and I. Buist. 1993. The effect of wind, ice and waves on the in-situ burning of emulsions and aged oils. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 735-748.
- Blinov, VI and G.N. Khudiakov. 1959. Certain laws governing diffusive burning of liquids. *Fire Research Abstracts and Review*. Vol 1(1), pp. 41-44.
- Brzustowski, T.A. and E.C. Sommer Jr. 1973. Predicting radiant heating from flames. Mid Year Meeting of the API; Philadelphia, PA.
- Brzustowski, T.A. and E.M. Twardus. 1982. A study of the burning of a slick of crude oil on water. Nineteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 847-854.

- Buettner, K. 1951. Effects of extreme heat and cold on human skin. *Applied Physiology*, 3, pp. 691-702.
- Buist, I.A. and L.R. McAllister. 1981. Dome Petroleum's fireproof boom — development and testing to date. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 479-497.
- Cabioc'h, F. 1993. Last French experiments in order to evaluate the burning possibilities of three water-in-oil emulsions. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario.
- Dome Petroleum Ltd. 1981. Fire proof boom development — OHMSETT trials. Dome Petroleum Ltd., Calgary, Alberta. 27 p.
- Dome Petroleum Ltd. 1982. Fate and behavior of water-in-oil emulsions in ice. Report to COOSRA. Calgary, Alberta. 55p.
- Energetex Engineering. 1977. Ignition and burning of crude oil on water pools and under arctic spring time conditions. Arctic Petroleum Operators Association Project 141. 70 p. APOA, Calgary, Alta.
- Energetex Engineering. 1978. Testing of air-deployable incendiary devices for igniting oil on water. Environment Canada, Ottawa, Ontario Report No. EPS-4-EC-78-11. 98 p.
- Energetex Engineering. 1980. A study to evaluate the combustibility and other physical and chemical properties of aged oils and emulsions. Report to Environment Canada, Ottawa.
- Energetex Engineering. 1981. Burning of crude oil under wind herding conditions. Report prepared for Canadian Marine Drilling Ltd.
- Evans, D., H. Baum, B. McCaffrey, G. Mulholland, M. Harkleroad, and W. Manders. 1986. Combustion of oil on water. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 301-336.
- Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1987. Environmental effects of oil spill combustion. Proceedings of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 91-130.
- Evans, D.D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1988. Burning, smoke production, and smoke dispersion from oil spill combustion. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 41-87.

- Evans, D., W. Walton, H. Baum, K.A. Notarianni, J.R. Lawson, H.C. Tang, K.R. Keydel, R.G. Rehm, D. Madrzykowski, and R.H. Zile. 1992. In-situ burning of oil spills: Mesoscale experiments. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 593-657.
- Glassman, I. and J.G. Hansel. 1968. Some thoughts and experiments on liquid fuel spreading, steady burning and ignitability. *Fire Research Abstracts and Reviews* 10(3):217-234.
- Glassman, I., J.G. Hansel, and T. Eklund. 1969. Hydrodynamic effects in the flame spreading, ignitability and steady burning of liquid fuels. *Combustion and Flame* 13:99-101.
- Gostintsev, Y.A., N.P. Kopylov, V.V. Lararev, M.A. Motin, Y.V. Shatskikh, and A.F. Solodovnik. 1984. Burning of petroleum on the surface of water (large scale experiment). *Combustion, Explosion and Shock Waves* 19(4):401-404.
- Hägglund, B. and L. Persson. 1976. The heat radiation from petroleum fires, FOA report C 20126-D6(A3) Stockholm.
- Hall, A.R. 1973. Pool burning. *Oxidation and Combustion Reviews* 6:169-225.
- Heskestad, G. 1983. Luminous height of turbulent diffusion flames. *Fire safety journal*, 5, pp. 103-108.
- Hossain, K. and D. MacKay. 1981. A study of the combustibility of weathered crude oils and water-in-oil emulsions. Environment Canada, Ottawa, Ontario. Environment Canada Report EE-12, 43 p.
- Kanury, A.M. 1988. Ignition of liquid fuels. *SFPE Handbook of Fire Protection Engineering*. National Fire Protection Association, Quincy, MA. pp. 1.315-1.325.
- Koseki, H. and G.W. Mulholland. 1991. The effect of diameter on the burning of crude oil pool fires. *Fire Technology* 27(1):54-65.
- Koseki, H. 1993. Thermography research for radiation measurement of an oil spill fire. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 833-842.
- Mackinven, R., J.G. Hansel, and I. Glassman. 1970. Influence of laboratory parameters on flame spread across liquid Fuels. *Combustion Science and Technology* 1(4):293-306.
- Maybourn, R. 1971. The work of the IP working group on the burning of oil. *Journal of the Institute of Petroleum* 57:12-16.

- Moorhouse, J. 1982. Scaling criteria for pool fires derived from large-scale experiments. I. Chem. Sym. 71. pp. 165-179.
- Muden, K. and P. Croce. 1988. Fire hazard calculations for large open hydrocarbon fires. SFPE Handbook of Fire Protection Engineering. Nat. Fire Protection Association, Quincy, MA. pp. 2.45-2.87.
- Murad, R.J., J. Lamendola, H. Isoda, and M. Summerfield. 1970. A study of some factors influencing the ignition of a liquid fuel pool. Combustion and Flame 15(3):289-298.
- Murty, K.A. 1988. Ignition of liquid fuels. The SFPE Handbook of Fire Protection Engineering; Quincy, MA: National Fire Protection Association; pp. 1.315-1.325.
- Oenbring, A.R. 1980. Flare design are current methods too conservative? Hydrocarbon processing. May 1980. pp. 124-129.
- Pagni, P.J. 1991. Fire modeling. Grant Report. Summaries of BFRL Fire Research Program In-house Projects and Grants. Gaithersburg, MD. NIST pp. 57-60.
- Pipkin, O.A. and C.M. Sliepcevich. 1964. Effect of wind on buoyant diffusion flames. Ind. & Eng. Chem. Fundamentals, (3), No. 2, p 147.
- Shokri, M. and C.L. Beyler. 1989. Radiation from large pool fires. Journal of Fire Protection Engineering 1(4):141-150.
- SINTEF and S.L. Ross. 1993. In-situ burning of water-in-oil emulsions. Draft report to NOFO. Stavanger, Norway.
- Sirignano, W.A. and I. Glassman. 1970. Flame spreading above liquid fuels: surface-tension driven flows. Combustion Science and Technology 1:307-312; 1969.
- S.L. Ross Environmental Research Ltd. and Energetex Engineering. 1986. In-situ burning of uncontained oil slicks. EETD report EE-60 revised. Environment Canada, Ottawa.
- S.L. Ross Environmental Research Ltd. 1989. Disposal of spilled Hibernia crude oils and emulsions: In-situ burning and the "Swirlfire" burner. Report to Canadian Coast Guard, Ottawa.
- Smith, N.K. and A. Diaz. 1987. In-place burning of crude oils in broken ice. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 383-387.
- Spiltec. 1987. Refinement of aerial ignition systems, (test and evaluation of the Heli-torch for the ignition of oil slicks). Report to Alaska Clean Seas, Anchorage, Alaska.

- Tam, W.K. and W.F. Purves. 1980. Experimental evaluation of oil spill combustion promoters. Proceedings of the Oceans '80 International Forum on Ocean Engineering in the 80's. IEEE, Piscataway, NJ. pp. 415-421.
- Thomas, P.H. 1963. The size of flames from natural fires. Ninth Symposium (International) on Combustion. Academic Press, New York, NY. pp. 844-859.
- Torrance, K.E. and R.L. Mahajan. 1974. Fire spread over liquid fuels: liquid phase Parameters. Fifteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 281-287.
- Twardus, E.M. and T.A. Brzustowski. 1981. The burning of crude oil spilled on water. *Archivum Combustionis* 1(1/2):49-60.
- Wakamiya, W., S.E. Petty, A. Boiarski, and A. Putnam, (Pacific Northwest Laboratory). 1982. Combustion of oils on water: an experimental program. U.S. Department of Energy Report No. NBM/1002. U.S. Department of Energy, Washington, D.C. 95 p.
- Walton, W.D., D.D. Evans, K.D. McGratton, H.R. Baum, W.H. Twilley, D. Madrzykowski, A.D. Putorti, R.G. Rehm, H. Koseki and E.J. Tennyson. 1993. In-situ burning of oil spills: Mesoscale experiments and analysis. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 679-734.
- Yumoto, T. 1971. Heat transfer from flame to fuel surface in large pool fires. *Combustion and Flame* 17:108-110.

5.0 Technology of In-Situ Burning

5.1 Introduction

This chapter deals with the technologies available for in-situ burning. Specific pieces of equipment are documented in the categories of igniters, fire proof containment booms, floating burners, and additives. The latter category includes ignition promoters, burn promoters, wicking agents and smoke suppressors.

Much of the technology discussed was conceived as a result of in-situ burning attempts at specific spill incidents. For example, the *Torrey Canyon* incident in 1967 prompted considerable research on both sides of the Atlantic on the subjects of slick ignition and combustion promoters. The *Burmah Agate* and IXTOC-1 spill incidents in 1979 accelerated the development of fire proof containment booms, and the *Exxon Valdez* spill in 1989 started research on smoke suppression additives.

Over the same 25-year period a greater understanding has developed of the processes involved in the ignition, steady burning, vigorous burning and extinction phases of in-situ combustion, and this has led to a refinement of existing ignition equipment and new tools and techniques.

5.2 Igniters

This section starts with a brief chronological history of the development of igniters. This is followed by a brief review of igniters that have been researched or developed but are no longer available, and this is followed in turn by a more detailed presentation of commercially available igniter systems.

5.2.1 Brief History of Igniter Development

Many different ignition devices have been used over the years to ignite or attempt to ignite marine oil spills. In 1967 four attempts were made to ignite seemingly thick oil slicks on the sea near the *Torrey Canyon* using pyrotechnic devices containing sodium chlorate, but these attempts were unsuccessful (Swift *et al.* 1968; Anonymous 1967). It was concluded that, after the Kuwait crude had been on the water surface for only 40 minutes, it had emulsified to such an extent that it would not ignite.

Oil on the shore from the *Torrey Canyon* spill also proved virtually impossible to ignite and burn, although some success was reported in burning unemulsified oil in pools between rocks (Swift *et al.* 1968). In this case, flame throwers and flame-thrower fuel were used to ignite the pools and they burned nearly to completion. Emulsified oil could be burned on the beach as long as the flame thrower was applied, but once the flame was removed the combustion stopped.

Kontax was an igniter developed at the time by Edward Michels GmbH of Essen, Germany. It was demonstrated on a test spill off Holland where it successfully ignited and burned 10 tons of heavy Arabian crude (Freiberger and Byers 1971, Energetex 1978). The potential of Kontax was also demonstrated at the *Arrow* spill in 1970 where some of the spilled oil was primed with two drums of fresh oil and ignited with a Kontax igniter (Coupal 1972).

Another igniter, Oilex Fire produced by Keltron Inc. of Switzerland consists of a sorbent (Oilex) plus a hydro-igniting agent. The company reported the chemical's use on small spills in Swiss lakes and in the Adriatic Sea (Freiberger and Byers 1971).

On December 27, 1976, the *Argo Merchant* went aground near Nantucket Island and spilled most of its cargo of 28,000 tons of No. 6 fuel oil. Part of the response by the U.S. Coast Guard involved attempts to burn the oil. One 30 m x 40 m x 15 cm thick slick was treated with Tullanox 500 (a wicking/insulating agent), primed with 200 L of JP-4 and ignited with JP-4-soaked cotton sheets set afire with a flare. About 95% of the Tullanox was blown off the treated slick by wind and the flames would not spread from the sheet to the primed slick. In another experiment, boxes of Tullanox 500 charged with JP-4 fuel were dropped onto a slick from a helicopter and ignited with timed thermite grenades. The isolated boxes burned but the flames did not spread (Det norske Veritas 1979, Battelle 1979).

On January 28, 1977, some 300,000 L of No. 2 fuel oil was spilled onto the ice-covered waters of Buzzards Bay, Massachusetts by the barge *Bouchard #65*. Boxes of Tullanox soaked with jet fuel were dropped from helicopters onto pools of oil in the broken ice with delay-fuses. Thermite grenades were used to ignite the boxes. The ensuing fires burned for 1½ to 2 hours and consumed 4000 to 8000 L of oil. The 38 to 46 km/hr (20 to 25 knot) winds drove the flames from pool to pool in areas where adjacent pools were nearby; in other areas the fires did not spread. Another series of burns were conducted at a later date. These burns were initiated by knotted rags soaked in diesel fuel (Schrier and Ediam 1979, Ruby *et al.* 1978).

Starting in 1977, considerable effort was devoted to developing an aerial ignition capability in support of potential spills from offshore exploration activities in the Beaufort Sea. Energetex Engineering evaluated and tested five devices (Kontax, Kontax with gasoline, solid propellant, solid fuel, and gasoline with sodium). Solid fuel and solid propellant igniters with a fuse wire were ranked highest (Energetex 1978). Subsequently, two igniters were developed in Canada: the Dome igniter (Buist *et al.* 1981; Energetex 1982a and b) and the EPS igniter (Meikle 1981a and b, Twardawa and Couture 1983).

Laser-based ignition systems received considerable attention in the 1970s and 80s (Waterworth 1987, Whittaker 1987, Frish *et al.* 1989, Laisk 1976). A land-based system proved capable of igniting oil slicks on water (Frish *et al.* 1989). The various components of a helicopter-borne system have been researched under contract to Environment Canada and the Minerals Management Service; however, further development to the prototype stage and subsequent commercialization await private sector involvement.

In Alaska, a forest-fire fighting tool known as the Heli-torch was discovered in the mid-1980s to be an effective aerial ignition system for oil spills (Allen 1986). Considerable testing and refinement of the device (Allen 1987) has resulted in the Heli-torch being stockpiled around the world as the igniter-of-choice for in-situ burning.

Currently, research efforts are focusing on extending the capabilities of ignition systems to deal with water-in-oil emulsions (S.L. Ross 1989, Bech *et al.* 1992, SINTEF and S.L. Ross 1993).

5.2.2 Summary of Disused Ignition Systems

The following ignition systems had been used or were researched at one time but are no longer available, recommended, or considered for use.

5.2.2.1 Kontax

The Kontax igniter was produced by Edward Michels GmbH of Essen, Germany. Production of the device ceased in the mid-to late-1970s (Energetex 1978). The device consisted of a 4 cm diameter cylindrical metal screen 30.5 cm long and capped at both ends. A metal bar coated with metallic sodium ran through the center of the cylinder. The annulus was filled with calcium carbide. The device weighed 1.2 kg. For safety reasons the Kontax igniter was stored in a sealed plastic bag.

The Kontax igniter had a unique feature: it did not require activation or a starter. When the device was exposed to water the sodium metal reacted to produce heat and hydrogen, which instantly ignited. At the same time the calcium carbide reacted with water to produce acetylene which was subsequently ignited by the burning hydrogen. The flame from the burning acetylene preheated and ignited oil vapors.

Tests to evaluate Kontax were conducted on July 1, 1969 by the Dutch government (Battelle 1979). The tests were conducted 25 miles offshore and on beaches; the oils used were heavy and light Arabian crude. The Kontax used was in 25 kg bags. One test involved a 9 tonne slick covering about 2000 m² (0.5 cm thick) in a free-floating lumber boom. The bags containing the Kontax were punctured and thrown into the slick. The igniters were successful; flames of 15 to 20 m high were reported and a 98 to 99% oil removal efficiency was estimated. A Kontax-to-oil ratio of 1:100 by weight was estimated to be appropriate.

Tests with the Kontax igniter (Energetex 1978) showed that it produced a large flame area (3000 cm²) with a relatively low flame temperature (770°C). This combination produced a relatively high flame emissivity of 2.25 kW/m². Although Kontax proved effective in both field and tank trials as a surface-deployed igniter (Freiberger and Byers 1971, Energetex 1978), the device proved less effective when dropped from a height of 11.5 m, simulating deployment from a helicopter. The ignition success rate declined from 100% in the surface tests to 60% in the aerial tests. The main reason for the latter result was that the large splash caused by the Kontax igniter entering the water drove the oil away; by the time the oil had returned, the igniter had generated a ring of calcium hydroxide foam that kept the oil away.

Energetex (1978) tested a modification to the Kontax igniter, which involved combining a small amount of gasoline with the device. This inclusion of gasoline was intended as a fuel to bridge the calcium hydroxide foam barrier. This modification resulted in a slightly higher flame temperature (790°C) and better aerial deployment ignition success (80%).

It is not clear why Kontax was taken out of production. It may have been due to a general lack of interest in in-situ burning at the time, or due to the dangers and stringent requirements for storing, transporting and using the igniters.

5.2.2.2 Solid Propellants

Solid propellants, also known as solid rocket fuels, are comprised of a solid mixture of various portions of ammonium perchlorate oxidizer, metal fuel (magnesium or aluminum), and an organic binder. They have been used in a variety of igniters. Solid propellant igniters, in various shapes and utilizing various starters (electrical, chemical or fuses) have been extensively tested (Energetex 1978). Such igniters exhibit very high flame temperatures (about 1230°C) and high flame emissivities (1.75 kW/m²) but are consumed rapidly. They require mounting in a housing to suspend them no more than 5 cm above the oil/air interface. In water surface tests, solid propellant gave an 89% ignition success rate; and an 80% success rate in aerial-deployment tests with a fuse-wire starter (all other starter mechanisms resulted in lower success rates).

Solid propellants were once considered but now are not recommended for use alone as an oil spill igniter. Rather, they and solid fuels (discussed next) are used in conjunction with other components in currently available igniter systems.

5.2.2.3 Solid Fuel

Solid fuel igniters employ gelled kerosene cubes (e.g., solid barbecue starter) suspended above the oil/air interface. Because of the lower flame temperatures (770°C) and flame emissivities (0.5 kW/m²) generated, it is necessary to suspend the cubes within 3 cm of the oil surface in order to successfully ignite oil. Surface ignition tests have given an 84% success rate while aerial tests have resulted in an 80% success rate using a fuse wire starter (Energetex 1978). Solid fuel is used in one commercially available oil slick igniter discussed in the following section.

5.2.2.4 Thermite

Thermite is a mixture of metallic aluminum powder and ferric oxide. Although producing extremely high temperatures (about 3500°C) the mixture requires a very high ignition temperature (about 2000°C) which necessitates specialized starters. Military incendiary devices utilize thermite.

Although thermite has been used with some success at several spills, as noted earlier, it is no longer recommended as an oil spill igniter due to its stringent storage and transport requirements.

5.2.2.5 Marker Flares

A number of types of marker flares have been considered or used as oil slick igniters. These include both road and marine flares of the phosphorous, calcium hydroxide, and magnesium types. They can be successful in igniting fuels at temperatures above the fuel's flash point or in igniting a primer liquid placed on a sub-flash fuel (Freiberger and Byers 1971). They are not effective in directly igniting sub-flash oils (Energetex 1978).

5.2.2.6 Proprietary Ignition Chemicals

Two proprietary ignition systems have been reported in the literature (Cabioc'h 1993). These are Westcom 2000 and Westcom 2001 (also known as Westcom II and III respectively). Westcom 2000 is a coarse granular mixture incorporating a hydro-igniting chemical and oxygen donation catalyst. It is contained in a sealed plastic bag that must be cut before being thrown onto the slick.

Westcom 2001 is a viscous colorless gel intended to be sprayed on the surface of an emulsified slick to ignite it and promote its combustion, with initial ignition provided by Westcom 2000. Experience with the product indicates that it offers only a small advantage over gelled diesel fuel and the on-site mixing and spraying is cumbersome. Furthermore, it has been noted that the use of Westcom 2001 reduces the capacity of sorbent pads on the residue that remains after a burn (Cabioc'h 1993). Although the product has been tested successfully in both temperate and arctic elements the current view is that it should not be considered for use, primarily because of safety concerns regarding the storage and handling of such hydro-igniting chemicals on vessels or aircraft.

5.2.2.7 Hypergols

Hypergols consist of two liquids stored separately; one is a strong oxidant (such as fuming nitric acid) and the other is combustible. When mixed, they burn rapidly, particularly when the oxidant provides its own oxygen. These have been considered for use as oil spill igniters, but are currently rejected because of the dangers in storing and mixing the reagents (Energetex 1978).

5.2.2.8 Sodium and Gasoline

Tests were done on an igniter consisting of a small plastic bag filled with gasoline connected to a wire enclosure containing a piece of metallic sodium (Energetex 1978). The device was unsuccessful during surface tests because the sodium failed to ignite the gasoline. This occurred for two reasons: sodium coated with gasoline or oil does not react vigorously enough with water; and, the sodium tended to escape from its container. Storage and handling problems would also be anticipated with this type of device.

5.2.2.9 Premo Aerial Ignition Device (AID)

The Premo AID is a system designed for the ignition of debris and backfires in forest fire control. The ignition component of the system consists of 3 cm diameter polystyrene spheres each containing approximately 3 grams of potassium permanganate. The igniter is started by injecting the cylinder with 1 mL of glycol. A highly exothermic reaction is initiated which results in combustion of the device and its contents for a period of 20 to 30 seconds. Flame size and ignition delay are varied by changing the grain size and mass of potassium permanganate, and by diluting the glycol with water.

The delivery component of the AID system consists of a mechanical dispenser comprising a storage hopper, injection chambers and exit chutes. The polystyrene balls are mechanically fed into the injection chambers, injected with glycol and then immediately ejected into the exit chute. The dispenser also contains a water reservoir and fire

extinguishing system should a ball jam after injection. The dispenser is designed to be strapped to the floor of a helicopter, extending out the open rear door. The device is equipped with tie down straps and a break-away electrical connection so it can be quickly jettisoned in an emergency.

When this device was tested for use as an oil spill igniter (Spiltec 1987), it was found that the igniter was easily doused and it sunk when water was splashed on the burning ball.

5.2.2.10 Lasers

The use of lasers mounted in helicopters to ignite oil spills has received considerable attention over the past 20 years (Laisk 1976, Frish *et al.* 1986, Waterworth 1987, Whittaker 1987, Frish *et al.* 1989). In static tests on land the concept proved to be capable of igniting fresh and weathered, unemulsified oil in 1 m² pools on ice (Whittaker 1987). Engineering studies to develop or source the various components of a helicopter-based system have been completed; however, the development of a commercial prototype awaits private-sector funding.

5.2.3 Presently Available Ignition Systems

There are several ignition systems that have proved to be effective and are either commercially available or can be constructed from technical designs. The discussion of these is divided into two sections: igniters for use from a vessel or from shore, and igniters for use from helicopters.

5.2.3.1 Surface-deployed Igniters

Both portable propane or butane torches, or weed burners, and rags or sorbent pads soaked in diesel have been used successfully many times in the past to ignite oil slicks on water. Experience has shown that propane torches tend to blow thin oil slicks away from the flames and are best utilized on thick contained slicks. Diesel is the best fuel to soak sorbents or rags for use as igniters; gasoline results in a less powerful flame (Buist *et al.* 1983d). A variation on this sorbent igniter was used at OHMSETT in the 1980s (Dome 1981a, Smith and Diaz 1987). It involved sorbent wrapped around a short length of Ethafoam log, dipped in diesel or crude oil, and then sprayed with dimethyl ether (also known as starter fluid). This ignited easily and burned for a long time, even in choppy wave action.

Another successful surface-based igniter is gelled gasoline. Allen (1990a or b) reports that the in-situ test burn during the *Exxon Valdez* spill was ignited by a plastic bag containing gasoline gelled with "Surefire" gelling agent. The contents of the bag were mixed by hand, placed on the water surface then ignited and allowed to drift from the tow boat into the contained oil in the fire containment boom being towed behind. The manufacturer of the Heli-torch (see below) also offers a land-based version called the Groundtorch (Spiltec 1987). The device consists of a storage drum and pump connected to a hand-held "wand" for application of the burning gelled gasoline. The system is designed for mobile use with a pickup truck or small trailer.

Variations on this igniter's fuel have been reported by Bech *et al.* 1992, who mixed "Surefire" gelling agent with gasoline, diesel, and fresh crude oil. The flame temperatures

measured by an infrared video system increased from gasoline to diesel to fresh crude. Further experimentation with other chemical additives such as ferrocene and emulsion breakers has indicated that further improvements with gelled petroleum igniters may be possible (SINTEF and S.L. Ross 1993).

5.2.3.2 Aerially-deployed Igniters

There are three aerially-deployed igniter systems that are currently available for use on oil spills, as discussed in the following section (adapted, with permission, from Spiltec 1986).

ENVIRONMENTAL PROTECTION SERVICE (EPS) IGNITER (after Twardawa and Couture 1983): The EPS igniter is an air-deployable pyrotechnic device developed by the Canadian Environmental Protection Service, division of Environment Canada, in cooperation with Canadian Department of National Defence Research Establishment, Valcartier (DREV) and the Arctic Marine Oilspill Program (AMOP). The igniter (Figure 5.1) is approximately 25 cm square and 13 cm high and weighs nearly 2 kg. The unit consists of a pyrotechnic device sandwiched between two layers of foam flotation and is activated by a self-contained firing mechanism. It is intended to be a hand-thrown device.

The EPS igniter was marketed in the past as the "PYROID" igniter manufactured by ABA Chemical Ltd., but the company is no longer in business. Although the device is not commercially available, the design is available from Environment Canada's Emergency Engineering Division.

The device is simple in design and operation, being activated by pulling on a firing clip which in turn strikes a primer cap. A 25-second delay column then provides sufficient time to throw the igniter and let it settle within the target oil slick. A specially formulated ring of fast-burning ignition composition is then ignited, and this in turn ignites the primary incendiary composition. The incendiary composition is a solid propellant consisting of typically 40% to 70% ammonium perchlorate, 10% to 30% metal fuel (magnesium or aluminum), 14% to 22% binder, and small amounts of other ingredients to aid in the casting and curing processes. These materials have an estimated shelf life of about 5 years.

The firing mechanism and the incendiary materials are sandwiched between two polystyrene foam slabs to provide both buoyancy and protection for the device on impact. All components except the firing mechanism are combustible, so that very little debris is left in the environment after a burn. These components have also been designed so that the igniter experiences a minimum of roll if dropped onto a hard surface (like ice) or shallow water. The igniter can float in as little as 5 cm of water/oil. The flame released will be oriented properly regardless of which side of the igniter is up. The EPS igniter has been designed to produce a ring of fire with temperatures approaching 2,000°C (4,170°F) immediately adjacent to the perimeter of the igniter. This intense flame has a typical duration of about 2 minutes.

The EPS igniter has been designed so that no open flames or sparks are experienced aboard the deployment helicopter. Once the igniter is activated, however, there is no way to deactivate the igniter — it must be thrown from the helicopter within the 25-second delay period. Prior to activation, there is very little chance of an accidental firing because there is a safety pin in the firing mechanism.

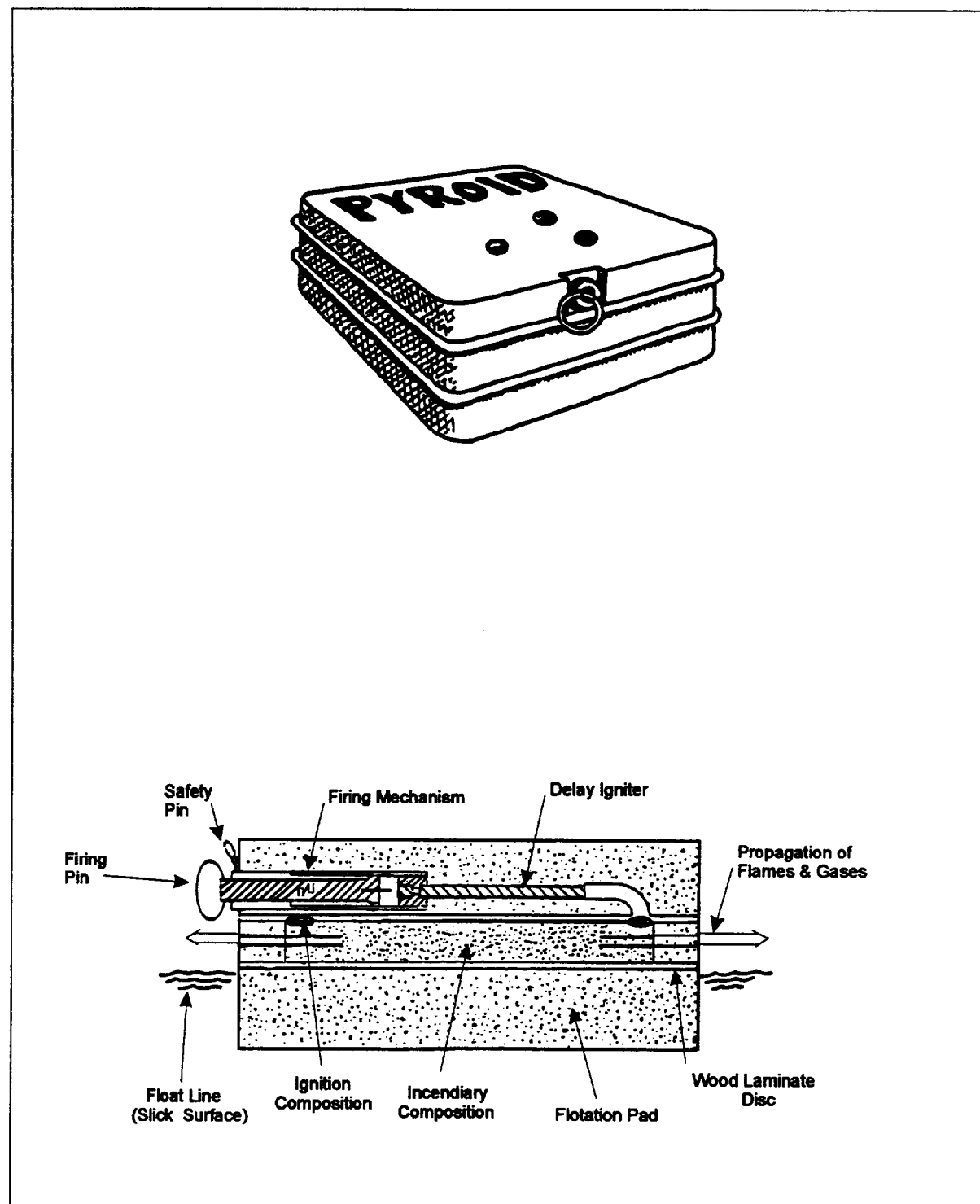


Figure 5.1 *Environmental Protection Service (EPS) igniter, or Pyroid igniter, showing internal firing mechanism and pyrotechnic components (adapted from Spiltec 1986)*

As with any pyrotechnic device, precautions must be taken during storage and handling to ensure that the igniters are properly isolated from any ignition sources and properly packaged and housed in a secure area. This area should be kept dry, and the packages should be labelled as "fireworks". The EPS igniter has been identified under the United Nations based system for classifying explosives as a Class 1 (explosives code within the Dangerous Goods grouping), Division 3 (pyrotechnic device), Group G material. The igniter is designed to withstand a broad range of temperature, humidity, and vibration conditions, including temperatures as low as -50°C and as high as 50°C. Environmental test procedures and results are presented in Twardawa and Couture (1983).

The EPS igniter was designed to provide a 75% probability of functioning properly when dropped at an airspeed of about 30 km/hr from an altitude of approximately 15 m. Actual field tests indicate that a high probability of success can be achieved with newly constructed devices but as the 5-year shelf life is approached, the probability of functioning properly begins to drop off. It is therefore important that stockpiled igniters be carefully dated and then reconstructed as their shelf lives expire. The cost of tearing down and replacing the pyrotechnic portion of the igniter is estimated to be about 25% of the original manufacturing price. The plans for the EPS igniter may be obtained from:

Emergencies Engineering Division
Environment Canada, Conservation and Protection
River Road Environmental Technology Center
3439 River Road
Ottawa, Ontario, Canada, K1A 0H3
Fax: (613) 991-1673

DOMe IGNITER: The Dome Igniter is a lightweight, air-deployable pyrotechnic device developed by Dome Petroleum Ltd., Calgary, Canada, in cooperation with Energetex Engineering, Waterloo, Canada. The igniter (Figure 5.2) measures approximately 30 cm by 18 cm by 11 cm and weighs a little over 0.4 kg. The unit consists of a wire-mesh fuel basket with solid propellant and gelled kerosene slabs suspended between two metal floats. Like the EPS igniter, the Dome unit is intended as a hand-thrown device.

The Dome igniter is currently manufactured by Energetex Engineering and has come to be known as the Energetex igniter or the "tin-can" igniter. It has gone through several design changes since it was first tested by Dome during the winter of 1979/80 (Buist *et al.* 1981). These changes have involved the igniter's mode of activation and the way in which certain components in its fuel basket are isolated from each other (Energetex 1982b). In order to avoid any need for open flame during activation, the fuse wire is now started with a specially designed electric ignition system referred to as the Energetex Engineering Ignition System (EEIS). Consisting of a 12-volt, spill-proof battery with a gel electrolyte and a heater element, the EEIS can provide sufficient heat to activate the igniter's fuse wire within two seconds of contact. Once started, the 25 cm long safety fuse provides about 45 seconds of delay for throwing the igniter and allowing it to settle within the target oil slick.

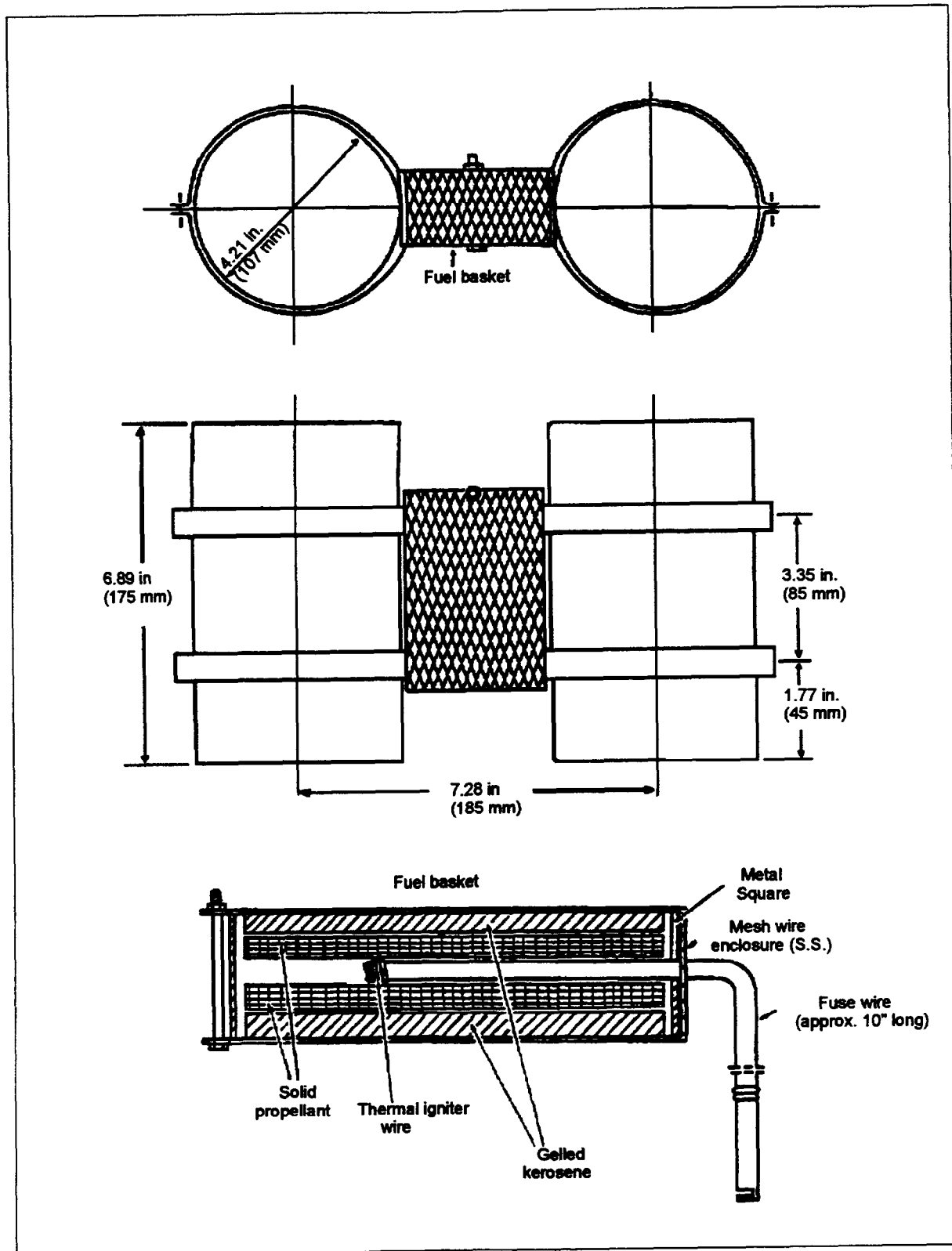


Figure 5.2 Basic design and internal components of the Dome or Energetex igniter (adapted from Spiltec 1986)

The fuse ignites a thermal igniter wire, which in turn ignites the solid propellant slabs located above and below the igniter wire. The solid propellant burns intensely for about 10 seconds with temperatures in excess of 1200°C. During this initial burn, the gelled kerosene begins to burn, producing temperatures of 700°C to 800°C. The total burn time for the igniter is about 10 minutes.

The device is designed so that the fuel basket housing the propellant and gelled kerosene is suspended above the oil layer. The oil between the floats and beneath the fuel basket is somewhat shielded from the wind to allow heating of the oil. The relatively long burn-time for the Dome igniter helps get the slick lit if winds temporarily separate the igniter from the heaviest concentrations of oil. Upon completion of the burn, all of the metal components of the igniter remain on the surface of the water and attached to the two floats.

The low weight and irregular shape of the igniter give the igniter a relatively low terminal velocity and a tendency to avoid rolling on impact with solid surfaces. The igniter has only two stable positions in which it can float, and either one keeps the igniter's flames in close proximity to and slightly above the oil.

The fuse wire of the Dome igniter must be kept away from any potential sources of ignition. Once activated, the igniter cannot be deactivated, and it must be released as soon as possible (at least 20 to 30 seconds before the end of the 45-second delay period). Proper packaging in separate plastic bags and storage of the units in cardboard boxes onboard the helicopter should be sufficient to prevent any accidental activation of an igniter.

The Dome igniter fits the same classification for explosives as the EPS igniter, and as a result need only be stored in a spark-free, dry area and be packaged and properly marked as a pyrotechnic firework. The igniters should be stored in a secure place, safely removed from any heat sources and other flammable materials. The Dome igniter has undergone rigorous testing (Energetex 1982b) involving a broad range of temperatures (-70°C to 50°C) and vibration and humidity conditions normally used for such explosives manufactured and used in Canada.

The simplicity of design of the Dome igniter should provide a good probability of success. Its starter fuse and ignition wire have at least a 95% reliability, and experience both in the U.S. and Canada suggests that the probability of activating the entire contents of the fuel basket is in excess of 90%. As with any pyrotechnic device, the probability of success is expected to diminish as the shelf life of each unit is approached.

The igniter has been extensively tested and shown to be capable of igniting fresh, weathered and emulsified oils (up to 60% water) in temperatures as low as -30°C and in winds up to 40 km/hr (Dome 1981b, Energetex 1978, 1979, 1981a, 1982b).

The shelf life of the Dome igniter is estimated at about five years, although experience with igniters stored in Alaska and Canada has shown that they will operate after 10 to 15 years (Allen 1992). It is important that any stockpiled igniters be carefully dated, periodically tested and reconstructed as necessary. It is estimated that tearing down and replacing the pyrotechnic portion of the igniter will cost approximately 50% of the original purchase price.

The current manufacturer of the Dome igniter is:

Energetex Engineering
505-125 Lincoln Road
Waterloo, Ontario, Canada, N2J 2N9
Fax: (519)-885-2738

HELI-TORCH (adapted with permission from Spiltec 1987): The Heli-torch (Figure 5.3) is a proved aerial ignition system commonly used by the U.S. Forest Service and Forestry Canada for burning forest slash and for setting backfires during fire-control operations. It is a completely self-contained unit consisting of a fuel barrel, pump, and motor assembly slung beneath a helicopter and controlled with an electrical connection from the Heli-torch to a panel in the cockpit. The fuel barrel can be filled with a gelled gasoline or gasoline-and-diesel mix which is then pumped upon demand to a positive-control shut-off valve and ignition tip. The gelled fuel mixture is ignited with electrically-fired propane jets as it exits one or more nozzles protected by wind shields. The burning gelled fuel falls as a highly viscous stream and quickly breaks up into individual globules before hitting the ground. Three models are available with 110 L, 205 L and 1100 L (30, 55 and 300 gal) capacities. Of these, the 205 L (55 gallon) model has been most extensively tested for use on oil spills.

In fighting forest fires, the Heli-torch may be operated from heights of several hundred feet and with speeds of 40 to 60 mph (65 to 95 km/hr). As discussed in this report, such heights and airspeeds are not desirable for the ignition of oil slicks at sea. Depending upon the actual nature of the slicks to be ignited, flying at much lower altitudes (8 to 23 meters) and with airspeeds of 40 to 50 km/hr may considerably enhance the accuracy, ignition success and distribution of burning globules.

The Heli-torch ignition system is manufactured by Simplex Manufacturing Co. in Portland, Oregon, and is approved by the U.S. Federal Aviation Administration (FAR Part 137). U.S. users of the system are cautioned that certain federal regulations (46 CFR) require approval by the Office of Hazardous Materials Transportation (OHMT), U.S. Department of Transportation, for transporting fuel beneath a helicopter (e.g., sling-loaded Heli-torch) and for transporting the fuel to support a gelling operation at a remote site. Exemptions from these requirements have been obtained for such operations as forest fire control; nevertheless, application for exemption involving oil spill control must be requested.

The Heli-torch can be carried by a helicopter with a cargo hook and a 24- to 28-volt power supply. When the single-point suspension cable system is used with helicopters employing swivel cargo hooks (e.g., Bell 250, 212, 412), the Heli-torch may experience rotation during flight that may alter its globule-distribution or accuracy capabilities.

Depending upon the helicopter used (i.e., with fixed or swivel cargo hook), the Heli-torch support assembly may be rigged to include a self-releasing horizontal support arm or stabilizing bar to keep the Heli-torch oriented properly. The stabilizing bar can be suspended at one end directly below the cargo hook, with the other end of the bar resting on one of the helicopter's skids. The Heli-torch's support cable assembly is then connected directly to the stabilizing bar. This approach provides a stable two-point connection while permitting the Heli-torch to be jettisoned if necessary. Both support systems (i.e., with and without the stabilizing bar) were used during field trials described in Spiltec 1987.

The weight of the Heli-torch with a full 205 L (55 gallon) drum is approximately 243 kg (534 pounds). The entire unit is connected to a helicopter with a support cable assembly that can be jettisoned quickly from the helicopter's cargo hook. The electrical cable has a quick-disconnect plug near the helicopter, and this plug can also be pulled apart easily if the unit is released in an emergency.

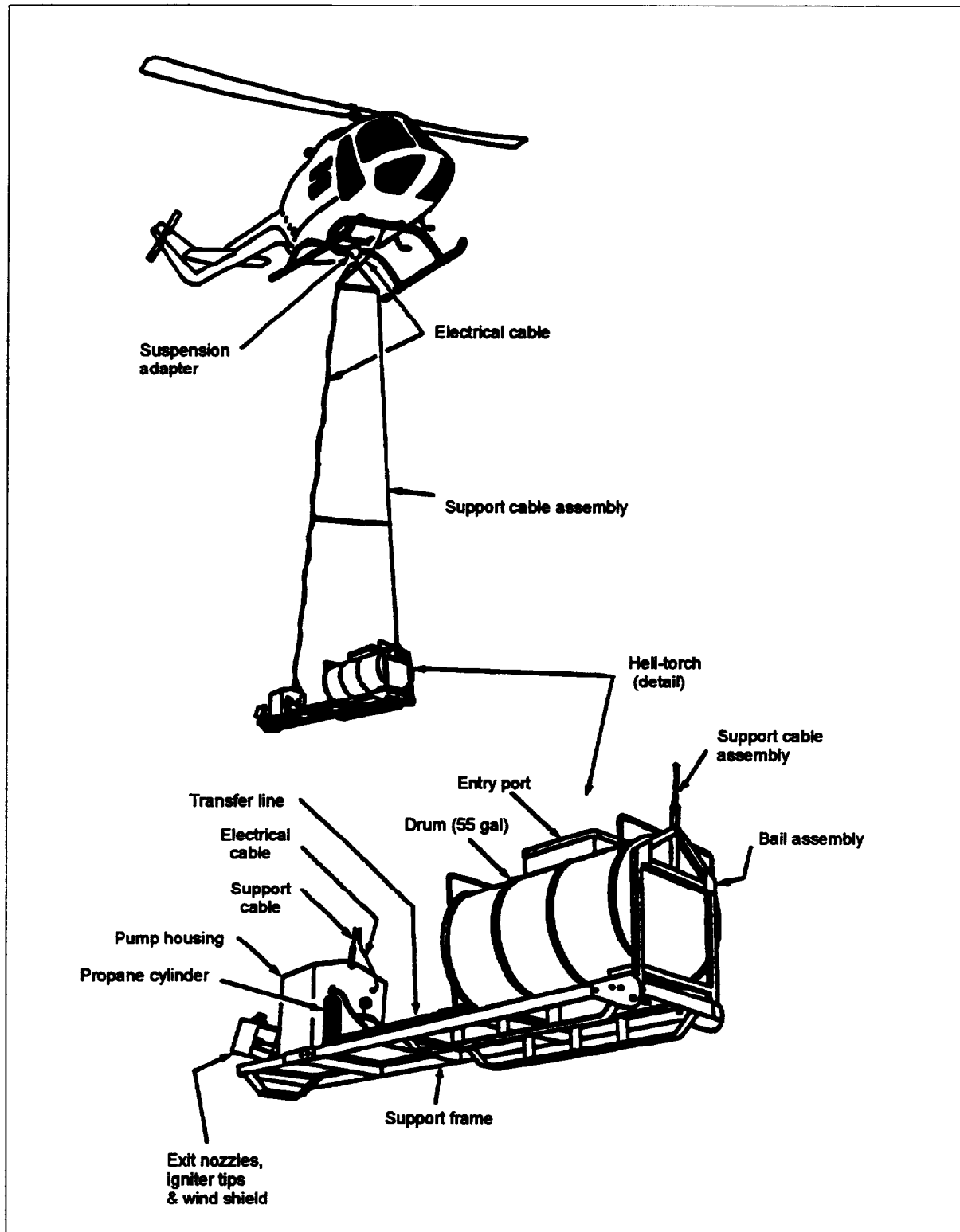


Figure 5.3 Heli-torch components and support system (adapted from Spiltec 1986)

The gelling mix used to thicken the gasoline (or diesel in some cases) is SUREFIRE, a gelling agent available from Simplex (Portland, Oregon) and from Fireflex Mfg. Ltd. (Langley, BC). SUREFIRE is a fine powder which when mixed with liquid fuel produces a smooth, viscous gel. When typical ratios of 1.8 to 2.8 kg (4 to 6 pounds) of SUREFIRE to 205 L (55 gallons) of fuel are used, adequate viscosities for Heli-torch use can normally be achieved within a matter of minutes at room temperature. At sub-freezing temperatures, ratios of 5 kg (11 pounds) to 205 L (55 gallons) are required for gelling to occur in 30 to 40 minutes. The gelling mix is poured through the entry port of the Heli-torch fuel storage drum, which is equipped with a hand crank for mixing. Separate, portable gelled fuel mixing tanks are available from the manufacturer.

The Heli-torch is operated with a positive-displacement pump producing a flow of approximately 55 L/min. When operated with a 205 L holding drum, the Heli-torch can provide a total application time of about 3 minutes and 40 seconds. The drum would then have to be refilled with gelled fuel or replaced with another drum already filled. The 205 L Heli-torch model is rigged so that an empty drum can be removed from the support frame and replaced with a full backup drum quickly and safely.

Burning gelled gasoline globules released from heights of a few m to 18 m remain burning after impact. Even without oil on the water's surface, splash effects are tolerable, and elongated "pancakes" of gelled burning fuel result with sizes (if expressed as a circle) typically 13 to 18 cm in diameter.

Experience suggests that the average globule sizes produced by the Heli-torch with its standard nozzle at heights of 20 meters or less will be between 60 and 120 mL. With gelling-mix-to-gasoline ratios of 2.5 to 5 kg per 205 L of fuel, such globules will spread to thicknesses of 6 to 8 mm on oil-free water surfaces. The globule burn times will range between 4 and 6 minutes.

Ignition of fresh and 2-week weathered, unemulsified crude oil layers is possible in winds of 15 to 25 km/hr; globules approximately 60 to 120 mL in volume are necessary to prevent blowout of the flame. During several successful ignitions of crude oil layers surface winds have reached speeds of 30 km/hr.

Experience (Allen 1992) has shown that the Heli-torch should be flown at altitudes of 8 to 23 m and with speeds of 40 to 50 km/hr. The suggested altitude range is to provide accuracy during the release, to reduce the loss of gelled fuel while burning in the air, and to prevent the blowout of smaller globules on the surface by downwash when the helicopter is flying at low speeds. A minimum speed of 40 km/hr is recommended to prevent such blowouts. At altitudes in excess of 30 m downwash is minimal and the Heli-torch can be used in a stationary mode.

SUMMARY: Table 5.1 gives a summary comparison of the three aerial ignition systems discussed above.

Table 5.1 Summary of Igniter Characteristics and Performance

ASSESSMENT CRITERIA	EPS IGNITER	DOME IGNITER	HELI-TORCH (205 L MODEL)
<u>SAFETY</u> Open flame or sparks inside aircraft Susceptibility to accidental activation Retrieval and handling of igniters that have misfired	None Highly unlikely (requires removal of safety pin) Safe to handle after 2-min. delay	None, if EEIS used Highly unlikely (requires separate ignition source) Safe to handle after 2-min. delay	None Unlikely (positive off/on control) Must return to base to repair/replace Heli-torch
<u>STORAGE</u> Shelf life Difficulty of replacement (all or in part) following normal shelf life Routine maintenance requirements Susceptibility to high or low temperatures during storage/transit Susceptibility to vibration or humidity during storage/transit	5 years Moderately simple replacement of pyrotechnic portion only (about 25% of initial cost) None Very low (tested between -50° C and +50° C) Very low (meets military requirements)	5 years (Dome igniters stored 10 to 15 years still operating) Simple replacement of pyrotechnic portion only (about 50% of initial cost) None Very low (tested between -70° C and +50° C) Very low (meets military requirements)	N.A. (Flammable mixture prepared at time of need) N.A. Minimal (pump, valves, stirring equipment, etc.) Gel-mixing process best carried out at or above freezing temperatures Vibration — No problem. Must keep fuel free of water
<u>GOVERNMENT REGULATIONS</u> Shipping and storage regulations	Basically treated as fireworks. Housed and locked in non-sparking container, properly marked as fireworks. Shipment by land, sea or chartered aircraft permitted; shipment by commercial passenger aircraft prohibited.	Basically treated as fireworks. Housed and locked in non-sparking container, properly marked as fireworks. Shipment by land, sea or chartered aircraft permitted; shipment by commercial passenger aircraft prohibited.	Subject to same storage and transit requirements as for petroleum products. Cannot fly Heli-torch over populated areas (FAR Part 137 approved).

Table 5.1 Summary of Igniter Characteristics and Performance, Continued

ASSESSMENT CRITERIA	EPS IGNITER	DOME IGNITER	HELI-TORCH (205 L MODEL)
<u>AVAILABILITY</u> Currently stockpiled	All stockpiles currently depleted	Approx. 1,700 igniters at Prudhoe Bay (owned by Alaska Clean Seas); approx. 4,000 igniters at Tuktoyaktuk, Canada (owned by Canadian Coast Guard)	Numerous units available in U.S. and Canada
Resupply capability	Now defunct manufacturer stated 2,000 to 3,000 igniters per month once raw materials on hand	Typically 4,000 to 6,000 igniters per month once raw materials on hand	Under emergency conditions, approx. 20 Heli-torches per month
<u>COST</u> Estimated cost (\$U.S./igniter) at factory in 1986	\$160 to \$200 (depending on volume purchased)	\$80 to \$120 (depending on volume purchased)	Approx. \$5,000 per application unit. Approx. \$20 to \$25 for gelling agent per drum of gasoline (or gasoline mix)
<u>OPERATIONAL CONSIDERATIONS</u> Level of field testing performed to date	Moderate. Mostly small controlled spills	Extensive. Many controlled spills and some actual spills	Extensive experience on land. Moderate experience with fresh oil on water
Reliance upon unique airborne application device	None	None	Yes. Heli-torch frame and pump assembly
Igniter (and/or application system) preparations — from storage to field use	None	None	Minor setup. Self-contained package quickly prepared and sling-loaded. Need mixing operations on ground to support
Average rate of application	Approx. 3 to 6 per min.	Approx. 3 to 6 per min.	Burning globules (golf ball size) over a swath 3 m wide; typically about 2 km runs per sortie at 40-50 km/hr and at 15 m altitude or less
Approximate number of igniters releasable per helicopter sortie	Typically 50 to 100 depending on helicopter selected and ability to set down for transfer of cargo to passenger area	Several hundred depending on helicopter selected and ability to set down for transfer of cargo and passenger area	Thousands of 60-120 ml globules
Accuracy of deployment on target oil slick	Good. New design reduces tendency to roll. Still may bounce/skip on ice. Some drift while airborne	Excellent. Irregular shape prevents rolling. Low drift while airborne	Random distribution of burning gel over target area
Durability (or resistance to damage during impact)	Good. Designed for typical drop heights of 15 to 30 m onto frozen surface	Good, designed for typical drop heights of 15 to 30 m on frozen surface	Burning globules flatten out on impact with water

Table 5.1 Summary of Igniter Characteristics and Performance, Continued

ASSESSMENT CRITERIA	EPS IGNITER	DOVE IGNITER	HELI-TORCH (205 L MODEL)
Performance in shallow pools (less than 4 in. deep) on solid ice	Good. Shallow draft	Good. Shallow draft	Good
Dependence on orientation for proper performance	Either of 2 stable, floating positions	Either of 2 stable, floating positions	N.A.
Nature and orientation of flame during ignition of oil	Symmetrical 360° burn from perimeter of igniter radially outward. Hot, lightly pressured flame parallel to water/oil surface	Hot, initial flame then soft, billowy flame concentrated over oil/water surface between floats	Soft flame from gelled fuel globule — 15 cm diameter
Splash effects during impact with oil and water	Significant, though oil layers greater than 1/10 in. quickly become re-established around igniter	Significant, though oil layers greater than 1/10 in. quickly become re-established around igniter	Minimal, does not extinguish flame
Temperature and duration of heat source	1400° C to 2300° C for 2 min.	More than 1200° C for 10 seconds followed by 700° C to 800° C for approx. 10 minutes	Approx. 800° C for up to 6 minutes
Reliability of starter	Typically greater than 95%	Typically greater than 95%	Unknown, but high
Reliability of igniter	Typically greater than 75% (begins to drop after 5-year shelf life)	Typically greater than 90% (begins to drop after 5-year shelf life)	Unknown, but high
Sensitivity to temporary submergence upon impact	None	None	Extinguishes
Sensitivity to wind, rain and sea state during ignition	Unknown	Blowoff wind velocity > 40 km/hr., insensitive to rain, unknown sensitivity to waves	Blowoff wind velocity for small globules < 10 km/hr.; for larger globules > 30 km/hr; insensitive to rain; unknown sensitivity to waves (successful with slightly weathered oil in 0.6 m waves)
Type and amount of debris after use	Small metal firing mechanism survives fire, but sinks	Entire metal float package and fuel basket survive fire and remain on water surface	No debris
Training requirements	Minimal (about 10 min.). Experience needed in identifying and hitting appropriate "targets"	Minimal (about 10 min.). Experience needed in identifying and hitting appropriate "targets"	Moderate training both for operation and mixing fuel

5.3 Fire Proof Containment Booms

5.3.1 Brief History

The efficacy of burning thick oil slicks has been noted in Chapter 4. Removal efficiency increases with increasing initial thickness as does burn rate. In order to thicken and contain oil spills for burning, a variety of fire proof or fire resistant booms have been developed over the years.

Efforts in North America to develop fire resistant booms began in 1976 with work on spray and air bubble barriers for containing burning oil from sub-sea blowouts (Purves 1978, Comfort *et al.* 1979, Purves *et al.* 1978). These were found to be impractical because of the poor efficiency of air bubble barriers and the operational complexity of water spray barriers. At about the same time and for the same application, work was begun on the development and testing of a "quickie" boom that could be constructed with empty 205 L oil drums and fire blanket (McAllister 1979). The device was tested in a small pond and proved reasonably efficient at containing oil burning on water.

Shortly after this in 1979, three large spills catalyzed renewed efforts to develop fire proof containment booms: the IXTOC-1 blowout, the *Burmah Agate* spill and the sinking of the *Atlantic Empress*. The IXTOC-1 offshore blowout illustrated the difficulties associated with dealing with large quantities of oil discharged continuously over a long period of time (Ross *et al.* 1979). This very large spill (some 500,000 m³ in total) also highlighted the potential of in-situ burning for dealing with such fixed-point spills. The *Burmah Agate* spill, which released 250,000 bbl of oil into the Gulf of Mexico in November, 1979, illustrated again the potential for in-situ burning to remove large amounts of surface oil (186,000 bbl burned or 74%) and highlighted the need to develop fire resistant booms to contain burning oil (Kana *et al.* 1981). The *Atlantic Empress* incident, in which all the oil released from the burning and sinking of a 288,000 dwt tanker was consumed in a fire, further illustrated the potential for in-situ burning to remove oil from the sea surface (Horn and Neal 1981).

Following these spills, from 1979 to 1981, Dome Petroleum Ltd., the main explorer for offshore oil in the Canadian Arctic, researched and developed a heavy-duty stainless steel fire proof boom for long term offshore use (Buist *et al.* 1983c). This test program involved field testing of various prototypes at the E.P.A. OHMSETT facility in New Jersey, and at facilities in Vancouver and Nova Scotia. Shortly thereafter, efforts were underway in Alaska to develop lighter fire resistant booms for short-term use (Industry Task Group 1983, Spiltec 1986), and in Canada to develop lighter, lower cost booms designs (Meikle 1983). Some work also continued with the air bubble boom concept (Williams and Cooke 1985) and the water spray concept (Comfort 1989).

The Alaskan work resulted in the development of the 3M Fire Boom. In July 1988, a field test of 3M Fire Boom was carried out in a fjord at Spitsbergen, Norway. The trials involved 90 m of boom and 1900 L of Statfjord crude. The fresh oil in the pocket of the boom was ignited with a Heli-torch and burned for approximately 30 minutes (Allen 1992).

In 1989, the *Exxon Valdez* went aground on Bligh Reef in Prince William Sound, Alaska and released 41,000,000 L of crude oil. During the evening of the second day following the accident an estimated 57,000 to 114,000 L of slightly emulsified (20 to 30% water) North Slope crude were burned in-situ using 136 m of 3M Fire Boom (Allen 1991a). This was the first recorded incident of the use of manufactured fire-resistant boom at a major

spill incident. The burn was initiated using a floating bag of gelled gasoline. The burn lasted 75 minutes, of which 45 minutes involved intense burning and flames reaching 60 to 90 m into the air. The residue remaining in the boom after the burn was about 1100 L of stiff, taffy-like material (Allen 1991b). By the time additional burns were attempted, a storm had further emulsified the slick rendering it unignitable (Exxon 1990).

On August 12, 1993 two experimental burns were conducted offshore St. John's, Newfoundland that involved 3M Fire Boom. The 210 m of boom survived the first 1.5 hour burn in 50 cm waves with 8-11 km/hr winds; it was then examined and, despite some signs of fatigue and self-abrasion, was considered acceptable for another burn. Seventy-five minutes into the second burn several flotation units were lost from one section of the boom and it began to leak oil. The test was stopped and the boom re-examined. Preliminary on-site results indicate that self-abrasion of the fire proof fabric had occurred (Raloff 1993, NOBE Facts 1993, OSIR 19 August 1993).

5.3.2 Summary of Disused Fire Resistant Booms

The following booms were at one time used or researched and developed but either are no longer commercially available or have been superseded by more recent technology.

5.3.2.1 Air Bubble Barriers

Several investigators have proposed the use of submerged, perforated air pipes or hoses to create a current to retain burning oil (Purves 1978, Comfort *et al.* 1979, Williams and Cooke 1985). There are three key drawbacks to this seemingly attractive approach: the severe logistics associated with providing high flowrates of compressed air at remote locations; the difficulties in correctly ballasting and maintaining level on a long length of submerged hose offshore in waves and currents; and the low failure velocity (as low as 0.2 m/s) of bubble barriers in currents. Williams and Cooke (1985) overcame the first limitation by investigating the use of a porous, canvas hose submerged just below (at most 1 m) the water surface; this allowed the air flow to be provided by a centrifugal blower, rather than a high pressure compressor. In calm water tests, a 23 m length of 10 cm diameter bubble barrier was used to encircle and contain burning diesel fuel. The authors concluded that the device was viable for quiescent water conditions but required testing in waves, and currents. No such tests have been reported in the literature.

5.3.2.2 Water Spray Barriers

Several designs for fire proofing oil containment barriers with water sprays have been proposed. Alba International (Aberdeen, Scotland) developed a prototype boom incorporating a built-in water tube jetting system for cooling and herding the burning slick. The system was tested at a firefighting school. The system has not been commercially developed because there is not sufficient interest to justify its high cost of manufacturing (McMurtie, pers. comm. 1992).

Another water spray system (Purves 1978) involved attaching small spray nozzles to the sail of conventional boom to keep the burning oil away from the boom and to shield it from radiant heat. This concept was considered but rejected due to the difficulties in correctly aiming water spray nozzles in waves and the likely failure of the entire containment system

if only one of many nozzles failed to keep the oil away. Other designs (Comfort *et al.* 1979, Comfort 1989) have considered floating spray barrier systems. Tests have shown that a small spray barrier will retain burning oil in quiescent conditions with or without waves (Tam and Purves 1980); however, further tests have shown that the use of larger, higher pressure systems designed to contain oil in currents tends to reduce the intensity and efficiency of the burn and quickly emulsify the oil (Comfort 1989). Another key problem, as with air bubble barriers, is that water spray or water jet barriers have severe logistical and operational requirements compared to alternative systems.

5.3.2.3 The GEMENG Concrete Boom

As part of a program undertaken in the early 1980s to develop cheaper and lighter alternatives to stainless steel booms, Environment Canada funded the development of the GEMENG concrete boom. The basic design was that of a bottom-tensioned, fabric-skirted boom with rigid, hexagonal shaped flotation units. These were strung together on a central, wire-rope towing cable. The final design of the flotation units consisted of a Foamingglass core with a castable refractory cement cover. The ends of each float strung on the tow cable were either a ball or socket to permit an oil-tight seal (Meikle 1983). The units were tested at OHMSETT (Borst 1983) and in protected waters (Solsberg and Belore 1982). The boom proved capable of containing burning oil at tow speeds up to 0.4 m/s with only minimal oil leakage; the oil that did leak burned in the stagnation zone aft of the towed boom section. No burn tests in waves were reported (Borst 1983). Some spalling of the concrete cover was reported. During a 72-hour field durability test in 30 to 60 cm waves with a 1.5 second period, the boom prototype suffered considerable damage. This resulted from self-induced abrasion of the ball and socket joint arrangement and banging of adjacent flotation units (Solsberg and Belore 1982). This boom is not commercially available.

5.3.2.4 The "Quickie" Fireproof Boom

In 1979, Dome Petroleum Ltd. (now part of Amoco Canada Petroleum) in support of its Arctic offshore drilling operations, funded the construction and testing of a fire proof boom made with empty 205 L oil drums connected with fire resistant cloth material. The boom was tested in a quiescent pond at Vancouver airport and proved capable of containing burning oil; long-term exposure (about 1 hour) to the high temperatures generated by in-situ burning caused rapid oxidation of the mild steel drums (McAllister 1979). This boom was superseded by the Dome stainless steel boom (see next section).

5.3.2.5 Rope Net Boom

In the late 1970s, as a result of offshore exploration for oil in the Arctic, a study was undertaken of the feasibility of burning off oil released from a subsea blowout (Arctec 1977). One concept attempted was that of a slightly buoyant cargo net floating on the water surface that would collect and thicken oil flowing past. The low freeboard of the net combined with water wicking into the net was supposed to maintain the integrity of the boom during an oil fire. Small-scale tests revealed that the boom did not contain oil at thicknesses sufficient to maintain combustion (Ewing 1979).

5.3.2.6 Asbestos/Ethafoam Fireproof Boom

In 1977 Environment Canada funded the construction of a fireproof boom consisting of 18 cm diameter Ethafoam logs surrounded by a blanket of ceramic wool and covered with an aluminized asbestos fabric used for fire suits (Roberts 1978). The boom was tested with burns of gasoline; the heat melted the aluminum, burned the organic binder out of the asbestos and the Ethafoam flotation was melted in several places (Ewing 1979, Roberts 1978).

5.3.2.7 Reynolds Aluminum

A now defunct subsidiary of Reynolds Aluminum called Reynolds Submarine Service Corp. manufactured containment boom in heights of 38 and 71 cm (Solsberg 1983). These were constructed from 3003H14 corrugated aluminum. These had been considered as potential fire proof booms, but never tested (Purves *et al.* 1977).

5.3.2.8 Firefence

Aqua Guard of Vancouver, B.C. once manufactured a lightweight fire proof boom fabricated from galvanized sheet steel. Known as the Firefence, the 4.5 kg/m boom was produced in 2.7 m sections which incorporated piano hinged flexing panels and was joined together with thumbscrews. The boom was evaluated at OHMSETT (Solsberg 1983). The boom is no longer marketed, due to low demand.

5.3.2.9 SWEPI Boom

Beginning in the early 1980s Shell Western Exploration and Production Inc. (SWEPI) began the development of a fire-resistant boom to support its offshore drilling operations in Alaska (Industry Task Group 1983, S.L. Ross 1983, Spiltec 1986). The boom, in its final form, was a bottom-tensioned, cylindrical flotation type with multiple layers of a fire-resistant fabric surrounding 20 L steel cans. The boom was encased in a sacrificial plastic sheet that was wrapped in chain link fencing material to provide abrasion resistance (Spiltec 1986). A 43 cm deep skirt was attached to the flotation. Five-mm wire cable in the flotation section acted as a tension member; additional tension capability and ballast was provided by a 7 mm chain sewn into the bottom of the skirt.

A unique feature of this boom was the use of the wicking action of the Thermoglas and K.O.Wool fabrics to wick water and cool the boom. The boom was tested several times (Industry Task Group 1983, S.L. Ross 1983, Spiltec 1986) for periods up to 24 hours in quiescent conditions and sections were deployed offshore in broken ice conditions (Industry Task Group 1983, S.L. Ross 1983). No further development work was undertaken with this boom after 1986 and it is no longer commercially available.

5.3.3 Presently Available Fire Proof Booms

The fire-proof booms that are presently available on the market are documented below. The suppliers of commercially available boom were identified through a mail survey of companies identified in Environment Canada's boom catalogue (Solsberg 1983), the World Catalogue of Oil Spill Response Products (Schulze 1993) and the International Oil Spill Control Directory (Cutter 1993). The available booms are divided into two categories: those constructed of stainless steel and those constructed from fire-resistant fabrics.

Before presenting the information on available fire-proof booms it is worthwhile to review materials-of-opportunity that have been used to construct booms to contain oil for in-situ burning. The most common material has been logs (McLeod & McLeod 1972, McAllister and Buist 1981, Robertson 1991). Generally, the logs have been either available as an already constructed boom from logging operations or chained together using logging equipment and techniques. Although very effective as a fire proof barrier (only the above-water portion of the log chars) they are restricted for use in calm waters. Several instances of using finished lumber to construct small fireproof booms for calm waters have also been reported (Dome 1981b, Smith and Diaz 1985, Burns 1988, and SINTEF and S.L. Ross 1993) including one instance where nine tonnes of oil were burned offshore during tests of the Kontax igniter (Battelle 1979).

The other material that has been extensively used as a fire-proof containment barrier is ice. Ice edges have proven to be excellent barriers against which to burn oil accumulations (Ramsier *et al.* 1973, Beckett 1979, Schrier and Ediam 1979, Dome 1981b, Industry Task Group 1983, Smith and Diaz 1985, S.L. Ross and Dickens 1987, Burns 1988).

The following sections present data on currently available booms constructed of either stainless steel or fire resistant fabrics. Where possible a summary sheet of boom characteristics is provided; this sheet is adapted, with permission, from the World Catalogue of Oil Spill Response Products (Schulze 1993).

5.3.3.1 Stainless Steel Booms

The first two steel booms are commercially available (Fireguard and Sandvik) and the next two (Dome and Merkalon) are not but their technical designs are available.

FIRE GUARD BOOM: is manufactured and distributed by:

Gamlén Industries S.A.

17, Route de Rouen

27950 Saint-Marcel, France

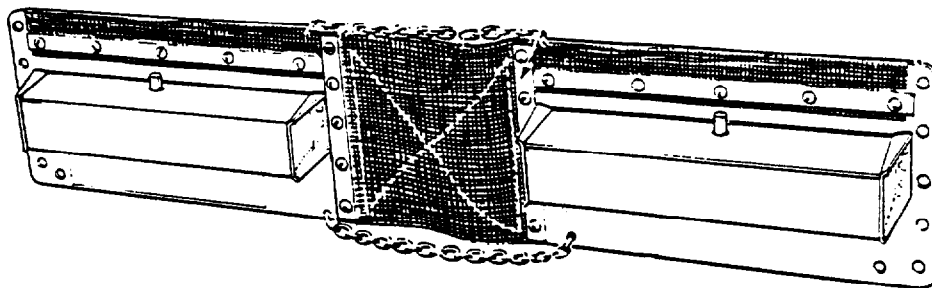
phone: (1) 32.21.13.60 fax: (1) 32.51.43.24

This boom (see attached Table 5.2) is made of short, rigid flotation units connected by flexible, fabric panes. The floats are made from 2 square tubes of AG-3 (presumed to be a grade of galvanized steel or acier galvanisé) that is 2 mm thick. These are attached to either side of a 3 mm thick plate of AG3 that serves as sail and skirt. For heat transfer purposes the floats and vertical plate are separated by a 1 cm gap and the connections between the two are insulated with asbestos strips. The design draft and freeboard have been calculated so that there is sufficient heat transfer at 1300°C temperatures to ensure that the boom does not melt.

Table 5.2

COMPANY

GAMLEN INDUSTRIES S.A.
 17, Route De Rouen
 27950 Saint - Marcel
 France
 Tel: (33) 32.21.13.60
 Fax: (33) 32.51.43.24
 Tlx: 180 052 F
 Contact: D. Desmichels



FIREGUARD

BOOM TYPE	Fence	Fence	
MODEL	Fireguard hd	Fireguard	
COST \$ US/m (\$/ft)	Inquire	Inquire	
FREEBOARD mm (in)	220 (9)	160 (6)	
DRAFT mm (in)	220 (9)	170 (7)	
BOOM HEIGHT mm (in)	440 (18)	330 (13)	
STANDARD LENGTH m (ft)	5 (16)	5 (16)	
END CONNECTORS	Bolts	Bolts	
SKIRT MATERIAL	AG-3/Asbestos	AG-3/Asbestos	
SAIL MATERIAL	AG-3/Asbestos	AG-3/Asbestos	
FLOTATION	R-A-H*	R-A-H*	
FLO. MEMBER LENGTH m (ft)	5 (16)	5 (16)	
WEIGHT kg/m (lb/ft)	12 (8.0)	6 (4)	
RES. BUOYANCY kg/m (lb/ft)			
RESERVE BUOYANCY/WEIGHT	14:1		
WATERLINE BEAM mm (in)	300 (12)	220 (9)	
VERTICAL CG mm (in)			
BALLAST MATERIAL			
BALLAST WEIGHT kg/m (lb/ft)			
TENSION MEMBER (1)/ STRENGTH (1) N (lb)	Cable (top & bottom) 75,000 (16,500)	Cable (top & bottom) 50,000 (11,000)	
TENSION MEMBER (2)/ STRENGTH (2) N (lb)			
TENSION MEMBER (3)/ STRENGTH (3) N (lb)			
TOTAL STRENGTH N (lbs)			
FABRIC TENSILE STRENGTH N/50mm (lbs/in)	500 (55)	500 (55)	
FABRIC TEAR STREN. N (lb)	160 (35)	160 (35)	
STORAGE VOL. m ³ /m (ft ³ /ft)	0.10 (1.08)	0.045 (0.5)	
OPERATION — OPERATING ENVIRONMENT — SEA STATE — TOW SPEED (knots) — PERSONNEL REQUIRED — DEPLOYMENT — RECOVERY AND STORAGE	C-P --- 2-4 --- --- manual	C-P --- 2-4 --- --- manual	

COMMENTS: Gamlen reports Fireguard boom is made of short, rigid flotation units connected by flexible panels. The flexible panels are made of 3-ply asbestos (96%) coated with PVC. Between two layers of material is inserted a fine mesh stainless steel screen that acts as a support for the asbestos and a means of dissipating heat. The boom will withstand heat up to 1300°C (2372°F). The survival time for this boom in tests is reported as 35 minutes. The asbestos portion of the boom must be refurbished after each use.

*R = rectangular block; A = attached to skirt; H = hollow, rigid; C = calm; P = protected.

The connectors consist of stainless-steel mesh enclosed in a 3 ply asbestos fabric coated with a sacrificial PVC covering. Stainless steel cables, top and bottom, carry tension loads, not the flexible panels. Each unit (float + connector) is 5 m long. Each section is apparently connected by means of 5 bolts.

The unit is claimed to have survived in a hydrocarbon fire for 35 minutes; after exposure to fire the asbestos strips and flexible connections panels must be replaced.

SANDVIK STEEL BARRIER (SSB): is produced and marketed by:

AB Sandvik Process Systems
Hedasvagen 55
S-81181 Sandviken
Sweden
phone + 46 26 27 09 50
fax + 46 26 25 95 79

This product (see Table 5.3) consists of sheets of cold-rolled stainless steel supported by pontoons of welded stainless steel cylinders. The boom sections are connected by a bolt joint arranged so the boom can move freely and follow waves. No test data (oil containment or fire resistance) were supplied by the manufacturer. It should be noted that it appears that the pontoons are sealed tightly, which could present air-expansion problems when exposed to high flame temperatures. The manufacturer claims that the product has performed as a containment boom for seven years without maintenance.

The following two stainless steel booms are no longer actively marketed.

DOME STAINLESS STEEL BOOM: was researched and developed by Dome Petroleum Ltd. over a four-year period from the late 1970s to the early 1980s. The boom, primarily the connector unit, (see Table 5.4) was redesigned several times as a result of failures in test-tank and field deployment trials. The boom is large (overall height = 1.8 m) and massive in order to meet its design criteria of long-term deployment offshore and resistance to ice impacts. The boom was fire tested for 2 hours in quiescent conditions near Vancouver, B.C. (McAllister and Buist 1980), fire and oil containment tested in waves and currents at OHMSETT (Dome 1981a) and deployed offshore four times for a total of 45 days.

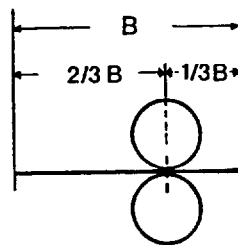
The boom's design consists of two units, the flotation and the connector. The flotation unit consists of a pentagonal cross-section chamber constructed of Type 310 stainless steel with a steel sail and skirt attached. Either end of the flotation unit is fitted with a slotted stainless steel pipe as one part of a double-slide connector. Each flotation unit incorporates a drain plug and wax-plugged vent pipe (for the release of overpressure air during burning and the ingestion of cold air during cooling). The connector units consist of a pleated, thin gauge 321 stainless steel sheet through which passes a universally jointed box beam. This design is necessary to avoid the self-abrasion problems associated with mineral-based fire resistant cloth when wetted and the stress cracking problems associated with simpler steel connector designs. Each section (flotation unit plus connector unit) weights 210 kg and is 2.58 m long, has a draft of 1.2 m and a freeboard of 0.57 m. The deployment and retrieval of this boom is a cumbersome process (Dome 1983).

Table 5.3**COMPANY**

AB SANDVIK PROCESS SYSTEM
Hedarsvagen 55
S-811 81 Sandviken, Sweden

Tel: 46 26-270950

Fax: 46 26-259579

**SSB-600 Steel Barrier**

BOOM TYPE	Fence	Fence	
MODEL	SSB-600 Steel Barrier	SSB-800 Steel Barrier	
COST \$ US/m (\$/ft)	Inquire	Inquire	
FREEBOARD mm (in)	200 (8)	266 (11)	
DRAFT mm (in)	400 (16)	533 (23)	
BOOM HEIGHT mm (in)	600 (24)	800 (34)	
STANDARD LENGTH m (ft)	2 (6.5)	2 (6.5)	
END CONNECTORS	Bolt-joint	Bolt-joint	
SKIRT MATERIAL	Stainless steel	Stainless steel	
SAIL MATERIAL	Stainless steel	Stainless steel	
FLOTATION	CS-A-H*	CS-A-H*	
FLO. MEMBER LENGTH m (ft)			
WEIGHT kg/m (lb/ft)	6.5 (4.4)	9.5 (6.4)	
RES. BUOYANCY kg/m (lb/ft)			
RESERVE BUOYANCY/WEIGHT			
WATERLINE BEAM mm (in)			
VERTICAL CG mm (in)			
BALLAST MATERIAL	None	None	
BALLAST WEIGHT kg/m (lb/ft)			
TENSION MEMBER (1)/ STRENGTH (1) N (lb)			
TENSION MEMBER (2)/ STRENGTH (2) N (lb)			
TENSION MEMBER (3)/ STRENGTH (3) N (lb)			
TOTAL STRENGTH N (lbs)			
FABRIC TENSILE STRENGTH N/50mm (lbs/in)			
FABRIC TEAR STREN. N (lb)			
STORAGE VOL. m ³ /m (ft ³ /ft)			
OPERATION — OPERATING ENVIRONMENT — SEA STATE — TOW SPEED (knots) — PERSONNEL REQUIRED — DEPLOYMENT — RECOVERY AND STORAGE	C* — — 2 from shoreline manual	C-P* — — 2 from shoreline manual	

COMMENTS: Boom has been used and tested in Sweden; claimed to have performed for seven years without maintenance. No containment or fire test data reported.

CS = segmented cylinder; A = attached to skirt; H = hollow rigid; C = calm; P = protected.

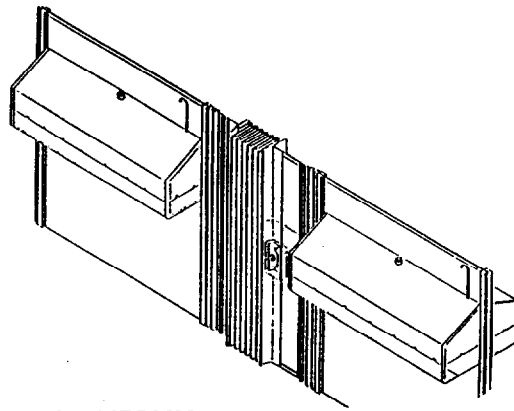
Table 5.4

COMPANY

AMOCO Canada
P.O. Box 200
Calgary, Alberta
Canada T2P 2H8

Tel: (403) 298-3514
Fax: (403) 298-2883

Contact: Nick Vanderkooy



DOMESTIC FIRE PROOF BOOM

BOOM TYPE	Fence		
MODEL	Fire Proof Boom		
COST \$ US/m (\$/ft)	Inquire		
FREEBOARD mm (in)	570 (22)		
DRAFT mm (in)	1200 (48)		
BOOM HEIGHT mm (in)	1700 (70)		
STANDARD LENGTH m (ft)	2.6 (8.5)		
END CONNECTORS	Slide		
SKIRT MATERIAL	310 stainless steel 321 stainless on connector		
SAIL MATERIAL	310 stainless steel 321 stainless on connector		
FLOTATION	R-A-H*		
FLO. MEMBER LENGTH m (ft)	1.7 (5.5)		
WEIGHT kg/m (lb/ft)	81 (54)		
RES. BUOYANCY kg/m (lb/ft)	90 (60)		
RESERVE BUOYANCY/WEIGHT	1.1:1		
WATERLINE BEAM mm (in)	710 (28)		
VERTICAL CG mm (in)			
BALLAST MATERIAL			
BALLAST WEIGHT kg/m (lb/ft)			
TENSION MEMBER (1)/ STRENGTH (1) N (lb)			
TENSION MEMBER (2)/ STRENGTH (2) N (lb)			
TENSION MEMBER (3)/ STRENGTH (3) N (lb)			
TOTAL STRENGTH N (lbs)	110,000 (75,000)		
FABRIC TENSILE STRENGTH N/50mm (lbs/in)			
FABRIC TEAR STREN. N (lb)			
STORAGE VOL. m ³ /m (ft ³ /ft)	1 (11)		
OPERATION - OPERATING ENVIRONMENT - SEA STATE - TOW SPEED (knots) - PERSONNEL REQUIRED - DEPLOYMENT - RECOVERY AND STORAGE	0 SS5 5 6 assemble on shore or aft. deck recover with crane		

COMMENTS: Has survived 30 day sea trial and several burn tests in calm, and wave conditions.

*R = rectangular block; A = attached to skirt; H = hollow, rigid.
O = open water; SS5 = Sea State 5

According to Dome (1983) the final design of the boom including the accordion pleated connector is able to:

- withstand flame temperatures of 980°C for extended periods in a salt water environment;
- contain burning oil in a "U" configuration in Sea State 3-4;
- survive Sea State 5;
- be flexible at temperatures to -20°C;
- be storable at temperatures to -50°C;
- resist abrasion; and
- withstand tensile loads of 110,000 N

Although not commercially available, the design for the boom is available from:

Amoco Canada Petroleum Ltd.
P.O. Box 200
Calgary, Alberta
Canada
T2P 2H8
phone: 403-298-3514
fax: 403-298-2883

MERKALON: stainless steel boom formerly produced by:

Mannesmann Italiano SPA
Div. Ecologia
Via Gabriele D'Annunzio
2/104 - 16121 Genova
Italy

The boom has an overall height of 70 cm of which 30 cm is freeboard. Each 1.5 m long section weighs 16 kg and connected via preformed male/female slides. The boom was reported to be able to withstand 800°C (Solsberg 1983). The manufacturer advises that they no longer produce this boom due to lack of demand, but could begin production again if demand warranted.

The following suppliers of stainless steel booms did not reply to the mail survey:

- Nouvelles Applications Technologique, France:
Bapinox Stainless Steel Booms (Solsberg 1983)
- Eimbecke Oilskimmer GmbH, Hamburg, Germany:
Stainless Floatbarrier (Cutter 1992)
- Oel-Nolte, Hemer, Germany:
Stainless steel booms (Cutter 1992).

One manufacturer advised that they have recently begun efforts to develop a stainless steel boom. Further information can be obtained from:

POL-E-MAR Inc.
P.O. Box 419
Greely, Ontario
Canada K0A 1Z0

5.3.3.2 Fire Resistant Fabric Booms

The following four fire containment booms constructed with fire-resistant fabrics are commercially available.

3M FIRE BOOM¹: is produced and marketed by:

American Marine, Inc.
401 Shearer Blvd.
Cocoa, Florida 32922
phone: 407-636-5783
fax: 407-636-5787

The product (Table 5.5) consists of high temperature resistant flotation sections constructed of a 3M-patented ceramic foam. This material is stable at temperatures up to 1100°C. The float core sections are held together with stainless steel knitted wire mesh. These 1.8 m long flotation sections are laid end to end and surrounded by a continuous blanket of 3M NEXTEL fibres. These non-flammable, poly-crystalline, metal oxide fibres are designed for applications at temperatures up to 1370°C. The NEXTEL layer is wrapped with another layer of stainless steel mesh. This entire package is covered with a sacrificial layer of PVC which extends below the flotation to form a skirt and double-layered pocket for a galvanized, proof coil chain tension member. Short stainless steel seaming bars rivetted through the layers underneath the flotation are used to hold the package together. Individual flotation sections are contained in 2.1 m long segments separated by a metal clamp fastened through the PVC/mesh/NEXTEL "sandwich". The connector for each 15.2 m section (consisting of 7 segments) is a stainless steel plate quick connector.

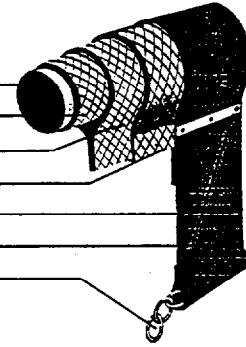
This product has evolved since the mid 1980s as a result of improvements made after a large number of tests. See Table 5.6 for results from one series of tests conducted in November, 1990. Initial testing of a 3M fire-resistant blanket designed to be attached over conventional boom was conducted in 1985 (Spiltec 1986); the blanket, which depended on wicking action, did protect the underlying conventional boom to some extent but had problems. Next was a series of tests in 1987 with an early prototype of the boom. First, an 8.5 m long section of 10" prototype survived 6 hours exposure to burning heptane (maximum recorded temperature of 815°C) with no sign of thermal stress and little loss of material strengths (Allen and Fischer 1988). Next, a 7.3 m long prototype section was exposed to

¹ The 3M Fire Boom was fully licensed to American Marine, Inc. in 1994. The boom is now called the American Fire Boom.

Table 5.5**COMPANY**

American Marine, Inc.
401 Shearer Blvd.
Cocoa, Florida 32922
Tel: (407) 636-5783
Fax: (407) 636-5787
Contact: Jim Pearce

1. High Temperature Resistant Flotation Core
2. Stainless Steel Knitted Mesh
3. High Temperature Resistant Ceramic Textile
4. Stainless Steel Knitted Mesh
5. PVC Cover
6. Stainless Steel Seaming Bar
7. Bottom Tension Member/Ballast



BOOM TYPE	Curtain, fire containment	Curtain, fire containment	Curtain, fire containment
MODEL	8" flotation by 12" skirt	12" flotation by 18" skirt	18" flotation by 24" skirt
COST \$ US/m (\$/ft)	Inquire	Inquire	Inquire
FREEBOARD mm (in)	152 (6)	229 (9)	381 (15)
DRAFT mm (in)	381 (15)	533 (21)	711 (28)
BOOM HEIGHT mm (in)	533 (21)	762 (30)	1,092 (43)
STANDARD LENGTH m (ft)	15 (50)	15 (50)	15 (50)
END CONNECTORS	Quick	Quick	Quick
SKIRT MATERIAL	Reinforced PVC	Reinforced PVC	Reinforced PVC
SAIL MATERIAL	PVC/steel mesh/Nextel	PVC/steel mesh/Nextel	PVC/steel mesh/Nextel
FLOTATION	CS-I-Ceramic F*	CS-I-Ceramic F*	CS-I-Ceramic F*
FLO. MEMBER LENGTH m (ft)	1.8 (6)	1.8 (6)	1.8 (6)
WEIGHT kg/m (lb/ft)	7.7 (5.1)	12.7 (8.4)	23.1 (15.3)
RES. BUOYANCY kg/m (lb/ft)	19.8 (13.3)	47.6 (31.9)	108 (72.6)
RESERVE BUOYANCY/WEIGHT	2.7:1	3.8:1	4.7:1
WATERLINE BEAM mm (in)	183 (7)	263 (10)	373 (15)
VERTICAL CG mm (in)	168 (7)	263 (10)	368 (14)
BALLAST MATERIAL	6mm (¼ in) galvanized chain	6mm (¼ in) galvanized chain	10mm (3/8 in) galvanized chain
BALLAST WEIGHT kg/m (lb/ft)	0.8 (0.5)	0.8 (0.5)	2.8 (1.9)
TENSION MEMBER (1)/ STRENGTH (1) N (lb)	Chain 16,800 (3,750)	Chain 22,500 (5,000)	Chain 47,700 (10,600)
TENSION MEMBER (2)/ STRENGTH (2) N (lb)	Fabric 130,500 (29,000)	Fabric 171,000 (38,000)	Fabric 234,000 (52,000)
TENSION MEMBER (3)/ STRENGTH (3) N (lb)	Connector 28,350 (6,300)	Connector 44,100 (9,900)	Connector 61,000 (13,700)
TOTAL STRENGTH N (lbs)			
FABRIC TENSILE STRENGTH N/50mm (lbs/in)			
FABRIC TEAR STREN. N (lb)	675 (150)	675 (150)	675 (150)
STORAGE VOL. m ³ /m (ft ³ /ft)	0.07 (0.70)	0.13 (1.40)	0.30 (3.20)
OPERATION — OPERATING ENVIRONMENT — SEA STATE — TOW SPEED (knots) — PERSONNEL REQUIRED — DEPLOYMENT — RECOVERY AND STORAGE	C-P* 1 0.5-0.75 (10) 2 Towed from tray	C-P* 1-2 0.5-0.75 (10) 3 Towed from tray	C-P* 2 0.5-0.75 (10) 4 Towed from tray

COMMENTS: See text for details on extensive testing. Boom as presently designed is good for 24 hour burning in quiescent conditions and about 3 hours in calm or protected waters.

CS = segmented cylinder; I = internal; F = foam; C = calm; P = protected.

Table 5.6 3M Fire Boom Test Summary

PARAMETER	FIRE BOOM MODEL			
	8" flotation by 12" skirt	12" flotation by 18" skirt	18" flotation by 24" skirt	8" flotation by 12" skirt
Test type	Salt water tank	Salt water tank	Salt water tank	Salt water tank
Duration	24 hour	24 hour	24 hour	48 hour
Date	Nov. 1990	Nov. 1990	Nov. 1990	Nov. 1990
Location	Corpus Christi	Corpus Christi	Corpus Christi	Prudhoe Bay
Fuel	Louisiana crude	Louisiana crude	Louisiana crude	N. Slope crude
Burn rate (L/min)	2.1	1.7	1.3	2.3-3.8
Exposure temp (°C) ^a	540-700	565-760	1010-1100	650-930
Max flame temp (°C)	945	835	1245	930
Freeboard before (cm) ^c	13-14	23-24	38-39	14-15
Freeboard after (cm)	12-13	22-24	37-38	11-14

a = Temperature detected at boom surface

b = Temperature exceeded instrument limit (1200°C)

c = Initial freeboard artificially high due to entrapped air

adapted from Allen 1992

crude oil flames for 24 hours. Maximum flame temperatures exceeded 1000°C. After 24 hours the boom succeeded in containing burning oil in a quiescent tank and appeared to have suffered little or no damage.

The next series of tests involved a calm water burn on seawater in a fjord at Spitsbergen, Svalbard, Norway in 1988. The boom was held in a "U"-configuration by two boats and 1900 L of Statfjord crude was burned off (Allen 1990).

The next use of the boom was for a test burn during the response to the *Exxon Valdez* spill in March 1989. About 57 to 114 m³ of North Slope crude oil was burned in the pocket of a 137 m long 3M Fire Boom of a second-generation design. The burn lasted a total of 75 minutes of which 45 involved intense burning. The second-generation boom suffered some damage due to thermal stress resulting in some loss of freeboard and embrittlement of the fabric between flotation sections (Allen 1990). Subsequent, in-house, test programs from July 1990 to May 1991 involved quiescent salt water tank tests with burns as long as 24 hours (Allen 1992). These tests resulted in design modifications to the 3M Fire Boom. In November 1990, Alaska Clean Seas conducted a 48 hour burn test of a new version of an 8" 3M Fire Boom. Although the boom survived the test, upon removal it was charred and brittle, there was some deterioration of the fire resistant components of the boom between the flotation sections, and the weight of the connectors was causing a loss of freeboard (Alaska Clean Seas 1991). Design changes were to be incorporated to address these issues.

Most recently, 212 m of the 18" version was used to contain the burning oil at the Newfoundland Offshore Burning Experiment (NOBE) in August 1993. These burns were conducted 45 km offshore of St. John's, Newfoundland in 0.5 m waves with 8-11 km/hr winds (OSIR, August 19, 1993; NOBE Newsletter September 1993). Two discreet burns were conducted. The first involved 48.3 m³ of slightly weathered crude oil burned over a 1.5 hour period. Initially, some splashover of the oil was observed; however, most of this oil was retained in the stagnation zone aft of the boom and subsequently ignited and burned by the main fire. At the end of the first burn, the boom was inspected. Some signs of fatigue in the stainless steel were observed at a point about 10 cm from the vertical stiffeners and some of the Nextel fabric was missing; however, the boom was considered fit enough for a second burn (NOBE Newsletter September 1993).

One hour and 15 minutes into the second burn several flotation sections from the boom came loose, oil began to leak and the oil pumping was stopped. After the fire had stopped (28.9 m³ had burned) the boom was again inspected. A section of the boom that incorporated a middle tension member had lost 3 flotation sections and a number of other sections were completely missing Nextel fabric near the vertical stiffeners (NOBE Newsletter September 1993; Raloff 1993). It is presumed that the combined action of heat, saltwater and wave action were to blame for this self abrasion problem; this has been noted before (e.g., Dome 1981a, Roberts and Chu 1978).

At the time of writing, 3M was examining the boom and evaluating the steps to be taken next. (*A license to manufacture and sell the boom was granted to American Marine, Inc. in 1994.*)

SEA CURTAIN FIREGUARD: is manufactured by:

Kepner Plastic Fabricators
3131 Lomita Boulevard
Torrance, California 90505
phone: 310-325-3162
fax: 310-326-8560

This boom (Table 5.7) is designed to be reel-able and self-inflating. As the boom is drawn off the reel a stainless steel coil springs from a flattened position to a helical position thus providing flotation and freeboard. Additional flexible flotation for the skirt and ballast is attached at the bottom of the inside of the continuous cylindrical flotation section. It consists of high temperature, closed cell foam protected by Thermoglas fabric. The erecting coil supports a double layer of Thermotex coated with a sacrificial abrasion resistant coating; this coating will burn away at 315°C. The skirt is constructed of a heavy-duty polyurethane coated polyester (PVC coated polyester and nylon are also available). Ballast and tensile strength are provided by a galvanized high test chain in a pocket at the bottom of the skirt.

The boom has been burn-tested several times in quiescent, freshwater and saltwater conditions and containment testing was conducted in a wave tank. The first test involved 8 hours exposure to burning diesel on water at the Texas A&M Fire School with peak flame temperatures of 1260°C.

The next burn test occurred in 1985 (Spiltec 1986). A 7.6 m long section of Model 1115 FG (26") boom was exposed to burning Cook Inlet crude in a quiescent tank of freshwater. Maximum flame temperatures of 915°C were recorded. On exposure to the flames the yellow sacrificial coating discolored to a pale green. Inspection of the boom after one hour's exposure revealed that the areas of discoloration were noticeably more brittle than the rest of the boom and were easily fractured by a pinch. This fracturing was reported to be particularly easy to induce at sharp bends or folds in the fabric. Gentle impacts on the surface of the boom also created fractures in the fabric and loss of the outer layer.

After six hours of exposure to flames and despite embrittlement of the Thermotex fabric, the boom shape, freeboard and configuration were still satisfactory (Spiltec 1986). However, the Thermotex fabric (both layers) that had been in direct contact with flames was susceptible to abrasion (Spiltec 1986).

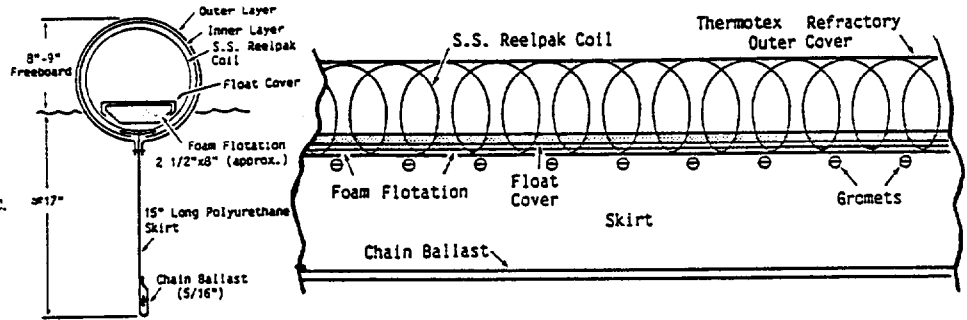
After 24 hours of exposure to flames the boom was still completely containing the fire with no loss of freeboard. The boom was removed from the tank at the end of the test and examined. It was noted that the outside Thermotex fabric was extremely susceptible to abrasion. Both covers were removed and the boom laid open for inspection. Wherever the sacrificial coating had burned off the outer layer of Thermotex, the inner layer's sacrificial coating had also disappeared. This left the inner layer susceptible to abrasion from the erecting coil. Internal oil staining indicated that some oil had penetrated to the boom's interior. The foam flotation was still intact and undamaged as was the stainless steel coil and the skirt (Spiltec 1986).

Subsequent tow tests on a new section of the boom at a test tank in Houston proved that the boom could contain oil at tow speeds up to 0.5 m/s in calm conditions. In 0.6 m x 12 m waves at tow speeds of 0.2 m/s some minor oil simulant losses were observed. The boom exhibited good towing and wave riding characteristics at speeds up to 0.5 m/s.

Table 5.7

COMPANY

KEPNER PLASTICS FABRICATORS, INC.
 3131 Lomita Boulevard
 Torrance, California 90505
 Tel: (310) 325-3162
 Fax: (310) 326-8560
 Contact: Brian Ashkenazi



BOOM TYPE	Curtain, self-inflat.	Curtain, self-inflat.	Curtain, self-inflat.	Curtain, self-inflat
MODEL	FireGard BTIP 812 FG	FireGard 1115 FG	FireGard BTIP 1418 FG	FireGard BTIP 1823 FG
COST \$ US/m (\$/ft)	Inquire	Inquire	Inquire	Inquire
FREEBOARD mm (in)	152 (6)	203 (8)	280 (11)	381 (15)
DRAFT mm (in)	356 (14)	457 (18)	559 (22)	660 (26)
BOOM HEIGHT mm (in)	508 (20)	660 (26)	839 (33)	1,041 (41)
STANDARD LENGTH m (ft)	31 (100)	31 (100)	31 (100)	31 (100)
END CONNECTORS	Bolted plates	Bolted plates	Bolted plates	Bolted plates
SKIRT MATERIAL	Urethane/PVC coated polyester	Urethane/PVC coated polyester	Urethane/PVC coated polyester	Urethane/PVC coated polyester
SAIL MATERIAL	Thermotex hi-temp fabric	Thermotex hi-temp fabric	Thermotex hi-temp fabric	Thermotex hi-temp fabric
FLOTATION	CC-I-I*	CC-I-I*	CC-I-I*	CC-I-I*
FLO. MEMBER LENGTH m (ft)	3.1 (2.2)	4.9 (3.3)	6.7 (4.5)	9.7 (6.5)
WEIGHT kg/m (lb/ft)				
RES. BUOYANCY kg/m (lb/ft)				
RESERVE BUOYANCY/WEIGHT				
WATERLINE BEAM mm (in)				
VERTICAL CG mm (in)				
BALLAST MATERIAL	H. T. chain	H. T. chain	H. T. chain	H. T. chain
BALLAST WEIGHT kg/m (lb/ft)	1.1 (0.8)			
TENSION MEMBER (1)/STRENGTH (1) N (lb)	6 mm (1/4 in) chain bottom			
TENSION MEMBER (2)/STRENGTH (2) N (lb)				
TENSION MEMBER (3)/STRENGTH (3) N (lb)				
TOTAL STRENGTH N (lbs)				
FABRIC TENSILE STRENGTH N/50mm (lbs/in)				
FABRIC TEAR STREN. N (lb)				
STORAGE VOL. m ³ /m (ft ³ /ft)	0.01 (0.12)	0.02 (0.18)	0.02 (0.25)	0.03 (0.40)
OPERATION - OPERATING ENVIRONMENT - SEA STATE - TOW SPEED (knots) - PERSONNEL REQUIRED - DEPLOYMENT - RECOVERY AND STORAGE	C-P* - 10 1 off reel on reel/manual	C-P* 1 10 1 off reel on reel/manual	P* - 10 1 off reel on reel/manual	P-O* - 10 1 off reel on reel/manual

COMMENTS: Self-inflatable with continuous layered foam flotation located at the bottom of the float chamber with foam buoyancy equivalent of about 2 times boom weight.

The manufacturer reports that the FireGard™ boom was designed to withstand continuous exposure to oil fires to over 1093°C (2000°F) and to be fully automatic with atmospheric self-inflating and self-deflating in deployment and recovery. Booms can be deployed from reels on elevated platforms using a single operator. All models have interchangeable covers.

*CC = continuous cylinder; I = internal; I = inflatable; C = calm; P = protected.

In November, 1992, two 6 m long sections of custom-built FireGard boom, incorporating several potential design changes for evaluation, were tested in conjunction with a large test burn at the USCG Fire Test and Evaluation Center in Mobile, Alabama (see Evans *et al.* 1992 for a description of these tests). The boom was exposed to a 17 m diameter fire of Louisiana crude oil on saltwater in a test pan. The burn lasted 24 minutes and consumed some 2200 L of oil; peak flame temperatures of up to 1100°C were measured.

The boom successfully contained the burning oil and the residue during a 30 minute post-burn cool-down period. After the fire extinguished, the Thermotex covers were still intact, although they were stiffened in places by hardened burn deposits. On removal from the tank the outer cover was torn when it snagged on the edge of the test tank; the inner cover remained intact. The internal float materials were damaged; this was surmised to have been caused by the incorporation of the aforementioned potential design changes. An internal sacrificial lining that had burned off had exposed the internal flotation to its flames and the lighter-than-normal insulation blanket on the flotation proved inadequate. The potential design changes were concluded to have degraded the performance of the boom rather than enhanced it (McManus 1993). As a result of these most recent tests, the manufacturer is returning to the original design with an enhanced thermal resistant coating on the covers and additional thermal protection for the internal float system (McManus 1993).

PYROBOOM: is a product developed by:

Applied Fabric Technologies, Inc.
P.O. Box 575
Orchard Park, NY 14124
phone: 716-662-0632
fax: 716-662-0636

This boom (Table 5.8) of the fence type, consists of a sail constructed of Fibrefrax fabric supported by Inconel wire mesh and coated with silicone rubber bonded to a PVC coated fabric skirt. A chain in a pocket at the bottom of the boom is provided for ballast and tension carrying (this replaces the lead ballast on earlier versions). Flotation is provided by a series of stainless steel hemispheres bolted together above and below the waterline. The floats are filled with a high temperature-resistant, closed cell foamed glass.

The boom was tested twice, but only the results from a series of tests in 1985 are available (Spiltec 1986); these tests involved both fire tests in quiescent conditions and towing and containment tests in a wave tank. The fire tests involved 7.6 m of Pyroboom containing burning Cook Inlet crude for a period of 24 hours. Peak recorded flame temperatures were 930°C. Within a few minutes of starting the burn the silicone coating on the upper part of the boom's sail began to discolor and small sections of the underlying wire were exposed. Shortly thereafter it was possible to see the flames through pinholes in the upper 5 cm of the sail. The discoloration continued to move down the sail as the first hour of testing progressed. After one hour an inspection of the boom revealed that the fire proof fabric was still flexible and strong. The steel hemisphere and connector showed no signs of thermal stress. After 6 hours exposure the boom was still containing oil and remained flexible. The upper 5 to 10 cm of the sail continued to degrade with several small holes where the internal inconel wires were exposed. About 5 to 7 cm above the waterline a few

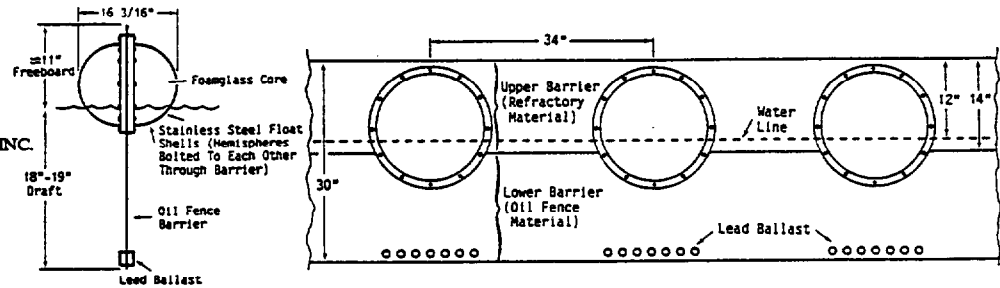
Table 5.8**COMPANY**

APPLIED FABRIC TECHNOLOGIES, INC.
P.O. Box 575
Orchard Park, New York 14127

Tel: (716) 662-0632

Fax: (716) 662-0636

Contact: Peter Lane

**PYROBOOM**

BOOM TYPE	Fence	Fence	
MODEL	Pyroboom 20	Pyroboom 30	
COST \$ US/m (\$/ft)	Inquire	Inquire	
FREEBOARD mm (in)	200 (8)	300 (12)	
DRAFT mm (in)	300 (12)	400 (18)	
BOOM HEIGHT mm (in)	510 (20)	760 (30)	
STANDARD LENGTH m (ft)	15 (50)	15 (50)	
END CONNECTORS			
SKIRT MATERIAL	PVC coated fabric	PVC coated fabric	
SAIL MATERIAL	Silicone coated Fibrefrax	Silicone coated Fibrefrax	
FLOTATION	S-A-SS/F*	S-A-SS/F*	
FLO. MEMBER LENGTH m (ft)			
WEIGHT kg/m (lb/ft)	10 (6.5)	14 (9)	
RES. BUOYANCY kg/m (lb/ft)			
RESERVE BUOYANCY/WEIGHT	4:1	2.5:1	
WATERLINE BEAM mm (in)			
VERTICAL CG mm (in)			
BALLAST MATERIAL	chain or lead	chain or lead	
BALLAST WEIGHT kg/m (lb/ft)			
TENSION MEMBER (1)/ STRENGTH (1) N (lb)			
TENSION MEMBER (2)/ STRENGTH (2) N (lb)			
TENSION MEMBER (3)/ STRENGTH (3) N (lb)			
TOTAL STRENGTH N (lbs)			
FABRIC TENSILE STRENGTH N/50mm (lbs/in)	9000 (1000)	9000 (1000)	
FABRIC TEAR STREN. N (lb)	230 (500)	230 (500)	
STORAGE VOL. m ³ /m (ft ³ /ft)	0.08 (0.9)	0.08 (0.9)	
OPERATION — OPERATING ENVIRONMENT — SEA STATE — TOW SPEED (knots) — PERSONNEL REQUIRED — DEPLOYMENT — RECOVERY AND STORAGE			

S = sphere; A = attached to skirt; SS = stainless steel; F = foam

small 1 to 1.5 mm diameter holes had appeared; however, these were plugged by baked-on burn residue. During the remainder of the 24 hour test the boom continued to contain the burning oil without loss of freeboard (Spiltec 1986).

On completion of the test, the boom was removed and examined. In the area 10 to 13 cm above the waterline there were numerous holes in the fire resistant fabric ranging in size from pinholes to 1 to 2 mm. Near the top of the sail a few holes on the order of 6 to 7 cm² could be found. The baked silicone rubber and fabric in the upper area of the boom was very susceptible to abrasion. From the waterline to a height of 10 to 13 cm the combination of silicone and burned oil residues had created a flexible and impermeable barrier protecting the boom. Although there were indications of some melting of the foam inside the floats, it was minimal and did not result in any loss of freeboard during the tests.

Subsequent towing tests in Houston (Spiltec 1986) resulted in significant oil simulant losses at tow speeds above 0.35 m/s; the manufacturer states that this was likely due to an overly stiff skirt fabric employed in the model tested. The design has been modified to include a more flexible skirt which is reported to have performed well during tests at OHMSETT with non-fire proof boom models of similar design. The Pyroboom boom also experienced some oil-simulant loss in waves of 0.6 m x 12 m during the 1985 tests.

AUTOBOOM - FIRE MODEL: is manufactured by:

Oil Stop Inc.
804 First Avenue
Harvey, Louisiana 70058
phone: 504-347-8888
fax: 504-347-9999

Little information was available at the time of writing on this boom. No details on construction materials or test results were supplied by the manufacturer. The boom is claimed to be of the pressure inflated (7 kPa) variety designed for deployment from a reel or compact storage without a reel.

The manufacturer claims a technology that creates heat transfer with the water to keep the internal temperature of the boom extremely low. The key dimensions of the various models are given in Table 5.9.

BOOMS UNDER DEVELOPMENT: two manufacturers are in the process of refining or developing fabric-based fire resistant booms. These are:

SLICKBAR
18 Beach Street
Seymour, Connecticut 06483
phone: 203-888-7700
fax: 203-888-7720

SUNSHINE TECHNOLOGY CORP.
P.O. Box 17041
West Hartford, Connecticut 06117
phone: 203-232-9227
fax: 203-523-0170

Table 5.9 Auto Boom Fire Model

	RIVER BOOM	HARBOR BOOM	BAY BOOM	OFFSHORE BOOM
Freeboard mm (in)	200 (8)	300 (12)	380 (15)	460 (18)
Draft mm (in)	250 (10)	460 (18)	560 (22)	640 (25)
Standard Section Lengths m (ft)	15 (50)	15 (50)	15 (50)	15 (50)
Ballast Weight kg/m (lbs/ft)	1.5 (1)	2.1 (1.4)	3.6 (2.4)	3.6 (2.4)
Combined Tensile Strength (Boom Plus Chain) N (lbs)	95,000 (21,000)	160,000 (35,000)	190,000 (41,500)	276,000 (60,750)
Inflation Pressure @ 21° C kPa (psi)	7 (1)	7 (1)	7 (1)	7 (1)
Working Temperature Range °C	5 to 1100	5 to 1100	5 to 1100	5 to 1100
Towing Speeds m/s (knots)	6 (12)	5 (10)	4 (8)	3 (6)

5.4 Additives

A variety of additives to assist in-situ burning have been developed and tested over the years. These can be categorized into three major groups: ignition promoters (or primers), combustion promoters (including wicking agents) and smoke suppression additives.

5.4.1 Brief History

The *Torrey Canyon* spill in 1967 seems to have spurred the initial development of in-situ burning additives. One combination ignition/combustion promoter, Pyraxon, was developed soon after the spill by the Guardian Chemical Corp. and was reported to liquefy heavy, weathered oils and promote burning (Anonymous 1968).

A multitude of wicking agents (or insulating agents) were also developed at this time, including SeaBeads by Pittsburgh Corning (Anonymous 1970), Cab-O-Sil by Cabot Corp. (Anonymous 1968), Ekoperl by Grefco Inc. (Freiberger and Byers 1971) and Tullanox (Battelle 1979). These agents were intended to wick and insulate difficult-to-ignite oils and permit their burning at sea. Sea trials by the EPA and by the U.S. Navy in the spring and summer of 1979 showed that the agents could accomplish these goals, but application was difficult (Freiberger and Byers 1971, Energetex 1978). They were used with some limited success on two heavy fuel oil spills in 1970. Testing of these and other natural wicking agents such as straw and peat moss continued throughout the 1970s, with particular application to spills in ice (Energetex 1979, Tam and Purves 1980, Coupal 1972).

In December, 1969, the cargo ship *Eiva* sank releasing 15,000 L of diesel fuel in the Gulf of Finland. Some of this oil was successfully burned on nearby shores and in bays using paraffin oil as an ignition promoter (Haaktela 1970). Six days later the tanker *Raphael* went aground west of Emäsoalo, Finland releasing more than 60 tons of crude. Peat moss (a natural wicking agent), fuel oil and petrol (ignition promoters) were used to remove more than 90% of the oil by burning (Coupal 1972, Haaktela 1970).

On February 4, 1970, the *Arrow* ran aground in Chedabucto Bay, Nova Scotia, and spilled most of its 16,000 ton cargo of Bunker C. SeaBeads were used successfully to burn isolated larger slicks (4.6 m diameter) and oil on some beaches. The slicks were primed with Varsol (Freiberger and Byers 1971, Battelle 1979). Part of the spill was burned by first adding two drums of fresh oil as ignition promoter (Coupal 1972).

In July, 1970, the U.S. Coast Guard conducted a series of small oil-in-ice experiments off Barrow, Alaska using North Slope crude oil. In-situ burning of oil on ice and water pools was tested, including five burning agents: peat, straw, silicate beads, asbestos powder and calcium carbonate (McMinn 1973).

In January, 1972, 600 tons of diesel fuel were accidentally discharged into the icy Ume River in Sweden. The oil spread downriver into a small lake. A particulate sorbent product "Saneringsull" was used as a wicking agent and about 400 tons of oil were burned over a period of a month from a mixture of oil, ice and snow on the lake (Jerbo 1973).

On December 27, 1976, the *Argo Merchant* went aground near Nantucket Island and spilled most of its cargo of 28,000 tons of No. 6 fuel oil. Part of the response by the U.S. Coast Guard involved attempts to burn the oil. One 30 m x 40 m x 15 cm thick slick was treated with Tullanox 500 (a wicking/insulating agent), primed with 200 L of JP-4 and ignited with JP-soaked cotton sheets set afire with a flare.

In the late 1980s, and early 1990s, as a result of increased concern regarding the smoke plume generated by in-situ burning, research began into organometallic derivatives that could be used as smoke suppressors (Mitchell 1990, Mitchell and Janssen 1991, Mitchell and Moir 1992, Moir *et al.* 1993). Ferrocene, and its derivatives, proved capable of virtually eliminating visible smoke emissions in small bench-scale and test tank fires at concentrations of about 2 to 4% by weight (Moir *et al.* 1993).

Cabioc'h (1993) reports that recently a system combining an ignition promoter and an igniter was tested in France for burning emulsions.

5.4.2 Ignition Promoters

Ignition promoters are defined as substances added to an oil slick in order to increase its ignitability or to promote spreading of flame over the surface of unignited oil.

5.4.2.1 Pyraxon

Pyraxon was a proprietary ignition promoter produced by the Guardian Chemical Corp. of Long Island City, New York. It is no longer commercially available. It was a two component system consisting of a liquid primer and a powder oxidant-catalyst (Freiberger and Byers 1971). The liquid primer was intended to act as a pour point depressant, to permit easy ignition and flame spreading, and to provide the heat necessary to initiate the catalytic cracking action of the powder. The powder was supposed to catalyze the conversion of heavy oils into more readily burnable fractions (Freiberger and Byers 1971). Tests were conducted by the manufacturer in a 36.17 m² water tank. The crude oil in the tank was initially 1.3 to 5 cm thick; the water temperature was near 0°C. The Pyraxon powder was applied at 5 g/L of crude oil and the liquid was applied at 1:25 (vol/vol). The slick was then ignited and burned. The residue was 0.32 cm thick. Pyraxon was found to be not effective as an ignition promoter for emulsified oil (Energetex 1979).

The EPA carried out tests of Pyraxon on slicks of Bunker "C" in an outdoor tank. The oil was initially 1.3 to 1.7 cm thick and could not be ignited "as is". Pyraxon liquid and powder were applied to the slick; although the Pyraxon liquid ignited, the Bunker "C" did not (Freiberger and Byers 1971). It was noted that, while both the liquid and powder were claimed to be stable in storage, care had to be exercised in their storage and handling.

5.4.2.2 Westcom

The Westcom products have been presented in the earlier section on igniters. Westcom 2001 (also known as Westcom III) could also be considered as an ignition promoter for emulsified oils. Cabioc'h (1993) states that it offers only a small advantage over gelled diesel fuel.

5.4.2.3 Volatile Fuel Oils

Gasoline, diesel, kerosene, aviation gasoline, and even crude oil have often been used as ignition promoters for in-situ burning. The middle distillates (diesel, kerosene, etc.) are considered better ignition promoters than the lighter petroleum products (gasoline, etc.) for two reasons: first, the lighter products evaporate faster than middle distillates which results

in faster cooling of the underlying oil slick (Coupal 1972, Buist *et al.* 1983d); and, second, the flame temperature is higher with middle distillates (Bech *et al.* 1992). It should be noted that with viscous oil slicks it is necessary to spray the fuel oil over an area of the slick; pumping oil onto one point only will result in a localized, thick, pool of fuel. Crude oil, with its wide range of components, is probably the best ignition promoter (Freiberger and Byers 1971, Energetex 1980, Bech *et al.* 1992).

5.4.2.4 Heli-torch Fuel Additives

Recently, research has been carried out to improve the capability of the Heli-torch, particularly in igniting emulsified oil. The addition of emulsion breaking surfactants and ferrocene to the fuel used by the Heli-torch shows promise for improving the performance of the device with some emulsions (SINTEF and S.L. Ross 1993).

5.4.3 Combustion Promoters

Combustion promoters can be defined as substances that are added to a slick to increase the oil removal efficiency by burning. These substances usually act as either a wicking agent or an insulator between the slick and the water substrate, or a combination of the two.

5.4.3.1 SeaBeads

These cellular glass beads were produced by Pittsburgh Corning for use as combustion promoters for heavy oil slicks (Anonymous 1970). The beads were 6 mm in diameter (3 mm diameter was also available) and made entirely of glass. When applied to an oil slick at the proper dosage they were intended to both wick the oil by capillary action and insulate it for better burning. Tests in small pools by Pittsburgh Corning gave good results with slicks as thin as 0.1 mm; little or no residue was reported from these tests (Anonymous 1970). Tests were carried out in 1969 with SeaBeads on slicks of Bunker "C" in tanks ranging in thickness from 2.5 to 6.5 mm (Freiberger and Byers 1971). The dose rate of SeaBeads was 0.32 to 0.41 kg/m². Burning was reportedly complete in areas where SeaBeads had been applied; the slick would not ignite in areas where the product had not been applied. SeaBeads were also tried on small Bunker "C" slicks from the *Arrow* spill in 1970. The product was applied to 4.6 m diameter slicks at a dosage of 0.5 kg/m². The slicks were primed with Varsol and ignited with a marker flare; only 50% of the oil was removed despite several ignition attempts (Freiberger and Byers 1971).

In May, 1970, tests of SeaBeads on slicks in the North Atlantic Ocean were conducted by the U.S. Navy (Freiberger and Byers 1971). During these tests a series of uncontained Bunker "C" slicks were created and ignition attempts made. It proved impossible to ignite untreated Bunker "C". Numerous unsuccessful tests of SeaBeads were conducted in a range of sea and weather conditions; the problem was an inability to broadcast the product onto the slick from a vessel. Winds of 25 to 40 km/hr and rain prevented seeding of the slicks; even gentle breezes prevented satisfactory application. Two slicks were successfully treated and burned; these were correctly dosed with SeaBeads applied by hand from the side of the vessel. An area approximately 1 m x 10 m was dosed and ignited in one test. The sea temperature was 7°C and the swells were 2.5 to 3 m in height. About 66% of the oil ignited

was estimated to have been burned (Energetex 1979).

Contained slick burning tests were conducted by EPA off the coast of New Jersey in the summer of 1970. These tests gave rise to the following conclusions:

- adequate broadcasting techniques did not exist for the SeaBeads; hand spreading was the technique used most effectively.
- contained crude oil could be burned without the use of a combustion promoter.
- Bunker "C" could not be ignited without a combustion promoter like SeaBeads; with SeaBeads an 80 to 90% reduction by burning was achieved.

In 1971, winter tests of SeaBeads in Alaska were conducted by the U.S. Coast Guard (Glaeser and Vance 1971). A series of burns of Prudhoe Bay crude on ice and water revealed that the application of combustion promoters did not conclusively reduce the amount of residue remaining after a burn.

SeaBeads were tested again in 1979 by Environment Canada (Tam and Purves 1980). These small-scale tank tests involved fresh and aged Alberta crude oil in 1.5 m² surface area tanks with various initial slick thicknesses and promoter loadings. SeaBeads produced effective burns, but its effectiveness was sensitive to loading. In areas where the slick was overdosed, the SeaBeads would tend to submerge the slick, get wet and prevent ignition. The optimum dosage for SeaBeads was estimated to be 0.25 to 0.5 kg/m² of slick area.

SeaBeads are no longer considered for use because of the high dosage rates required and the difficulty in properly applying the product to large areas.

5.4.3.2 Cab-O-Sil, Aerosil, Tullanox

These three commercial powder products have been grouped together because they all are silicon dioxide treated with a silane coating for hydrophobicity. Cab-O-Sil ST-2-0 was produced by the Cabot Corporation of Boston. Aerosil R972 is produced by Degussa Inc. in Teterboro, NJ and Tullanox 500 was produced by Tulco, Inc. Cab-O-Sil was the most tested of the three products, having been assessed in four experiments (EPA Laboratory Tests — Freiberger and Byers 1971; U.S. Navy field tests — Freiberger and Byers 1971; Arctic tests — Glaeser and Vance 1971; and Environment Canada tests — Tam and Purves 1980) and at least one spill, The *Othello* in 1970 (Battelle 1979). Tullanox was used to aid ignition at two spills (*Arrow* and *Bouchard #65* — Schrier and Eidam 1979, Battelle 1979). Aerosil tests were reported by Tam and Purves (1980).

All three products seem able to wick and insulate otherwise unignitable oil and promote its efficient combustion; however, the difficulty in applying these powders at sea, particularly in winds, the high dose rates required (7 to 10% by weight), and their inhalation toxicity make their use difficult in many spill situations.

5.4.3.3 Fibreperl, Ekoperl, Wonderperl

These three products produced respectively by Brefco Inc. of Los Angeles, CA, Grefco Inc. of New York, NY, and Perlite Popped Products of Santa Fe, CA respectively were all expanded perlite (aluminum silicate) products treated with a surface agent so as to be hydrophobic. Fibreperl was a mixture of expanded perlite and cellulose fibres.

Ekoperl was tested in 1969 by the EPA. About 0.1 kg of Ekoperl was added to 2 L of Bunker "C" in a 2 cm thick slick. The oil was ignited but only 33% burned (Freiberger and Byers 1971). Tam and Purves (1980) report that tests of Fibreperl resulted in almost complete removal of crude oil slicks by burning and left a dry, buoyant, cohesive residue. They gave the optimum dosage as 0.64 to 1 kg/m².

Because of the difficulties in applying these products and the high dosages required, their use is not recommended on larger spills.

5.4.3.4 Vermiculite

Vermiculite is expanded mica and is available locally from garden supply stores. Tam and Purves (1980), who conducted tests with Vermiculite on crude oil, reported that it produced effective burns, but in overloaded areas tended to submerge the oil, get wet and thus prevent ignition in these areas. They gave the optimum dosage as 0.2 kg/m². Vermiculite is not considered a viable combustion promoter for large spills because of its high dosage rates and the probable difficulty of applying the product to spills at sea.

5.4.3.5 Natural Products as Combustion Promoters

Straw was tested by the EPA in 1969 as a combustion promoter. Eighty grams of straw were applied to a 2 cm thick Bunker "C" slick containing 2 L of oil. The straw was ignited with a gas torch. The straw appeared to burn down to a web of filamentous carbon which subsequently ignited the oil and sustained its burning through a wicking action. About 80% of the oil was consumed. Glaeser and Vance (1971) also tested straw with Prudhoe Bay crude spills on ice and found no advantage to its use. Tam and Purves (1980) tested straw with crude oil on water and found that it resulted in a fairly effective burn but the heavy carbonized straw residue was difficult to collect. They recommended an application rate of 20% straw by weight.

Peat moss has been extensively tested as a combustion promoter. Peat moss was used in 1968 at the cleanup of the *Raphael* spill off the coast of Finland. Responders used 300 bales of peat moss soaked with 10,400 gallons of fuel oil and petrol to burn 90% of the spilled oil trapped in ice. Coupal (1972 and 1976) reported on tests with peat moss soaked with diesel oil as a combustion promoter for Bunker "C" and crude oil fires. With peat loadings of about 7% by weight and diesel loadings of 1% by weight removal efficiencies of 70 to 90% were obtained with test slicks of Bunker "C" ranging in volume from 30 to 400 L. Crude oil removal efficiencies of 80 to 95% were obtained with peat loadings of 3 to 5% by weight and diesel loadings of 1%. Tam and Purves (1980) reported good results with peat moss as a combustion promoter. They recommended loadings of 10% by weight for crude oil burns. Peat burn residue was much easier to recover than straw. Energetex (1981c) assessed burning as a shoreline cleanup technique and showed that the use of peat moss as a combustion promoter improved the efficiency of the approach. A residue remained

afterwards that would require removal.

Of all the combustion promoters, only peat moss with diesel fuel is recommended for consideration primarily due to its low cost and ready availability. Due to anticipated problems with application over large areas it should be considered for use on smaller spills where it can be manually applied.

5.4.3.6 Sorbent Products as Wicking Agents

A variety of manufactured sorbents have been used successfully as wicking agents, including Saneringsull (Jerbo 1972) and polypropylene sorbent sheets and pads (Buist *et al.* 1983d). Their use is restricted to smaller spills where access is available for manual application of the sorbent.

5.4.3.7 Emulsion Breakers

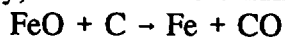
The concept of applying emulsion breakers to a slick from an aircraft or ship has been addressed recently (S.L. Ross 1986, Lunel and Lewis 1993, Hayward-Walker *et al.* 1993). The objective is to break the emulsion in-situ, remove water, lower the slicks viscosity and promote its natural dispersion. This approach would also offer the possibility of extending the "window-of-opportunity" for successful ignition of the slick. SINTEF and S.L. Ross (1993) have explored the possibility of including emulsion breaking surfactants in the fuel for a Heli-torch. The technique shows promise at the laboratory scale.

5.4.4 Smoke Suppressants

The beneficial effects of adding certain organometallic compounds to fuels to reduce smoke has been recognized since the early 1960s (Salooja 1972). The compounds that have been studied for use in engines and combustors include derivatives of barium, manganese, iron, lead, copper, magnesium, nickel, cobalt and boron. Of these, the compound that has been researched the most for oil spill use is ferrocene and its derivatives (Mitchell 1990, Mitchell and Janssen 1991, Mitchell and Moir 1992, Moir *et al.* 1993).

Ferrocene is the common name for bis-cyclopentadienyl iron with the formula $(C_5H_5)_2Fe$. It is a "sandwich" compound with the iron atom placed between two hydrocarbon rings. It is an orange-colored, crystalline solid that is insoluble in water and slightly soluble in hydrocarbons up to about 2% to 4% by weight (Mitchell 1990, Moir *et al.* 1993). Its density is greater than that of water. Ferrocene is used commercially for many applications as an additive, including in rocket propellant to promote more efficient burning, as a smoke suppressant in diesel fuel, and in heating oils in Europe to reduce particulate emissions to regulated levels (Moir *et al.* 1993).

Mitchell (1990) has proposed the following mechanism by which ferrocene inhibits soot formation. First, the ferrocene oxidizes to form microscopic iron oxide particles; the carbon then condenses out of the flame onto the iron oxide particles which act as nucleating centers. Finally, the carbon is oxidized by the iron oxide via:



with the solid carbon converted to carbon monoxide rather than condensing into large soot

agglomerates. Ferrocene is relatively non-toxic and is thus attractive for use on marine spills (Moir *et al.* 1993).

Tests with ferrocene (Mitchell 1990, Mitchell and Janssen 1991) have shown that 90 to 95% reductions in soot production can be realized with the addition of 2% by weight ferrocene to the oil. The major difficulty with ferrocene powder is the fact that it dissolves slowly in oil and its density exceeds that of water. This makes it difficult to mix into an oil spill, and if the powder misses the slick it sinks.

Over 30 derivatives of ferrocene have been tested to overcome the application problems associated with ferrocene (Mitchell and Janssen 1992, Mitchell and Moir 1992, Moir *et al.* 1993). The derivatives tested tend to be liquids at room temperature and are much more soluble in oils than the parent ferrocene. Although the various derivatives have various degrees of effectiveness (as the formula weight increases the soot reduction per unit weight generally decreases), on a "per unit ferrocene" basis the derivatives are all of almost constant effectiveness (Mitchell and Moir 1992). Mitchell and Moir (1992) discovered that the effectiveness, even on a "per unit ferrocene" basis was a function of the oil type. Moir *et al.* (1993) give a formula that relates likely soot reduction to the composition of the oil for one proprietary ferrocene derivative, RMS 9757:

$$\text{Soot reduction} = 1 - ((1.7P + 4.5N + 2A)/(1.8P + 7.2N + 16A))$$

where

P	=	concentration of normal paraffins (wt%)
N	=	concentration of branched hydrocarbons (wt%)
A	=	concentration of aromatic hydrocarbons (wt%)

This equation predicts increased ferrocene derivative effectiveness with increasing aromatic and branched hydrocarbon concentration and with decreasing paraffin content.

Moir *et al.* (1993) report that the latest ferrocene hybrid, RMS 9757, reduces soot up to 70% at dose rates of 0.5 wt% ferrocene equivalent, is easily applied as a liquid concentrate that can be sprayed onto a slick, and dissolves quickly. The product is stated to be under consideration for commercial production by Esso Resources Canada Ltd., in Calgary, Alberta.

5.4.5 Floating Incinerators

Ever since the *Torrey Canyon* spill, designs for the construction of floating burners have been proposed. The purpose of these has been twofold: to increase the amount of the heat of combustion that is radiated back to the slick; and, to improve the mixing of combustion air with fuel.

5.4.5.1 Pittsburgh Corning Floating Incinerators

Two of the systems patented by Pittsburgh Corning are shown in Figures 5.4 and 5.5. Both concepts employ a system of oil wicking and radiant energy capture. As stated in Battelle (1979) for the first system:

"Oil residues and emulsions floating on a body of water are burned by confining the layer of residue within a furnace chamber (Figure 5.4). The furnace is equipped with a combustion air inlet adjacent to the upper surface of the residue and a stack with inlets for

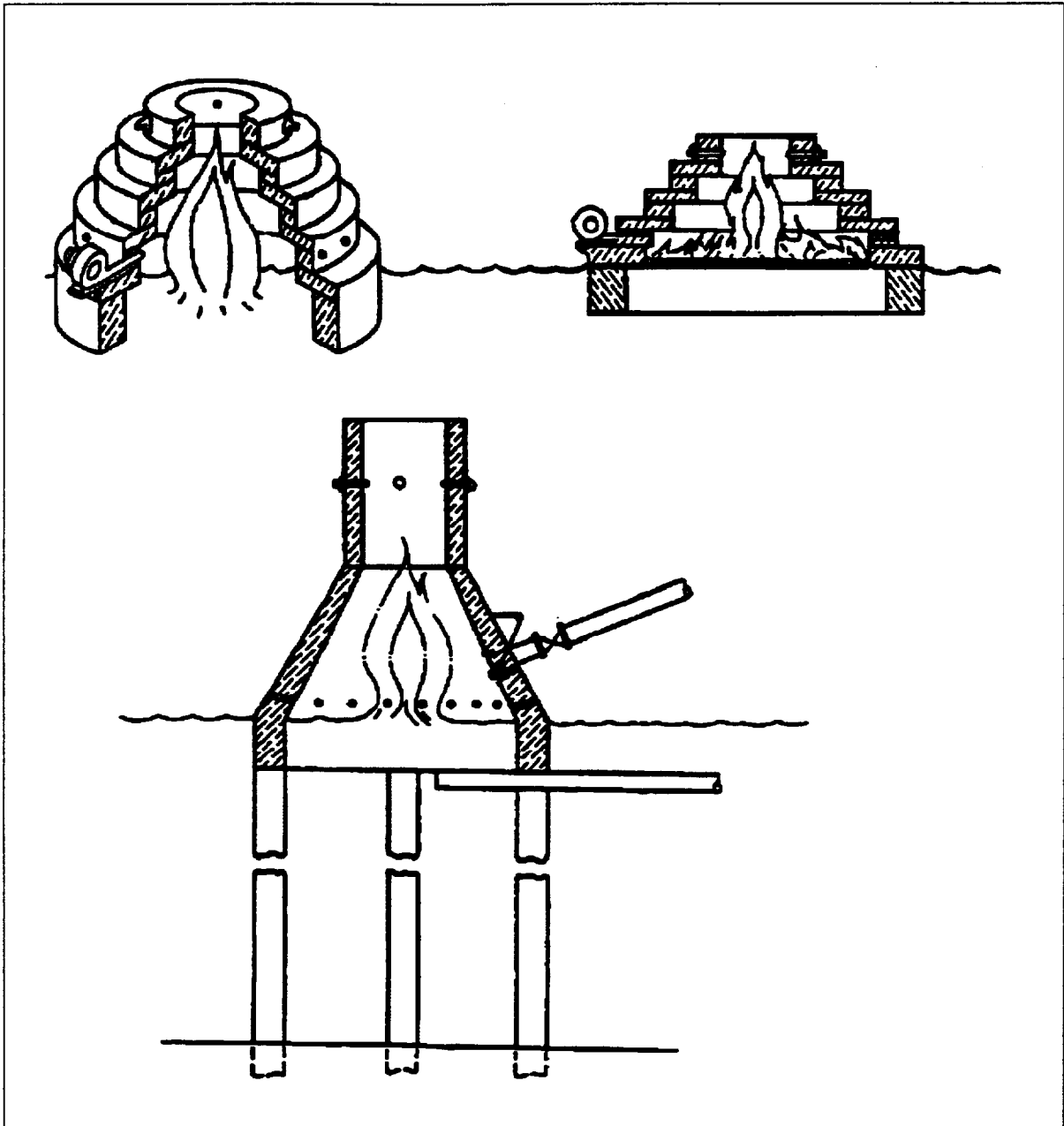


Figure 5.4 Floating oil spill furnace (from U.S. Patent 3,695,810 - October 3, 1972)

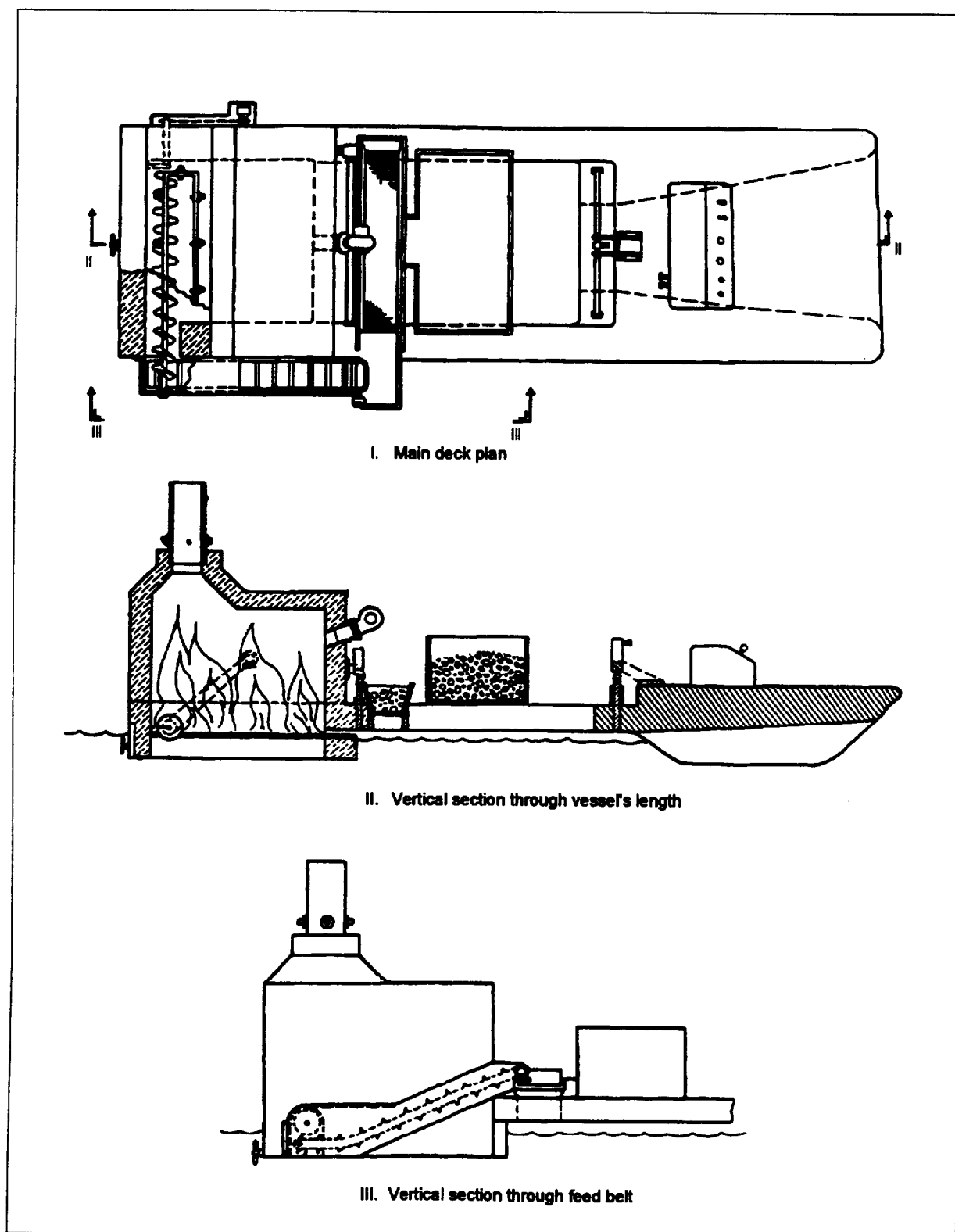


Figure 5.5 Oil spill incinerator vessel (from U.S. Patent 3,663,146 - May 16, 1972)

combustible gas. The combustible gas burns the combustible material from pyrolysis of the liquid residue to provide a relatively smokeless combustion process. The furnace is fabricated from a refractory material having insulating properties so that a substantial portion of the heat given off by the combustion of the residue is retained within the furnace to propagate further combustion of the residue and aid in the complete combustion of the difficult to burn portions of the residue. The furnace is preferably fabricated from a material that permits the furnace to float partially submerged in the body of water and may be easily transported from one location on the body of water to another location thereon. The furnace may be supported from suitable pipings and the residue conveyed directly into the furnace chamber."

"For certain types of difficult to burn residues, a layer of cellular glass nodules (see SeaBeads above) with a textured outer surface is positioned to float on the upper surface of the residue within the furnace chamber."

The Battelle (1979) report discussed the second Pittsburgh Corning system as such:

"A generally U-shaped, buoyant, self-propelled vessel (Figure 5.5) floats partially submerged in a body of water and has a longitudinal channel portion with a front opening. The vessel has an open bottom portion beneath the longitudinal channel portion. As the vessel advances into a body of water, a band of water with the layer of combustible liquid floating thereon enters the channel of the vessel. The rate at which the combustible liquid, as a layer, enters the channel is dependent on the forward speed of the vessel. This speed is controlled so that substantially all of the liquid is removed by burning before the band of water passes under the rear or exit portion of the vessel. As the vessel advances, the band of water with the layer of combustible liquid moves through a mixing chamber within the channel portion where a monolayer of cellular ceramic nodules are positioned on the top surface of the layer of combustible liquid. The layer of combustible liquid with the nodules floating thereon moves toward the rear with the forward advance of the vessel. The oil moves into a combustion chamber where it is ignited and burned. The glass nodules within the combustion chamber are recycled to the mixing chamber where they are re-positioned as a monolayer on the upper surface of the layer of combustible liquid. Combustion air is provided for the combustion chamber and the combustion gases can be subjected to a secondary burning in the stack to remove the combustible materials in the gases to provide a substantially smoke-free waste gas. Apparatus is provided to seal the combustion chamber and mixing chamber if the burning of the combustible liquid tends to spread beyond the receiver."

Neither of these concepts was pursued commercially.

5.4.5.2 BP Elijah Burner (adapted from Battelle 1979)

"Some of British Petroleum's oil burning investigations were conducted in the late 1960s when the burner called "Elijah" was created. This burner drew oil into a concentrated pool within the lower part of the burner by a vortex-forming, submerged pump. The oil would get several inches thick and was continuously thrown as a spray up into the upper part of the inverted cone-shaped burner in a stream of hot air. The burner, which was 1.5 m wide x 3 m long x 2 m high, consumed about 40 L/hr in a highly luminous, minimal smoke producing manner. Burning continued even though oil surrounding the burner was substantially less than 2 cm thick. British Petroleum wished to handle 100 tons/hr; therefore, this system was abandoned for other physical removal systems."

5.4.5.3 Pipeline Rupture Burner (adapted from Battelle 1979)

"Another system which may have application is illustrated in Figure 5.6. This system illustrates a method which is proposed to prevent oil pollution of water in the vicinity of an offshore production operation. The apparatus is provided for use on a ruptured oil and/or natural gas pipe where fluid is issuing under pressure from the pipe. A heat dissipating screen is disposed in the path of the fluid and raised to a predetermined position. The fluid is then intentionally ignited (thus preventing pollution), and the heat dissipating effect of the screen confines the flame to a region above the screen spaced from the open end of the well pipe. A thermal radiation shield can be provided in addition to water cooled members for the screen and shield."

This device never was developed beyond the design stage.

5.4.5.4 Dome Sub-Sea Blowout Burner

Dome Petroleum (now part of Amoco Canada Petroleum) researched a device that could be deployed over a sub-sea blowout and used to collect and burn off the oil and gas (Figure 5.7). The idea was to position an inverted cone collector over the blowing well so as to direct oil, gas and water to the surface by flexible risers. The oil/gas and water mix would enter the bottom of a floating, ice-strengthened burner where the oil and gas would be combusted. Preliminary designs, load studies and scale-model burn tests were conducted on the idea; however, it was never constructed because of the high capital cost compared to the low probability of occurrence of a sub-sea oil well blowout (Buist and Potter 1982).

5.4.5.5 Continuously-Burning Wicking Devices

Twardus (1978) reports on the development and testing of a small (2 L/hr) burner that could be aerially deployed onto small slicks in remote areas. The devices (Figure 5.8) would ignite in the presence of oil and slowly burn off surrounding oil. The wicking blanket would provide a steady supply of oil to a drip-type burner that combusted the oil without igniting the surrounding slick. Materials were selected and several prototypes constructed and tested but the concept was abandoned in favor of aerial igniter techniques.

5.4.5.6 Acoustic Burner

Since the mid 1970s acoustical energy has been known to lift oil off the surface of water (Curzon and Ahlborn 1978). The use of focused acoustic energy atomizes the oil and allows it to be burned in a floating incinerator (Koblanski 1981, 1983, 1985). One such concept (Figure 5.9) was constructed and tested (Koblanski 1983, Lipski 1986). Tests by Environment Canada concluded that the transducer effectiveness was too sensitive to position to be effective in a wave environment and that the oil droplets created were too large (ca. 5 mm) for efficient burning (Lipski 1986, Caron 1988). Incorrectly positioning transducers also rapidly emulsified the oil. The device has been commercialized and can be obtained from:

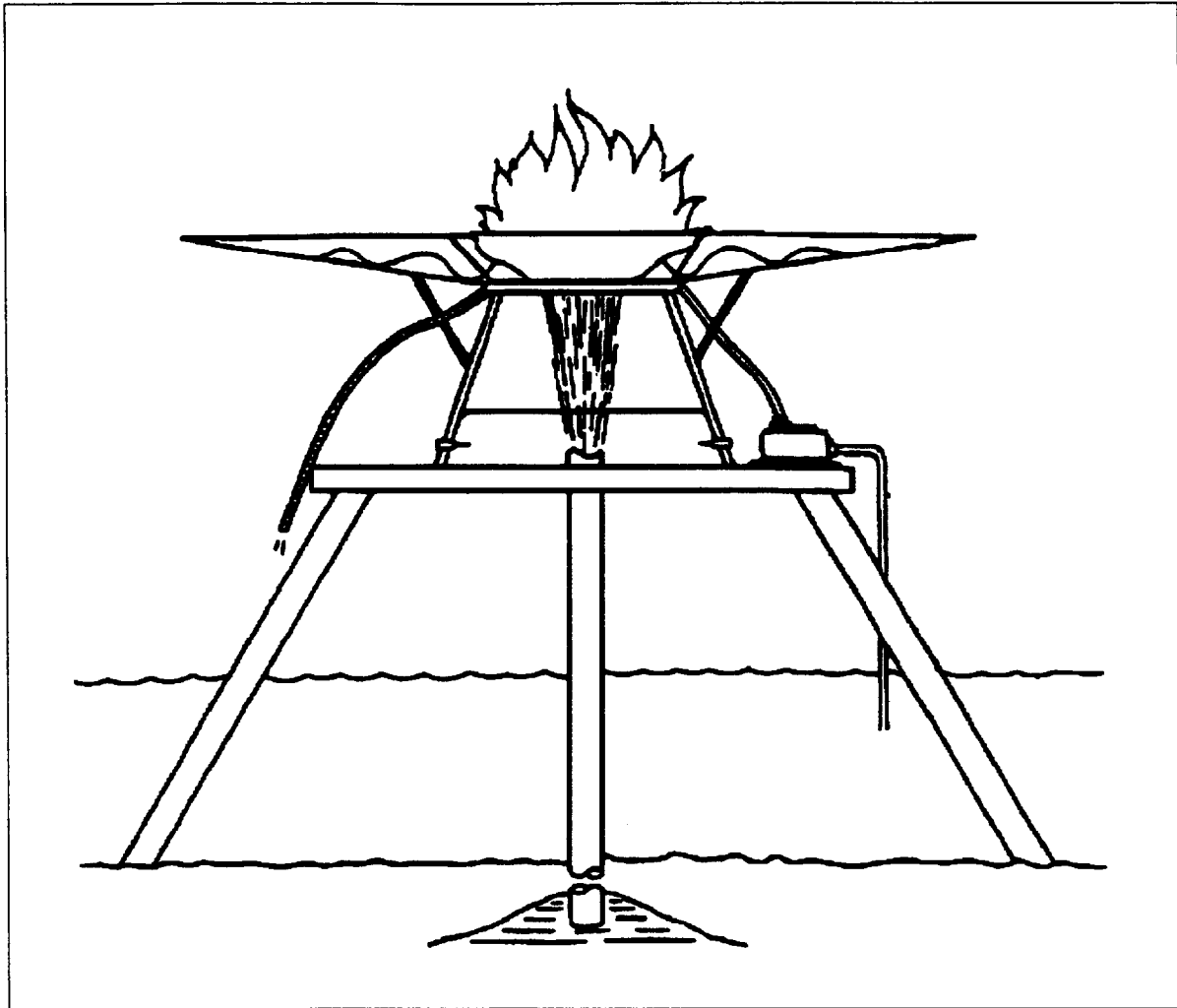


Figure 5.6 Combustion system for pipeline leaks (from U.S. Patent 3,602,299 - August 31, 1971)

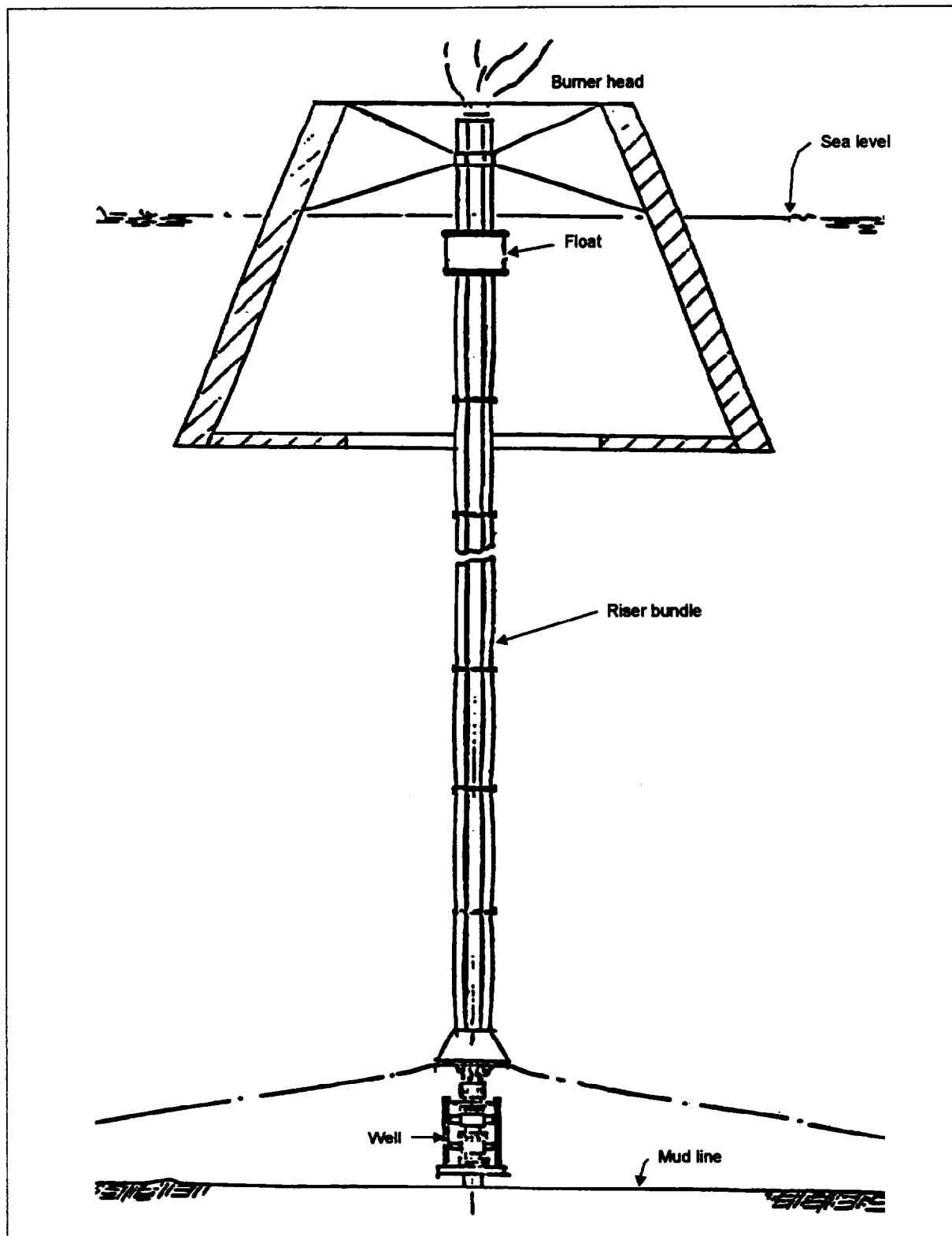


Figure 5.7 Dome subsea blowout burner (from Buist and Potter 1982)

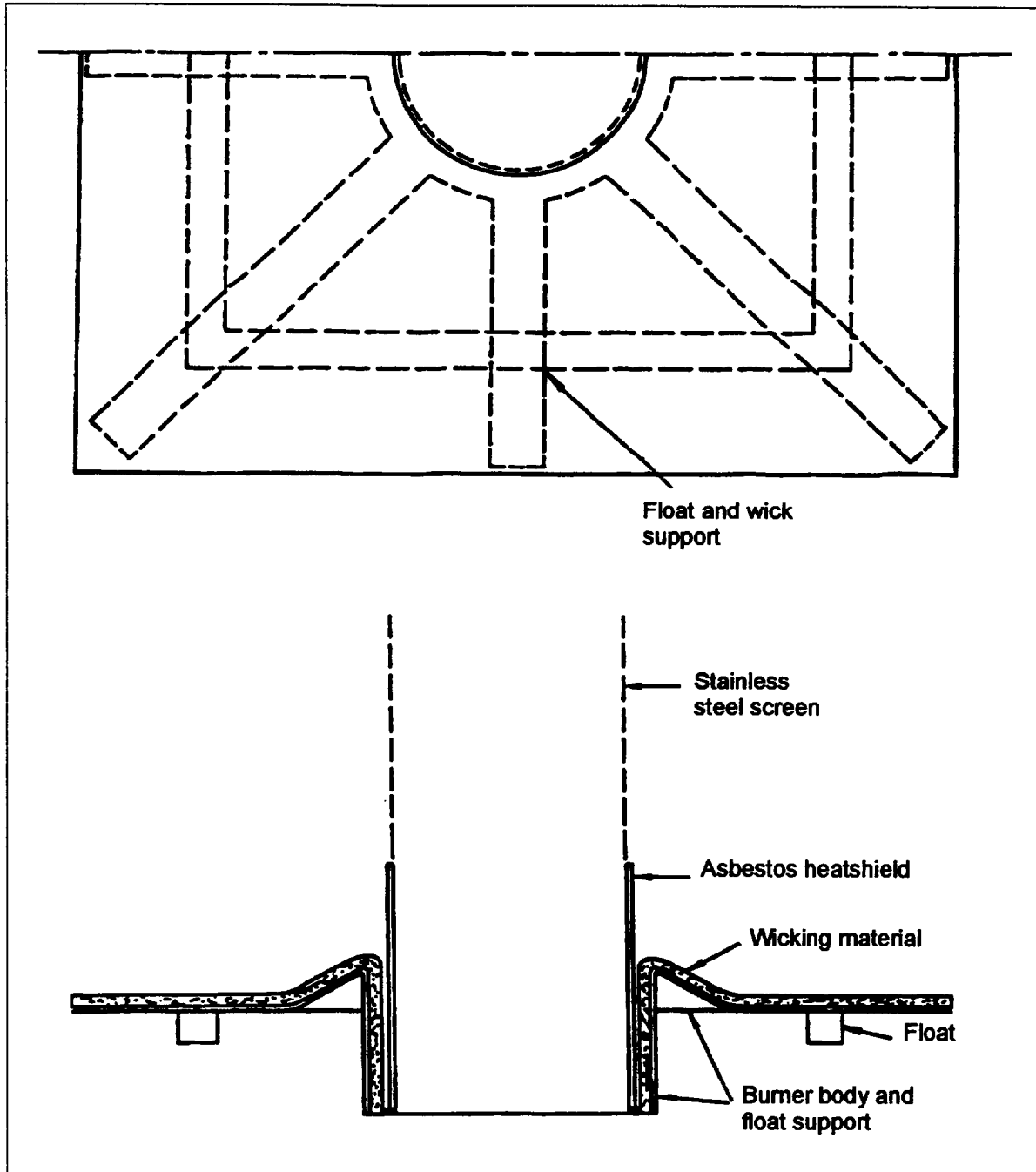


Figure 5.8 Wicking burner (from Twardus 1978)

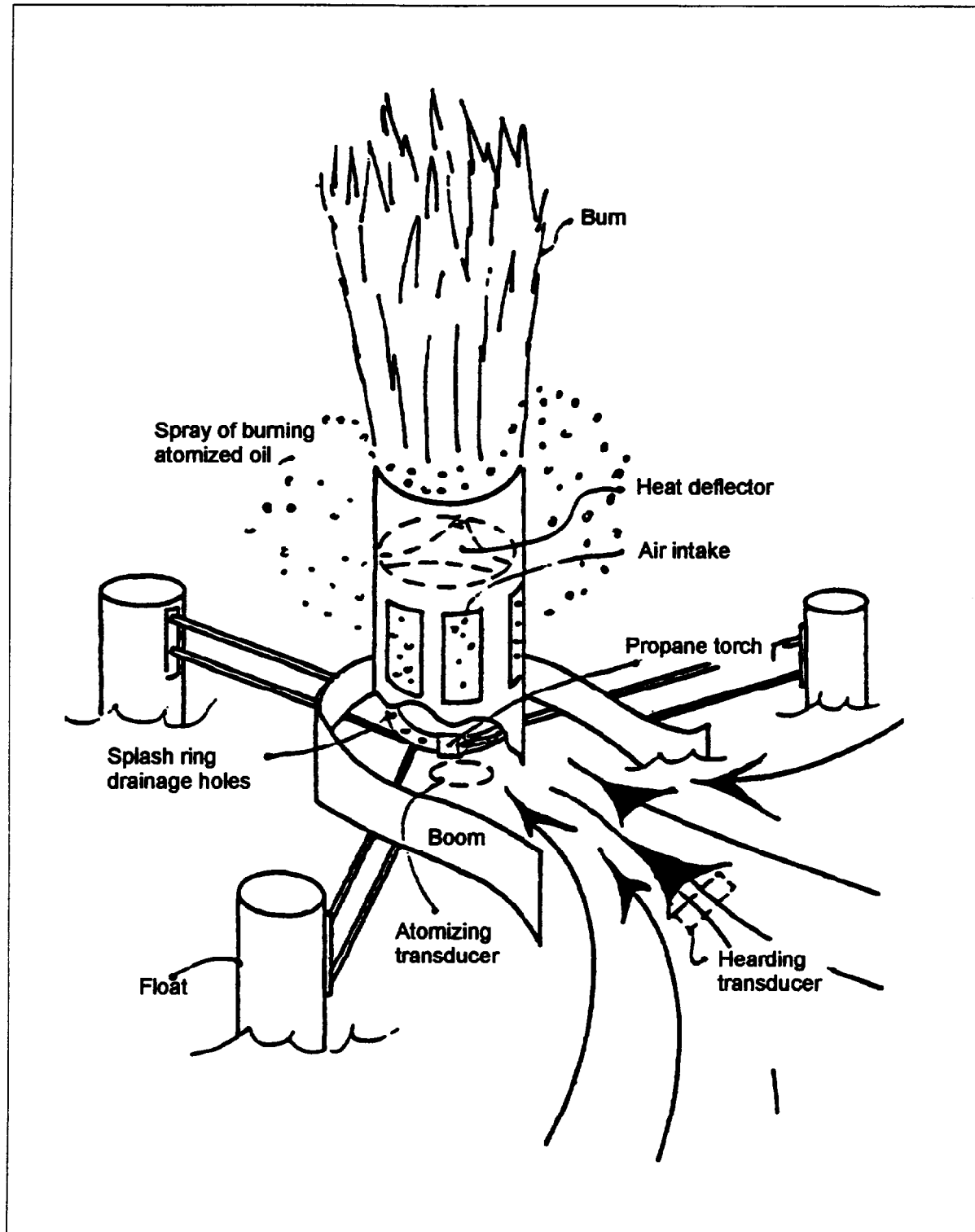


Figure 5.9 Combination of oil herding and atomizing device

Ocean Ecology Ltd.
1177 Hornby Street
Vancouver, B.C.
Canada
V6Z 2E9

5.4.5.7 Air Jet Atomizing Burner

As a result of work on acoustical methods of atomizing oil directly off the water, the concept of using submerged pneumatic nozzles to entrain and atomize oil was researched (Lipski 1986, Caron 1988, Belore and Seeley 1990). The concept involved positioning a simple pneumatic jet near the oil/water interface. The jet is oriented vertically upward and draws oil to it, entrains the oil and atomizes it.

Tests (Lipski 1986, Caron 1988 and Belore and Seeley 1990) showed that:

- if the nozzle was placed deeper than 2 cm below the water surface no atomization occurs — a spout of mostly water was created;
- with the nozzle in the water within 2 cm of the water surface atomization occurred but water contents ranged from 80 to 100%;
- with the nozzle at the oil/water interface or in the oil the water content reduced — with a 0.5 mm thick slick the water content was 50%, with 2 and 4 mm thick slicks the water content was less than 10%; and
- larger diameter nozzles and reduced pressure (from 275 to 140 kPa) increased the oil atomization rate. The maximum oil uptake rate measured was 1.75 L/min for one 6 mm diameter nozzle with an air pressure of 140 kPa in 4 mm of oil.

Tests of a fixed burner with 6 mm diameter nozzles were conducted in a tank (Belore and Seeley 1990). A stack (or chimney) was supported 15 cm above the water surface with five 6 mm nozzles arranged beneath it at the water surface. A slick thickness of 2 mm, and air pressures of 200 to 600 kPa were used. The test results indicated that the method had merit and could produce reduced smoke levels if operating parameters were correctly maintained; the most crucial of these was keeping the nozzles positioned in the oil layer just above the oil/water interface. Optimum burn conditions were realized at an air pressure of 415 kPa; a 5 L/min burn rate was achieved. It was noted that the slick beneath the burner always ignited and, if the burner were in slicks greater than 1 to 3 mm thick the fire would spread to the surrounding oil slick engulfing the burner in flames.

The air jet atomization technique was further engineered and commercialized by Sprayburn Systems Inc. Their device (Figure 5.10) incorporates a single, controllable height nozzle mounted in a floating, disc-shaped burner. A propane ignition system is also incorporated into the design. No test data are available. The device can be obtained from:

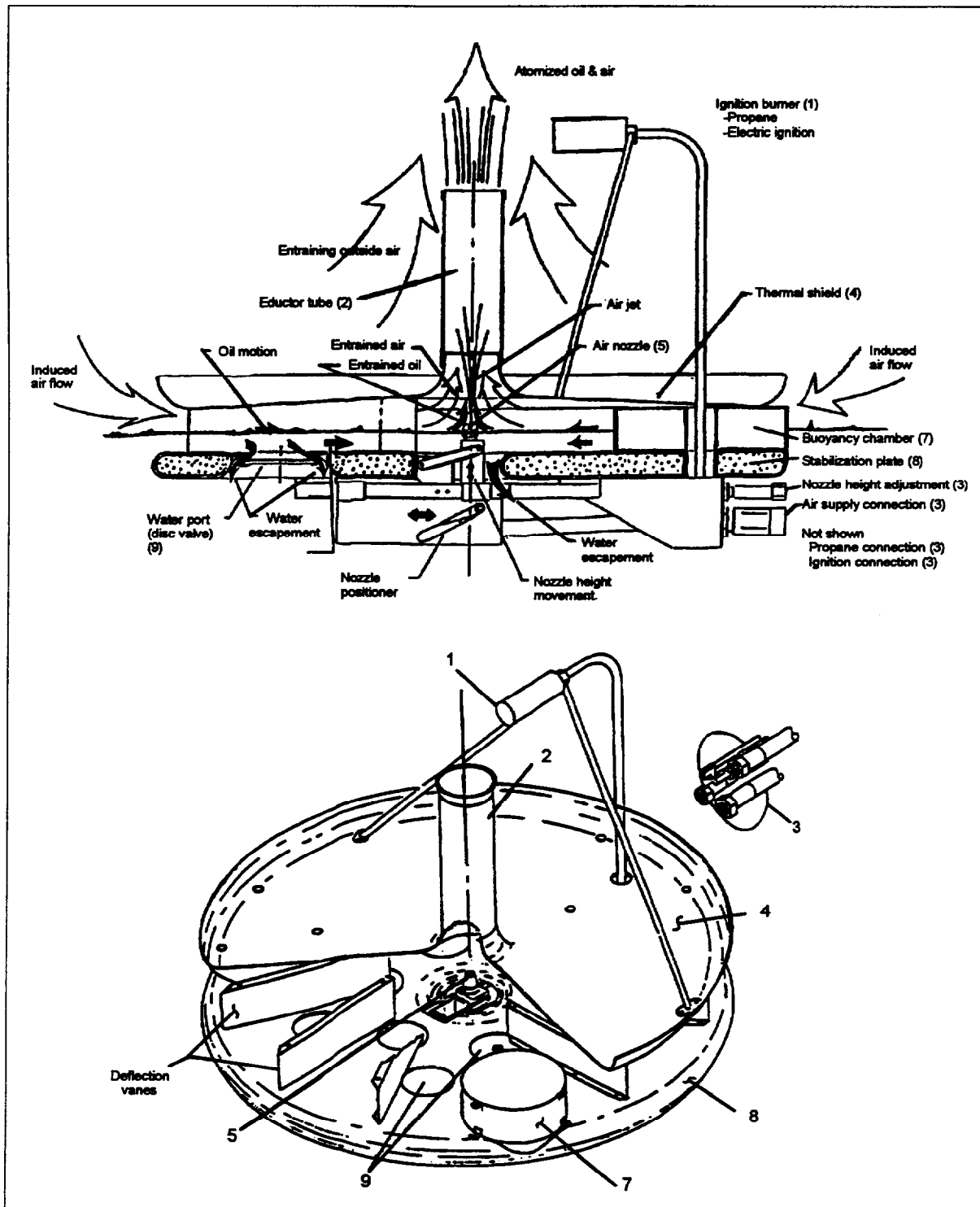


Figure 5.10 *Sprayburn floating oil burner*
 (Source: Sprayburn Systems Inc., Patent Pending, 1990)

Sprayburn Systems Inc.
 2040 West 12th Avenue
 Vancouver, B.C. Canada V6J 2G2

5.4.5.8 University of Arizona Burners

Recently, research has been undertaken on methods to enhance in-situ combustion of oil on water (Franken *et al.* 1992) by mechanically enhancing air entrainment into the combustion zone. Any buoyant column of heated rising air or hot combustion gases tends to have a swirl component, commonly referred to as the "Fire Whirl". This is a desirable effect as it encourages the entrainment of surrounding air and thereby increases aeration at the center of the flames. Several approaches to augmenting this fire whirl have been studied.

One method involves deploying sheet metal vanes about a burning pool in order to guide the in-flowing air into a cyclonic pattern. Experiments performed in 0.6 m, 1.2 m, and 2.4 m diameter pools 10 cm deep indicate that the addition of vanes increased the flame height by 200%, produced 50% less smoke and burned faster and more efficiently than identical experiments performed without the vanes (Franken *et al.* 1992). Tests were also carried out with both curved (semi-circular) and straight fins; no significant difference was found. It was determined that the vanes definitely helped augment the combustion by supplying additional air to the center of the blaze, but the configuration or shape of the vanes seemed to have little impact on the combustion rate. The effect of burn pan depth was not investigated.

For the most successful runs, each container used eight vanes, mounted on, and arranged tangentially to, the top of the containment pool, with their dimensions being 0.6 m x 0.4 m, 1.2 m x 1.2 m, and 1.2 m x 1.8 m respectively. However, Alaska Clean Seas tested the use of vanes around a burn test of fire proof boom in a large tank (ACS 1991) and found no induced vortex and no reduction in smoke.

Several experiments designed to determine an effective method of augmenting the ducting effect described above were performed by Franken *et al.* (1992) from May through September 17, 1990. It was concluded from these experiments that it was not effective in practice to supply all the stoichiometric air needed for combustion using low velocity, high volume air blowers; rather, it would be more efficient to have other processes in place which would increase the natural flow of air (the Fire Whirl) into the combustion zone. The conclusion of the report was that "the addition of a few hundred cfm of compressed air is more utilitarian than the addition of more than 50,000 cfm of low velocity streams" (Franken *et al.* 1992).

An effective arrangement for the 1.2 m diameter pool with the vane ducting structure, as described above, was to employ four low volume (8 m³/min in total), high velocity (high pressure) air jets, with one placed about 1 m above the liquid surface, aimed straight up the axis of the flames, and the remaining three each placed about 0.6 m from the central axis, a few feet above the liquid and canted by some 30° from vertical (Figure 5.11). These jets produced a "cyclonic" or "whirling" action within the flame in the same rotational sense as produced by the external vanes. The addition of the high velocity air increased the burning rate by about three and one half times, over that of the ducting alone (Franken *et al.* 1992).

The final incineration idea developed and tested by Franken *et al.* 1992 was a variation of the air jet atomizer described above. A refractory lined, 1.8 m diameter culvert

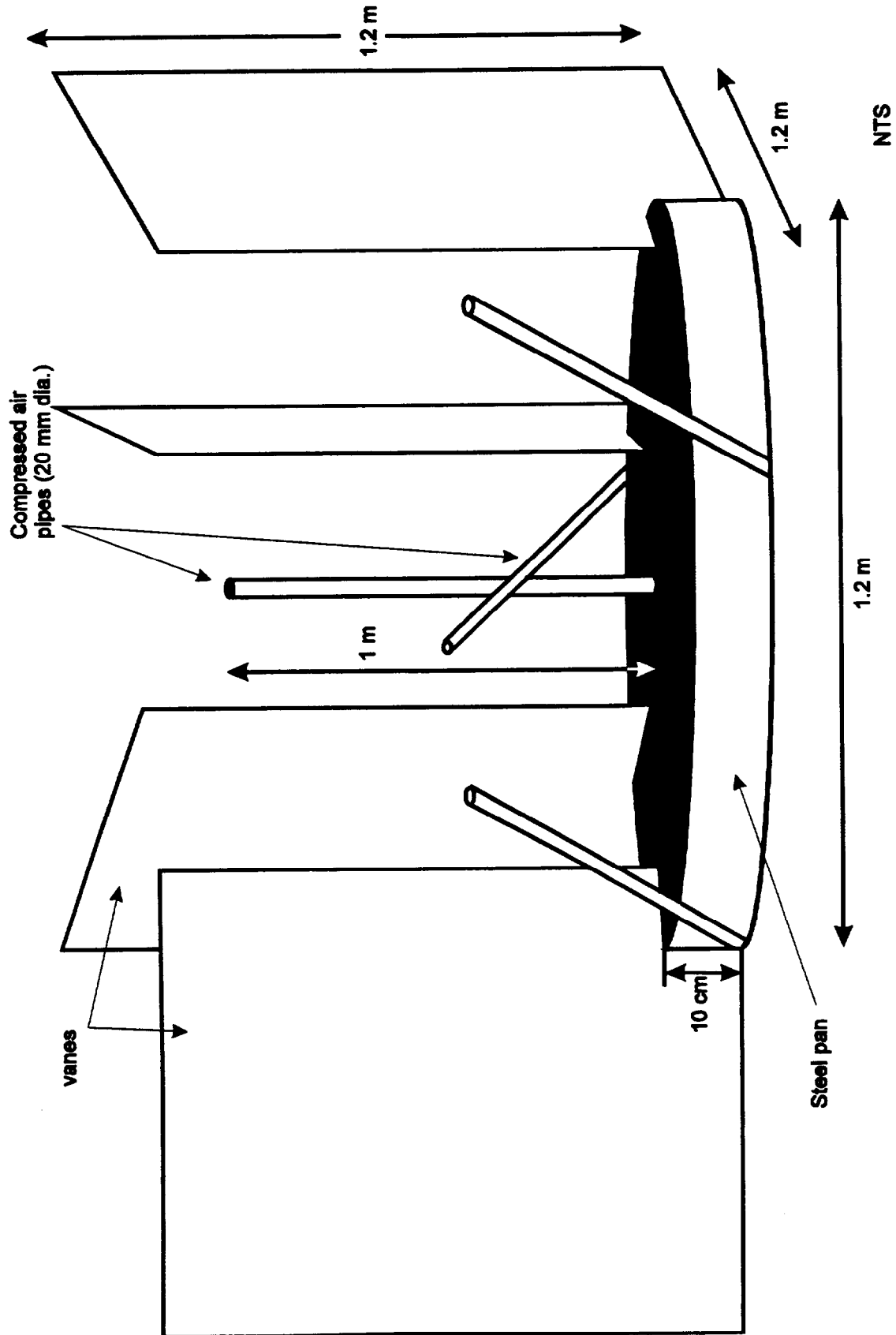


Figure 5.11 Sketch of burn pool with vanes and compressed air supply - front four vanes not shown

9.4 m in length was positioned vertically over a series of compressed air nozzles (Figure 5.12). Several of these directed air downwards at the oil/water interface to create a spray of oil for burning while others were directly tangentially upward to induce swirling in the combustion chamber. Tests with an 18 cm thick slick of crude oil on 25 cm of water resulted in an average burn rate of 95 L/min (24 mm/min); peak burn rates were estimated at 280 L/min (60 mm/min). Temperatures in the stack peaked at 1650°C, well above normal in-situ burning flame temperatures (Franken *et al.* 1992).

A conceptual design for a floating model of the incinerator to be connected to a skimming system was proposed (Figure 5.13); no further development of this concept has been undertaken.

5.4.5.9 Arctic Environment Incinerator Barge

In 1990, Shell Western E&P in Alaska undertook a study of the concept of a floating incinerator capable of concentrating and burning spilled oil in open water and broken ice conditions typical of the Chukchi and Beaufort Seas (Glosten *et al.* 1991). The final design concept (Figure 5.14) incorporates an ice-strengthened barge and a double-wall incinerator. The barge is designed to be towed forward to the spill site then operated aft-first. Oil would be directed to the stern of the barge into the cylindrical, 11 m diameter, 10.3 m high incinerator. The incinerator would be of a double wall design (Figure 5.14) whereby cool air is pumped in the top and travels downwards through the shell to exit at the bottom and provide swirling action and preheated combustion air. The incinerator shell would be supported on the barge by slanted vanes that permit the entrainment of air under the shell and also give it a rotational moment to help air/fuel mixing (as per the work of Franken *et al.* 1992 noted above). No testing or further design work on the concept has been undertaken.

5.4.5.10 Radiative Evaporation

Summerfield (1993) has proposed the use of a high temperature (1130°C) radiator powered by natural gas to vaporize oil (but not burn the vapors). The radiator would be mounted on a boat trailing the apex of the boom; this boat would also carry the compressed natural gas supply. Summerfield (1993) estimates that it would require about 5 hours to evaporate 4000 L of oil. Besides low capacity concerns, the concept presents several fire hazard and emissions concerns.

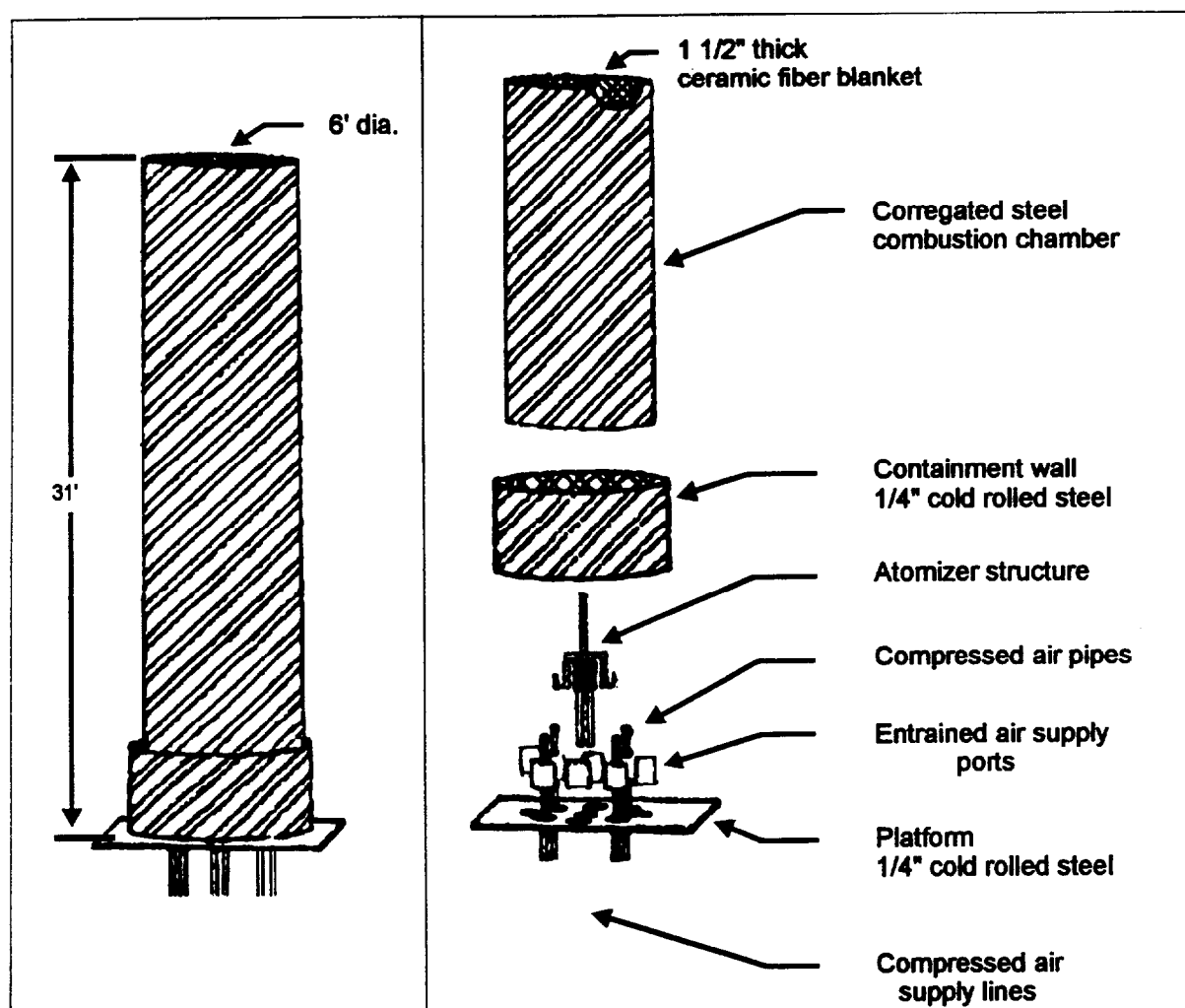
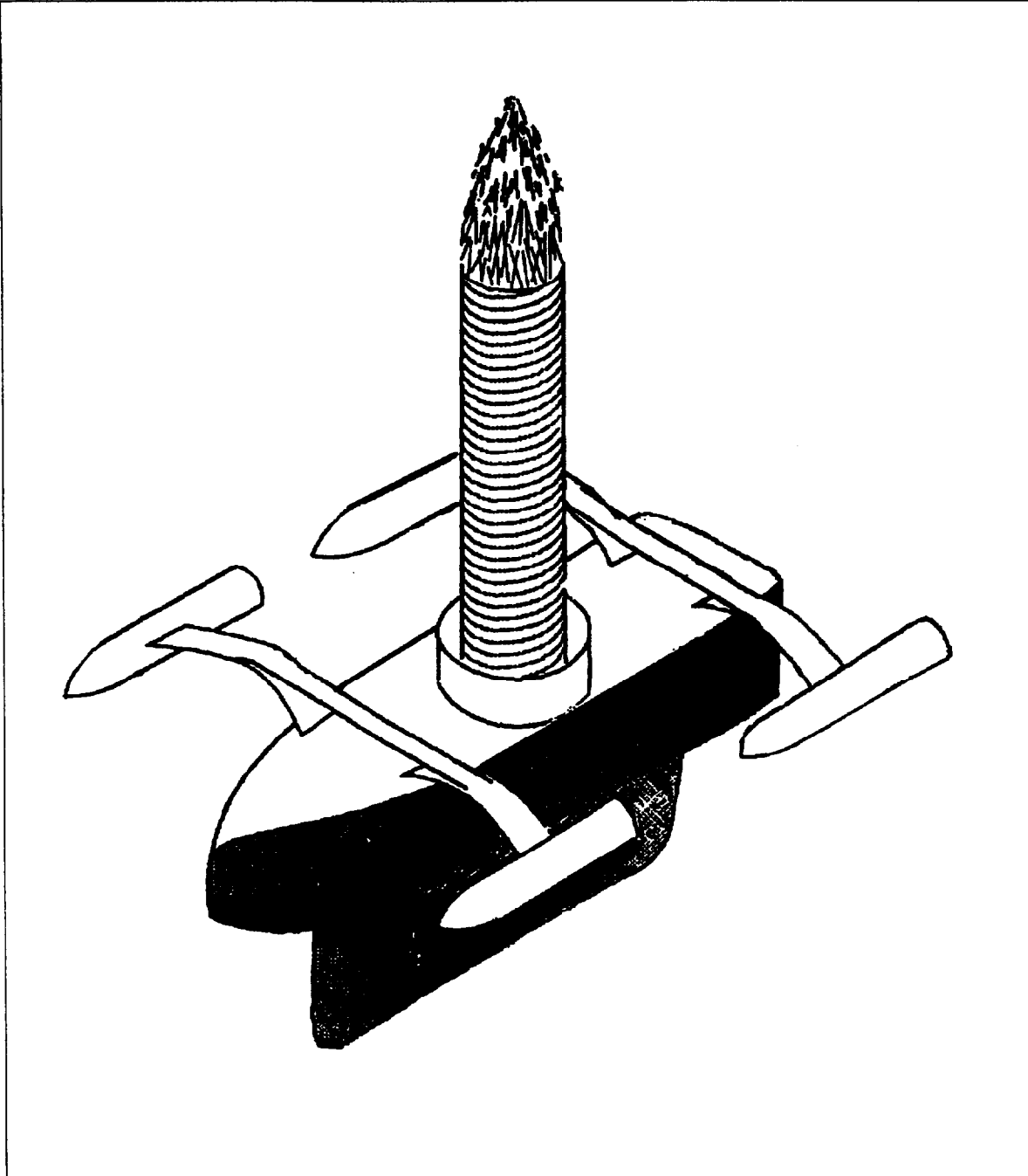


Figure 5.12 Two-meter diameter incinerator (from Franken et al. 1992)



*Figure 5.13 Conceptual sketch of seagoing incinerator
(adapted from Franken et al. 1992)*

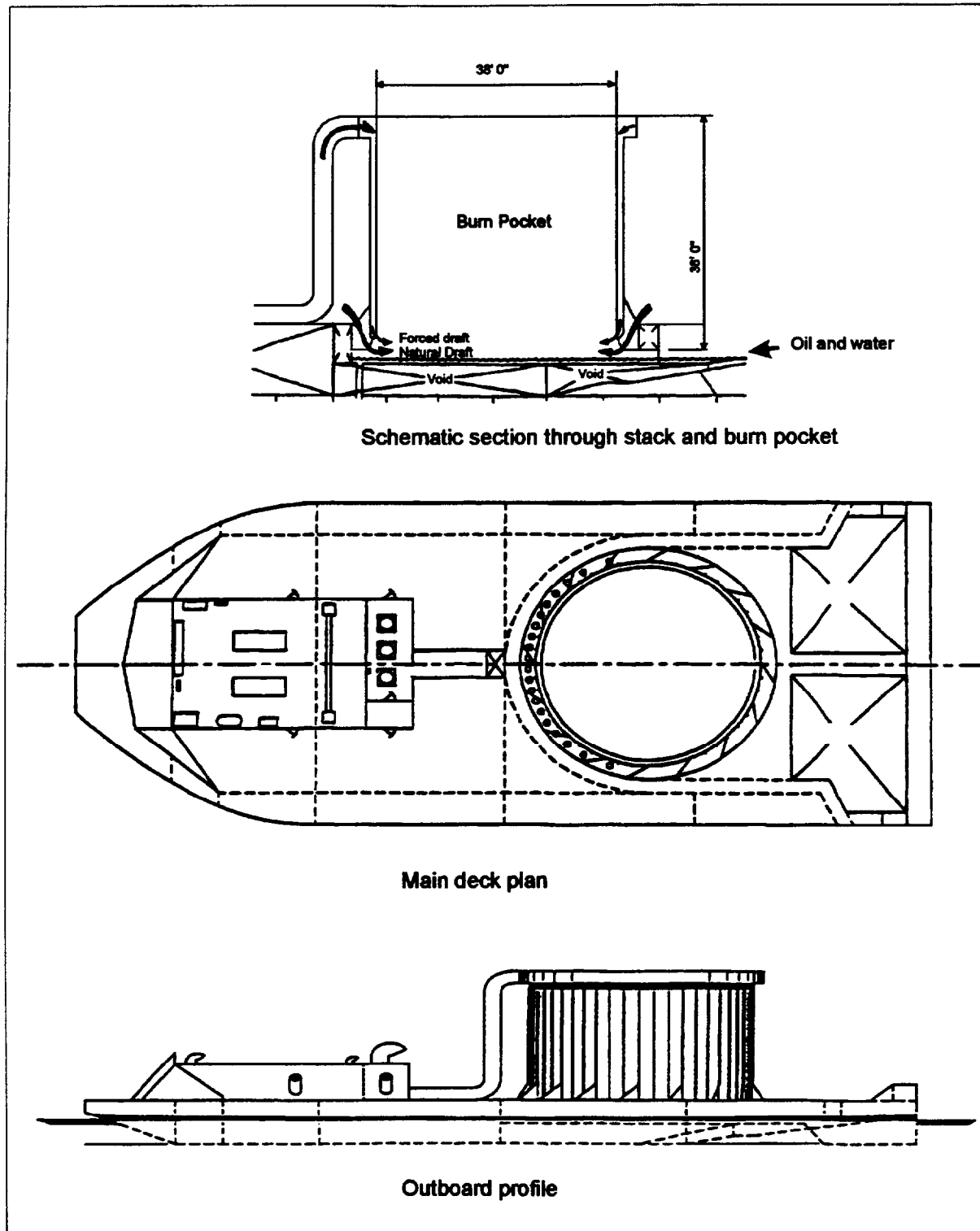


Figure 5.14 *General arrangement of Arctic incinerator barge (from Glosten et al. 1991)*

5.5 References to Chapter 5

- Alaska Clean Seas. 1991. Long duration test burn: 3M 8-inch fire containment boom. ACS Newsletter. Vol (1), No. 1, March 31, 1991. Anchorage.
- Allen, A.A. 1986. Alaska Clean Seas survey and analysis of air-deployable igniters. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 353-373.
- Allen, A.A. 1987. Test and evaluation of the helitorch for the ignition of oil slicks. Proceedings of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 243-265.
- Allen, A.A. and E.M. Fischer. 1988. Test and evaluation of a new and unique fire containment boom. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 185-199.
- Allen, A.A. 1990a. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p 305-313.
- Allen, A.A. 1990b. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. Spill Technology Newsletter, vol. 15, no. 2, pp. 1-5.
- Allen, A.A. 1991a. Controlled burning of crude oil on water following the grounding of the *Exxon Valdez*. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 213-216.
- Allen, A.A. 1991b. In situ burning of spilled oil. Spill Technology Newsletter 16(4):1-12.
- Allen, A.A. 1992. In-situ burning field operations manual. 3M Ceramic Materials Department. St. Paul, MN.
- Anonymous. 1967. Chemicals vs. crude oil. Chemical Week 100(20):49.
- Anonymous. 1968. A product that is an irritant in chemical warfare can also combat ocean oil spills. Chemical Engineering 75(26):54.
- Anonymous. 1970. Materials applications. Industrial Research 12(3):67-68.
- Arctec Canada Ltd. 1977. Novel countermeasures for an arctic offshore well blowout. Report No. EPS-3-EC-77-14: Fisheries and Environment Canada, Ottawa, Ontario. pp. 18-24.

- Battelle. 1979. Combustion: An oil spill mitigation tool. Report for U.S. Department of Energy, Contract No. EY-76-C-06-1830, U.S. Dept. of Energy, Washington, D.C.
- Bech, C., P. Sveum, and I.A. Buist. 1992. In situ burning of emulsions: the effects of varying water content and degree of evaporation. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 547-559.
- Beckett, C.J. 1979. The grounding of the *Imperial St. Clair* — a case history of contending with oil in ice. Proceedings of the 1979 Oil Spill Conference, March 19-22, New Orleans, Louisiana. American Petroleum Institute, Washington, D.C. pp. 371-375.
- Belore, R.C. and C. Seeley. 1990. Air jet atomization and burning of oil slicks. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 289-304.
- Borst, M. 1983. GEMENG lightweight fireproof boom: oil containment testing at OHMSETT. Environment Canada, Ottawa, Ontario. Report No. EPS 4-EP-83-5, 18p
- Buist, I., W. Pistruzak and D. Dickins. 1981. Dome Petroleum's oil and gas under sea ice study. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 647-686.
- Buist, I. and S. Potter. 1982. Sub-sea containment: COOSRA research to date. Proceedings of the Fifth Arctic and Marine Oilspill Program Technical Seminar, June 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 129-150.
- Buist, I.A., R.C. Belore, and L.B. Solsberg. 1983a. Countermeasures for a major oil spill from a tanker in arctic waters. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, June 14-16, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 168-189.
- Buist, I.A., R.C. Belore, and L.B. Solsberg. 1983b. Behaviour of and response to a major oil spill from a tanker in arctic waters. Spill Technology Newsletter 8(3):50-77.
- Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy, and I.R. McAllister. 1983c. The development and testing of a fireproof boom. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, June 14-16, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 70-84.
- Buist, I.A., S.G. Potter, and D.F. Dickins. 1983d. Fate and behaviour of water-in-oil emulsions in ice. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, June 14-16, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 263-279.

- Burns, R.C. 1988. Cleanup and containment of a diesel fuel spill to a sensitive water body at a remote site under extreme winter conditions. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 209-220.
- Cabioc'h, F. 1993. Last French experiments in order to evaluate the burning possibilities of three water-in-oil emulsions. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario.
- Caron, P. (Department of Civil Engineering and Applied Mechanics). 1988. Atomization methods for burning oil spills. McGill University, Montreal, Quebec. 29 p.
- Comfort, G., B. Menon, and W. Purves (Arctec Canada Ltd). 1979. The feasibility of pneumatic and water spray barriers as fireproof oilslick containment devices. Spill Technology Newsletter 4:93-110.
- Comfort, G. (Fleet Technology Ltd.). 1989. Tests to evaluate the effect of a waterjet barrier on the burning efficiency of a floating oil slick. Environment Canada Report EE-112, Environment Canada, Ottawa, Ontario.
- Coupal, B. 1972. Use of peat moss in controlled combustion technique. Environment Canada, Ottawa, Ontario. Environment Canada Report No. EPS 4-EE-72-1, 32 p.
- Coupal, B. 1976. Controlled combustion tests carried out near Rimouski. Environment Canada Report EPS-4-EC-76-2. Environment Canada, Ottawa, Ontario.
- Curzon, F. and B. Ahlborn. 1978. Oil removal system using acoustical radiation. Unpublished report to Environment Canada. Ottawa.
- Cutter Information Corp. 1992. The international oil spill control directory. Eleventh Edition 1991-92. Cutter Information Corp. Arlington, MA.
- Cutter Information Corp. 1993. The international oil spill control directory. Twelfth Edition. Cutter Information Corp. Arlington, MA.
- Det norske Veritas. 1979. Tanker oil spill analysis study. Technical report for Canadian Marine Drilling Limited. Det norske Veritas Ship Division.
- Dome Petroleum Ltd. 1981a. Fire proof boom development — OHMSETT trials. 27 p. Dome Petroleum Ltd., Calgary, Alberta.
- Dome Petroleum Ltd. 1981b. Oil and gas under sea ice. Final report volume one. Report to COOSRA. Calgary, AB.
- Dome Petroleum Ltd. 1983. Fireproof boom field testing. COOSRA Report. Dome Petroleum Ltd., Calgary, Alta.

- Energetex Engineering. 1978. Testing of air-deployable incendiary devices for igniting oil on water. Environment Canada, Ottawa, Ontario. Report No. EPS-4-EC-78-11. 98p
- Energetex Engineering. 1979. A review of oil slick combustion promoters. Environment Canada, Ottawa, Ontario. Environment Canada Report EPS-3-EC-79-8. 48 p.
- Energetex Engineering. 1980. A study to evaluate the combustibility and other physical and chemical properties of aged oils and emulsions. Report to Environment Canada, Ottawa.
- Energetex Engineering. 1981a. Burning of crude oil under wind herding conditions. Report prepared for Canadian Marine Drilling Ltd.
- Energetex Engineering. 1981b. Arctic field trials of the DREV/AMOP incendiary devices. Environment Canada, Ottawa, Ontario. Report EE-17. 25 p.
- Energetex Engineering. 1981c. In situ combustion: an oil spill countermeasure for arctic shorelines. Report for Environment Canada. Environment Canada, Ottawa, Ontario.
- Energetex Engineering. 1982a. Improvement of air-deployable oil slick igniters. Arctic Petroleum Operators Association Project 165. APOA, Calgary, Alta.
- Energetex Engineering. 1982b. Environmental testing of Dome air-deployable igniter. Final report prepared for Dome Petroleum Ltd. 28 p.
- Evans, D., W. Walton, H. Baum, K.A. Notarianni, J.R. Lawson, H.C. Tang, K.R. Keydel, R.G. Rehm, D. Madrzykowski, and R.H. Zile. 1992. In-situ burning of oil spills: Mesoscale experiments. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 593-657.
- Ewing, H. 1979. Devices to contain oil for in-situ burning. Spill Technology Newsletter. Vol 4(3). May-June 1979. Environment Canada, Ottawa. pg 175.
- Exxon. 1990. Valdez oil spill technology. Exxon Production Research Company.
- Franken, P., D. Perry, R. Randt, R. Petersen, and C. Thorpe. 1992. Combustive management of oil spills — Final report. University of Arizona.
- Freiberger, A. and J.M. Byers. 1971. Burning agents for oil spill cleanup. Proceedings of the 1971 Conference on Prevention and Control of Oil Spills, June 15-17, Washington, D.C. American Petroleum Institute, Washington, D.C. pp. 245-251.
- Frish, M., P. Nebolsine, M. DeFaccio, H. Scholaert, W. Kung, and J. Wong. 1986. Laser ignition of arctic oil spills — engineering design. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 203-221.

- Frish, M., V. Gauthier, T. Frank, and P. Nebolsine. 1989. Laser ignition of oil spills: telescope assembly and testing. Environment Canada, Ottawa. Environment Canada report EE-113.
- Glaeser, J.L. and G.P. Vance. 1971. A study of the behavior of oil spills in the Arctic. U.S.C.G. Report CG-D-53-74. Washington.
- Glosten Associates, Inc., D.F. Dickins Associates Ltd., and S.L. Ross Environmental Research Ltd. 1991. Conceptual design for a 144' x 60' x 11' Arctic environment incinerator barge. Report to Shell Western E&P, Anchorage, AK.
- Haaktela, I. 1970. Oil spills off Finland. *Marine Pollution Bulletin* 1(1):19-20.
- Hayward-Walker, A., D.L. Ducey, J.R. Gould and A.B. Nordvik. 1993. Formation and breaking of water-in-oil emulsions: Workshop proceedings, June 14-15, Kananaskis, AB. MSRC Technical Report Series 93-018. Marine Spill Response Corporation, Washington, D.C.
- Horn, S.A. and P. Neal. 1981. The *Atlantic Empress* sinking — a large spill without environmental disaster. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 429-435.
- Industry Task Group. 1983. Oil spill response in the Arctic. Part 2. Field demonstrations in broken ice. Industry Task Force comprised of Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company, U.S.A., and Amoco Production Company, Anchorage, Alaska.
- Jerbo, A. 1973. Two types of oil spills in Swedish inland waters — Tests of new materials, ideas and methods. Proceedings of the 1973 Conference on Prevention and Control of Oil Spills, March 13-15, Washington, D.C. American Petroleum Institute, Washington, D.C. p 559.
- Kana, T.E., E. Thompson and R. Pavia. 1981. *Burmah Agate*: chronology and containment operations. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 131-138.
- Koblanski, J.N. 1981. Oil spill removal in the marine environment utilizing acoustic energy. *Journal of Canadian Petroleum Technology* 20(3):92-96.
- Koblanski, J.N. 1983. An acoustical method of burning and collecting oil spills on cold open water surfaces. Proceedings of the 1983 Oil Spill Conference, February 28 — March 3, San Antonio, Texas. American Petroleum Institute, Washington, D.C. pp. 25-28.
- Koblanski, J.N. 1985. Design improvements in a sonic burner for the in situ combustion of oil spills. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. p643.

- Laisk, E. 1976. Feasibility of oil slick removal from seawater using power lasers. *Environmental Science and Technology* 10(8):814-815.
- Lipski, C. 1986. Study of in-situ combustion of oil spills. Environment Canada, Ottawa, Ontario. Report to the Environmental Emergencies Technology Division, 24 p.
- Lunel, T. and A. Lewis. 1993. Oil concentrations below a demulsifier treated slick. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 955-972.
- McAllister Engineering Ltd. 1979. Development and testing of a "quickie" fire resistant oil containment boom. Report to Canadian Marine Drilling, Dome Petroleum Ltd.
- McAllister, I.R. and I.A. Buist. 1980. Fireproof boom development. Phase III — prototype construction and testing. Report for Dome Petroleum Ltd.
- McAllister, I.R. and I.A. Buist. 1981. Dome Petroleum's fireproof boom — development and testing to date. Proceedings of the Fourth Arctic Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario.
- McLeod, W.R. and D.L. McLeod. 1972. Measures to combat offshore Arctic oil spills. *Offshore Technology Conference paper #1523 (2):14*. pp. 141-162.
- McManus, S. 1993. Personal communication, fax of 15/11/93 re test results for fire boom. Kepner Plastics Fabricators Inc. Torrance, CA.
- McMinn, T.J. 1973. Crude oil behavior on Arctic winter ice. U.S. Coast Guard Project 734108. Washington, D.C. NTIS AD-754, 261.
- Meikle, K. 1981a. An oil slick igniter for remote areas. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 617-621.
- Meikle, K.M. 1981b. Incendiary device for oil slick ignition. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 499-513.
- Meikle, K.M. 1983. An effective low-cost fireproof boom. Proceedings of the 1983 Oil Spill Conference, February 28 — March 3, San Antonio, Texas. American Petroleum Institute, Washington, D.C. pp. 39-42.
- Mitchell, J.B.A. 1990. The effectiveness of ferrocene in reducing smoke emission from burning crude oil. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment, Canada, Ottawa, Ontario. p. 75-85.

- Mitchell, J.B.A. and E. Janssen. 1991. The use of additives for smoke reduction from burning pool fires. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. p. 391-397.
- Mitchell, J.B.A. and M.E. Moir. 1992. Smoke reduction from pool fires using ferrocene and derivatives. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 681-689.
- Moir, M.E., S. Charbonneau and J.B.A. Mitchell. 1993. Soot reduction chemicals for in-situ burning. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 761-764.
- NOBE Newsletter. September 1993. Environment Canada, Ottawa.
- OSIR (Oil Spill Intelligence Report). Published weekly by Cutter Information Corp., 37 Broadway, Arlington, MA 02174-5539.
- Purves, W. 1978. Design and development of equipment to aid in the burning of oil on water. Proceedings of the First Arctic and Marine Oilspill Program Technical Seminar, March 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p190.
- Purves, W.F. and A. Daoust. 1978. Booms for in-situ burning of oil spills. Report to Environment Canada, Ottawa.
- Raloff, J. 1993. Burning issues: Is torching the most benign way to clear oil spilled at sea? Science News 144 (14):220-223 (October 2, 1993). Washington, D.C. pp. 220-223.
- Ramsier, R.O., G.S. Gantcheff and L. Colby. 1973. Oil spill at Deception Bay, Hudson Strait. Scientific Series No. 29. Inland Waters Directorate. Water Resources Branch. Environment Canada, Ottawa.
- Roberts, D. 1978. Development of oil spill burning equipment. Proceedings of the First Arctic and Marine Oilspill Program Technical Seminar, March 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 191-193.
- Roberts, D., and D.K.T. Chu. 1978. Development of oil spill burning equipment. Report by Bennett Pollution Control to Environment Canada, Ottawa.
- Robertson, I. 1991. Operational examples of in-situ burning: Lessons from the burning of two recent diesel spills on the B.C. coast. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 411-419.

- Ross, S.L., C.W. Ross, F. Lepine and K.E. Langtry. 1979. Ixtoc I oil blowout. Environmental Protection Service Spill Technology newsletter, July-August. Environment Canada, Ottawa.
- Ruby, C.H., L.G. Ward, I.A. Fischer, and P.J. Brown. 1978. Buzzards Bay oil spill — an arctic analogue. International Conference on Ports and Ocean Engineering under Arctic Conditions (POAC '77), 4th Conference, St. John's, Newfoundland, 1977
- Salooja, K.C. 1972. Burner fuel additives. Journal of the Institute of Fuel 45(371):37-42.
- Schulze, R. 1993. World catalog of oil spill response products: fourth edition. Robert Schulze Environmental Consultant, Inc. Elkridge, MD.
- Schrier, E. and C. Eidam. 1979. Cleanup efficiency of a fuel oil spill in cold weather. Proceedings of the 1979 Oil Spill Conference, March 19-22, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 419-427.
- SINTEF and S.L. Ross. 1993. In-situ burning of water-in-oil emulsions. Draft report to NOFO. Stavanger, Norway.
- Skinner, S.K. and W.K. Reilly. The *Exxon Valdez* oil spill — a report to the President. The National Response Team. Washington, D.C.
- S.L. Ross Environmental Research Ltd. 1983. Evaluation of industry's oil spill countermeasures capability in broken ice conditions in the Alaskan Beaufort Sea. Report to Alaska Department of Environmental Conservation. Juneau, AK.
- S.L. Ross Environmental Research Limited. 1986. An experimental study of oil spill treating agents that inhibit emulsification and promote dispersion. Environment Canada, Environmental Protection Directorate, Report EE-87, Ottawa.
- S.L. Ross Environmental Research Ltd. and DF Dickins Associates Ltd. 1987. Field research spills to investigate the physical and chemical fate of oil in pack ice. Environmental Studies Revolving Funds Report No. 062, 95 p.
- S.L. Ross Environmental Research Ltd. 1989. Disposal of spilled Hibernia crude oils and emulsions: in-situ burning and the "Swirlfire" burner. Report to Canadian Coast Guard, Ottawa.
- Smith, N.K. and A. Diaz. 1985. In-place burning of crude oil in broken ice — 1985 testing at OHMSETT. Proceedings of the Eighth Arctic and Marine Oilspill Program Technical Seminar, June 18-20, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 176-191.
- Smith, N.K. and A. Diaz. 1987. In-place burning of crude oils in broken ice. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 383-388.

- Solsberg, L. and R.C. Belore. 1982. An operational evaluation of the prototype Gemeng lightweight fire proof boom. Report to Canadian Coast Guard and Environment Canada, Ottawa.
- Solsberg, L. 1983. A catalog of oil spill containment barriers. Environment Canada report EPS 9/SP/1. Environment Canada, Ottawa.
- Spiltec. 1986. Test and evaluation of fire containment boom. Report to Alaska Clean Seas, Anchorage, AK.
- Spiltec. 1987. Refinement of aerial ignition systems (test and evaluation of the Heli-torch for the ignition of oil slicks). Report to Alaska Clean Seas, Anchorage, Alaska.
- Summerfield, M. 1993. Radiative exposure of oil spills on seas or rivers. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pg 849.
- Swift, W.H., C.J. Touhill, and P.L. Peterson. 1968. Oil spillage control. Chemical Engineering Progress Symposium Series 65(97):265-273.
- Tam, W.K. and W.F. Purves. 1980. Experimental evaluation of oil spill combustion promoters. Proceedings of the Oceans '80 International Forum on Ocean Engineering in the 80's. IEEE, Piscataway, NJ. pp. 415-421.
- Twardawa, P. and G. Couture. 1983. Incendiary devices for the in-situ combustion of crude oil slicks. DND DREV report 4282/83. Environment Canada, Ottawa.
- Twardus, E.M. 1978. Development and evaluation of continuously-burning wicking devices for burning oil slicks. Proceedings of the First Arctic and Marine Oilspill Program Technical Seminar, March 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 164-178.
- Waterworth, M.D. 1987. The laser ignition device and its application to oil spills. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 369-372.
- Whittaker, H. 1987. Laser ignition of oil spills. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 389-394.
- Williams, R.E. and T.S. Cooke. 1985. Feasibility of using a bubble barrier for the containment/incineration of spilled Oil. Proceedings of the Eighth Arctic and Marine Oilspill Program Technical Seminar, June 18-20, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 212-227.

6.0 Operational Considerations

6.1 Introduction

This chapter focuses on issues and criteria for planning and implementing a safe and effective burn of spilled oil at sea. These are considered within the context of the following categories:

- the feasibility of burning;
- the resources necessary to carry out a successful burn; and
- avoiding or minimizing health risks and environmental impacts.

Once discussed, the criteria for each of the above categories are condensed into a checklist of critical items that should be considered before burning is attempted.

It should be recognized that operational experience with controlled in-situ burning in open water conditions is extremely limited. The method has only been used once, and only on a trial basis, at the *Exxon Valdez* spill. Thus, many of the suggested techniques in this chapter had to be extrapolated from knowledge gained from small tests of in-situ burning or derived from experience with conventional spill containment operations. As knowledge of controlled in-situ burning increases through R&D and actual use, the concepts presented in this chapter will undoubtedly be expanded, revised or even rejected. As such, the aspects of in-situ burning discussed here should be considered a "work-in-progress" only.

Many of the ideas in this chapter were taken directly from or were inspired by the "Burn Plan Approval Check List" developed in 1991 by the Alaska Regional Response Team and the "In-Situ Burning Field Operations Manual: 3M Fire Boom" published by 3M Ceramics Materials Dept. in 1992. The Alaska RRT checklist is reproduced in Appendix A.

6.2 Feasibility of Burning

There are basic constraints to be considered in determining the feasibility of burning a particular spill. These include the type and condition of the oil to be ignited, the environmental conditions at the time of the spill, and the location and availability of the equipment and trained personnel needed to conduct the burn. The practicality of burning will also depend on the influence of burning on other activities such as spill source control measures, personnel evacuation efforts, and other spill or shoreline cleanup activities. The acceptability of burning will depend on the location of the oil relative to populations, facilities and natural resources that could be adversely affected by the burn or burn byproducts. All these factors that relate to the feasibility and acceptability of a burn operation are now discussed in turn. Whenever possible the subject is addressed in quantitative terms.

6.2.1 Oil Type and Condition

Most freshly spilled petroleum oils will burn on water. The key parameter that controls the efficiency of in-situ burning is oil slick thickness. Slicks, once ignited, will burn until the thickness of the underlying oil reaches about 1 mm. The oil removal efficiency is thus proportional to the thickness of the slick at ignition.

During the early stages of a batch spill, thick slicks of fresh oil are usually available for burning; however, depending on wind and sea conditions, the flow rate at source, and the spreading characteristics of the oil, suitable thicknesses for burning may only exist over small areas. During large spills with relatively calm conditions and spread-resistant oils (e.g., the first few days of the *Exxon Valdez* spill), combustible layers could extend over large areas.

For ignition to occur the heat supplied by the ignition source must be sufficient to raise the temperature of the slick surface to that greater than the oil's fire point. For this to occur the slick must be thick enough to insulate itself from the underlying water >2-3 mm for weathered crude oils and lighter fuel oils; >5 mm for light (30% water) emulsions; and >10 mm for residual fuel oils. Once ignition takes place, sustained burning of the slick requires that sufficient heat be radiated to the slick to maintain the slick at temperatures above the oil's fire point. Once about one square meter of slick is on fire the burn will usually be underway.

In order for in-situ burning to result in high removal rates and efficiencies it is also necessary that the flames spread to cover as much of the slick surface as possible. Flame spreading is accomplished by radiation from the burning part of the slick warming adjacent oil to a temperature above its fire point, allowing the flame to ignite the resulting vapors. As well, the differential heating of the slick by the flames can cause hot oil from the fire zone to spread out over unignited portions of the slick. In either case the rate of flame spreading is a strong function of oil weathering processes. For example, as evaporation progresses the remaining oil's fire point increases; this results in a greater heat demand for ignition and thus slower flame spreading. As well, the increase in oil viscosity due to evaporative losses (or emulsification) reduces flame spreading by increasing resistance to surface-tension flow of hot oil over cold oil.

In addition to evaporation, water-in-oil emulsification greatly affects the feasibility of in-situ burning. Experimental burns with certain oils emulsified with 50% water or more have shown that effective in-situ burning may be feasible. On the other hand, other oils with as little as 10 % to 20% water have been extremely difficult to ignite with conventional ignition systems. In any case, the formation of water-in-oil emulsions generally hampers flame spreading by raising both fire points and slick viscosities. More research is needed to correlate emulsion water content and the ignition of various types of oils. In the meantime it should be assumed that any oil that has become emulsified to levels of 30% to 50% water will be difficult to ignite; any oil emulsified to levels in excess of 50% water should be assumed to be unignitable. Any successful ignition of emulsions may require relatively calm conditions and the use of ignition techniques that can produce sufficient heat to break the emulsion, volatilize the oil and promote flame spreading. A single ignition point may not be sufficient. Also, it may be necessary to enhance the situation by: 1) increasing the dosage of the igniting material onto the emulsion, thus creating a larger initial ignition area; 2) adding special ignition promoters to the igniting mixture; or 3) applying a primer, emulsion breaker or wicking agent to the oil before attempting ignition.

Any decision to burn spilled oil should include an assessment of the ease with which burning can be achieved with the type and condition of oil involved. It may be advisable in certain cases to collect samples of the spilled oil to assist in an assessment of the oil's ignitability and to support post-burn analysis of the operation. Prior to any burn effort, operators may be requested by regulators to conduct a limited test burn on a portion of the spill at an approved location safely removed from the spill source and any major oil slicks. It must be remembered, however, that there is only a limited time window in which in-situ burning can be initiated; the conduct of test burns and their subsequent review can use up valuable operational time.

Summarized below are the parameters related to oil type and condition that should be addressed in assessing the feasibility of a particular in-situ burn:

- type of product or crude oil released;
- emulsion formation tendency and stability of released product;
- estimated volume of release and estimated volumes that could still be released;
- estimated spill area (thick and thin portions) and estimated thickness of thick portions of the slick;
- estimated emulsification of oil in thick slick at 12, 24 and 48 hours;
- estimated evaporation rate of oil in thick slick at 12, 24 and 48 hours;
- estimated natural dispersion losses at 12, 24, and 48 hours; and
- estimated ignitability of oil in thick slick.

6.2.2 Environmental Constraints

Temperature, wind, currents, and waves promote various physical and chemical changes to a spill that can make the oil difficult or impossible to ignite. High temperatures and winds result in the rapid loss of volatile components and reduction of film thickness. High wind and sea states can increase the rate of emulsion formation and the rate of heat transfer through the slick, both of which reduce ignitability.

In evaluating burn feasibility, aerial or surface observations need to be made to assess the spreading, transport and weathering effects of the environment on the spill. The assessment should also include the effects of wind and sea conditions on the use of igniters and fire containment booms if they are to be utilized, and all necessary support operations. As with physical recovery approaches, excessive winds, waves, currents or debris can make it difficult or impossible to collect and hold the oil. In situations where burning is being considered in an uncontained mode (i.e., without the use of fire containment booms) it is even more important to take into account the spreading and weathering of the surface oil due to wind and wave conditions.

Although there are few data on the effects of sea state on in-situ burning, what little experience exists suggests that the sea-state limit for effective burning is from 1 to 2 meters significant wave height or less. Of course, burning will not be effective if the fire proof boom fails to hold oil in these sea state conditions.

Winds of approximately 30 to 40 km/hr (15 to 20 knots) are considered to be the upper limit for ignition of oil pools in the absence of waves. These constraints reflect both the current state-of-the-art in proven ignition and fire containment booms systems, as well as the environmental conditions under which most oils will be quickly weathered beyond a combustible state.

Another important environmental factor favoring burning is the presence of good visibility. For a safe and effective burn to take place it should be possible to see 1) the oil to be collected, 2) the vessels towing the fire containment booms, and 3) the proximity of the intended burn location relative to the spill source, other vessels in the area, and other potentially ignitable slicks. As a guide, VFR flying conditions (greater than 4 km visibility and a minimum 300 m ceiling) could be used. If helicopters are to be used, VFR flying conditions must exist both at the site and at the helicopter base. If burning is to be conducted at a remote, fixed, continuous source of spilled oil (e.g., offshore blowout), it may be feasible to burn spilled oil safely at or near the source during limited visibility conditions (e.g., less than VFR flying conditions, dusk, dawn, etc.).

The environmental conditions that should be assessed prior to conducting an in-situ burn are summarized below:

- wind speed at site and forecast for next 12, 24 and 48 hours;
- sea state at site and forecast for next 12, 24 and 48 hours;
- visibility (VFR flying conditions) at site and forecast for next 12, 24 and 48 hours;
- speed and direction of residual current;
- tidal current forecast over next 48 hours;
- weather conditions and forecast for next 12, 24 and 48 hours; and
- sea temperatures and water depths in area in relationship to vessel operations.

6.2.3 Compatibility with other Response Activities

Attempts to burn oil during a spill response should not interfere with other critical operations such as the stabilization of the spill source or the evacuation of personnel from the stricken vessel. Also important to understand is the influence burning might have on other spill control activities such as mechanical skimming, the application of chemical dispersants, and the protection and cleanup of shorelines. The following summaries for the above response activities need to be considered prior to and during a burn operation.

Stabilization of spill source: During the early hours of a major spill, there may be attempts to seal leakage points, transfer oil from one compartment to another, or reduce the potential for a fire or explosion at the spill site. There may also be efforts underway to move the source of spillage to a new location where the source or its release of oil can be better controlled. At the same time there may be a decision to keep essential personnel onboard. In each of these situations, it is imperative that the stricken ship be protected from fire and explosion hazards. Under such conditions the use of controlled burning on any portion of the spill should only be considered if and when all responsible parties are confident that the burn can be accomplished with no possibility of endangering property and personnel.

Evacuation of personnel: During an accidental oil spill there may be a need to evacuate personnel from the immediate area. When evacuation efforts are underway it is important that spill control operations be conducted in a manner that does not impede the evacuation process. Any attempt to burn spilled oil should be conducted only if it can be accomplished at a safe, isolated location and if it is certain that the burn will not interfere with the visibility and movement of vessels or aircraft used during the evacuation. It should also be determined that the personnel, vessels and aircraft needed to conduct the burn are not needed for the more important task of transferring personnel from the source to a safe location.

Mechanical cleanup: The use of burning should be planned and implemented not necessarily as a response technique to replace mechanical cleanup, but rather as an additional response option to be used where and when it is safe to do so. When the spill source is already ignited it may be appropriate to conduct burning operations as the primary technique near-source with mechanical cleanup as the secondary technique down-stream. In other situations, particularly where there are ample containment and recovery systems, it may be possible to position the skimming equipment closest to the spill source and use controlled burning techniques at a safe distance downstream as a backup to the mechanical systems. Careful attention must be paid in this instance to avoiding flashback.

Many issues must be considered in coordinating mechanical removal and burning resources at a spill incident and these need to be examined for a broad range of specific spill scenarios. Guidelines should be established in advance so that time is not lost on this during a spill.

Dispersant application: Under the right conditions, dispersants can be used to disperse large quantities of spilled oil from the sea surface. It is considered one of the primary options for response to oil spills, particularly when physical containment techniques or equipment are not practical or available. The use of in-situ burning might be appropriate to back up a dispersant-use operation or vice versa, and these possibilities require examination, again on a scenario-specific basis.

Dispersants and in-situ burning both work best on spills involving relatively fresh, non-viscous oils. Again, in joint operations on the same spill, it is important to establish response guidelines well in advance to ensure that one method does not interfere with the other. In particular, burning has the potential for reducing the effectiveness of a dispersant-use operation by affecting the viscosity of oil left on the surface and creating dangerous flying conditions due to smoke production. It is thus reasonable to suggest that each operation should focus on separate parts of the spill remote from each other.

Many spill scenarios can be envisioned in which mechanical, burning and dispersant systems could be used simultaneously on a major spill at sea. For example, following a sudden "batch" spill that results in the oil coverage of many square kilometers, specific zones

could be identified for each mode of response allowing each technique to be used independently and without interference. It could also be possible to use all three response techniques in close proximity to each other immediately downstream of an ongoing continuous spill source. In this case, mechanical systems might concentrate and recover a portion of the oil near the source; fire containment booms might be positioned a safe distance downstream of the skimming; and any oil missed by or entrained beneath the fire containment booms could then be sprayed with dispersants, again a safe distance downstream. Theoretically, there are many possible scenarios that could involve joint operations. These should be analyzed carefully in contingency planning exercises.

Shoreline protection and cleanup: In spill situations where one might consider burning close to shorelines, the appropriateness of such burning would depend on the type of shoreline and the potential ignitability of backshore areas, the existence of human-use facilities, and the performance of any shoreline protection or cleanup activities nearby. Under certain conditions it may be feasible to utilize fire containment booms in a deflection mode to support controlled burning against the shoreline. In other situations it may be advisable to use fire containment booms in an exclusion mode to prevent burning oil from entering a sensitive area. In any event, burning near or adjacent to a shoreline should never be conducted where there is any chance of starting fires onshore or endangering other shoreline protection and cleanup activities.

The following list summarizes the issues that should be addressed when assessing the implications of in-situ burning operations to other spill-related activities:

- whether the spill source is already ignited and, if so, whether it should be extinguished;
- status of spill source (abandoned, rescue underway, source control operations underway, etc.)
- distances and directions to nearby shores;
- type of accident (e.g., grounding, collision, transfer spill);
- location of burn and smoke with respect to source;
- location of burn with respect to other slicks;
- location of burn and smoke with respect to shorelines;
- location of burn and smoke with respect to countermeasures; and
- status of other response operations.

6.2.4 Requirement for Regulatory Approvals

Prior to conducting a burn it is necessary to obtain appropriate permits and approvals. This issue is dealt with in a subsequent chapter. Guidelines for the approval to burn spilled oil in U.S. waters are currently being examined by the U.S. Coast Guard, the U.S.

Environmental Protection Agency and other federal and state agencies. Controlled burns have been approved by Regional Response Teams for both onshore and offshore spills, but the approval process has been time-consuming. Since the late 1980s there have been several attempts to streamline the approval process and to provide a set of guidelines that could be used by the Incident Commander at a spill. One example is the “checklist” developed by the Alaska Regional Response Team in cooperation with several federal and state agencies. The checklist, reproduced in Appendix A, is to be used in Alaska for evaluating burn requests on a case-by-case basis.

During an actual spill, a situation may develop where the approval process is still underway as the spilled oil approaches a condition and/or location where it may be impractical or impossible to burn. Under such circumstances, the Incident Commander may elect to mobilize equipment for burning with clear instructions not to ignite any oil until authorization is received. In this way valuable time can be saved by getting vessels, booms and aircraft on location, and by containing oil within booms should the decision to burn be reached. If burning is not approved, it may be possible to initiate a conventional recovery operation on the oil contained within the fire containment booms.

6.3 Resources Necessary for a Burn

This section discusses the resources that are normally required to carry out a safe and effective controlled burn: trained personnel, vessels and aircraft, and fire containment boom and igniters. It is recognized that certain types of burning may not require all of these resources. For example, a situation involving accidental burning of oil following a ship accident would not require igniters to start the burn process; and, an intentional program to burn a thick, uncontained spill would not involve fire proof boom.

6.3.1 Trained Personnel

Individuals involved with the planning and implementation of controlled burning of oil at sea should be trained in both the theory and hands-on aspects of contained in-situ burning. The amount and focus of the training should reflect the job and level of responsibility assigned to each member of the burn team. Areas of instruction should include:

- Response organization and management, including specific job assignments;
- Government regulations and permitting procedures;
- Communications (specific to command and control interfacing, and vessels and aircraft involved with the burning operations);
- Strategies and priorities for response, including procedures for coordinating with other spill control activities;
- Basic combustion theory and fire prevention and control techniques;

- Safe equipment handling procedures (fire containment booms, igniters, vessels, etc.);
- Personal protection equipment and first aid;
- Backup response strategies (i.e., identification of potential emergency conditions and appropriate response procedures); and
- Avoidance and minimization of environmental impacts.

It is important that trained personnel be available on each vessel and aircraft used for the burning operation. Individuals assigned to field-operation positions should be familiar with the deployment and use of fire containment boom, aerial and surface ignition systems, and other equipment necessary to carry out a safe and effective burn. Response personnel training should satisfy all Occupational Safety and Health Administration (OSHA) regulations (both federal and state) and they should have received appropriate levels of training in the Hazardous Waste Operations and Emergency Response (HAZWOPER) training program.

It is imperative that all personnel and equipment be protected from any harmful exposure to heat and combustion products. All personnel that could be exposed should be provided with adequate personal protection equipment (such as respirators, goggles, and protective clothing) based on the requirements of the response organization in control and/or the regulatory agency for the region involved. Such protective measures would not normally be used since it is relatively easy for response vessels and aircraft to remain well outside any zone of potentially dangerous exposure to heat or combustion products. However, personnel may experience brief exposures due to wind shifts, vessel power failures, and oil and emission sampling activities. Because of these short, though potentially significant exposures, personnel should be trained on how to avoid such conditions and what to do or wear in the event that exposure is unavoidable.

6.3.2 Vessels and Aircraft

Prior to the ignition of spilled oil all vessels and aircraft should be properly selected and positioned in predesignated safe operating zones. These zones should be identified so that no one could come into contact with harmful concentrations of oil (or combustion products) due to deliberate or accidental ignition. The operation of boom towing vessels must continually take into account the size, thickness and volatility of nearby slicks, as well as vapor clouds that could come into contact with potential ignition sources such as the vessels and the burning oil. All vessels should be equipped with explosimeters.

It is important that all vessels used during offshore burning operations have sufficient power to pull the size and length of fire containment boom being considered. Vessels with twin variable-pitch propellers are generally preferred; and powers in the 100 to 150 kw (150-200 hp) range are generally sufficient for boom tow boats. Large vessels (e.g., 45 m to 60 m supply vessels) make ideal platforms for large containment booms and recovery systems, although such vessels are often over-powered for the needs of pulling boom. Experience has shown that small towing boats in the 8 m to 12 m range are usually much better for controlling a simple track-down and collection operation, particularly when towing speeds need to be maintained for extended periods at 0.4 m/s or less. This size of towing boat can

often be transported to the burn area with a larger vessel and deployed and recovered from the larger vessel. Regardless of the size of vessel selected, it is important that its propulsion system permit the vessel to maintain steerage at speeds in the 0.4 m/s and lower range.

Vessels used for the towing of fire containment boom need to be equipped with properly positioned tow-posts or bitts and adequate lengths of tow line (typically 150 m to 250 m). The tow lines need to be strong enough to accommodate the maximum drag forces that would likely be experienced during the towing of boom in open water conditions. For example, working with an anticipated maximum drag force of about 11,000 to 13,000 Newtons (N) (2500 to 3000 lbs) and a safety factor of 7, a polypropylene tow line with a 33 mm (1 5/16") diameter would be required. A similar tension strength (i.e., about 93,000 N or 21,000 lbs) could be achieved with the use of a 27 mm (1 1/16") nylon line or a 25 mm (1") polyester line.

Vessels should also have space to carry fire containment booms to the burn site and space to deploy them. The size and weight of the boom must conform to the deck space and safe load-carrying capacity of each vessel. When the boom-towing boats are too small to carry the entire boom on deck, the fire containment booms may be pulled in a straight-line tow (typically at speeds of about 9 to 18 km/hr [5 to 10 knots]), or the boom can be transported to the oil collection area with the aid of an additional vessel or barge. In some cases, helicopters may be used to transport boom from shore or from a vessel to the spill site.

With respect to aerial support operations, helicopters will provide an effective platform not only for the possible transport of boom and personnel, but for the release of igniters onto the oil to be burned. Helicopters will also be of value for the spotting of oil slicks, the directing of vessels to the heaviest concentrations of the spill, and the monitoring of burn effectiveness and smoke plume transport and dispersion. Because of the diversity of tasks for which helicopters may be used and the distances that may have to be travelled offshore, it is important that the type and size of aircraft, the number of engines, and the need for pontoons be properly considered.

It should be recognized that while aircraft will usually play a key role during burning operations, there will be potential burn situations where controlled burning could be initiated without them. For example, as long as surface operations are located a safe distance from property and other vulnerable resources, boats could begin to concentrate and ignite oil with hand-held igniters released from one of the boom towing vessels.

6.3.3 Fire Booms and Igniters

From an operational standpoint, it is the specific location and nature of spillage to be contained that will determine the type, size, length and mode of deployment of fire containment boom required. The location and nature of the spill, together with the boom deployment mode will then determine the best type of igniter and the most appropriate scheme for igniting the contained oil. It is important to remember that certain spill scenarios may not require the use of fire containment booms for the effective burning of large quantities of spilled oil. In such situations, extra safety precautions may be necessary to avoid unexpectedly large initial burn areas and harmful exposure levels.

When spilled oil has spread to thin layers covering large areas, fire containment boom will be required to concentrate the oil to thicknesses that will support combustion. If there is a chance that burning could spread dangerously to oil outside the towed boom configuration, the contained oil should be towed and ignited well away from the main slick.

Should a tanker accident involve spillage without fire, fire containment boom could be used to collect oil in one or more U-configurations and then be towed to a safe location for ignition. If oil is already burning at the source, this mode of controlled burning should be considered if it is impractical or unsafe to burn near the stricken vessel.

During burning operations on the leeward or downstream side of an already burning tanker, it may be impossible to deploy fire containment booms immediately at the spill source. In such a situation, it may only be necessary to periodically release igniters into any unignited oil as it concentrates under the influence of wind and current eddies in the lee of the burning tanker. If safe to do so, it may be possible to position fire containment booms on the leeward side of the spill in order to thicken and burn oil before it spreads downstream.

In all of the above three examples the fire containment boom in U-configurations should be used with 150 m to 300 m of boom each. The larger fire containment booms would usually be used during open water conditions, while smaller fire containment booms could be utilized in calmer or protected waterways. When wind and sea conditions require the use of large fire containment booms configurations, each U-configuration could be established with a short length of the large boom forming the apex, and with medium-sized boom serving as the deflection boom forward along each leading side of the "U". In this situation care must be taken to ensure that the connection point between the two boom sizes can withstand the extra loads imposed by the differing wave response characteristics of each boom type. Where it is safe to do so (i.e., in situations where the oil is too thin to burn except where it is thickened within the apex), conventional boom could even be used to deflect oil directly into the fire containment boom portion of the U-configuration.

Some fire containment booms are heavy and difficult to handle, but are also durable and able to survive burning in an offshore marine environment for long periods. These are typically metal booms. Others are lighter and easier to handle and deploy but are not designed for long-term deployment offshore or long-term exposure to fire. These usually employ fire resistant, mineral-based fabric and ceramics. It is important for planners and field personnel to anticipate the full range of constraints that may be imposed on the burning operation because of a boom's particular weight and handling requirements. With proper training, experience has shown that fire containment booms can be deployed quickly and used in the same manner as most comparably sized conventional booms. If the fire containment boom is subsequently not used for the combustion of oil, it can be recovered, cleaned and stored for use again at a later time.

When fire containment boom is used to contain burning oil, there will almost always be some degree of thermal stress and material degradation with time. Some fire containment booms have been constructed of materials designed to strongly resist the effect of fire (e.g., steel). Other fire containment boom designs have outer coverings that protect the more fragile underlying material from abrasion during handling and storage, but are destroyed during the early phase of a burn. The underlying materials are refractory in nature and designed to withstand the effects of burning and to remain intact for subsequent burns over a period of several hours. Wave action may accelerate the degradation of these boom types. The actual number of times that a fire containment booms can be used will vary from one product to another and from one application to another. Repeated use will clearly depend on the intensity and duration of the burns, the sea conditions at the time of burning and the manner in which the boom is handled during and between each burn. As with some conventional booms, the extent of use and the degree of damage may make it cost-effective to discard the boom upon completion of use, rather than attempting to clean and restore it.

When using fire containment booms for multiple burns, the boom should be inspected (at least along segments exposed to the most thermal stress) for any significant breaks, tears, or deterioration which could result in mechanical failure or loss of containment. Any damaged sections should be repaired or removed and replaced as necessary. If it is necessary to tow used fire containment booms of the sacrificial-coating type to a new site for additional burns, care should be taken to avoid any excessive speeds (more than 4 to 8 km/hr or 2 to 4 knots) even in a straight-line tow. This is because exposed areas where the protective outer cover has burned away will experience excessive drag and be less resistant to abrasion. Even with metal construction boom, care should be used in transporting and reusing the boom due to the cumulative effects of mechanical and thermal stress upon its components.

With respect to igniters, this report has described several devices for igniting spilled oil. Of these, the Heli-torch is one of the most cost-effective, reliable and flexible systems for the aerial application mode. The Heli-torch provides an off-the-shelf ignition system that has been used for many years by forest fire fighting organizations in different parts of the world. Because of the quantity of gelled fuel that can be carried (typically from 100 to 1000 L), it is possible to release ignition fluid as individual ignition points or in a continuous mode. With the Heli-torch operated from a hovering position (at altitudes of 8 to 80 m or more), it is possible to create very large initial ignition areas for difficult-to-ignite weathered or partially emulsified oil layers.

In spill situations where a helicopter's staging area is distant from the proposed burn region, it may be advisable to locate nearby temporary landing sites where the helicopter could set down between ignitions. A single drum of gelled fuel within the Heli-torch would normally be large enough to support the ignition of numerous individual burns. During an extensive ongoing burn operation it may be helpful to move backup Heli-torches, fuel, mixing facilities and gelling agent to forward landing sites in order to avoid delays because of long transit distances to the primary staging location. Ships with appropriate heli-decks may also be used, if the transport and mixing of the gasoline-based Heli-torch fuel is allowed onboard.

6.4 Avoidance of Risk to People and Property

Any attempt to ignite and sustain combustion safely, effectively and with minimal disturbance to other spill control operations must include an assessment of the burn location and its proximity to:

- the spill source;
- other potentially ignitable oil slicks;
- shorelines, man-made structures, natural areas onshore that could catch fire, population centers, airports, roads, and other areas of human use;
- sensitive biological resources; and
- other vessels and ongoing response operations.

If the spill source is not already burning and its ignition is undesirable, it is essential that burning be considered only if it can be accomplished at a safe distance from the spill

source and any free-floating, potentially ignitable oil slicks. The safe distance should be confirmed by the use of portable explosimeters to detect flammable vapor concentrations. In calm conditions (winds less than 2 km/hr or 1 knot) burning should not be considered in close proximity to a flammable spill source. Under all conditions, consideration must be given to the possibility of wind shifts.

For a safe in-situ burn to take place it is important that the location and timing of ignitions be established and thoroughly understood by all response personnel in the area. It must be possible to identify, and communicate to all responders, zones that have been selected as acceptable burn areas as well as specific areas where ignition and sustained burning operations will not be permitted. The nature of the spill and its slicks, the weather conditions, and the reliability of communications and spotter aircraft, should all be considered carefully in establishing a well understood and clearly defined burn plan.

In assessing the appropriate time and place for a burn, one must consider the proximity of the intended burn to coastal features, population centers and sensitive natural resources. The potential exposure of human and environmental resources to the effects of burning spilled oil should always be given high priority before the initiation of a burn. The burn must be completed without exposing people, equipment, facilities, forests and animals to any harmful levels of the products of combustion.

In the event that some unexpected condition (e.g., a wind shift or vessel power failure) requires the early termination of an ongoing burn, personnel must be familiar with the appropriate responses, and there must always be ample maneuvering room to complete such operations.

The following sections address safety and control measures and possible mitigation techniques that should be considered during every burn.

6.5 Safety and Control Measures

Burn Plan: A detailed burn plan should be prepared by any response organization intending to use in-situ burning as a spill control measure. The plan should include:

- a clear set of objectives for the types and magnitudes of spills that could take place within the area of interest;
- guidelines and a "checklist" for securing approval to burn;
- an "Operational Checklist" to ensure that all information needs and resources are identified or in place to conduct a successful burn;
- an "Immediate Action Plan" including response team organization, notification procedures, mobilization guidelines, communications networks, backup logistics support, etc.;
- specific response procedures for spill scenarios most likely to occur in the area of interest (including equipment deployment, oil collection, ignition, towing during combustion and residue recovery);

- a summary of safety and control measures to minimize risks, protect personnel and facilities and interface with other response activities; and
- guidelines for monitoring and documenting burn performance, smoke plume trajectories and environmental impacts;

Training: All response personnel should meet all OSHA and HAZWOPER requirements (as noted earlier), and take part in annual classroom and hands-on training with an emphasis on the potential effects of burning on personnel, equipment, communities and facilities. Training should include such topics as safe operating practices for vessels and aircraft, fire containment boom deployment and towing procedures, oil ignition techniques and burn residue recovery guidelines.

Communications: Good communications must be maintained prior to and throughout the in-situ burning operation. Specific radio links need to be established for all vessels, aircraft and ground-based operations. All personnel on location must be in constant radio contact with the on-site burn supervisor who should have sole responsibility to authorize ignition of a slick. Dedicated radio links should be established for the exclusive use of the boom towing vessels as the operators of those vessels will need to be in frequent contact regarding their position relative to each other, the leading edge of the burning oil, the spill source and other slicks in the area. In the event of loss of radio contact with the burn supervisor during a burn, the lead tow boat should have authority to extinguish the burn if necessary.

Fire Control: Depending on the nature and magnitude of the proposed burn, a dedicated fire control vessel and team should be established. This team could provide backup support for the monitoring of safety measures and supply additional personnel, booms, igniters and supplies as needed. The fire control team could also assist with the use and maintenance of adequate fire-free zones (or fire breaks) between certain vessels or burning operations, between the spill source and the controlled burn, and between the burning operations and certain facilities or sensitive shorelines. An example of this is shown in Figure 6.1. The fire control group could also provide an additional level of protection should it be necessary to assist or relieve a vessel with engine trouble, to watch for other oil slicks in proximity to the burn, and to operate fire monitors or foam dispensers should they be needed.

Aerial Surveillance: Aerial support using airplanes or helicopters can be highly important in providing an ongoing update on the status of the spill source and the resultant oil slicks. As with mechanical containment and recovery operations, spotter aircraft can provide guidance for surface vessels involved with the location and removal of oil. Aerial observers can keep boom towing vessels apprised of their location relative to fresh, thick oil layers and they can ensure that burns are conducted to minimize interference with other response activities. The maintenance of an aerial surveillance program will also permit the early detection of any sudden shifts in wind direction (and resulting smoke plume trajectories), allowing for the warning of any downwind operations or population centers.

Traffic Control: Prior to and during all burning operations, the Incident Commander should ensure that all field activity is coordinated closely with the Federal Aviation Administration (FAA), local airports and the U.S. Coast Guard because burn activity can affect the movement of vessels and/or aircraft in the general vicinity. It is important that appropriate surface and air traffic control corridors be identified and maintained throughout the spill response.

Personnel Protection: The best form of protection that can be provided for all participants in controlled burning is to keep all vessels and aircraft within predesignated safe operating zones. The "Burn Plan" for each type of burn scenario should contain specific guidelines as to where boom-towing vessels, support vessels, and aircraft will be permitted to operate prior to, during and following the ignition and combustion phases of each burn. A properly conducted burn is one in which all personnel directly involved with the burn are located upwind of the oil to be ignited. In addition, longer-than-normal tow-line lengths should be used by the boats towing the fire containment booms. For example, even though 150 m tow lines were used along with a 137 m long fire containment boom during the burn conducted on the second day of the *Exxon Valdez* oil spill, personnel on the towing vessels could still feel the heat of the fire. However, even at the peak of intense burning (flames estimated to be greater than 60 m high), the radiated heat level was not uncomfortable.

Once ignited, the size and magnitude of the fire will dictate the extent to which personnel locations can be changed safely during a burn. Section 4.7 of Chapter 4 has shown theoretically that the safe approach distance is 3.5 pool diameters from the edge of the fire. The use of four fire diameters as the safe approach distance is recommended. This is quite conservative as it does not take into account the effects of clothing and wind cooling on the safe heat flux.

If personnel are exposed to bright sunlight in addition to fire radiation, the contribution of sunlight should be taken into account. Closer approaches can be made to the edge of the fire for short periods of time. The following table (also from Chapter 4) shows the calculated safe approach distance (measured in fire diameters) to in-situ burns for various exposure times.

Calculated Safe Approach Distances to In-Situ Oil Fire

Exposure Time (min)	Safe Approach Distance for Personnel (fire diameters)
infinite	4
1/2 hour	3
5 minutes	2

Radiant heat fluxes necessary to cause charring and ignition of wood would be experienced within one diameter of the center of the fire (0.5 diameters from the edge). Exposed, non-combustible materials such as vessel hulls can become very hot over time near a fire. Because the cooling characteristics of the materials cannot be accurately predicted, care should be taken regarding such surfaces that are exposed to the fire.

Once ignited, it should be easy for all personnel to see the flames and the smoke plume and to remain outside of their areas of influence. Personnel located on boats or aircraft that could conceivably be in close proximity to the burn or find themselves temporarily in the path of the smoke plume should be equipped with appropriate personal protective equipment. Such protection might include fire resistant outer garments, full-mask or half-mask respirators (with safety goggles) and filters designed to handle particulates as well as organic vapors.

6.6 Recovery of Burn Residue

The amount of unburned oil residue left on completion of a burn is a strong function of the type, nature and amount of oil involved in the burn. During static, contained burns of relatively fresh crude oil, the amount may be as little as 1% to 2% of the original oil volume, but generally is in the 5 to 10% range. In cases where the operation is a continuous process of burning oil as it floats into a containment barrier (e.g., downstream of a continuous leak), the percent remaining should be smaller than that from a static burn.

In some situations the burn may result in large quantities of original oil remaining unburned. If possible, this unburned oil should be reignited in subsequent burns as additional oil is collected within the fire containment booms. While the residue remaining after a burn does not have as much of the lighter volatiles as it started with, every effort should be made to collect the residue and store it for disposal at a later time. During experimental burns of lighter oils the residue has almost always remained buoyant and of a consistency that could be removed from the water easily with nets, snares and other such manual systems; the use of conventional skimmers on the residue from an efficient burn may not be advisable due to the extremely high viscosity and tackiness of the residue. In some burn situations, for example burning against a barrier in a high current, the viscosity and density of the remaining oil could increase to a point where it is entrained beneath the barrier. It is possible that as residue cools from its temperature beneath the fire to the temperature of the surrounding water it could become neutrally buoyant or sink and become unrecoverable.

6.7 Possible Mitigation Efforts

The following are brief descriptions of actions that could be taken to mitigate the effects of an in-situ burning operation or to improve its efficiency.

Burn and Plume Location: One of the most obvious ways to mitigate the potentially harmful influences of smoke products is to conduct the burn under favorable atmospheric circumstances. To the extent feasible, every effort should be made to ensure that the products of combustion are released during periods when the smoke plume is dispersed and transported over unpopulated areas.

Minimization of Burn Time: Because the oil elimination rate is directly proportional to the burn area, a controlled burning operation can be speeded up by increasing the area of the burn on the water. This is done by carefully slowing down the boats pulling fire containment boom in a U-configuration, thereby allowing the oil to spread forward within the boom. It is possible to expand the normal oil surface area (associated with a 0.9 to 1.3 km/hr or 1/2 to 3/4 knot towing speed) to an area that is up to two times larger. The burn time, therefore, is reduced by a factor of two. This may result in larger amounts of burn residue, but the savings in time could be important in freeing up equipment to access more of the spill within the "window of opportunity" for burning. It should be noted that increasing fire area will increase radiant heat fluxes.

Use of Ignition Enhancement Techniques: The efficiency of ignition and the time for flames to cover the entire slick will affect the overall time required to complete a particular in-situ burn operation. Improvements could be realized by including the use of floating wicking agents such as wood chips or hollow glass microspheres to provide enhanced insulation from the cooling effect of the underlying water and thus allow greater heating for

oils of low volatility. Other techniques might involve the use of promoters such as petroleum products or chemicals to increase flame temperatures or to assist flame spreading or the use of de-emulsifiers to help break water-in-oil emulsions.

Use of Smoke Reduction Chemicals: Ferrocene, discussed earlier in Chapter 5, is one of a number of organo-metallic additives that are available for reducing smoke emissions during the burning of petroleum. Applied either as a powder or in the form of a slurry, ferrocene can be added to a broad range of oils to reduce soot emissions by as much as 90%. Presently, the required amounts of such additives (ferrocene dose rates are typically a few percent by weight), their costs, and the complexities of applying them efficiently in the field would constrain their use on a large scale in an actual spill.

6.8 Operational “Checklist” for In-situ Burning

The following list is provided as a condensed “checklist” of critical conditions, concepts or pieces of equipment that should be considered prior to the initiation of an in-situ burn at sea.

Approval and Notification Considerations:

- Approval “checklist” completed and submitted to federal and state Regional Response Teams (RRT) and Federal On Scene Coordinators (FOSC).
- Any other burn plan or permit and approval requests completed and submitted to appropriate agencies.
- All approvals received from federal, state and local organizations
- Coast Guard notified regarding Notice To Mariners for proposed burn time and locations in which no unauthorized vessels would be allowed.
- FAA notified regarding Notice To Aviators for proposed burn time and locations in which no unauthorized aircraft would be allowed.
- Local public radio and television announcements of intent to burn, along with information on estimated times, duration of burn(s), potentially affected areas, possible health effects, and unauthorized zones for public use.
- State or local emergency services groups on standby for any possible assistance in notifying or evacuating certain populations.

Oil and Environmental Conditions:

- Oil type and condition -- sufficiently combustible (thickness, evaporation, emulsification) under existing weather conditions.

- Visibility -- suitable for vessels and aircraft in carrying out burn. Consideration given to number of daylight hours left to initiate burn.
- Wind and waves -- suitable for oil collection, ignition and sustained combustion. General wind, speed and direction, and atmospheric mixing (now and predicted) acceptable to initiate and sustain burn.

Location, Timing and Compatibility of Response:

- Proposed burn site(s) properly located with respect to population centers and other sensitive natural resources.
- Sufficient time available to mobilize response personnel, transport and deploy equipment, ignite and complete burn(s).
- Timing and conditions appropriate for consideration of night-time burn(s). Possibility of night-time oil collection with burns initiated at daybreak
- Burning operations safe and practical in light of spill status (ignited versus non-ignited, proximity to shore).
- Burning safe and practical in light of vessel traffic lanes.
- Burning safe and practical in light of spill source stabilization efforts.
- Burning safe and practical in light of any personnel evacuation efforts.
- Burning compatible with mechanical cleanup operations.
- Burning compatible with dispersant application techniques
- Burning compatible with shoreline protection & cleanup activities.

Personnel Requirements:

- All personnel trained and qualified for burning operations.
- All personnel briefed and familiar with burn plan.
- Full response team(s) and supervisor(s) for vessels on location or enroute.
- Pilot and support personnel for aerial support functions on location or enroute (e.g., reconnaissance, Heli-torch operations).
- Backup Fire Control Team on location or enroute.

- Everyone has protective clothing, respirators, personal flotation devices, etc.

Vessel Requirements:

- Two fire containment booms towing vessels available for each U-configuration.
- One fire control vessel available for each burn region. More than one vessel possibly needed should individual burns be widely separated.
- Backup support vessel(s) as needed for personnel transport; refuelling operations; recovery and storage of burn residue; transport, deployment and recovery of fire containment booms, boom towing vessels.

Aircraft Requirements:

- Helicopter(s) as appropriate for number of burns anticipated, modes of ignition to be employed, and distances to be covered from staging area(s) to assigned region(s) of coverage.
- Fixed-wing aircraft as appropriate to supplement helicopter operations involving oil reconnaissance missions, direction of vessels to collection sites, monitoring of smoke plume trajectories, etc.

Fire containment booms and Igniter Requirements:

- Inspected and ready-to-deploy fire containment boom (typically 160 m to 320 m per U-configuration), along with long tow lines (typically 160 m to 250 m per tow vessel), towing bridles, and anchoring systems as appropriate.
- Backup fire containment boom (160 m to 320 m per U-configuration), along with additional lengths of boom for any alternate modes of deployment (e.g., containment at spill source, deflection booming into designated nearshore burn sites, exclusion booming).
- Inspected and ready-to-deploy Heli-torch(es) as needed for any aerial ignition activities (backup drums available for rapid turn-around).
- Batch mixers for gelling large quantities of fuel mix for Heli-torch(es) if necessary (backup fuel supplies such as gasoline, diesel or crude oil, and gelling mix).
- Supply of hand-held igniters (at least 10 per vessel and helicopter) for potential use (backup supply of at least 200 igniters or a means of acquiring or constructing additional units on short notice).

Communications Requirements:

- Dedicated radio links (and equipment) with specific frequencies for air-to-air and air-to-surface communications.
- Dedicated radio links (and equipment) with specific frequencies for vessel-to-vessel and vessel-to-command communications.
- Repeater stations as appropriate for distant or blocked communication paths.

Fire Safety Considerations:

- Possible use of dedicated personnel and vessels with vapor emission monitoring equipment (explosimeter)
- Backup fire fighting vessels, if necessary, for unique situations involving a burning spill source and/or unusual potential exposures of personnel/vessels to burning oil.
- Small fire fighting packages (extinguishers, monitors, foam, etc.) aboard the boom towing boats for backup use in the event of an emergency on or near one of the response vessels.
- An explosimeter on each vessel involved in burning operations.

7.0 Review of Environmental and Human-Health Effects

7.1 Introduction

The objective of this chapter is to summarize the documented ecological and human health effects of combustion products and residues from the burning of marine oil spills. The information is used in the risk analysis that follows (Chapter 8) to identify the advantages and drawbacks of burning spilled oil.

Any hesitancy that exists surrounding the use of in-situ burning as a spill countermeasure is due, in part, to the concern over potential adverse effects on people or the environment, or that not enough information is known about the consequences of burning. This chapter summarizes the existing knowledge concerning the fate and effects of burning oil and identifies important gaps in our knowledge base. The risks of effects from burning are determined by the composition of the burn products and their environmental fates and effects. In this chapter: Section 7.3 deals with composition and fate of burn products and residues; Section 7.4, environmental effects; and Section 7.5, human health effects.

7.2 Methodology

7.2.1 Technical Subjects

Understanding the environmental and human health effects of in-situ burning of oil spills on water was approached from the following perspectives:

- effects of the combustion itself on the environment,
- fate and effects of burn residues and products in the aquatic environment, both at the water surface and in the water column,
- fate and effects of the burn residue and products that may settle through the water column,
- fate and effects of the smoke or emissions plumes on air quality, and
- ultimate fate and effects of airborne particles.

7.2.2 Information Sources

A review was undertaken of literature and documentation of in-situ burning of oil spills. Cases considered included mesoscale and laboratory experiments, and actual spills where burning was used as a response tool or when accidental or incidental burning of oil occurred (e.g., well blowouts, the Kuwait fires). A systematic search of published literature was done using commercially-available databases (Table 7.1). The bibliography resulting from the literature search is provided at the end of the chapter. The search extended to the

databases shown in Table 7.1 but was restricted to materials published since 1982.

Table 7.1 Abstract Databases Searched for In-Situ Burning of Oil

POLTOX Abstracts
Life Sciences
Selected Water Resources Abstracts
Aquatic Sciences and Fisheries Abstracts
ENVIRO/ENERGYLINE Abstracts
Applied Science and Technology Index
NTIS Abstracts

Although the literature search identified numerous publications with themes related to burning of oil, the number of publications that specifically document the potential risks of in-situ burning to human health and ecology are quite limited and mostly pertain to small experimental burns. Some studies that address the effects of the Kuwait burning oil fields offer knowledge of very large-scale burns of crude oil (Bakan *et al.* 1991, Browning *et al.* 1991, Ferek *et al.* 1992, Laursen *et al.* 1992, Sharratt and Butler 1992) but the information is of limited use here because the Kuwait oilfield fires differ from what may be expected from on-water fires. For example, the Kuwaiti blowout fires produced much less smoke than would be expected from on-water burns (partly because the oil was discharged into the air in atomized form and thus was efficiently burned). Other publications identified during literature searches but not included in this study are those addressing the effects of combustion of hydrocarbons (gasolines, diesels, oils) from vehicles and power plants. These articles generally describe studies related to the effects on air quality and water quality (mostly through stormwater runoff).

Substantial literature is available on both experimental burns and burns at actual accidents. Over forty burns form our basis of understanding of this spill countermeasures technique. Table 3.1 in Chapter 3 presents a synopsis of these burns. A number of actual spill cases involved accidental burning, but only nine are identified in which purposeful burning of oil on water was used as an experimental procedure. The most detailed information on the processes and chemistry of in-situ burning and on the fate of burn products comes from laboratory and mesoscale experiments, including studies conducted by Environment Canada and the U.S. National Institute of Standards and Technology's (NIST) Center for Fire Research (see for example Fingas and Laroche 1990 and Evans *et al.* 1991, 1992).

Unfortunately, very few studies have documented the ecological or human health effects or hazards of oil spill burning. There is literature on accidental burns of inland spills involving refined oil products such as gasoline or diesel from tanker trucks or railroad cars, and literature on accidental marine spill burns involving crude oil discharges; in neither case can one find documentation on the environmental or human-health effects of the burning oil.

In summary, the literature is very limited regarding studies on the environmental and human health aspects of in-situ burning, and what is available is mostly associated with in-situ burning experiments involving small amounts of oil.

7.3 Behavior and Fate of Combustion Products and Residue

The risks posed to ecological resources and to human health from burning oil on water are directly related to the composition, behavior, and fate of the burn products. This section reviews the state of knowledge concerning these subjects. The effects of spill burning are discussed in a later section (Section 7.4).

In-situ burning of oil spills on water results in burn products reaching the air, water, seabed sediments, and land (Figure 7.1). The most obvious effect of burning is to transfer the burn components to the atmosphere, with contaminants largely converted from a liquid to an airborne plume of burn emissions composed of burn gases and particulates (soot). The soot in the atmosphere will eventually settle in the aquatic environment or on soils. The burn residue remaining on the sea surface can remain on the water for some time or can ultimately reach the seabed or shorelines. The fate of combustion products and burn residue in these three environmental sectors (water, air, and sediments) is discussed below.

7.3.1 Water or the Aquatic System

Burning oil slicks on the sea changes the fate and potential effects of the spill on the aquatic environment in several ways, including the following:

1. burning reduces the total volume of the slick dramatically and quickly may reduce the overall impact of the slick proportionately;
2. the oil remaining after the fire (residue) may differ in composition from the parent oil; and
3. the fire itself may indirectly affect the water-column by altering the dissolution, dispersion or sinking of the slick.

As discussed in an earlier chapter (Section 4.4) the efficiency with which burning removes oil is strongly influenced by slick thickness. Slicks that have been thickened by booming may be burned with 90% to 99% efficiency depending on the composition of the oil and state of emulsification. Uncontained slicks which are thinner burn less efficiently. In one study, S.L. Ross and Energetex Engineering (1986) achieved from 20 to 70% efficiency in burning small uncontained oil slicks.

Mesoscale experiments have indicated that the chemical composition of the residue remaining after a burn can differ substantially from the parent oil. One difference is that the burn residue is depleted in short-chain alkanes and cycloalkanes relative to the parent oil (Evans *et al.* 1986). A comparison of concentrations of dioxin/furan and volatile organic compounds (VOCs) from the original oil to the burn residue show a reduction in these toxic components. Some of this reduction can be attributed to evaporation. Both lower and higher molecular weight polynuclear aromatic hydrocarbons (PAHs) have been shown to be reduced in the burn residue relative to the parent oil (Evans *et al.* 1988, Li *et al.* 1992)¹. On the other hand, the latter authors found that some metals were enriched in the burn residues by

¹ The issue of PAHs is presented in great detail in the next chapter.

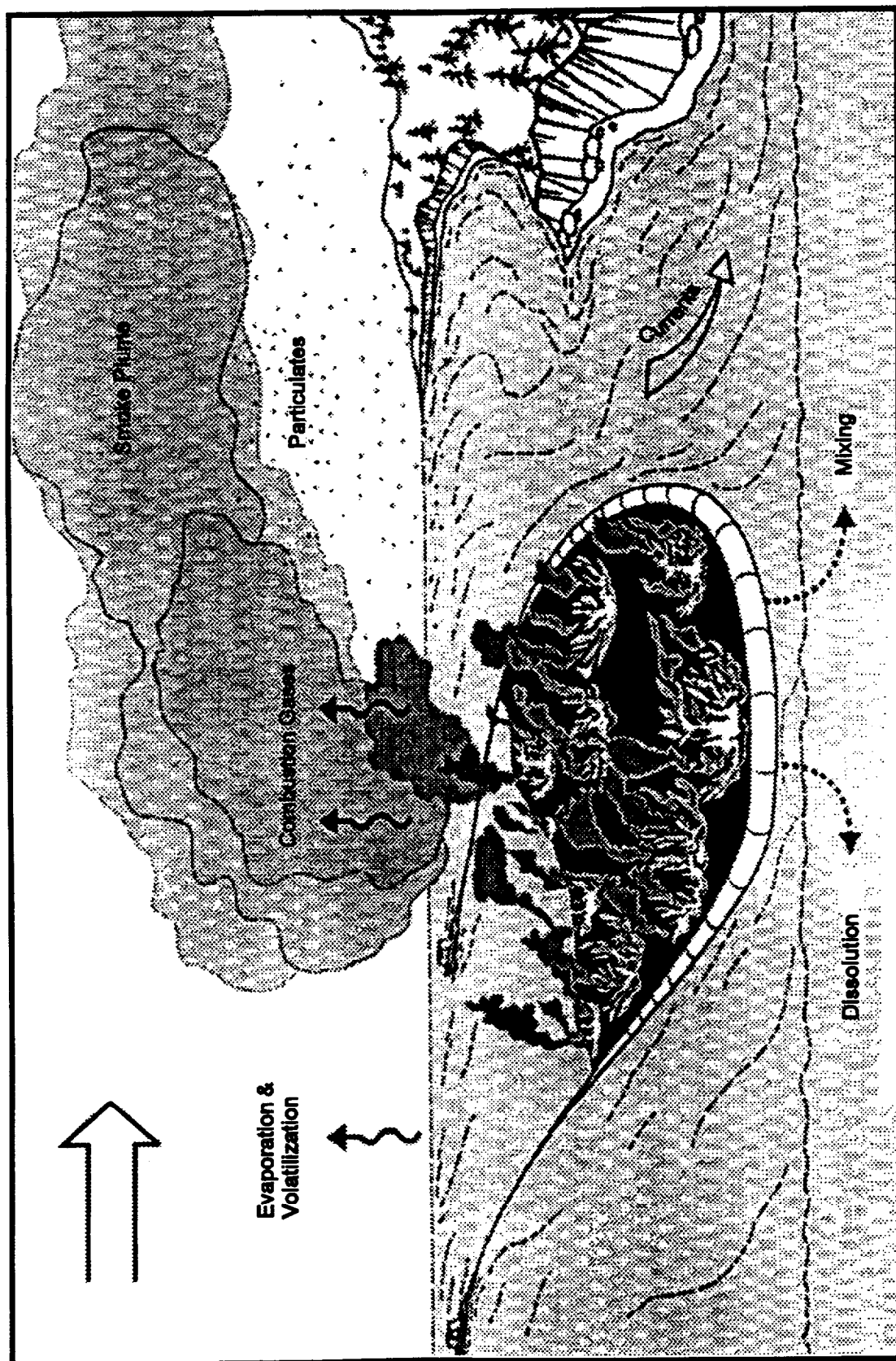


Figure 7.1 Aspects of burning oil on water and pathways for spill and burn products into the environment

a factor of 2 to 4. It is difficult to draw conclusions from this because the concentrations of metals in this study only barely exceeded the level of detection of the analytical method used.

Another consideration in the fate of the burn residue is its specific gravity, which determines whether the residue will float or sink into the water column. The notion that specific gravity might be important was raised by the report that during the *Haven* tanker spill in 1991 burning of the heavy Iranian crude resulted in some of the heavy, tarry residue sinking to the sea floor (Moller 1992, Turbini *et al.* 1993). A similar case of oil sinking from burning was reported for the burn of Arabian heavy crude following the *Honam Jade* spill (Moller 1992). To date, however, there is little systematically gathered information concerning the composition and properties of burn residue or the environmental fate and effects of its constituents.

No studies to date have addressed the effects of burning on the dissolution, dispersion or sinking of spilled oil into the water column. In an ordinary oil spill some dissolution of hydrocarbons takes place generating measurable contamination in the upper meter of the water column. It is not clear whether burning would significantly modify the dissolution process. Analysis of water collected from below a mesoscale burn revealed no detectable PAHs, while BTEX (benzene-toluene-ethylbenzene-xylene) and TPH (total petroleum hydrocarbons) were found at concentrations of 1 ppm or less (Fingas *et al.* 1993). This suggests that burning does not increase the rate of dispersion of oil from slicks into the water column. One known effect of burning on this pathway is that burning quickly reduces the volume of oil exposed to the water column, and the length of time that fresh oil is exposed to the water. This should greatly reduce the overall amount of contaminants into the water column (Allen and Ferek, 1993).

The available data concerning heat transfer from the burn to the water column suggest that although some heat transfer occurs, the effect on water temperature is minor. In an experimental burn in a 1.13 m² pan, the temperature of the water immediately beneath the burning oil was raised from 10°C to 60°C during the short burn (Evans *et al.* 1988). Measurements of temperature change in a series of mesoscale experiments showed that during the burn tests the water temperature in the upper 35 mm of the water column increased by 5 to 40°C; at depths of 70-115 mm, temperatures increased by 1 to 4°C; and at a depth of 145 mm temperatures increased by 2°C or less (Walton *et al.* 1993). These results suggest that while some heat is transferred from the fire to the water-column, the amount of heat transferred is minor and would be of no consequence in burns on the open sea.

In summary, in-situ burning of spilled oil has at least three major effects on the fate of the oil that might have significant environmental consequences in the aquatic environment. The first and most important effect is that burning rapidly reduces the volume of oil on the sea surface; in some cases this reduction can be up to 90 to 99% in contained burns. The second effect is that the chemical composition and properties of the residue may be altered somewhat with certain constituents being depleted (e.g., VOCs, PAHs, dioxins) and others, including perhaps metals, being enriched. The specific gravity of the residue may be sufficiently increased due to compositional changes to cause some of the residue to sink through the water column to the seabed. Finally, available data suggest that the heat transfer from the fire to underlying water is and should not be a significant concern.

7.3.2 Air

Burning of oil slicks produces plumes of airborne emissions made up of gases and particulate matter (soot). The composition, fate and behavior of this smoke plume and its constituents are important because these airborne emissions may have adverse effects on humans or other organisms some distance away from the site of the burn.

The most abundant components of the smoke plume are the gases including CO₂, water vapors, CO and SO₂ and the particulate materials which are mostly unburned carbon particles (Table 7.2). Other materials such as NO_x, volatile organic carbons (VOCs) and polynuclear aromatic hydrocarbons are present in small quantities in the smoke (see Section 8.3 below).

Table 7.2 Major Constituents of Airborne Emission Plume (from Fraser 1991)

Component	Mass per kg of oil burned
Carbon dioxide	2.7 kg
Water	1.2 kg
Particulates	0.1 kg
Carbon monoxide	0.07 kg
Sulfur dioxide	0.02 kg

The amount of smoke, particulates and soot, will vary depending on the type of oil burned, the state of emulsification, and the thickness of the slick. In several well-documented experimental burns of crude oil, between 6 and 15% of the oil was converted to smoke (Evans *et al.* 1992)².

Smoke particles from a burn typically are an agglomeration of carbon spherules. These spherules are relatively uniform in size and have an average diameter of 0.06 µm (Evans *et al.* 1992). The median size of smoke particles measured in burns is less than 1 µm (Figure 7.2). Concentrations of particulate matter within smoke plumes generated from in-situ burns are greatest near the burn site and decrease exponentially with distance downwind (Fingas *et al.* 1993, Walton *et al.* 1993). Particulate concentrations measured in the plumes in the 1992 NIST mesoscale burn tests³ were approximately 30 to 40 mg/m³ within 100 to 200 m downwind and less than 2 mg/m³ at 500 m downwind (Fingas *et al.* 1993, Walton *et al.* 1993). The decline in the concentration of particles in the plume is due to diffusion or scattering of the cloud and settling out of the particles from the plume. The rate at which such particles settle out of the air column is a function of wind speed, air density stratification, soot size and shape, and secondary transport vectors such as precipitation (rain,

² The Kuwait oil fires of 1991 produced smoke yields that were much less, about 2 percent of the fuel burned (Ferek *et al.* 1992, Laursen *et al.* 1992). This greater efficiency of burning was likely due to the nature of the land-based blowouts: the oil was discharged from a point source in the form of small droplets; this initial condition is far more amenable to efficient combustion than thick layers of oil on a surface.

³ Tests involved burning pools of 2000 to 5000 bbl of Louisiana crude oil in a square pan measuring 51' x 51'.

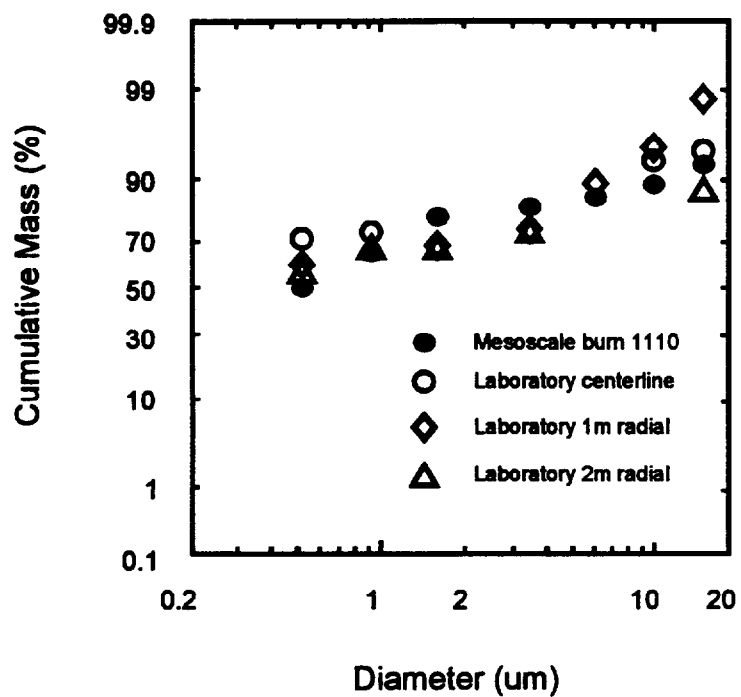


Figure 7.2

Smoke Particulate Cumulative Size Distribution for a 1992 Mesoscale Burn and Laboratory Burn (from Walton et al., 1993)

snow, fog). As expected, models of particulate fallout from point source burns suggest an exponential decrease in the concentration of fallout with increased distance from the source (Figure 7.3).

Another aspect of the impact of burning oil on air quality is the effect of burn gases. The principal combustion gases are CO_2 , CO, NO_x , and SO_2 . Other gas emissions include light, volatile organic compounds that naturally evaporate from the oil slick or might be generated by the burn. Carbon dioxide (CO_2) makes up by far the largest proportion of the burn gases. Measurements of CO_2 , CO, and SO_2 were made at three locations in the smoke plume downwind from burns (33 m, 45 m, 76 m) during the 1992 mesoscale experiments at NIST (Fingas *et al.* 1993). The CO_2 concentrations varied considerably with space and time. The greatest concentration of CO_2 in mid-plume was 927 ppm which occurred at 33 m from the fire. Peak concentrations at ground level were 651 ppm at 33 m downwind of the burn. Average CO_2 concentrations at stations 33 and 45 m downwind of the burn ranged from 340-360 ppm, which is equivalent to background levels of CO_2 (Fingas *et al.* 1993, Walton *et al.* 1993).

Measurements of CO and SO_2 were made, as with CO_2 , at three downwind locations in the smoke plume. CO and SO_2 measurements were most commonly at background levels except for occasional slightly elevated readings. SO_2 readings only slightly exceeded background at the sampling station nearest to the burn (33 m).

Polycyclic aromatic hydrocarbons (PAHs) such as anthracene and benzopyrenes, that are associated with burning oil, have been a major concern from the perspective of air quality and hazards to human and ecological resources. Polycyclic aromatic hydrocarbons are aromatic compounds that contain two or more fused aromatic rings (e.g., naphthalene, benzopyrene). Smoke from oil fires can be expected to contain some PAHs due to the fact that all crude oils contain up to 1% PAHs. Some experimental work has suggested that in-situ burning of oil on water results in a decrease in the overall mass balance of all PAHs (Benner *et al.* 1991). The latter did demonstrate, however, that concentrations of PAHs composed of five or more rings were enriched 10 or 20 times in smoke particles, and the heavier PAHs were enriched by four to five times in terms of overall mass balance (Benner *et al.* 1991). The subject of PAHs is discussed more fully in the next chapter.

7.3.3 Sediments and Soils

Sediments and soils may be contaminated with either the fallout from the smoke plume or the residue remaining following the burn. Smoke particles will eventually settle out of the smoke, on land or water. In the latter case the particles might sink through the water column and become incorporated into seabed sediments. No literature was found on the ultimate fate of fallout material in either land or water environments. Because particulate fallout from point-source burns are expected to decrease exponentially with distance from the source (Figure 7.3), the concentrations of particles settling at any distance from the burn site in either case would be very low.

On the other hand, the burn residue will either stay on the sea surface, be swept onto shorelines or sink to the seabed. In any case, the fate and effects of the residue should be similar to those of naturally weathered oil except that there would be far less burn residue than there would be weathered oil. The case histories involving sinking of burn residue indicate that this aspect of the fate and effects requires further research (Moller 1992).

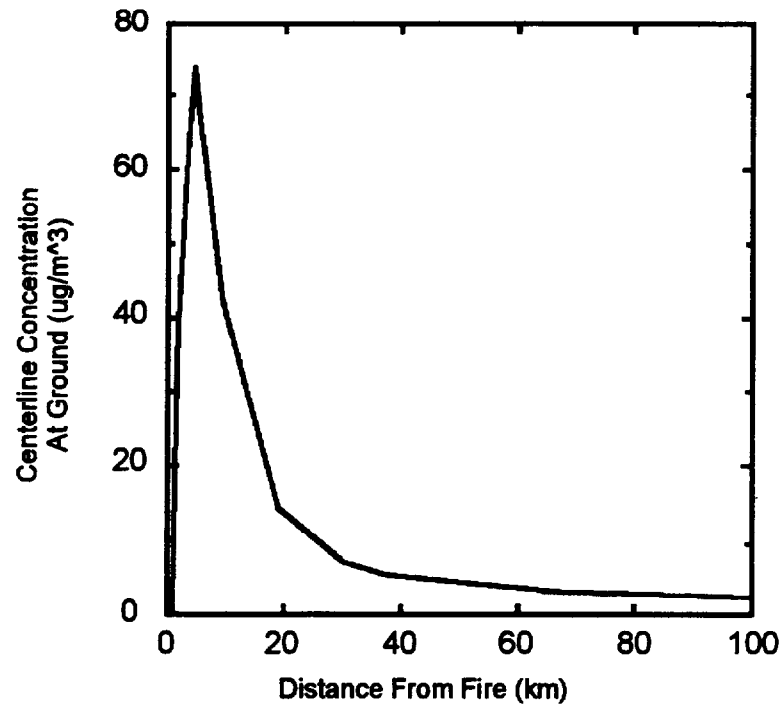


Figure 7.3 Screen Model Prediction of Ground Level Average Smoke Particulate Concentration Over One Hour for a Smoke Particulate Emission Rate of 0.5 kg/s and a Wind Speed of 6 m/s (from Evans et al., 1992)

7.4 Environmental Effects of In-situ Burning

The following sections identify the known or reasonably expected environmental impacts of in-situ burning of oil. The environmental effects identified in this review are those resulting from physical impacts of the fire, toxic effects of burn products and residue, and general environmental impacts from spill response and burn activities.

7.4.1 Effects of Fire and Heat

Potential effects of the combustion itself include burning of resources and possible damage resulting from heat. Allen (1990) found that while burning oil during the *Exxon Valdez* incident, heat could be felt to about 200 m of the site, but no other effects were reported. The effects of heat on the water column have been studied in several experiments. During burning, the surface of crude oil maintains a temperature of about 300°C. As the fuel is consumed, heat transfer through the oil to the water below can result in warming of the surface layer of water. In large bodies of water where circulation is possible, thermal effects on the water column will be negligible. Direct thermal effects on the water column would be limited to the surface microlayer within the immediate vicinity of the burn. Although this layer may contain eggs and larvae of many fish species, the relatively confined area of a burn will be very small and hence the possible net impact on fish populations will certainly be negligible.

7.4.2 Effects of Combustion Products and Residue

Case histories contain little definitive information concerning the ecological effects of combustion products and burn residue. Particulate matter will precipitate out of the smoke plume. The amount of fallout and its impact will depend on the amount of oil burned, efficiency of the burn, prevailing wind speed and direction, and proximity to sensitive areas (Mitchell and Janssen 1991). Results from an experimental burn of 4000 gallons (15,000 L) of South Louisiana crude in Mobile Bay showed that most particulate deposition occurred within 0.5 km downwind of the burn (Fraser 1991). No reports of ecological effects of particulate fallout in water or on land were encountered in the literature search.

Sheppard *et al.* (1983) tested the effects of burn products and parent oils for mutagenicity on bacteria. Prudhoe Bay crude oil and burn products were tested for mutagenicity utilizing strain ta98 in the Ames Salmonella typhimurium/liver microsome test. Samples of both oil and burn products showed some mutagenicity, with most activity being related to a specific fraction separated from the samples using thin layer chromatography. This fraction, described as the most polar fraction of oil, probably contained most of the PAHs. This polar fraction isolated from precipitated smoke particles displayed the greatest mutagenic activity, followed by polar fraction from burn residues, weathered oil, and fresh crude. The compounds responsible for the mutagenicity activity were not identified. Sharratt and Butler (1992) noted that though solvent extracts of the smoke revealed mutagenicity, it is impossible to interpret these results in terms of human health hazards. Bioassay tests planned for samples from the Newfoundland Offshore Burning Experiment (NOBE) should provide new and necessary information with respect to the environmental hazards of in-situ burning.

Burn residue that remains on the water could affect ecological resources at the water surface or on the seabed should the residue sink. The heavier, more viscous residue that remains after a burn represents only a small volume of the original oil and therefore poses much less of a hazard than the original oil. Burn residue that sinks can reach resources that are not threatened by floating oil. Moller (1992) reported that much of the residue remaining after the accidental burn aboard the *Haven* settled to the seafloor. This precipitated residue could impact organisms that inhabit or feed off of the bottom. Moller provided an example of such an impact in the case of the *Honam Jade* burn off South Korea in which sinking burn residue affected crab cultivation pens.

7.4.3 Other Environmental Effects

Environmental effects of in-situ burning may also include those associated with the countermeasure operation itself. Traffic and noise disturbance associated with the burning operation may disturb nesting birds or mammals. However, these same effects could be expected from conventional spill response measures and may in fact aid in hazing tactics needed to keep wildlife from coming into direct contact with the oil.

In a very large spill, the production of a smoke cloud could arguably affect atmospheric temperature and weather patterns. Models of atmospheric effects of the smoke from the Kuwait fires predicted a potential delay of the onset of the monsoon in 1991 (Rao *et al.*, 1991); however, even this tremendous input of soot into the atmosphere, could not be linked to actual changes in regional weather patterns (Bakan *et al.*, 1991). These fires, however, did cause localized reductions in visibility and surface temperatures while smoke plumes prevailed (Cofer *et al.*, 1992).

7.5 Human Hazards and Health Effects

Human health and safety concerns surrounding in-situ burning fall into four categories:

1. physical hazards to cleanup workers and nearby residents;
2. hazards related to ingestion of residues or burn products (eating or drinking);
3. hazards from the inhalation of airborne burn products; and
4. hazards from dermal contact with burn products.

The following review discusses the effects of in-situ burning on human health under each of these four categories.

7.5.1 Physical Hazards

Physical risks to workers and the general public related to in-situ burning are those arising from explosions, heat, or loss of control of burning oil (including flashback to the spill source and loss of containment of boomed burns). These hazards affect spill response workers

more than the general public. Securing the spill site will further reduce potential hazards to the public. No documented injuries from use of in-situ burning as a countermeasure have been recorded, but flames and intense heat are obviously a serious potential threat to the health and safety to anyone near the burn. Case studies of actual burns reveal that spill response workers must be properly supervised and trained to avoid serious injuries in burning situations (Robertson, 1991).

7.5.2 Air Quality and Inhalation

One major concern with in-situ burning is the potential for acute or longer-term effects of the smoke inhalation on human health. Airborne burn products that may affect human health include smoke particles, carbon monoxide, sulfur dioxide, PAHs, VOCs and metals. Exposure to these burn products will depend on the proximity of people to the burn, the volume of oil burned, the efficiency of the burn, wind direction and speed, and atmospheric stability. Weather may also be a factor since rain and snow will influence the fate of burn emissions. Risks from each of the significant burn emission products are discussed below.

No studies were found in the literature search that directly document the effects of in-situ burning of marine oil spills on human health. A number of studies involving research on vehicle and power plant emissions have provided information on effects of burn products on human health and much of the following is based on these studies. The burn products include CO, NO_x and SO₂ and particulates. Human health criteria and air quality standards established by Federal and State agencies identify the exposure limits of certain chemicals and particulates that, if exceeded, pose a threat to human health. Air quality criteria for U.S. maritime and Great Lakes coastal states are provided in Table 7.3.

Particulates less than 10 µm in diameter (PM10) pose the greatest concern from a respiratory point of view. For PM10s the 24-hour exposure standard is 150 µg/m³ (Table 7.3). In the mesoscale tests run in Mobile, Alabama in 1991 and 1992⁴, the peak concentration of particles commonly measured 10,000 to 30,000 µg/m³ and 4000 to 10,000 µg/m³ at ground level stations at 33 m and 66 m respectively, downwind of the fires. These values greatly exceed the 24-hour standard. On the other hand, the average concentrations at these stations ranged from 40 to 2690 (mean = 750) µg/m³ and 10 to 1500 (mean = 249) µg/m³ (Fingas *et al.* 1993). These however, are small fires compared to the 1000 barrel parcels of oil likely to be burned during actual spill operations. To better understand risks in actual spill conditions, burning of 1000 barrel parcels of crude oil was simulated using the SCREEN 2 model (see Appendix B below). The model output in Table B.3 suggests that under worst-case environmental conditions particulate carbon concentrations would exceed the 150 µg/m³ standard no further than 5 km from the burn site.

Concentrations of CO measured at ground level and in smoke plumes during the above mesoscale burns were consistently near background values (Fingas *et al.* 1993). On the other hand, concentrations of SO₂ within the smoke plume near the burn site reached levels of 4.4 to 14.2 ppm, which exceed all air quality standards. However, average SO₂ concentrations downwind fell below critical threshold values (Table 7.3) within 100 m of burn sites in these

⁴ Burns involved 2000 to 5000 gallons of Louisiana crude burned in 51' x 51' pans.

**Table 7.3 COMPARISON OF CRITERIA POLLUTANT AMBIENT STANDARDS
(NATIONAL AND SELECTED MARITIME STATES)**

Pollutant	Avg Pd	units	Ambient Standards		STATES									
			NATIONAL											
			primary	secondary	WA	OR	CA	ME	NJ *	NY	HI	GROUP 1**	GROUP 2***	
PM10	annual	µg/m3	50		50	50	30	40	50			50	50	
	150	24-hour	µg/m3	150	150	150	50	150	150	150			150	
TSP	annual	µg/m3	75	60	60	60			60	((1))		60	60	
	24-hour	µg/m3	260	150	150	150			150	250		150	150	
CO	8-hour	ppm	9		9	9	9.0	9	9	9	9	9	9	
	1-hour	ppm	35		35	35	20	35	35	35	35	35	35	
NOx	annual	ppm	0.05		0.05	0.053		0.05	0.05	0.05	0.04	0.05	0.05	
	1-hour	ppm					0.25							
SO2	annual	ppm	0.03		0.02	0.02		0.02	0.03	0.03	0.03	0.03	0.03	
	24-hour	ppm	0.14		0.1	0.1	0.05	0.09	0.14	0.14	0.14	0.14	0.14	
	3-hour	ppm		0.50		0.5		0.44	0.5	0.5	0.5	0.5	0.5	
	1-hour	ppm			0.40		0.25							
	1-hour ****	ppm			0.25									
Ozone	1-hour	ppm	0.12		0.12	0.12	0.09	0.08	0.08	0.08	0.05	0.12	0.12	

NOTES:

* Secondary standards for SO2: 0.02 ppm (annual), 0.10 ppm (24-hour); Ozone: 0.12 ppm (1-hour) can be exceeded only twice a year

** Group 1: CT, NH, PA, OH, IN, IL, MN, VA, DE, GA, AL, MS, TX

*** Group 2: RI, MA, WI, NC, FL, LA

**** not to be exceeded more than twice in seven days

((1)) Annual TSP Standard depends on land use as follows:

45 µg/m3 in rural areas

55 µg/m3 in residential areas

65 µg/m3 in urban areas (non-industrial)

75 µg/m3 in industrial areas

tests.

The Kuwait oil fires of 1991 provided an opportunity to study the transport and effects of burn products on a large scale. Studies performed during May and June 1991 indicated that the fires consumed approximately 4.6 million barrels of oil per day ($0.73 \times 10^6 \text{ m}^3/\text{d}$) in the Greater Burgan field alone (Ferek *et al.* 1992). Workers estimated that approximately 2% of the mass of fuel burned resulted in particulate matter in smoke (Ferek *et al.* 1992, Laursen *et al.* 1992). PAHs and heavy metals were in low concentrations in smoke samples taken from populated areas or from oil fields (Campagna and Humphrey 1992).

The lighter hydrocarbons in spilled oil pose a health threat regardless of whether the spill is burned or not. Exposure to these hydrocarbons by inhalation poses the greatest risk because the absorption of hydrocarbons through the lungs generally is highly efficient. Following the *Amoco Cadiz* spill which reportedly released about 40,000 tonnes of light hydrocarbon crude into the atmosphere, workers and coastal inhabitants reported symptoms of acute petroleum vapor toxicity, including headaches, dizziness, nausea, sensations of inebriation, vomiting, and abdominal pain (Menez *et al.* 1978, Dowty *et al.* 1981). Burning of such spills would reduce the exposure of workers and coastal inhabitants to the fumes of evaporating oil, but only at the risk of exposing them to the products of combustion.

Some PAHs in burn products have been identified as having carcinogenic potential (Grimmer *et al.* 1991). The concentrations of these chemicals will vary depending on environmental conditions during the burn. The potential risk from these compounds is described in the next chapter.

Despite the apparent potential risks, no reports have been found in our literature search of injuries or health effects from smoke or fallout despite the numerous oil fires resulting from tank car fires, accidental oil tanker burns, or burning oilwell blowouts. As might be expected, any effects on human health have been acute, such as death due to explosions or asphyxiation resulting from smoke inhalation by personnel present during the accident. Ship fires, such as the *Haven* and *Aegean Sea*, which have occurred within a kilometer or two of populated areas have not resulted in any known impact. In the latter case, smoke from the fire was carried directly over the city of LaCoruña requiring officials to evacuate nearly 100 homes near the harbor. Despite the proximity, no acute affects were reported. Similarly, intentional burns of oil on marshes, which is a common practice in Texas and Louisiana, have resulted in no known impacts to human health.

In summary, burning of oil reduces the length of time that fumes from evaporating oil may pose a threat to spill workers or the public, but chemicals in the burn emission may affect health. Potentially harmful burn products include particulate carbon, PAHs, VOCs, NO_x , and SO_2 . The concentrations of these pollutant chemicals will vary depending on environmental conditions during the burn, and as such can be more accurately predicted at the time of the burn for local conditions. Data from mesoscale burns and computer simulations suggest that potentially hazardous exposure conditions may exist near the burn site during the period of the burn. A more detailed consideration of risk will be undertaken in the following chapter (Chapter 8).

7.5.3 Water Column and Ingestion

This section deals with the risks posed by burn residue to marine organisms and to humans that may be exposed by direct ingestion of whole residue or by ingesting contaminated food. As pointed out above the burn residue poses some risk of contamination

and toxicity to marine organisms and it also poses a risk of contamination to the human population via contaminated water and food vectors. Burning greatly reduces the length of time that fresh oil is in contact with the water column and therefore may greatly reduce the total amount of hydrocarbons that enter the water column and reduces the overall exposure of marine species. Equally important, the residue that remains after the burn is similar in composition to heavily weathered oil, but there may be much less of it remaining after a burn than after several days of normal weathering.

Humans may be at some risk from ingesting hydrocarbons from burn residue during a spill, but the health risks generally are less than risks from physical hazards of the fire. Spill workers may suffer acute exposure by consuming small quantities of hydrocarbons by consuming water containing traces of oil, eating contaminated seafood, or by consuming food without completely decontaminating hands or clothing. The general population can be chronically exposed to low levels of hydrocarbons, from drinking water or eating seafoods, if residual oil remains in the environment following cleanup.

Our literature search failed to identify any information concerning the toxicity of ingested burn residue. Fresh and weathered crude oils are known to be toxic to wildlife when ingested, but it is not completely clear to what degree burn residues differ in their chemical composition (hence toxicity) from fresh or weathered crudes. Pure petroleum distillates (refined products) can be acutely toxic to humans in even small quantities, affecting the lungs, gastrointestinal tract, liver kidneys, central nervous system and hematopoietic systems. Vomiting may result from oil ingestion, but in most cases the symptoms disappear within 48 hours (World Health Organization 1982).

Ingestion of oil as a result of a spill is an unlikely event, for both spill workers or the population at large. In addition the small quantities of hydrocarbons may be ingested (eaten or drunk) during a spill have generally not produced significant effects in the past. Hence, the risk of adverse affects in humans via this vector appear to be limited.

In summary, documented cases of hydrocarbon-related health problems arising from ingestion of spilled oil are rare, and there are none that describe effects associated with burn residue. A review of case histories of hydrocarbon exposures research through TOXNET and MEDLINE, two medical databases of case histories and effects of specific compounds, revealed no cases of health problems associated with chronic ingestion from spilled oil. Most cases related to hydrocarbon ingestion were those arising from accidental ingestion of gasoline (siphoning) or of unlabelled liquids, or from intentional intake. Closure of water intakes, fishing grounds, and shellfish collection areas directly exposed to oil from a spill provide the greatest safeguards against accidental ingestion of oil. Furthermore, most people will avoid inadvertent consumption because the petroleum odor associated with tainted seafood or affected water is sufficient to alert them to a problem.

7.5.4 Dermal Contact

Acute dermal exposure of humans to fresh crude oil and refined products can result in dermatitis and skin injury. Politzer *et al.* (1985) reported specific information about dermal effects of a number of petroleum products. Effects in animals generally include sporadic diarrhea and dermal irritation; few systemic effects have been reported. Primary dermal irritation is greatest for middle distillates and kerosene, which elicited blanching, subcutaneous hemorrhage, and fissuring. Workers with direct contact to oil during the *Amoco Cadiz* oil spill reported skin irritation and erythema on hands and limbs, although no systemic

effects were found from examination of blood.

Direct contact of smoke and burn residue with skin is not expected to be a hazard to health. Smoke particulates may contact the skin as they precipitate; however, people in populated areas are exposed daily to combustion products from car emissions, with no apparent injury. Dermal contact with the burn residue on water is a hazard mainly to cleanup workers; however, these individuals should be equipped with appropriate protective clothing and should be trained in procedures for the safe handling of oil and oily waste.

7.5.5 Other Effects and Impacts

Other potential effects of an in-situ burn include impacts on visibility, aesthetic values, local human use activities, and transportation. Smoke plumes will reduce visibility at a local scale and may require changes in air traffic routing. The smoke plume and particulate deposition may also cause limited spatial and temporal aesthetic impact. Reports of soot deposition at small villages downwind of the burn during the *Exxon Valdez* response indicated a perceived aesthetic and visual impact to the local communities. Human use activities such as fishing (commercial and sport), recreation, and tourism may be temporarily affected by the requirements to provide a safety zone around the burn area.

7.6 Summary

Our literature search identified little published evidence of health or environmental effects from burning in either actual spills or in laboratory tests. However, a number of studies have examined the composition and environmental fate of burn emissions. These studies showed that at least some burn emissions (e.g., particulate carbon, sulfur dioxide) may pose a threat to wildlife or human health in the area immediately downwind of a burn, but exposure conditions would fall below threshold levels at most within a few kilometers downwind of the burn.

Burn residues may pose some threat to aquatic resources and human use of water resources, but the volume of residue left after a burn would be much reduced over the parent spill and the toxicity of the residue appears to be similar to that of the normally weathered, unburned oil.

Case studies of burns in major spills have revealed no significant impacts to human or ecological resources. Spills in which tankers have caught fire have resulted in little if any impact of the smoke plume or burn residue on the environment and even the most significant burn event ever experienced, the Kuwait oil fires of 1991, does not appear to have caused lasting environmental or human health impacts.

7.7 References to Chapter 7

- Alaska Clean Seas. 1991. Proposed plan for 1992 full-scale in-situ burn test, Beaufort Sea, Alaska. Unpublished proposal.
- Allen, A.A. 1990. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. *Spill Technology Newsletter*, vol. 15, no. 2, pp. 1-5.
- Allen, A.A. and Ferek, R.J. 1993. Advantages and disadvantages of burning spilled oil. *Proceedings of the 1993 Oil Spill Conference*, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 765-772.
- Bakan, S., A. Chlond, U. Cusbach, J. Feichter, H. Graf, H. Grassl, K. Hasselmann, I. Kirchner, M. Latif, E. Roeckner, R. Sausen, V. Schlese, D. Schrieffer, I. Schult, U. Schumann, F. Sielmann, and W. Welke. 1991. Climate response to smoke from the burning oil wells in Kuwait, *Nature*, **351**, 367-371.
- Bech, C., P. Sveum, and I.A. Buist. 1992. In-situ burning of emulsions: the effects of varying water content and degree of evaporation. *Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar*, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 547-559.
- Benner, Jr., B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, R.C. Lao, and M.F. Fingas. 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. *Environmental Science and Technology*, v 24, n 9, pp. 1418-1427.
- Benner, B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, D.D. Evans, M.F. Fingas, and K. Li. 1991. Emissions of polycyclic aromatic hydrocarbons from the combustion of crude oil on water. *Spill Technology Newsletter*, 16 (1).
- Bobra, M. and S. Callaghan. 1990. A catalogue of crude oil and product properties: Environment Canada, Environmental Protection Directorate Unpublished Report EE-125, Ottawa, 542 pp.
- Campagna, P.R. and A. Humphrey. 1992. Air sampling and monitoring at the Kuwait oil well fires. *Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar*, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 575-592.
- Cofer, W.R. III, R.K. Stevens, E.L. Winstead, J.P. Pinto, D.I. Sebacher, M.Y. Abdulraheem, M. Al-Sahafi, M.A. Mazurek, R.A. Rasmussen, D.R. Cahoon, and J.S. Levine. 1992. Kuwaiti oil fires: Compositions of source smoke. *Journal of Geophysical Research*, Vol. 97, No. D13, pages 14,521-14,525.
- Day, T., D. Mackay, S. Nadeau, and R. Thurier. 1979. Characteristics of atmospheric emissions from an in-situ crude oil fire. *Environ. Canada Technol. Develop. Report EPS 4-EC-79-1*. 79 p.

- Dowty, B.J., J.W. Brown, F.N. Stone, J. Lake, and J.L. Lasetar. 1981. GC-MS analysis of volatile organics from atmospheres impacted by the *Amoco Cadiz* oil spill. In *Amoco Cadiz: Fates and Effects of the Oil Spill*. Proc. Int. Symp., Centre Oceanog. de Bretagne, Brest, France, 19-22 November 1979. Centre Nationale Pour Exploitation des Oceans. Paris, pp. 13-22.
- Evans, D., H. Baum, B. McCaffrey, G. Mulholland, M. Harkleroad, and W. Manders. 1986. Combustion of oil on water. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 301-336.
- Evans, D., G. Mulholland, D. Gross, H. Baum, W. Walton, and K. Saito. 1988. Burning, smoke production, and smoke dispersion from oil spill combustion. NISTIR 89-4091, (U.S. Dept. of Commerce, National Institute of Standards and Techn.), 57 p.
- Evans, D., W. Walton, H. Baum, R. Lawson, R. Rehm, R. Harris, and A. Ghoniem. 1990. Measurement of large scale oil spill burns. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p 1(38).
- Evans, D., W. Walton, H. Baum, G. Mulholland, J. Lawson, H. Koseki, and A. Ghoniem. 1991a. Smoke emission from burning crude oil. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 421-449.
- Evans, D.D., G.W. Mulholland, J.R. Lawson, E.J. Tennyson, M.F. Fingas, P.A. Tebeau, and J.R. Gould. 1991b. Burning of oil spills. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. p. 677-680.
- Evans, D., W. Walton, H. Baum, K.A. Notarianni, J.R. Lawson, H.C. Tang, K.R. Keydel, R.G. Rehm, D. Madrzykowski, and R.H. Zile. 1992. In-situ burning of oil spills: Mesoscale experiments. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 593-657.
- Ferek, R.J., P.V. Hobbs, J.A. Herring, K.K. Laursen, R.E. Weiss, and R.A. Rasmussen. 1992. Chemical composition of emissions from the Kuwait oil fires. Jour. Geophys. Research, v. 97 (D13); p. 14483-14489.
- Fingas, M. and N. Laroche. 1990. An introduction to in-situ burning of oil spills. Spill Technology Newsletter, Dec 90, v15, n4, p. 1-9.

- Fingas, M.F., K. Li, F. Ackerman, P.R. Campagna, R.D. Turpin, S.J. Getty, M.F. Soleki, M.J. Trespalacios, J. Pare, M.C. Fissonnette, and E.J. Tennyson. 1993. Emissions from Mesoscale in-situ oil fires: The Mobile 1991 and 1992 tests. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 749-821.
- Fraser, J.P. 1991. Initial environmental evaluation — oil burning experiment offshore southern Louisiana. Unpublished proposal.
- Grimmer *et al.* 1991. Relevance of polycyclic aromatic hydrocarbons as environmental carcinogens. Jour. Analyt. Chem., v. 339; p. 792-795.
- Laursen, K.K., R.J. Ferek, P.V. Hobbs, and R.A. Rasmussen. 1992. Emission factors for particles, elemental carbon, and trace gases from the Kuwait oil fires. Jour. Geophys. Research, v. 97 (D13); p. 14491-14497.
- Li, K., T. Caron, M. Landriault, J.R. Pare, and M. Fingas. 1992. Measurement of volatiles, semivolatiles, and heavy metals in an oil burn test. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 561-573.
- Menez, J.R., F. Berthov, D. Picart, and C. Riche. 1978. Impacts of the oil spill (*Amoco Cadiz*) on human biology. Penn. Ar. Bed. 94:367-378.
- Milne, A.R. and R.H. Harinveaux. 1978. Crude oil in cold water. Ministry of Supply and Services, Canada. 119p.
- Mitchell, J.B.A. 1990. The effectiveness of ferrocene in reducing smoke emission from burning crude oil. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 75-85.
- Mitchell, J.B.A. and E. Janssen. 1991. The use of additives for smoke reduction from burning pool fires. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. p. 391-397.
- Mitchell, J.B.A. 1991. Smoke reduction from burning crude oil using ferrocene and its derivatives. Combustion and Flame, v. 86, 179.
- Mitchell, J.B.A. and M.E. Moir. 1992. Smoke reduction from pool fires using ferrocene and derivatives. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 681-687.

- Moller, T.H. 1992. Recent experience of oil sinking. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 11-14.
- Rao, U.R., M.G. Chandrasekhar, K. Radhakrishnan, V. Jayaraman, P.S. Desai, P.K. Pal, and P.C. Joshi. 1991. Environmental impacts of the Persian Gulf oil spill and oil-fire smoke. CURR. SCI., vol. 60, no. 8, pp. 486-492.
- Robertson, I. 1991. Operational examples of in-situ burning: Lessons from the burning of two recent diesel spills on the B.C. coast. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 411-419.
- Sharratt, M. and M. Butler. 1992. Toxicological effect of oil smoke. In, The Environmental and Health Impacts of the Kuwaiti Oil Fires, Proc. of and International Symposium, Oct. 1991. Birmingham, England; p. 51-56.
- Sheppard, E.P., R.A. Wells, and P.E. Georghiou. 1983. The mutagenicity of a Prudhoe Bay crude oil and its residues from an experimental in situ burn. Env Research, v30, n2, p. 427-442.
- Turbini, W., E. Fresi and F. Bambacigno. 1993. The *Haven* Incident: Lessons learned with particular reference to environmental damages. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 179-183.
- Walton, W.D., D.D. Evans, K.B. McGrattan, H.R. Baum, W.H. Twilley, D. Madrzykowski, A.D. Putorti, R.G. Rehm, H. Koseki, and E.J. Tennyson. 1993. In-situ burning of oil spills: Mesoscale experiments and analysis. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 679-734.
- World Health Organization. 1982. Environmental Health Criteria 20. Selected petroleum products, WHO, Geneva, Switzerland.
- Zieserl, E. 1979. Hydrocarbon ingestion and poisoning: Comprehensive Therapy, 5, 35-42.

7.8 Bibliography to Chapter 7

- Allen, A.A. 1990. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. *Spill Technology Newsletter*, vol. 15, no. 2, pp. 1-5.
- Allen, A. 1990. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. *Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar*, June 6-8 Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p 305-314.
- Allen, A.A. and Ferek, R.J. 1993. Advantages and disadvantages of burning spilled oil. *Proceedings of the 1993 Oil Spill Conference*, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. p. 765-772.
- Anderson, E., E. Howlett, W. Knauss, D. French, M. Spaulding, M. Reed, S. Puckett, T. Isaji, and D. Mendelsohn. 1990. The Alyeska tactical oil spill model. *Mar. Technol. Soc. J.*, vol. 24, no. 4, pp. 33-38.
- Benner, Jr., B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, R.C. Lao, and M.F. Fingas. 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. *Environmental Science and Technology*, v 24, n 9, pp. 1418-1427.
- Benner, B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, and R. Lao. 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. *Govt Reports Announcements & Index (GRA&I)*, Issue 01, 1991.
- Benner, B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, D.D. Evans, M.F. Fingas, and K. Li. 1991. Emissions of polycyclic aromatic hydrocarbons from the combustion of crude oil on water. *Spill Technology Newsletter*, 16 (1).
- Bowker, R.R. 1991. The environmental impact of the Gulf War; *Ecologist*, Jul-Aug 91, v 21, n 4, p 166(6).
- Buist, I.A., W.M. Pistruzak, and D.F. Dickins. 1981. Dome Petroleum's oil and gas undersea ice study. *Spill Technology Newsletter*, May-Jun 81, v6, n3, p. 120-147.
- Cofor, W.R. III, R.K. Stevens, E.L. Winstead, J.P. Pinto, D.I. Sebach, M.Y. Abdulraheem, M. Al-Sahafi, M.A. Mazurek, R.A. Rasmussen, D.R. Cahoon, and J.S. Levine. 1992. Kuwaiti oil fires: Compositions of source smoke. *Journal of Geophysical Research*, Vol. 97, No. D13, pages 14,521-14,525.
- Dickins, D.F., I.A. Buist, and W.M. Pistruzak. 1981. Dome's Petroleum study of oil and gas under sea ice. *Proceedings of the 1981 Oil Spill Conference*, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. p. 183-190.

- Evans, D., H. Baum, B. McCaffrey, G. Mulholland, M. Harkleroad, and W. Manders. 1986. Combustion of oil on water. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario pp. 301-336.
- Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1988. Environment effects of oil spill combustion. Govt Reports Announcements & Index (GRA&I), Issue 02, 1989.
- Evans, D.D., G. Mulholland, D. Gross, H. Baum, W. Walton, and K. Saito. 1988. Burning, smoke production, and smoke dispersion from oil spill combustion. NISTIR 89-4091, (U.S. Dept. of Commerce, National Institute of Standards and Techn.), 57 p.
- Evans, D., H. Baum, G. Mulholland, N. Bryner, and G. Forney. 1989. Smoke plumes from crude oil burns. Proceedings of the Twelfth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p.1-22.
- Evans, D., W. Walton, H. Baum, R. Lawson, R. Rehm, R. Harris, and A. Ghoniem. 1990. Measurement of large scale oil spill burns. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p 1(38).
- Evans, D., W. Walton, H. Baum, R. Lawson and R. Rehm. 1990. Measurement of large scale oil spill burns. Govt Reports Announcements & Index (GRA&I), Issue 22, 1990.
- Evans, D., W. Walton, H. Baum, G. Mulholland, J. Lawson, H. Koseki, and A. Ghoniem. 1991a. Smoke emission from burning crude oil. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 421-449.
- Evans, D., W. Walton, H. Baum, K.A. Notarianni, J.R. Lawson, H.C. Tang, K.R. Keydel, R.G. Rehm, D. Madrzykowski, and R.H. Zile. 1992. In-situ burning of oil spills: Mesoscale experiments. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 593-657.
- Fingas, M. and N. Laroche. 1990. An introduction to in-situ burning of oil spills. Spill Technology Newsletter, Dec 90, v15, n4, p. 1-9.
- Fingas, M.F., K. Li, F. Ackerman, P.R. Campagna, R.D. Turpin, S.J. Getty, M.F. Soleki, M.J. Trespalacios, J. Pare, M.C. Fissonnette, and E.J. Tennyson. 1993. Emissions from mesoscale in-situ oil fires: The Mobile 1991 and 1992 tests. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 749-821.

- Massie, L.C., A.P. Ward, J.M. Davies, and P.R. Mackie. 1985. The effects of oil exploration and production in the northern North Sea. Part 1. The levels of hydrocarbons in water and sediments in selected areas, 1978-1981. *Mar. Environ. Res.*; vol. 15, no. 3, pp. 165-213.
- McKendrick, J.D. and W.M. Mitchell. 1978. Effects of burning crude oil spilled onto six habitat types in Alaska. *Arctic*, v. 31 (3), p. 277-295.
- Mitchell, J.B.A. and E. Janssen. 1991. The use of additives for smoke reduction from burning pool fires. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. p. 391-397.
- Moldan, A.G.S. and L.F. Jackson *et al.* 1985. Some aspects of the Castillo de Bellver oil spill. *Marine Pollution Bulletin* 16(3): p. 97-102.
- Moller, T.H. 1992. Recent experience of oil sinking. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 11-14.
- Nakata, K., S. Kanamaki, and T. Kojima. 1991. Numerical model development for oil spill dispersion into the marine environment. IN: Hydraulic Engineering. Proceedings of the 1991 National Conference. American Society of Civil Engineers, New York. 1991. p 644-649.
- Natl. Inst. Oceanogr., Reg. Cent., Versova. 1985. Investigations on oil patches around M.T. Lajpatrai Bombay Harbour. *Mahasagar.*, vol. 18, no. 4, p. 511-516.
- Politzer, I.R., I.R. DeLeon, and J.L. Lasetar. 1985. Impact on human health of petroleum in the marine environment. Report prepared for the American Petroleum Institute, Washington, D.C. 162 pp.
- Rainio, K., R.R. Linko, and L. Ruotsila. 1986. Polycyclic aromatic hydrocarbons in mussel and fish from the Finnish Archipelago Sea. *Bull. Environ. Contam. Toxicol.*, vol. 37, no. 3, p. 337-343.
- Rao, U.R., M.G. Chandrasekhar, K. Radhakrishnan, V. Jayaraman, P.S. Desai, P.K. Pal, and P.C. Joshi. 1991. Environmental impacts of the Persian Gulf oil spill and oil-fire smoke. *CURR. SCI.*, vol. 60, no. 8, pp. 486-492.
- Robertson, I. 1991. Operational examples of in-situ burning: Lessons from the burning of two recent diesel spills on the B.C. coast. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 411-419.

- Sheppard, E.P. and P.E. Georghiou. 1981. The mutagenicity of Prudhoe Bay crude oil and its burn residues. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 195-213.
- Sheppard, E.P., R.A. Wells, and P.E. Georghiou. 1983. The mutagenicity of a Prudhoe Bay crude oil and its residues from an experimental in situ burn. *Env Research*, v30, n2, p. 427-442.
- Siron, R., E. Pelletier, and C. Brochu. 1991. Suivi d'une contamination petroliere accidentelle dans l'estuaire moyen du Saint-Laurent: Le cas de l'Ile-aux-Grues (Results of an accidental oil spill in the St. Lawrence middle Estuary: The Ile-aux-Grues case). *Water Pollut. Res. J. Can.*; vol. 26, no. 1, p. 61-86.
- Strobel, C.J., J.H. Gentile, S.C. Schimmel, R.S. Carr, J.W. Williams, and D.A.F. Redford. 1988. Proposed biological testing methods for the United States incineration-at-sea research program. *MAR. POLLUT. BULL.*, vol. 19, no. 11B, pp. 605-610.
- Walton, W.D., D.D. Evans, K.B. McGrattan, H.R. Baum, W.H. Twilley, D. Madrzykowski, A.D. Putorti, R.G. Rehm, H. Koseki, and E.J. Tennyson. 1993. In-situ burning of oil spills: Mesoscale experiments and analysis. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 679-734.

8.0 Risk Evaluation of the Acceptability of Burning Spilled Oil

8.1 Objective

During the initial stages of a marine oil spill a decision must be made as to whether or not burning presents acceptable risks to the environment and to human health and safety. This chapter examines the important issues associated with the burn/no-burn decision and evaluates situations in which in-situ burning can be considered to be a safe and ecologically-sound countermeasures technique. The risks associated to human health from burning are discussed in Section 8.4 and ecological risks in Section 8.5. Implications for decision-making are discussed in Section 8.6.

8.2 Description of Assumptions Supporting Risk Evaluation

This evaluation is based on the following assumptions:

- Crude oil spilled has a composition similar to Prudhoe Bay, South Louisiana, or Kuwait crude. Properties of these crudes are given in Table 2.1 in Chapter 2 and in Table 8.1 of this chapter.
- Burning is effective in quickly removing at least 75% of the oil targeted for burning.
- Offshore waters that are key breeding or migrating areas need to be protected.
- Nearshore spills are adjacent to shoreline and on-shore resources that are potentially impacted by a burn/no-burn decision.
- The type and abundance of shoreline resources are critical to the burn/no-burn decision.
- Nearshore and estuarine areas possess a diversity of habitats and larger numbers of species and populations than found in offshore environments.
- Nearshore areas include human exposure points.
- Estuarine waters are considered to be habitats sensitive to oil, and contain economically important species.

Table 8.1 Chemical Composition of Three Crude Oils*

Characteristics or Component	Prudhoe Bay	South Louisiana	Kuwait
API Gravity	27.8	34.5	31.4
Sulfur (wt %)	0.94	0.25	2.44
Nitrogen (wt %)	0.23	0.69	0.14
Nickel (ppm, mg/kg)	10	2.2	7.7
20-205° C Boiling Point Fraction (wt %)			
Alkanes	12.5	8.8	16.2
Cycloalkanes	7.4	7.7	4.1
Aromatic Hydrocarbons	3.2	2.1	2.4
Above 205° C Boiling Point Fraction (wt %)			
n-Alkanes (C11-C32 plus)	5.8	5.2	4.7
Isoalkanes	---	14.0	13.2
Cycloalkanes	28.5	37.7	16.2
Aromatic Hydrocarbons	25.0	16.5	21.9

* From: World Health Organization. 1989.

8.3 Chemical and Physical Properties of Oil and Combustion Products

8.3.1 Crude Oil Characteristics

One should understand at least the basics of petroleum chemistry to understand the fate and effects of marine oil spills and the consequences of in-situ burning. Crude oil is a mixture of thousands of specific hydrocarbon compounds ranging from highly volatile liquids to near-solid tars. In Chapter 2 an attempt is made to summarize the key characteristics of petroleum oil that affect oil spill behavior and in-situ burning. Suffice to emphasize here that crude oils vary widely. Light crudes contain larger percentages of the low boiling, smaller molecular weight hydrocarbons than do heavy crudes. Heavy crudes have higher boiling points, viscosities, and specific gravity than lighter crudes. Burn emissions and risks will vary with the type of oil. The present discussion of risk relates to oils similar in properties to those described in Table 8.1, which lists the composition and characteristics of three "typical" crude oils.

8.3.2 Oil Spill Behavior

The behavior and weathering of spilled oil are important considerations in deciding whether to leave the oil alone or whether to ignite and burn it. The behavior of spilled oil includes the following key processes: advection, evaporation, spreading, emulsification, dispersion and dissolution. Please refer again to Chapter 2 for a brief description of these processes and their importance to the in-situ burning problem.

8.3.3 Chemical Properties of Crude Oil Combustion Products

As discussed in the previous chapter, the combustion products of crude oil include heat, gases, particulates, and residue. The heat generated is directed upward and away from the burn site, and little heat is absorbed by the water. The smoke plume consists of particles and gases. The gases include CO_2 , CO , NO , NO_x , and SO_2 .

Particulates typically represent two to ten percent of the mass of burned crude. Polynuclear aromatic hydrocarbons or PAHs, are both present in crude and are produced by high temperature and oxygen-poor combustion of oil, and would likely be emitted from burning crudes. The majority of PAHs are generally associated with particulates, but represent a small fraction of the total amount of particulate matter associated with combustion.

Several air sampling programs were conducted following the Gulf War in 1991. The results of these programs and other studies (Evans *et al.* 1989, Allen and Ferek 1993, Benner *et al.* 1991) have been analyzed and used here to estimate emissions for an in-situ burn expressed as emission factors (kilograms chemical per kilograms of oil burned). The results are presented below in Table 8.2.

Table 8.2 Emission Factors for Airborne Chemicals from an In-Situ Burn

Emitted Chemical	Emission Factor (kg chemical/kg burned)
SO ₂	0.02
NO _x	0.0061
CO ₂	2.7
CO	0.00175
VOCs	0.00028
PAHs	0.000004
Total Particulates	0.1

The above table was developed as follows: Where there was agreement among references for a particular emission factor, that factor was used. When there was little agreement for a value, the factor was modified according to the general consensus of what is currently understood about emissions from these kinds of fires and by weighing the relevant comments about order of magnitude emissions from these events. For instance, Allen and Ferek suggest that the NO_x emission factor is 0.00061 kg/kg oil burned, but other references imply an order of magnitude increase in NO_x emissions under some conditions. The value used for NO_x emission factor, 0.0061 kg/kg, reflects the general order of magnitude recommendations from available literature, and is conservative (higher emission rate). Best engineering judgements were also made for CO and VOCs emission factors.

The emission rate thus derived for SO₂, NO_x, CO, CO₂ and particulates are used in computer dispersion modeling in this evaluation to determine the change of concentration of pollutants as a function of distance from the burn site. This modeling analysis is described in Appendix B.

8.4 Human Health Risk Evaluation

8.4.1 Introduction

This section evaluates the potential health risks to members of the public from burning oil in a nearshore marine environment. Burning in an offshore environment is not evaluated because public health risks would generally be negligible. Nor are potential risks to spill response personnel addressed because responders are assumed to be properly trained and equipped to minimize hazardous exposures. This human health risk evaluation describes the chief pathways by which humans could be exposed to chemicals produced during burning of oil in a nearshore environment, identifies the chemicals of concern for adverse health effects, and estimates carcinogenic and noncarcinogenic risks associated with exposures to those chemicals. Health risks are estimated using conservative (health-protective) assumptions

regarding chemical concentrations, toxicity, and exposure conditions so that potential risk will not be underestimated.

It will be shown in the following analysis that human health effects due to toxicity or carcinogenicity of chemicals of concern in smoke from the burn are low and should not affect decisions on implementing burning as a spill countermeasure. However, people between 1200 and 2500 m of the burn site could be exposed to concentrations of particulate matter (PM) that exceed U.S. national or state ambient air quality standards by factors of about 1.5 to 2 depending on the size of the burn and meteorological conditions (see smoke plume model in Appendix B). These exceedances would be temporary and transient, and would not represent a continuing violation of the PM standard.

8.4.2 Human Exposure Pathways

The chief pathways by which humans may be exposed to chemicals of concern during burning of an oil spill are:

1. inhalation of airborne contaminants in particulate matter (soot); and
2. incidental ingestion of soot or soot-contaminated soil.

Other possible exposure routes are dermal absorption of chemicals from skin contact with soot and ingestion of contaminated seafood. Dermal absorption of chemicals adhered to soot is expected to be negligible, because organic compounds bind tightly to soot (carbons), and they are not likely to partition to skin in significant amounts, especially under short-term exposure conditions as would occur during an oil burn. The dermal absorption pathway is therefore not evaluated quantitatively in the risk assessment. The seafood ingestion pathway is considered negligible for the burn scenario because burning considerably reduces the quantity of oil that could result in contamination of aquatic species compared to other control measures. Therefore this pathway is not important in assessing the human health risks associated with burning the spill.

Direct human contact with the burn residue is not evaluated because the opportunity for exposure of the public is low.

8.4.3 Chemicals of Concern for Health Risk Assessment

Chemicals of concern for human health risk assessment are those chemicals released to the environment that, at certain exposure levels, could have significant adverse health effects. The greatest concern in a burn scenario is for exposure to contaminants in the smoke plume. Therefore, this section focuses on chemicals of concern in the plume to which the general human population might be exposed.

8.4.3.1 Constituents of Crude Oil

Crude oil is a complex mixture of thousands of organic compounds, most of which are saturated hydrocarbons or aromatics. Table 8.3 lists concentrations of C₁₂ — C₂₄ straight-chain alkanes (n-paraffins) and aromatic hydrocarbons in the API reference oils (Kuwait Crude and Louisiana Crude) and in Alberta Sweet Crude (PAHs only). Benzene and alkyl-substituted benzenes are present in the crude oil at concentrations of 8 to 9 percent, and naphthalenes are present at concentrations of 0.5 to 0.8 percent. PAHs, many of which are known to be toxic or carcinogenic, are present in much lower concentrations; total PAHs constitute less than 0.1 percent of the total hydrocarbons in these oils.

Table 8.3 does not include the lower molecular weight saturated hydrocarbons (C₁ — C₁₁) that are present in crude oil. Pentanes through decanes dominate in this group. These compounds are volatile and would be quickly lost from oil slicks during spills.

Compounds containing sulfur and nitrogen, and metals such as vanadium, nickel, and zinc are also present in low concentrations ranging from less than 10 ppm to several hundred ppm depending on the metal and the type of crude. The metals occur primarily as large, high molecular weight, stable organometallic complexes that are not readily soluble or biologically available. Other trace metals are also found in crude oil, generally in concentrations much less than 1 ppm.

8.4.3.2 Constituents of Concern During Burning

Only some of the constituents of crude oil are known to be carcinogenic or toxic at low dosages. The following paragraphs describe which chemicals are of concern for risk assessment and which are not.

Volatile Organic Compounds (VOCs): Many of the low molecular weight constituents that are potentially hazardous, such as benzene, toluene, n-hexane, and naphthalenes, are readily volatilized and combusted during burning. These compounds are normally released to air during an oil spill and can contribute to acute health effects in humans (such as nausea and headache) if exposure to high concentrations occurs. Since the concentrations of these compounds in the air are much reduced by burning (Fingas *et al.* 1993), burning will reduce risk of exposure of shoreline receptors to potentially hazardous concentrations of volatile organics. Therefore, since burning an oil spill results in lower air concentrations of volatile organic compounds compared to other remedial actions, these compounds are not considered chemicals of concern for public health effects during a burn.

Metals: Metals are present in crude oil; however, when present they occur only in low concentrations and are generally bound up in organometallic complexes that are largely retained in the burn residue (to which exposures are expected to be minimal). For this reason, metals are not considered chemicals of concern during in-situ burning and no risk assessment has been conducted here.

Table 8.3 Concentrations of N-Paraffins and Aromatic Hydrocarbons in Crude Oils in ppm

Compound	Kuwait Crude ¹	Louisiana Crude ¹	Alberta Sweet Crude ²
Total C ₁₂ -C ₂₄ n-paraffins	40,000	39,800	
Benzenes	80,000	92,000	
Naphthalene	400	400	
1-Methylnaphthalene	500	800	
2-Methylnaphthalene	700	900	
Dimethylnaphthalenes	2,000	3,600	
Trimethylnaphthalenes	1,900	2,400	
Biphenyls	<100	<100	
Acenaphthylene			13
Acenaphthene			57
Anthracene			11
Fluorenes	<100	200	209
Phenanthrene	26	70	150
1-Methylphenanthrene	-	111	-
2-Methylphenanthrene	89	144	-
Fluoranthene	2.9	5.0	6
Pyrene	4.5	3.5	17
1-Methylpyrene			39
Benzo(a)anthracene	2.3	1.7	-
Chrysene	6.9	17.56	30
Triphenylene	2.8	10	30
Benzo(ghi)fluoranthene	<1	1	-
Benzo(b)fluoranthene	<1	<0.5	4
Benzo(j)fluoranthene	<1	<0.9	-
Benzo(k)fluoranthene	<1	<1.3	-
Benzo(a)pyrene	2.8	0.75	-
Benzo(e)pyrene	0.5	2.5	5
Perylene	<0.1	34.8	-
Benzo(ghi)perylene	<1	1.6	-
2-Methylcholanthrene	-	-	3

¹ From Neff, J.M. and J.W. Anderson. 1981.

² From Benner, et al. 1991.

PAHs: The primary chemicals of concern in the smoke plume are the toxic or carcinogenic PAHs. Some of the PAHs in the crude oil are not destroyed during burning, and some may be created during incomplete combustion. Table 8.4 lists PAHs in particulates and burn residue measured in a laboratory scale burn of Alberta Sweet Crude (Benner *et al.* 1990). The PAHs are grouped as carcinogenic, noncarcinogenic (toxic), and other. "Other PAHs" are PAHs that either have not been tested, have no observed adverse effects, or for which data are insufficient to demonstrate toxicity. These "other PAHs" are not evaluated in the human health risk assessment.

The relative proportions of the PAHs shown in Table 8.4 (derived from Benner *et al.* 1990) are comparable to those measured in recent mesoscale experiments conducted near Mobile, Alabama (Fingas *et al.* 1993), but a greater number of individual PAHs were identified in the laboratory experiments. Acenaphthene and phenanthrene were detected in the greatest concentrations in both the laboratory and mesoscale experiments. Toxic or carcinogenic effects for these compounds have not been established. Pyrene, fluoranthene, and other noncarcinogenic PAHs with known non-cancer effects were detected in relatively low concentrations. Carcinogenic PAHs were detected in still lower concentrations in both the laboratory and mesoscale experiments. Benzo(a)pyrene and benzo(a)fluoranthene were detected in both series; additional carcinogenic PAHs were identified in the laboratory experiments. Therefore, the data in Table 8.4 are considered to be an accurate representation of PAH concentrations in smoke from an oil burn.

Inorganic Air Pollutants: NO_x, SO₂ and PM (particulate matter) that are emitted during an oil burn can be respiratory irritants and can aggravate existing respiratory or cardiac ailments in humans. There is also some evidence that they may enhance carcinogenic effects of PAHs (see Section 8.4.4). However, it appears that ground-level concentrations of NO_x and SO₂ are not likely to exceed short-term air quality criteria within the area of plume impact. Table 8.5 lists modeled maximum ground-level air concentrations of these pollutants from a hypothetical burn (see Appendix B) and compares them to U.S. National Ambient Air Quality Standards and the most limiting standard. The hypothetical burn scenario used in modeling assumes that 1000 barrels of oil in a 30 m diameter pool are ignited as a single event, rather than being separated by booms into smaller pools for controlled burning. Air dispersion modeling for a large single event is likely to predict greater emissions impacts at greater distances from the source than would be predicted for several smaller sources. As shown in Table 8.5, only modeled concentrations of particulates (PM) exceed national or state criteria for short-term air concentrations at distances between 1200 and 4500 meters from the burn. This is consistent with the findings of Fingas *et al.* (1993), where it was concluded that ground-level air concentrations of combustion gases, including SO₂, were not of concern during mesoscale oil burn tests.

In conclusion, only the PAHs in smoke are considered to be chemicals of concern from the perspective of risks to human health. The specific PAHs of concern for quantitative risk assessment are shown in Table 8.4.

Table 8.4 Concentrations of Carcinogenic and Noncarcinogenic PAHs (Vapor and Particulate) Produced by Combustion of Alberta Sweet Crude Oil¹
(μg of PAH/g of sample)

PAHs	Crude	Soot ²		Residue ²	
	<u>Oil</u>	<u>Minimum</u>	<u>Maximum</u>	<u>Minimum</u>	<u>Maximum</u>
Carcinogens ³					
benzo(a)anthracene	30	155	260		
chrysene/triphenylene		78	260	24	34
benzofluoranthenes ⁴		260	430		
benzo(a)pyrene	3	190	310	3	4
2-methylcholanthrene				3	3
indeno(1,2,3-cd)pyrene		120	200		
Sub-Totals		803	1460	30	41
Non-Carcinogens ⁵					
acenaphthene	57			10	15
fluorene		59		35	47
2-methylfluorene	150			110	160
anthracene	11	210	440	13	19
fluoranthene	6	580	950	11	22
pyrene	17	610	1070	25	30
benzo(a)fluorene		70	70		
benzo(b)fluorene		70	70		
1-methylpyrene	39	56	56	16	19
Sub-Totals	339	159	2656	220	312
Other ⁶					
acenaphthylene	13	1740	1740	26	54
phenanthrene	150	910	1820	120	140
3-methylphenanthrene		16	36		
2-methylphenanthrene		21	40		
1-methylphenanthrene		12	33		
methylphenanthrenes	370			330	330
dimethylphenanthrenes	500			520	520
acephenanthrylene		330	520		
perylene		5	56		
benzo(e)pyrene	5	90	140	6	6
benzo(ghi)perylene		120	250	2	2
coronene		45	252		
Sub-Totals	1038	3289	4887	1004	1052
Totals	1410	5688	9003	1254	1405

1 From laboratory-scale experiments; Brenner *et al.* 1990.

2 Thickness of oil slicks ranged from 2 mm to 30 mm.

3 Based on identification of carcinogenicity by U.S. EPA (IRIS) or NAS 1972.

4 Benzofluoranthenes are grouped together as carcinogens, although some isomers are not known to be carcinogenic (such as benzo(ghi)fluoranthene).

5 Based on U.S. EPA (IRIS) and assumption that methylated and benzo-compounds are also toxic.

6 No or insufficient evidence of carcinogenicity or toxicity.

Table 8.5 Modeled Maximum 24-Hour Air Concentrations of Criteria Pollutants Compared to Ambient Standards, $\mu\text{g}/\text{m}^3$

Constituent	Modeled 24-hr Maximum Concentration in Plume ¹	U.S. National Ambient Air Standard	Most Limiting State Standard
PM	323 806 (1 hr)	150 (24 hr)	50 (annual)
CO	10 (8 hr)	10,000 (8 hr)	10,000 (8 hr)
NO _x	120	100 (annual)	100 (annual) 1,300 (3 hr)
SO ₂	65	365 (24 hr)	365 (24 hr)

1 24-hour maximum, except where noted. Results of modeling a 10,000-barrel burn using emission factors estimated from the Kuwait oil field fires showed maximum concentrations at 1540 m downwind of the source. See Appendix B for modeling approach and assumptions.

8.4.4 Toxicity Assessment

This section briefly describes the toxic and carcinogenic effects of PAHs and presents toxicity factors established by the U.S. Environmental Protection Agency (EPA) that are used to estimate carcinogenic risk and noncarcinogenic hazards. A brief discussion of the effects on PAHs of inorganic air pollutants and sunlight is also included.

8.4.4.1 Health Effects of PAHs

Carcinogenic PAHs: EPA has identified the following PAHs as carcinogenic, based primarily on experimental evidence in animals: benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, indeno(1,2,3-cd)perylene, and dibenzo(a,h)anthracene. Other carcinogenic PAHs listed in Table 8.4 are identified as carcinogenic by NAS (1972). Benzo(a)pyrene (BaP) is one of the most carcinogenic of the PAHs.

In laboratory studies, ingestion and inhalation of BaP by mice, rats and hamsters, and dermal and subcutaneous administration of BaP to these animals have produced a variety of tumors in the kidney, stomach, lungs, respiratory tract, and skin. Tumors have also been produced in some but not all studies performed in primates. Most tumors occur at the point of contact.

The carcinogenicity of some PAHs in humans is supported by evidence from workers exposed for many years to soot, other products of coal combustion and gasification, lubricating oils, and cigarette smoke, all of which contain significant quantities of carcinogenic PAHs. For example, a number of studies and observations from the late 1700s through the mid 1900s show increased cancers of the skin and scrotum among English chimney sweeps exposed since childhood to coal soot, industrial workers whose clothing was saturated with lubricating oils, and workers routinely exposed to pitch, tar, and asphalt. Past unhygienic working conditions contributed to these hazardous exposures. Lung cancer has also been associated with occupational exposures at coal gasification plants and coke ovens and with cigarette smoking.

It should be noted that the doses given to laboratory animals are many thousands of times higher than conservative estimates of doses from exposure to smoke from an oil burn. For example, daily doses given to laboratory animals in the experiments used to quantify the cancer potency of BaP ranged from approximately 2×10^{-2} to 1 milligram BaP per kilogram body weight per day (mg/kg-day) (EPA IRIS). These high doses can be compared to the much lower dose of 6.5×10^{-6} mg/kg-day total carcinogenic PAHs estimated for smoke inhalation and particulate ingestion from oil burning (this value is the sum of doses shown later in Table 8.8). These low doses in humans are not likely to produce a measurable increase in cancer incidence (see risk evaluation in Section 8.4.5). Furthermore, exposures in the occupations listed above far exceed exposures that would occur to a smoke plume from an oil burn.

Noncarcinogenic PAHs: The PAHs acenaphthene, fluoranthene, fluorene, and pyrene have been shown to affect the liver, spleen, kidney, and blood in laboratory mice. Pyrene has adverse effects at somewhat lower doses than the others, and is therefore the most conservative (health-protective) measure of potential toxicity. The lowest dose of pyrene that elicited toxic effects in laboratory animals was 125 mg/kg-day (EPA IRIS). No effect was seen at 75 mg/kg-day. This dose is many thousands of times higher than those to which the public would be exposed during burning of an oil spill. The maximum dose estimated later in Table 8.9 for human exposures is 0.02 mg/kg-day (child eating soot for 5 days). This dose would not be expected to have adverse effects. Furthermore, the acute toxicity of pure PAHs appears low when administered orally or dermally to rats or mice (EPA IRIS).

Effects of Other Air Pollutants and Sunlight on PAHs: There is some epidemiological and experimental evidence to suggest that exposure to certain inorganic air pollutants, such as SO₂, NO_x and ozone, may potentiate the carcinogenic effects of PAHs. It is possible that irritation of respiratory passages by inorganic air pollutants increases the sensitivity of respiratory tissues to carcinogenic PAHs. Some supporting evidence from laboratory experiments is available. For example, in one experiment (Laskin *et al.* 1970, reported in NAS 1972), simultaneous exposure to SO₂ and BaP appeared to enhance the tumor rate in rats but not in hamsters. Exposure was to 10 ppm SO₂ for 6 hours/day plus 10 mg/m³ BaP and 3.5 ppm SO₂ for 1 hour/day. These concentrations are considerably higher than those to which humans would be exposed at the maximum concentration location, 1500 to 2000 meters from a burn site, and the exposure conditions do not include weathering, photooxidation, and other processes that degrade chemicals in a smoke plume. Therefore, the experimental conditions are not representative of human exposures in the environment and, because combustion gases such as SO₂ are not likely to be of concern at a distance of a few thousand meters from the burn, this possible potentiating effect can be neglected.

Furthermore, the possible potentiating effects of other air pollutants may be offset by natural degradation of PAHs, especially as a result of photooxidation. In some experiments, exposure for about 40 minutes to light equivalent to one-fourth that of noon sunlight caused 35 to 65 percent loss of BaP in smoke samples (Tebbens *et al.* 1966 and Thomas *et al.* 1968, reported in NAS 1972). Other experiments have provided comparable results. Half-lives of PAHs in air may therefore be on the order of hours. Some experiments have shown that the carcinogenic potency of a crude mixture is lower than expected when the potency of the known carcinogenic constituents is considered (Falk *et al.* 1964). It appears that the presence of a related but less potent compound can inhibit the activity of the more potent compound. Anticarcinogenic as well as co-carcinogenic mechanisms are both likely to occur. Therefore, the potentiating and degradation effects of other chemicals and environmental factors are likely to offset each other and are neglected in estimating potential risk.

8.4.4.2 Toxicity Factors

The EPA has established toxicity factors that are used to provide a quantitative estimate of health risk from exposure to chemicals in the environment. Toxicity factors for carcinogenic effects are called slope factors (SFs) and those for non-cancer toxic effects are called reference doses (RfDs).

Toxicity factors are derived primarily from laboratory studies in animals. There is considerable uncertainty in extrapolating from animal studies to humans because of

differences in the doses to which experimental animals and humans are exposed and because of the considerable variability in responses to chemicals among different species. Where possible laboratory experiments are conducted in susceptible species; humans may be more resistant to the effects of the chemical than the animals used in many experiments. Therefore, SFs and RfDs are conservative (health-protective) measures of potential carcinogenicity or toxicity in humans.

SFs and RfDs for PAHs are shown in Table 8.6. Their derivation and application in risk assessment are described in more detail below.

Slope Factors for PAHs: The SF describes a dose-response relationship between the level of exposure to a carcinogen and the probability of getting cancer from the exposure. The SF has units of risk per mg chemical/kg body weight per day, usually expressed as $(\text{mg/kg-day})^{-1}$. The SF is multiplied by the lifetime average daily intake of a chemical, expressed as mg chemical/kg-day, to yield an estimate of lifetime excess cancer risk.

In establishing SFs for carcinogens, the EPA has taken a conservative (health protective) approach in assuming: (1) that exposure even to very low doses of a carcinogen has the potential to increase the risk of cancer (i.e., it is assumed that there is no threshold dose below which a response, however small, does not occur); and (2) that responses to high doses given to susceptible laboratory animals can be extrapolated to responses to low doses in humans using a simple linear model. Furthermore, the SFs are upper 95th percentile confidence limits of a linear model based on dose response relationship determined in the laboratory. EPA states that carcinogenic risks estimated using this approach are upper-bound estimates and that actual risks are likely to be lower (EPA 1989a) and could be zero.

Using such an approach, EPA has developed an oral slope factor for benzo(a)pyrene of $7.3 (\text{mg/kg-day})^{-1}$. The inhalation slope factor of $6.1 (\text{mg/kg-day})^{-1}$ was withdrawn for further review in 1993. For purposes of this risk assessment, the oral slope factor is adopted to assess risk from both oral and inhalation exposures.

Table 8.7 shows the relative carcinogenic potency of other PAHs compared to BaP, which is assigned a relative potency of 1. Other PAHs have lower relative potency. In this risk assessment, the SF for BaP is used for all carcinogenic PAHs identified in the plume (Table 8.4). This is a reasonable approach that is not likely to underestimate potential risk because:

- BaP is among the most carcinogenic of the PAHs and therefore its SF overestimates the potency of most other PAHs (see Table 8.7).
- Adopting the BaP slope factor for other PAHs that are less carcinogenic helps account for possible increased carcinogenicity of some methylated PAHs and for possible synergistic effects resulting from the presence of other pollutants that may enhance carcinogenicity.

Reference Doses for PAHs: The RfD is a daily dose of a chemical that is considered safe for a lifetime of exposure. The RfD has units of mg chemical / kg body weight per day

Table 8.6 Toxicity Factors for PAHs

Compound	Slope Factor (mg/kg-day) ⁻¹		Reference Dose (mg/kg-day)		
	Oral	Inhalation	Oral		Inhalation
			Subchronic	Chronic	
Benzo(a)pyrene ⁽¹⁾	7.3E+0	(2)			
Pyrene			3E-1	3E-2	NA
Acenaphthene			6E-1	6E-2	NA
Anthracene			3E+0	3E-1	NA
Fluoranthene			4E-1	4E-2	NA
Fluorene			4E-1	4E-2	NA

Sources: U.S. EPA. 1993. Health Effects Assessment Summary Tables (HEAST) (subchronic RfDs).

U.S. EPA. Integrated Risk Information System (IRIS). On-line database.

(1) SF has been established only for benzo(a)pyrene. Relative carcinogenicity of other PAHs is shown in Table 8-7.

(2) Value of 6.1E+0 (mg/kg-day)⁻¹ was withdrawn in 1993. The oral slope factor is adopted for both oral and inhalation exposures.

NA Not available.

Table 8.7 Relative Potency Estimates for Carcinogenic PAHs

Compound	Relative Potency
Benzo(a)pyrene	1.0
Benzo(a)anthracene	0.145
Benzo(b)fluoranthene	0.140
Benzo(j)fluoranthene	0.061
Benzo(k)fluoranthene	0.066
Chrysene	0.0044
Indeno(1,2,3-cd)pyrene	0.232

Source: Clement Associates 1989.

(mg/kg-day). RfDs are derived for subchronic exposures (defined by EPA as 2 weeks to 7 years) and for chronic exposures (7 years or more). Subchronic RfDs are used to evaluate exposure to smoke during an oil burn of several days, whereas chronic RfDs are used to evaluate longer-term exposures of many years to deposited PM. In establishing RfDs for toxic effects, EPA usually identifies the highest dose that did not cause an adverse effect in laboratory animals and reduces that dose by "uncertainty factors" to account for extrapolating from one species to another, for extrapolating from short-term high doses to long-term low doses, and for the level of confidence in the experimental data. Therefore RfDs are conservative measures of the potential for adverse effects.

In this risk assessment, the toxicity of PAHs with known non-cancer effects identified in the smoke plume is represented by the oral RfD for pyrene. The chronic RfD for pyrene is 3×10^{-2} mg/kg-day and the subchronic RfD is 3×10^{-1} mg/kg-day (EPA IRIS). This is a conservative approach because the RfD for pyrene is lower than the RfDs for other noncarcinogenic PAHs (Table 8.6). The oral RfD is adopted to assess both oral and inhalation exposures since no inhalation RfDs for PAHs have been established.

8.4.5 Risk Assessment

This section provides conservative estimates of potential carcinogenic risk and noncarcinogenic hazard from exposure to PAHs in smoke emanating from an oil burn via the inhalation and incidental ingestion exposure routes. The risk assessment shows that, even under highly conservative exposure assumptions, health risks from exposure to carcinogenic and toxic constituents of the plume are so low that they would not be a significant factor in the burn/no-burn decision. However, somewhat elevated concentrations of PM, which can have acute respiratory effects, could occur a few thousand meters from the burn site, depending on size of the burn and meteorological conditions. As such, burning should not be considered if the burn is to occur close to a populated shore, unless all shoreline residents can be temporarily relocated during the period of the burn.

8.4.5.1 Exposure Assumptions

The risk assessment is based on several assumptions regarding exposure point concentrations and exposure conditions. Conservative assumptions are mostly used so as not to underestimate potential risk. The chief assumptions are outlined below.

- Emergency response workers wear appropriate protective equipment and are not addressed in the risk assessment.
- Benzene and other volatile compounds present in crude oil are evaporated or combusted and are not significant constituents of the smoke plume (see Section 8.4.3).
- All particulate matter (PM) in the plume is assumed to be respirable.

- PM concentration at the exposure point is 1 mg/m^3 . This is a conservative value based on estimates from mesoscale burns ($\text{PM} < 2 \text{ mg/m}^3$ at 500 m downwind; Walton *et al.* 1993) and is supported by results of screening-level air modeling described in Appendix B. Results of the air modeling showed a maximum 1-hr PM concentration of $806 \text{ } \mu\text{g/m}^3$ and a maximum 24-hr concentration of $323 \text{ } \mu\text{g/m}^3$ at 1540 meters downwind of the burn site. The concentration of 1 mg/m^3 used in this risk assessment probably overstates typical ground-level concentrations to which people would be exposed during a burn lasting several days by a factor of 3 ($1/0.323 \text{ mg/m}^3$) or more, given that smoke from large-scale tests was nearly invisible from the ground at 800 m (one-half mile) (Raloff 1993) and that most people would be exposed to concentrations significantly lower than the maximums).
- Burning will not be undertaken if population centers or unprotected persons are within 5 km downwind of the burn site (based on "worst-case" exposure conditions predicted involving SCREEN 2 model in Appendix B).
- For purposes of calculating PAH intake based on mg PAH per mg PM in air, PAHs measured in smoke, whether in vapor or particulate phase, are assumed to be associated with PM.
- Concentrations of carcinogenic PAHs in smoke ($0.0015 \text{ mg PAHc/mg PM}$) and of noncarcinogenic PAHs ($0.003 \text{ mg PAHnc/mg PM}$) are based on laboratory experiments using Alberta Sweet Crude, a medium crude oil (see Table 8.4). These data are assumed to be representative of smoke emitted from burning most crude oils shipped by tanker. These PAH/PM ratios and the resulting estimates of air concentrations of PAHs are highly conservative estimates of exposure concentrations. They are comparable to concentrations measured at less than 100 m downwind of mesoscale burns reported in Fingas *et al.* (1993). For example, using the maximum total concentration of PAHs in soot from Table 8.4 of $9,000 \text{ } \mu\text{g/gm}$, a PM concentration at the exposure point of 1 mg/m^3 , and a conversion factor of 1 g/1000 mg yields a total PAH concentration of $9 \text{ } \mu\text{g/m}^3$ at 500 m. In the 1991 mesoscale burns, ground-level concentrations of total PAH ranged from $10.5 \text{ } \mu\text{g/m}^3$ at 30 m to $3 \text{ } \mu\text{g/m}^3$ at 60 m (Fingas 1993). Dilution and dispersion would reduce these concentrations significantly at greater distances. A second round of mesoscale tests performed in 1992 measured even lower PAH concentrations than reported for the 1991 tests. Therefore, the concentrations of PAHs used in the risk calculations are considered worst-case and are not likely to be exceeded. Resulting risk estimates are also considered worst-case.

- The potency of known carcinogenic PAHs measured in smoke is represented by the oral slope factor for BaP. This approach is likely to overestimate risk (see Section 8.4.4). The oral slope factor is used to assess both oral and inhalation exposures.
- The toxicity of known toxic PAHs measured in smoke is represented by the RfD for pyrene. This is a conservative assumption because pyrene has the lowest RfD (i.e., is the most toxic) of the known toxic PAHs.
- For purposes of this analysis we have assumed that the burn will last 5 days, and concentrations of hazardous materials in the smoke plume will remain constant for 5 days. Therefore, the exposure duration for inhalation is 5 days.
- Inhalation rate used to calculate chemical dose from inhalation exposure is 20 m³/day (EPA 1989a; 1991a).
- Long-term PM concentrations in soil are estimated by assuming that particulate deposition results in an evenly distributed film of soot 0.5 mm thick and that over time the soot is either dispersed by wind erosion or mixes in the top 10 cm of soil, resulting in a dilution factor of 0.005. Therefore long-term PM concentration in soil is expressed as 0.005 mg PM/mg soil. Assuming an even distribution of deposited PM of 0.5 mm is extremely conservative. In large-scale tests, little fallout was apparent at 800 m from the burn site (one-half mile) (Raloff 1993).
- Risks from ingestion of deposited particulate matter are calculated for three scenarios and summed: child ingestion of soot for 5 days, child ingestion of contaminated soil for 6 years, and adult ingestion of contaminated soil for 8,760 days (24 years). Total exposure duration to contaminated soil is therefore 30 years (EPA 1989a; 1991a). The rationale for dividing the long-term soil exposure into 6 years (child) and 24 years (adult) is that young children ages 0 < 6 years are thought to ingest more soil via hand-to-mouth behavior than do older children and adults (see next point).
- A soil/dust ingestion rate of 200 mg/day is used for children ages 1 — 6 (EPA 1989a) and a rate of 10 mg/day is used for adults (EPA 1989b).
- A soil matrix effect of 0.5 (50 percent inhibition) is applied to represent the inhibition of uptake in the gastrointestinal tract resulting from contaminant adsorption to a solid matrix such as soil. PAHs and other organic compounds such as pesticides and polychlorinated biphenyls (PCBs) bind tightly to particulate matter (Calderbank 1989). The matrix effect is conservatively estimated at 50 percent and could be 10 percent (i.e., a 90 percent reduction in uptake) (McConnell *et al.* 1984; Shu *et al.* 1988; Goon 1991).

- For carcinogens, the averaging time used to calculate average daily dose over a lifetime is 25,550 days (70 years). For noncarcinogens, the averaging time is the exposure duration (5 days for soot inhalation and ingestion, 6 years for childhood soil ingestion and 24 years for adult soil ingestion) (EPA 1989a; 1991a).
- Average adult body weight is 70 kg; average body weight of children ages 0 — 6 is 15 kg (EPA 1989a; 1991a).

8.4.5.2 Carcinogenic Risk Calculation

Carcinogenic risks are estimated as the incremental probability (additional risk above the normal rate of getting cancer) of an individual developing cancer over a lifetime as a result of exposure to a carcinogen. For example, an excess cancer risk of 1×10^{-6} (1 in 1 million) means that there is a 1 in 1 million chance of getting cancer from the exposure, and that an individual's overall risk of getting cancer has been increased by 0.000001. This is a very low risk level that could not be measured or detected in individuals or even in large populations.

Cancer risk estimates are usually interpreted within policy guidelines that establish acceptable risk levels. EPA policy, expressed in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (40 CFR Part 300) and other guidance documents, states that "For known or suspected carcinogens, acceptable exposure levels are generally concentration levels that represent an excess upper bound lifetime cancer risk to an individual of between 1×10^{-4} and 1×10^{-6} ." Measures to restrict exposure are not usually considered warranted unless cancer risk exceeds 1×10^{-4} (1 in 10,000) (EPA 1991b).

The estimate of cancer risk is calculated by multiplying the daily chemical dose averaged over a 70-year lifetime by the cancer slope factor:

$$\text{Cancer risk} = \text{Dose} \times \text{SF} \quad (1)$$

where: Dose is the chemical intake (mg/kg-day).
SF is the chemical-specific slope factor (1/mg-kg-day).

Dose is calculated using equation (2). Definitions and values for each parameter are discussed below and are based on the assumptions outlined in the previous Exposure Assumptions section.

$$\text{Dose} = \frac{\text{PM} \times \text{PAHc/PM} \times \text{ME} \times \text{IR} \times \text{ED}}{\text{AT} \times \text{BW}} \quad (2)$$

Dose is the chemical intake (mg/kg-day).

PM is the particulate matter concentration in air (mg/m^3) or soil (mg/mg). The concentration of PM in the plume is assumed to be $1 \text{ mg}/\text{m}^3$ at the exposure point downwind. The concentration of PM mixed in soil is $0.005 \text{ mg PM}/\text{mg soil}$

PAHc/PM is the ratio of carcinogenic PAHs to PM (mg/mg). As shown in Table 8.4, this is

estimated to be 1460 µg/g, or 0.0015 g/g.

IR is the inhalation rate (m³/day) or soil/dust ingestion rate (mg/day). An inhalation rate of 20 m³/day is used. A soil/dust ingestion rate of 200 mg/day is used for children ages 0 — 6 and a rate of 10 mg/day is used for adults. These rates are based on EPA guidance for risk assessment (EPA 1989a; 1989b; 1991a).

ME is the soil matrix effect that inhibits uptake of particulate-bound contaminants in the gastrointestinal tract. An ME of 0.5 is used (see Section 8.4.4).

ED is the exposure duration (days). For this evaluation, a 5-day burn is assumed. For long-term exposures to residual contamination in soils, a 10,950-day (30-year) exposure duration is used (EPA 1989a; 1991a).

AT is the averaging time, expressed in days, that is used to calculate a daily intake over the exposure duration. For carcinogens, a 70-year lifetime (25,550 days) is used (EPA 1989a; 1991a).

BW is the average body weight, expressed in kg, that is used to calculate a dose per kg. An average weight for children age 0 to 6 is 15 kg; an average adult weight is 70 kg (EPA 1989a; 1991a).

Table 8.8 shows the calculation of chemical dose using these concentrations and exposure factors. The dose is multiplied by the cancer slope factor for BaP (representing all carcinogenic PAHs in the plume) to estimate cancer risk. Risks from inhaling carcinogenic PAHs in the smoke plume and from ingesting carcinogenic PAHs deposited in the soil are summed to yield a total excess cancer risk of 5×10^{-5} (5 in 100,000). The largest contributors to the total risk estimate is childhood ingestion of pure soot and contaminated soil (see Table 8.8). The excess cancer risk estimate is a worst-case estimate that probably overestimates actual risk because it assumes no degradation of PAHs in air or in soil over a 30-year exposure duration (whereas the half-life of PAHs in air may be on the order of hours; see Section 8.4.4).

The excess cancer risk of 5 in 100,000 is within EPA guidelines for acceptable risk levels. In the United States, the overall chance of getting cancer is 1 in 3 (American Cancer Society 1990). An excess cancer risk of 5 in 100,000 would increase the overall rate from 1 in 3 to 1.00005 in 3. This is a very small increase that would not be observable in individuals or in most populations.

8.4.5.3 Noncarcinogenic (Toxic) Hazard Calculation

The potential for adverse noncarcinogenic effects resulting from exposure to a chemical is evaluated by comparing an exposure level or dose with a reference dose (RfD). The resulting ratio is called a Hazard Quotient. If the Hazard Quotient is 1 or below, there is no cause for concern for noncancer effects. In general, the greater the value of the

Table 8.8 Estimated Cancer Risk from Inhalation and Ingestion of Carcinogenic PAHs in Smoke

		Cancer Risk = SF x Dose								
		Dose = (PM x PAHc/PM x IR x ME x ED) / (AT x BW)								
where:	SF	=	Slope factor for benzo(a)pyrene (7.3 per mg/kg-day).							
	Dose	=	mg chemical/kg BW-day.							
	PM	=	mg/cu. m air or mg/mg soil.							
	PAHc/PM	=	Ratio of carcinogenic PAHs to PM (mg/mg); see Table 2-2.							
	IR	=	Inhalation rate (cu.m/day) or soil/dust ingestion rate (mg/day).							
	ME	=	Soil matrix effect.							
	ED	=	Exposure duration (days).							
	AT	=	Averaging time (days).							
	BW	=	Body weight (kg).							

See text for explanation of all parameters.

Exposure Route	PM	PAHc/PM	IR	ME	ED	AT	BW	Dose	SF	Risk
Inhalation										
	1	0.0015	20	1	5	25,550	70	8.4E-08	7.3	6.1E-07
Child (age 0 < 6) Soot Inhalation (5 days)										
	1	0.0015	200	0.5	5	25,550	15	2.0E-06	7.3	1.4E-05
Child Soil Ingestion (6 years)										
	0.005	0.0015	200	0.5	2,190	25,550	15	4.3E-06	7.3	3.1E-05
Adult Soil Ingestion (24 years)										
	0.005	0.0015	10	0.5	8,760	25,550	70	1.8E-07	7.3	1.3E-06
Total Cancer Risk										4.8E-05

Hazard Quotient above 1, the greater the level of concern. However, since the HQ does not define dose-response relationships, its numerical value should not be construed as a direct estimate of risk.

To assess the overall potential for noncarcinogenic effects posed by exposure to multiple pathways, Hazard Quotients are summed. The resulting sum is referred to as the Hazard Index (HI). The HI approach assumes that exposures to several chemicals at doses that are not hazardous in themselves could cumulatively result in an adverse health effect. For the purposes of this report, pyrene is used as a worst case surrogate to represent the non-cancer effects of PAHs in the smoke plume. Additivity of effects is implicit in this approach.

The Hazard Quotient for exposure to a chemical is calculated using the following equations:

$$HQ = \text{Dose} / \text{RfD} \quad (1)$$

$$\text{Dose} = \frac{\text{PM} \times \text{PAHnc/PM} \times \text{ME} \times \text{IR} \times \text{ED}}{\text{AT} \times \text{BW}} \quad (2)$$

The parameter definitions are the same as those described earlier except that the ratio of noncarcinogenic PAHs to PM is 0.003 mg PAHnc/mg PM (see Table 8.4) and the parameter AT (averaging time) is equivalent to ED (exposure duration) instead of a 70-year lifetime as was the case for averaging carcinogenic dose. That is, the dose for noncarcinogens is not averaged over a lifetime of exposure but rather over just the period of actual exposure.

The calculation of a Hazard Index for noncarcinogenic effects is shown in Table 8.9. The overall Hazard Index is 7.3×10^{-2} (0.073). Since the value is below 1, there is no cause for concern for adverse noncarcinogenic effects, even under the conservative exposure assumptions used in the analysis.

Conclusions

The potential cancer risk level and noncarcinogenic hazard index associated with exposure to PAHs in smoke from burning an oil spill are below levels of concern and indicate that adverse health effects from toxic and carcinogenic constituents of smoke are not a significant factor in making a burn/no burn decision.

However, it is apparent from observations and from air modeling that somewhat elevated concentrations of particulate matter can occur a few thousand meters from the burn location, depending on site-specific conditions. Exposure to elevated PM concentrations can have acute respiratory effects and exacerbate existing ailments. Therefore precautions may need to be taken to minimize such exposures if a burn is conducted 1000 to 2000 meters from a population center. Temporary and transient exceedences of ambient air quality standards could be considered acceptable if burning is conducted for the overall protection of the environment.

Table 8.9 Estimated Noncarcinogenic Hazard from Inhalation and Ingestion of Toxic PAHs in Smoke

Hazard Quotient = Dose / RfD Dose = (PM x PAHnc/PM x IR x ME x ED) / (AT x BW)										
where:	Dose	=	mg chemical/kg BW-day							
	RfD	=	Subchronic or chronic Reference Dose for pyrene (mg/kg-day)							
	PM	=	mg/cu. m air or mg/mg soil							
	PAHnc/PM	=	Ratio of noncarcinogenic PAHs to PM (mg/mg); see Table 2.2							
	IR	=	Inhalation rate (cu.m/day) or soil/dust ingestion rate (mg/day)							
	ME	=	Soil matrix effect							
	ED	=	Exposure duration (days)							
	AT	=	Averaging time (days)							
	BW	=	Body weight (kg)							
See text for explanation of all parameters										
Exposure Route	PM	PAH/nc/PM	IR	ME	ED	AT	BW	Dose	RfD	Hazard Quotient
Inhalation	1	0.003	20	1	5	5	70	8.6E-04	0.3	2.9E-03
Child (age 0<6) Soot Inhalation (5 days)	1	0.003	200	0.5	5	5	15	2.0E-02	0.3	6.7E-02
Child Soil Ingestion (6 years)	0.005	0.003	200	0.5	2,190	2,190	15	1.0E-04	0.0	3.3E-03
Adult Soil Ingestion (24 years)	0.005	0.003	10	0.5	8,760	8,760	70	1.1E-06	0.0	3.6E-05
Cumulative Hazard Index										7.3E-02

8.5 Ecological Risk Evaluation

This section is a qualitative evaluation of the relative ecological risks associated with a burn/no-burn decision. The purpose is to assess risks from exposure to toxic chemicals in crude oil and the physical and physiological effects of the oil and its residue. The first step in conducting the risk evaluation is an exposure assessment which identifies the ecological groups at risk from the burned or unburned spill. This is followed by a discussion of chemicals of concern and the ecological risk evaluation for all ecological groups that are generally at risk from in-situ burning.

8.5.1 Exposure Assessment

The various exposure pathways from the crude oil spill to ecological receptors under the burn/no-burn alternatives were evaluated to identify pathways through which organisms might realistically be exposed to hydrocarbons for the spill. To be complete an exposure pathway requires five basic elements:

- A source of chemicals (e.g., the oil spill or one of the secondary sources);
- A mechanism of chemical release (e.g., weathering, burning);
- An environmental transport medium (e.g., water, air);
- An exposure point where receptors are present; and
- An intake route (e.g., ingestion, direct contact, inhalation).

If any one of the elements is missing, the pathway is not complete and exposure of the ecological receptors cannot occur.

The mechanisms of chemical release from unburned oil spills were discussed in an earlier chapter (Chapter 2) in terms of the “weathering” processes that lead to oil losses from the surface (volatization, dissolution, natural dispersion) and those that involve the floating, remaining surface oil (emulsification, advection, spreading). Potentially complete exposure pathways are identified through the use of a conceptual site model (CSM), a schematic representation of the various exposure pathways from the source (i.e., crude oil spill) through the release mechanisms, secondary sources, and transfer mechanisms to the ecological receptor categories (e.g., plankton, finfish, waterfowl). These CSMs are developed by tracing the movement of the oil from the primary source (crude oil spill) through the release mechanisms (e.g., spill is burned), to the secondary sources (e.g., burn residue), through the transfer mechanisms (e.g., floats and moves onshore), to the ecological receptors. Tracing the movements of crude oil or its constituents through the other pathways and environments permits evaluation of the many potential exposure pathways.

As an example, for burning oil in the CSM for the offshore environment (Figure 8.1), plankton, shellfish, and finfish are thought to be “possibly” exposed to the burn residue, and the remaining ecological receptors are “unlikely” to be exposed. Spills in different parts of

the marine environment pose different types of risks to different ecological receptors. The marine environment has been divided into three parts; offshore, nearshore, and estuarine, and CSMs have been developed for each part.

The CSMs for the three environments are illustrated in Figures 8.1, 8.2, and 8.3. When using the CSMs to assess exposure risks, a number of important considerations should be kept in mind, as follows.

- For purposes of this exposure assessment the “nearshore environment” is taken to be that portion of the open-coastal environment where spilled oil could directly impact the benthic (bottom) and water tidal habitats.
- The “offshore environment” is that portion of the marine environment far enough offshore so that spilled oil poses little risk to the intertidal habitats and so that depths are great enough that spills pose no threat to benthic habitats.
- The “estuarine environments” are areas that receive fresh water inflow off the land, where nutrient concentrations are increased, salinities are lowered, and as a result biological productivities are typically much greater than in nearshore areas.
- Exposure assessments in the CSMs considers relative quantities of oil or its components under the burn/no-burn alternatives.
- Because burning greatly reduces the volume of oil on the sea surface, the probability of a complete exposure pathway is substantially lower for the burn residue than for unburned spill constituents for all receptors in all environments. Therefore, exposure assessments in the CSM recognize that burning reduces the probability of oil exposure in all environments.
- Burning preferentially consumes the volatile and soluble fractions of a crude oil spill. Therefore, burning significantly reduces exposure risks from volatile or water-soluble fractions.
- Typical, relative abundances and distributions of ecological receptors are assumed to be present in the three environments.
- The release mechanisms listed in the CSMs are considered to be the primary processes that determine the fate and movement of spilled oil or constituents through marine habitats.
- The transfer mechanism “collected” refers to that portion of the residue that is the object of physical recovery activities. This oil may not be recovered for many hours or days after the spill, and during this time it can do ecological damage.

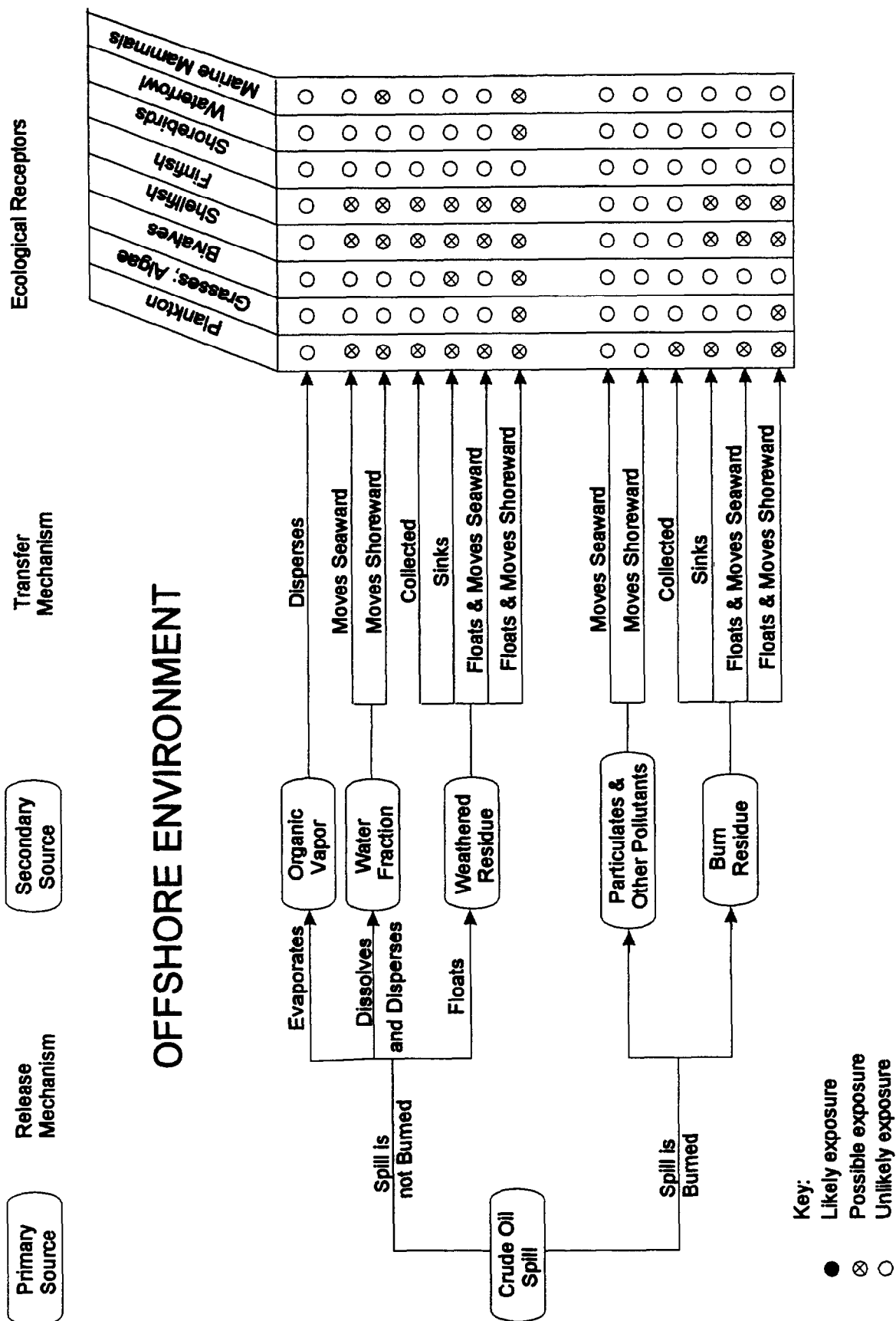


Figure 8.1 Ecological conceptual site model of offshore environment

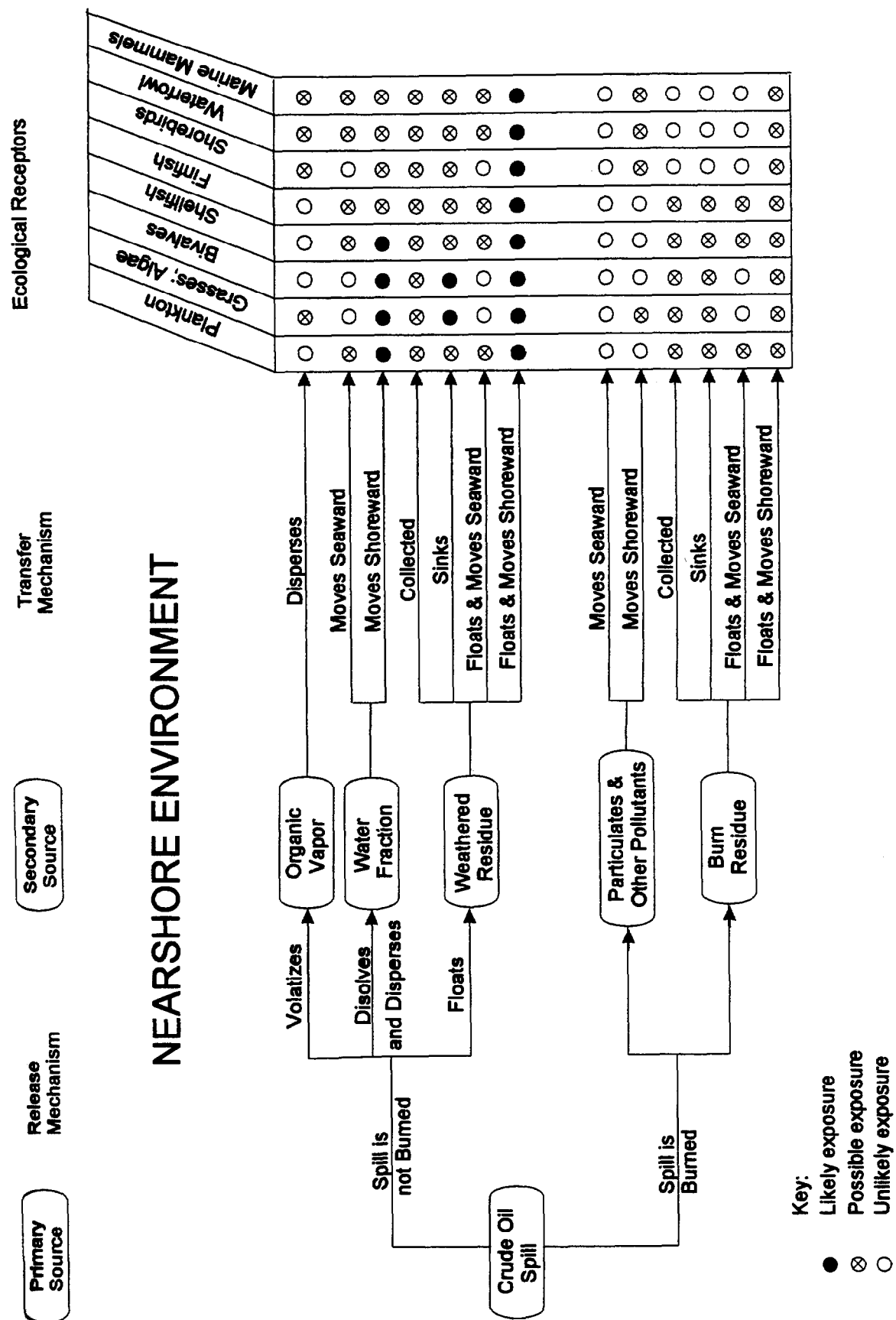


Figure 8.2 Ecological conceptual site model of nearshore environment

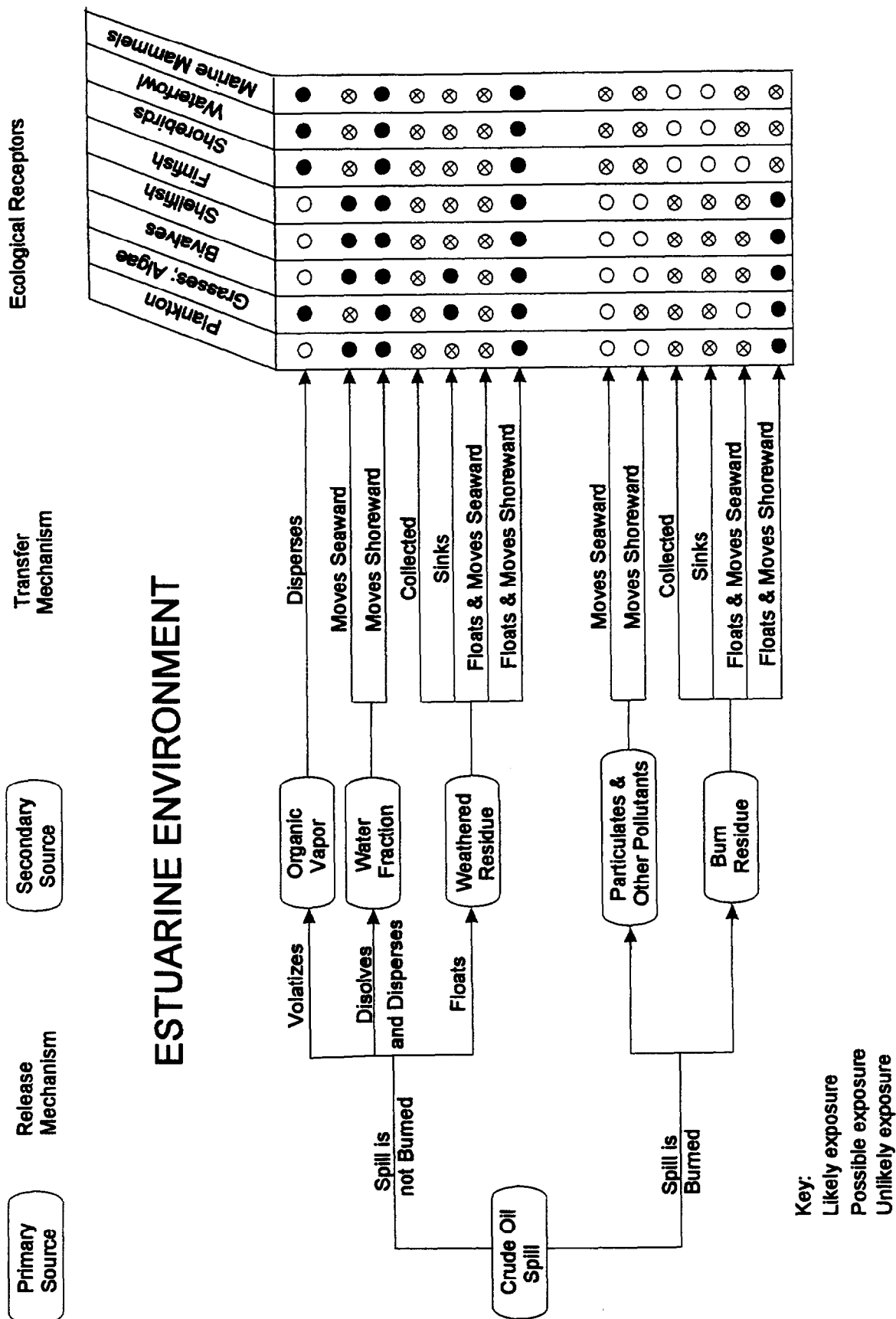


Figure 8.3 Ecological conceptual site model of estuarine environment

- In the offshore environment, movement of residues or particulate plumes “shoreward” should be interpreted as movement toward shore and shallower water, but not necessarily onto the shoreline.
- The potential for exposure of ecological receptors to oil or petroleum hydrocarbons are described as “likely”, “possible”, or “unlikely”. To provide a general frame of reference, these qualitative descriptors could be thought of as exposure probabilities of 50 percent or greater, 10 to 50 percent, and less than 10 percent, respectively.
- In both the nearshore and estuarine environments, some portion of the sinking residues will wash into the intertidal zone.
- In the estuarine environment, movement “seaward” should be interpreted as movement toward open water of the estuary (e.g., center of a bay) and away from fringing marshes and other intertidal habitats.
- Definitions of certain of the ecological receptors can be clarified as follows:
 - i) Bivalves — sedentary, benthic species refer primarily to commercially and recreationally important species (e.g., oysters, clams).
 - ii) Shellfish — epibenthic and pelagic crustaceans (shrimps, crabs).
 - iii) Marine birds — water fowl and marine birds.
 - iv) Marine mammals — refers primarily to hairy mammals such as otters and seals.

In order to obtain an overview of this assessment of exposure risk, the numbers of occurrences of “likely”, “possible”, and “unlikely” designations in Figures 8.1 to 8.3 have been summarized and presented in the following table.

Summary of Conceptual Site Model Assessments

	Offshore			Nearshore			Estuarine			Totals		
	L ¹	P	U	L	P	U	L	P	U	L	P	U
Spill is not burned	0	24	32	14	32	10	26	26	4	40	82	46
Spill is burned	0	11	37	0	25	23	5	26	17	5	62	77

1 Exposure: L - Likely; P - Possible; U - Unlikely

Obviously, great care must be taken in interpreting results from this type of analysis. However, the analysis suggests that in all environments burning reduces the likelihood that ecological receptors will be exposed to oil or petroleum hydrocarbons.

In this analysis the result is due to the fact that burning reduces the volume of oil on the sea, thereby reducing the risk of a great number of ecological receptors. The smoke plume generated by burning increases the risk to a much smaller number of ecological receptors. Therefore on balance burning appears to reduce the overall exposure risk.

The toxicity of burn residues are discussed below.

8.5.2 Chemicals of Concern for Ecological Risk Evaluation

The potentially toxic constituents of crude oil, its residues and combustion products are similar to those of concern for human health. Of the many compounds and elements present in crude oil (Table 8.3), two classes of chemicals, PAHs and metals (nickel and vanadium), are considered more toxic to ecological receptors than the alkanes, cycloalkanes or the lower molecular weight aromatics (e.g., benzene, xylene). Also these VOCs volatilize from a fresh oil spill and are combusted during burning. However, both the PAHs and metals are in relatively low concentrations in crude oil and are not in a form that is readily bioavailable to ecological receptors.

Several of the individual PAHs are recognized as potent carcinogens while other PAHs can adversely affect survival and growth of organisms. PAHs vary widely in their toxicity to aquatic organisms, with toxicity generally increasing with increased molecular weight (Eisler 1987).

Individual PAHs are in low concentrations in crude oil and have limited mobility in an aquatic setting. Although there can be approximately 15 to 30 percent aromatic hydrocarbons in crude oil (Table 8.1), most of these aromatics are comprised of lighter weight benzenes and naphthalenes (Table 8.3). Recognized carcinogenic or toxic PAHs such as benzo[a]pyrene and pyrene are typically found at concentrations less than 5 mg/kg (Table 8.3). Low concentrations of the lighter PAHs can be found in water beneath oil spills, but as discussed earlier most PAHs have low solubilities in water and high partition coefficients

$(K_{o/w})^1$ that limit the mobility of PAHs from oil into the water. The following table lists the solubilities and Log $K_{o/w}$ for some of the PAHs found in crude oil.

SOLUBILITIES AND PARTITION COEFFICIENTS FOR POLYCYCLIC AROMATIC HYDROCARBONS

PAH	Solubility in Water (mg/L)	Log $K_{o/w}$ Values
Naphthalene	31	3.4
Pyrene	0.13	5.3
Anthracene	0.06	4.4
Benzo[a]anthracene	0.014	5.6
Benzo[a]pyrene	0.004	6.0
Benzo[g,h,i]perylene	0.0003	7.2

Sources: Eisler (1987); Varanasi (1989); Callahan *et al.* (1979)

An example of the limited mobility can be illustrated for benzo[a]pyrene. This PAH has a reported concentration of 2.8 mg/kg in Kuwait crude oil (Table 8.1). The $K_{o/w}$ for benzo[a]pyrene is $K_{o/w} = 1 \times 10^6$ (Log $K_{o/w} = 6.0$), which means:

$$K_{o/w} = \frac{\text{concentration of B[a]P in oil}}{\text{concentration of B[a]P in water}} = 1 \times 10^6$$

The equilibrium concentration of benzo[a]pyrene in the water phase in an oil water mixture could be estimated to be:

$$\text{concentration of Benzo[a]pyrene in water} = \frac{\text{concentration of Benzo[a]pyrene in oil}}{K_{o/w}} = 2.8 \times 10^{-6}$$

Therefore, the concentration of benzo[a]pyrene in water immediately beneath an oil slick might be as much as 2.8×10^{-6} mg/L ($\approx 2.8 \times 10^{-6}$ ppm). This is four orders of magnitude less than the concentration of benzo[a]pyrene reported by Neff (1979) as toxic (LC_{50}) to the sandworm (*Neanthes arenceodentata*). An LC_{50} is the concentration that is lethal to 50 percent of the test organisms.

For pyrene (4.5 mg/kg in crude oil; Log $K_{o/w}$ of 5.3), the highest concentration expected in water directly beneath a spill would be 2.3×10^{-5} mg/L ($\approx 2.3 \times 10^{-5}$ ppm). No aquatic toxicity data were found for pyrene in a review of applicable toxicity summaries (Eisler 1987; USEPA 1980); however, the expected pyrene concentration is three orders of

¹ The octanol/water partition coefficient is defined as the ratio of a chemical's concentration in the octanol phase to its concentration in the water phase of a two-phase octanol/water system at equilibrium.

magnitude lower than the lowest toxic concentration listed in Eisler (1987) (50 ug/L for a copepod [zooplankton] exposed to naphthalene).

For naphthalene, the PAH with the lowest Log K_{ow} (3.4), the highest concentration expected in water directly beneath a spill having 400 mg/kg naphthalene would be 0.16 mg/L. This concentration of naphthalene may be toxic to zooplankton (depending on exposure duration and other factors) but would not be toxic to fish or shellfish, which have toxicities (LC_{50} s) of 0.92 mg/L for pink salmon to 150 mg/L for mosquitofish (Eisler 1987).

The primary metals found in crude oil, nickel and vanadium, are found in concentrations of 1 to 20 mg/kg, but may be present at concentrations up to 200 mg/kg nickel and 1,200 mg/kg vanadium in some crude oils (WHO 1989). These metals occur primarily as organometallic complexes known as porphyrins (Costantinides and Arich 1967) which can be distilled at temperatures above 500°C (WHO 1989), and are therefore stable at ambient temperatures. Because these metals are complexed in porphyrins, they are unlikely to represent a risk to ecological receptors.

Because PAHs and metals in crude oil are in low concentrations and have limited bioavailability in water, the risk to ecological receptors is likely more closely related to the probability of direct exposure to oil and its physical and cumulative toxic effects than to the individual chemicals found in the oil. As discussed in Chapter 2, one of the most important toxic effects of oil on birds and marine mammals is fouling of feathers and fur (Freedman 1989). This fouling causes a loss of the properties of insulation and buoyance and leads to death by drowning or extreme heat loss (hypothermia). Sea otters and other furred marine mammals are especially vulnerable to oil spills because of their reliance on fur rather than blubber for insulation (Stoker 1992). Birds and marine mammals can also suffer toxic effects by ingesting or inhaling oil while in direct contact with the spill or during attempts to clean feathers or fur by preening. There continues to be long-term chronic effects in fish and waterfowl resulting from direct contact with oil spilled from the *Exxon Valdez* as reviewed by Schneider (1993).

8.5.3 Relative Risk Evaluation

The relative risk evaluation discusses whether burning or not burning spilled crude oil presents fewer risks to ecological receptors in the offshore, nearshore, and estuarine habitats. Because the relative risks to ecological receptors is more directly related to the probability of direct exposure to crude oil and its constituents than to the individual compounds in the oil, the results of the risk evaluation closely parallel those of the exposure evaluation:

- Because burning a targeted crude oil slick reduces the volume of oil on the sea by at least 75 percent, the overall probability of ecological risk is substantially less for burn residue than for the spilled oil in all three marine environments.
- Because burning effectively eliminates the volatile/soluble fraction of a crude oil spill, two potential exposure pathways and their related risks are eliminated.

- Because of the low number of “likely” or “possible” complete exposure pathways, the less likely risk would be due to smoke (i.e., particulates and other pollutants) inhalation and direct contact by the ecological receptors most of which are under water.

It appears, based on the results of the ecological risk evaluation, that under practically all combinations of physical conditions (e.g., winds and currents) and ecological receptors, the preferred decision would be to burn a crude oil spill rather than not to burn. Burning the spill may pose an overall increase in risk to ecological receptors only if the most sensitive and important (e.g., threatened or endangered species) receptors are physically isolated from the marine/estuarine waters, and yet are close enough to the potential burn site that they would be exposed to the fire or soot (particulates and other airborne pollutants). Such a situation may exist if significant terrestrial receptors were located onshore directly downwind from a crude oil spill and there were only limited receptors in the nearshore habitats. Because this scenario is highly unlikely, it was not evaluated.

8.6 Human and Ecological Factors Important to a Burn/No-Burn Decision

Burning spilled crude oil may be appropriate if the potential human and environmental impacts of burning are judged to be less than those of the unburned slick. Evaluating the potential impacts of leaving the oil unburned and of burning the oil, and comparing the overall effects is the logical approach for making a burn/no-burn decision.

Estimates of impact are based on the fate of unburned oil and the products of burning, the distribution of resources, and the sensitivities of those resources to unburned oil and to burning. The foregoing risk evaluations were conducted to assist in estimating the sensitivity of resources, and characterizing the potential impact on those resources resulting from burning or from unburned oil. Conclusions from those evaluations provide factors that are important to making a burn/no-burn decision.

The human health risk evaluation identifies the following factors that need to be considered in making a burn/no-burn decision:

Health Risks from Unburned Oil Spills

- Oil spills, even large spills, rarely pose major health risks to nearby people. The most probable route of exposure to humans is through inhalation of hydrocarbon vapor, although this only rarely leads to detectable effects on humans. Ingestion of contaminated seafood and ingestion of contaminated drinking water (in fresh water spills) may be of concern in some instances. These health risks can be reduced by burning but only at the cost of incurring other risks.

Health Risks from Exposure to PM in Burn Emissions

- It is apparent from observations and from results of air quality modeling that high concentrations of particulate matter can occur within several hundred meters of a burn location. Exposure to high concentrations of PM one or two kilometers from the burn can have acute respiratory effects and exacerbate existing ailments. Measures to prevent human exposures to smoke may be required if a burn is conducted one or two kilometers from a downwind population center. "Safe distances" will depend on the size of the burn.

Health Risks from Toxic and Carcinogenic Compounds in Burn Emissions

- The potential cancer risk level and noncarcinogenic hazard index associated with exposure to PAHs in burn emissions are below levels of concern. This suggests that adverse health effects from toxic and carcinogenic constituents of smoke are not significant factors in making a burn/no-burn decision.

The ecological risk evaluation identifies the following factors that need to be considered in making a burn/no-burn decision:

Spill Residue Volume Reduction

- The overall probability of ecological risk is substantially less for burn residue than for the unburned spill in all three marine environments because burning substantially reduces the volume of oil on the sea surface.

Risks from Oil Burning

- Burn emissions (smoke) may pose a risk to wildlife in the vicinity of the spill, but it poses minimal risk to other marine species which are underwater.
- Burning effectively eliminates much of the volatile/soluble fraction of spilled crude oil, and thus the ecological risks associated with the dissolved/dispersed and evaporated components of spilled oil are eliminated.

Risk to Onshore Species

- A decision not to burn an oil spill may possibly represent less overall risk to ecological receptors if the most sensitive and important (e.g., threatened or endangered species) receptors are physically isolated from the marine/estuarine waters yet are close enough to the potential burn site that they would be exposed to the fire or soot (particulates and other airborne pollutants). Such a unique situation may exist if significant terrestrial receptors were located onshore directly downwind from a crude oil spill and there were only limited receptors in the nearshore habitat.

Decisions on whether or not to burn all or part of a marine oil spill can be made without reference to other spill control possibilities or can be made with reference to burning as but one cleanup option to be used in conjunction and coordination with other techniques (specifically, physical recovery and dispersant-use). In either case, this evaluation supports the view that in almost all circumstances burning crude oil on water reduces the potential risks to humans and the environment, compared to leaving the same oil unburned.

8.7 References to Chapter 8

- Allen, A.A. and R.J. Ferek. 1993. Advantages and disadvantages of burning spilled oil. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. p. 765-772.
- American Cancer Society. 1990. Cancer Facts & Figures — 1990. American Cancer Society. Atlanta, GA.
- Benner, Jr., B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, R.C. Lao, and M.F. Fingas. 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. *Environmental Science and Technology*, v 24, n 9, pp. 1418-1427.
- Benner, B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, D.D. Evans, M.F. Fingas, and K. Li. 1991. Emissions of polycyclic aromatic hydrocarbons from the combustion of crude oil on water. *Spill Technology Newsletter*, 16 (1).
- Calderbank, A. 1989. The Occurrence and Significance of Bound Pesticide Residues in Soil. *In* Review of Environmental Contamination and Toxicology 108: 71-103. Springer-Verlag. New York.
- Callahan, M., M. Slimak, N. Gabel, I. May, C. Fowler, R. Freed, P. Jennings, R. Durfee, F. Whitmore, B. Maestri, M. Mabey, B. Holt and C. Gould. 1979. Water-Related Environmental Fate of 129 Priority Pollutants. Chapter 97. EPA 440/4-79-029a.

- Casarett, L.J. and J. Doull. 1991. Toxicology: The Basic Science of Poisons. 4th ed. Pergamon Press.
- Clark, R.C. and W.D. MacLeod. 1977. Impacts, transport mechanisms and observed concentration of petroleum in the marine environment. In D.C. Malins (ed). Effects of petroleum on arctic and subarctic marine environments and organisms. Vol. 1. Nature and fate of petroleum. Academic Press, Inc. New York, N.Y., pp. 91-223.
- Clement Associates. 1988. Comparative Potency Approach for Estimating the Cancer Risk Associated with Exposure to Mixtures of Polycyclic Aromatic Hydrocarbons. Interim Final Report. EPA Contract No. 68-02-4403.
- Costantinides, G. and G. Arich. 1967. Non-hydrocarbon compounds in petroleum. In: WHO, 1989.
- Eisler, R. 1987. Polycyclic Aromatic Hydrocarbon Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review. U.S. Fish and Wildlife Service. Biological Report 85(1.11).
- Falk, H.L., P. Kotin and S. Thompson. 1964. Inhibition of carcinogenesis: The effect of polycyclic hydrocarbons and related compounds. Arch. Environ. Health 9: 169-179.
- Ferek, R.J., P.V. Hobbs, J.A. Herring, K.K. Laursen, R.E. Weiss, and R.A. Rasmussen. 1992. Chemical composition of emissions from the Kuwait oil fires. Jour. Geophys. Research, v. 97 (D13); p. 14483-14489.
- Fingas, M.F. 1979. The Basics of Oil Spill Cleanup. Environmental Canada.
- Fingas, M.F., K. Li, F. Ackerman, P.R. Campagna, R.D. Turpin, S.J. Getty, M.F. Soleki, M.J. Trespalacios, J. Pare, M.C. Fissonnette, and E.J. Tennyson. 1993. Emissions from Mesoscale in-situ oil fires: The Mobile 1991 and 1992 tests. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 749-821.
- Freedman, B. 1989. Environmental Ecology: the Impacts of Pollution and Other Stresses on Ecosystem Structure and Function. Academic Press, Inc., San Diego, CA.
- Goon, D. 1991. Oral Bioavailability of "Aged" Soil-Adsorbed Benzo(a)pyrene (BaP) in Rates. Society of Toxicology Annual Meeting Abstracts #1356.
- Laskin, S.M., M. Kushner and R.T. Drew. 1970. Studies in pulmonary carcinogenesis. M. G. Hanna *et al.*, eds. Inhalation Carcinogenesis. AEC Symposium Series No. 18. Washington, D.C.: U.S. Atomic Energy Commission.
- Lippson, A.J. and R.L. Lippson. 1984. Life in Chesapeake Bay. John Hopkins University Press. Baltimore, Maryland.

- McConnell, E.E., G.W. Lucier, R.C. Lumbaugh, P.W. Albro, D.J. Harvan, J.R. Hass and M.W. Harris. 1984. Dioxin in Soil: Bioavailability After Ingestion by Rats and Guinea Pigs. *Science* 223:1077-1079.
- National Academy of Sciences (NAS). 1972. *Biologic Effects of Atmospheric Pollutants: Particulate Polycyclic Organic Matter*. Washington, D.C. NAS.
- Neff, J.M. 1979. *Polycyclic Aromatic Hydrocarbons in the Aquatic Environment: Sources Fates and Biologic Effects*. Applied Science Publ. Ltd., London. In: Eisler, 1987.
- Neff, J.M. and J. W. Anderson. 1981. *Response of Marine Animals to Petroleum and Specific Petroleum Hydrocarbons*. Halsted Press, New York.
- Raloff, J. 1993. Burning issues: Is torching the most benign way to clear oil spilled at sea? *Science News* 144 (14):220-223 (October 2, 1993).
- Schneider, D. 1993. Oil Spill Has Long-Term Effects. *Water, Environ. Technol.* September, 1993.
- Shu, H., D. Paustenbach, F.J. Murray, L. Marple, B. Brunck, D. Dei Rossi and P. Teitlebaum. 1988. Bioavailability of Soil-Bound TCDD: Oral Bioavailability in the Rat. *Fundam. Appl. Toxicol.* 10:648-654.
- Stoker, S.W. 1992. *Biological conditions in Prince William Sound, Alaska following the Valdez oil spill: 1989-1992*. Prepared by Beringian Resources, Arthur D. Little, Inc., Cook Inlet Fisheries Consultants, Woodward-Clyde Consultants. September 1992.
- Tebbens, B.D., J.F. Thomas and M. Mukai. 1966. Fate of arenes incorporated with airborne soot. *Amer. Ind. Hyg. Assoc. J.* 27:415-422.
- Thomas, J.F., M. Mukai and B.D. Tebbens. 1968. Fate of airborne benzo(a)pyrene. *Environ. Sci. Tech.* 2:33-39.
- U.S. Environmental Protection Agency (EPA). 1980. *Ambient water quality criteria for polyaromatic hydrocarbons*. EPA 440/5-80-069.
- U.S. EPA. 1989a. *Risk Assessment Guidance for Superfund. Volume 1: Human Health Evaluation Manual*. EPA/540/1-89/002.
- U.S. EPA. 1989b. *Exposure Factors Handbook*. EPA 600/8-89/043.
- U.S. EPA. 1991a. *Human Health Evaluation Manual, Supplemental Guidance: "Standard Default Exposure Factors."* OSWER Directive.
- U.S. EPA. 1991b. *Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*. OSWER Directive 9355.0-30.

- U.S. EPA. 1993. Health Effects Assessment Summary Tables (HEAST). Environmental Criteria and Assessment Office. Cincinnati, OH.
- U.S. EPA. Integrated Risk Information System (IRIS). On-line database.
- Varanasi, U. (Ed.) 1989. Metabolism of Polycyclic Aromatic Hydrocarbons in the Aquatic Environment. CRC Press, Inc., Boca Raton, FL.
- Walton, W.D., D.D. Evans, K.B. McGrattan, H.R. Baum, W.H. Twilley, D. Madrzykowski, A.D. Putorti, R.G. Rehm, H. Koseki, and E.J. Tennyson. 1993. In-situ burning of oil spills: Mesoscale experiments and analysis. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 679-734.
- World Health Organization (WHO). 1989. IARC monographs on the evaluation of carcinogenic risks to humans. Occupational exposures in petroleum refining: Crude oil and major petroleum fuels. International Agency for Research on Cancer. Vol. 45. Lyon, France.

9.0 Survey of Regulatory Issues and Regulations

9.1 Introduction

The use of in-situ burning as an oil spill countermeasure hinges on its approval by the Federal On-Scene Coordinator (FOSC) and State On-Scene Coordinator (SOSC) through the Regional Response Team (RRT) process, as specified in the National Contingency Plan (NCP). On a local basis the acceptance of in-situ burning as a response tool varies widely from region to region. This brief chapter summarizes the approaches taken by regions to regulate the use of in-situ burning, and summarizes certain of the problems facing regulators and operators in implementing in-situ burning.

9.2 Issues

From a regulatory perspective, the major issues surrounding the use of in-situ burning relate to impacts on air quality. The Clean Air Act and State Air Quality regulations delineate acceptable concentration levels of pollutants generated from oil incineration. In general, concentrations of particulates smaller than 10 μm (PM10) and duration of exposure are the major focus and concern from an air quality perspective. Local Air Quality Boards and State Spill Response Teams are frequently at odds over the use of burning, as each group seeks to protect the resources under its stewardship. An analysis of total environmental impacts resulting from different options is required to provide both parties with a mechanism to either accept or reject burning as a countermeasures option.

9.3 Procedure for Review

The following section presents an overview of in-situ burning policies in U.S. coastal regions as of January 1994. In November and December of 1992, all USCG Marine Safety Offices (MSO) in coastal regions (except Alaska and Hawaii) were canvassed in order to compile a list of local issues and concerns, procedures, and state regulations concerning in-situ burning of an oil spill on water. A questionnaire was sent to each USCG MSO office and verbal and written responses were received which reflected the state of planning and preparedness at the end of 1992 in regards to the in-situ burning issue. The results of this canvassing is summarized in Table 9.1.

In December 1993 all RRT's and NOAA Scientific Support Coordinators (SSCS) were canvassed for their comments on the information in Table 1. At the time of this report, only two responses had been received from this second canvassing. The 1992 and 1993 questionnaires are presented in Appendix C.

STATE	RESPONSIBLE AGENCIES	GUIDELINES	CHECKLIST	USE LIKELY?	EXCLUDED AREAS	APPROVED IN EXERCISE	COMMENTS
REGION I							
ME	RRT Dept. of Pollution Prevention Oil and Hazardous Materials	NRT Guidance None. Case-by-case.		P		Y	New Brunswick wetland burn, March 93
RI	Dept. of Environmental Management Division of Water Resources	None. Case-by-case.		P			
CT	Dept. of Environmental Protection, Oil & Chem. Spill Response Div.	None. Case-by-case.		N			Approval not likely, but may reconsider.
NH	Dept. of Env. Services, Water Supply & Pollution Control Div.	None. Case-by-case.		N			
MA	Environmental Protection. HazWaste Cleanup	None. Case-by-case.		N			
REGION II							
NY	RRT Dept. of Environmental Quality	NRT Guidance None. Case-by-case.					
NJ	Dept. of Env. Protection	None. Case-by-case.		P			Developed policy. Would consider use offshore.
REGION III							
PA	RRT Dept. of Env. Resources	NRT Guidance None. Case-by-case.		P		Y	Developed policy. Would consider use offshore.
MD	Dept. of Env., Haz. & Solid Waste Mgmt. Admin., Oil Control	None. Case-by-case.		P	Chesapeake Bay		1991 exercise approved. Unlikely in State waters.
DE	Dept. of Nat. Resources & Env. Control, Div. of Air & Haz. Waste	None. Case-by-case.		P	Delaware Bay		Would consider use offshore.
VA	Dept. of Waste Management	None. Case-by-case.		N			
REGION IV							
NC	RRT Dept. of Env., Health and Natural Resources Water Resource Division	Regional None. Case-by-case.		Y			Approval probably limited to outside 3 mile State limit.
SC	Dept. of Health and Env. Control Solid and Hazardous Waste	Developing policy. None. Case-by-case.	Y**	?		Y	State DHEC is reviewing.
GA	Dept. of Natural Resources, Env. Protection Div.	None. Case-by-case.	Y**	?		Y	State is reviewing.
FL	Dept. of Natural Resources Dept. of Env. Regulation	None. Developing policy	Y**	P	On land	Y	Approval in Key is proposed and has good support.
REGION V							
AL	RRT Dept. of Env. Management	Regional and pre-approved ANNEX		Y	Over coral beds or hard rocks		Pre-approved for OSC decision in areas > 3nm offshore
MS	Dept. of Env. Quality Bureau of Pollution Control	Guidelines available.	Y	P			
LA	Dept. of Env. Quality Dept. of Human and Health Services	Guidelines available. Form available to request burn	Y	P			Historical use in marsh spills
TX	Tx. Air Control Board	Application procedure.	Y	P			Historical use in marsh spills
REGION IX							
CA	RRT CA Fish and Game, Air Quality Management Districts, Air Resources Board	None.	Y	N			Possible use in State waters. Monitoring required.
REGION X							
OR	RRT Dept. of Env. Quality	New guidelines expected in June		P			OR and WA expected to use AK computer model for decision-making. New policy due in June 94
WA	Dept. of Ecology	New guidelines expected in June		P	Puget Sound	Y	Exercise approval for Straits of Juan de Fuca in 1992, denied in Puget Sound 1993
AK	Dept. of Environmental Conservation	Guidelines with pre-approved areas	Y	Y	None	Y	Pre-approved North of Arctic Circle. Pre-approval expected for Prince William Sound and Cook Inlet. Historical use along TAPS pipeline, Prudhoe Bay.
CARIBBEAN							
PR and VI		None, developing guidelines	N	?			Clean Caribbean has fire boom - working on development of RRT policy

*Y: yes / N: no / P: possible

**in Region IV Policy (expected to be revised by mid 1994)

Table 9.1 Summary of Regulatory Status for Use of In-Situ Burning

9.4 Summary of Review

In-situ burning has received more attention during 1993 than in previous years, perhaps as a result of the OPA 90 planning process. In previous years particular attention was dedicated to the issue of dispersants, but in 1993 burning and bioremediation were also given considerable attention as viable spill countermeasures. The National Response Team (NRT) has issued a statement specifying in-situ burning is a viable oil spill countermeasure that should be considered as part of a response. The Emergency Response Division of the EPA has issued guidelines for the use of in-situ burning at present. Region VI and Alaska have their plans authorizing pre-approval of in-situ burning under specified conditions.

Areas Plans that have been developed under OPA 90 show that regulators from different states vary in their acceptance of in-situ burning. The State of Alaska was the first to adopt in-situ burning as a spill response technique, subject to the on-scene commander's approval. Pre-authorization was applicable to all regions north of the Arctic Circle, and is expected to become the policy for Prince William Sound and Cook Inlet in 1994. Actual burning under this pre-approval process took place for the first time in the U.S. at an inland spill in Alaska during 1992 (OSIR, 25 Nov. 1992). Also within RRT Region VI, the States of Texas and Louisiana have established that burning is a preferred response option beyond three miles offshore. An exclusion zone exists within seven miles of the populated area of Grand Isle and near the offshore areas where coral and hard banks exist. In addition, certain area plans in Region VI indicate many nearshore zones in which burning is considered as a method of preference. Within RRT Region IV the Mobile, Alabama COTP zone is being considered as a pre-approval zone for in-situ burning, and the MSO has prepared a guidance document for in-situ burning in that area (see Appendix D). In other regions some of the RRTs and states were working on policies and procedures at the time of our survey, while others had not addressed the issue at all.

Based on Area Plans it is clear that some jurisdictions have accepted in-situ burning as a viable response tool, and have gone so far as to develop burn application guidelines. However, even in areas where in-situ burning is accepted, industry and government still share two common concerns. One is that unless a commitment to use in-situ burning is in place, the necessary preparations will not be made to make burning a truly viable operational option in the event of a spill. The second concern is that the time required to apply for and obtain permission for burning may exceed the window-of-opportunity for burning. Delays in obtaining permission for a burn have been noted in several recent spill exercises. In addition, many areas are expected to require that plans for air sampling and air quality monitoring be submitted with the applications for burning.

The Commandant of the Coast Guard and the NRT have actively sought input from each RRT regarding in-situ burning. In 1992, the USCG canvassed each RRT to answer questions concerning whether research being conducted was sufficient to allow RRTs to develop policy regarding the use of in-situ burning, and what additional information, if any, would be needed in a Region before it could fully adopt in-situ burning as a response tool. Coast Guard questionnaires and a summary of research being conducted are included in Appendix E.

The information received regarding policies and issues is summarized in Table 1. Specific comments and contacts at local levels are provided in Appendix F.

9.5 Burn Application Process

Many coastal regions of the U.S. recognize that in-situ burning provides a certain operational and environmental advantages when compared to mechanical recovery. However, they also recognize that in-situ burning of spills also has environmental drawbacks in terms of impact on air quality. As a consequence most regions have developed or are developing guidelines for in-situ burn application. These guidelines are generally located in the Alternative Countermeasures, Chemical Response, or similar sections of Area Response Plans developed under OPA 90. The following provides a summary of the type of information generally requested as part of the application process.

Spill Information:

- Cause
- Location
- Date/Time of Spill
- Volume of Spill
- Trajectory

Character of Spilled Oil:

- Oil Type/Name
- Specific Gravity
- Flash Point
- Aromatics/Asphaltenes/Saturates
- Pour Point
- State of Weathering

Weather and Oceanographic Conditions:

- Air/Water Temperatures
- Wind Speed/Direction
- Sea State
- Water Depth
- Tides Forecasted
- Wind Direction/Speed
- Visibility
- Air Mass Stability
- Pollution Level

Environmental Habitats:

- Bird Colonies
- Rookeries/Haulouts
- Nesting Areas
- Fixed resources (kelp/coral)
- National/State Parks or Wildlife Preservation Areas

Human Resources:

Distance/Direction to Nearest Populated Area
Vessel/Air Traffic Routes

Implementation Information:

Operations Plan
Equipment for Containment/Control
Ignitors
Schedule/Duration
Number of Trained Personnel
Monitoring Plan Burn Location
Smoke Reduction Chemicals
Communications Plan

An example of the type of information required by the RRT Regional Co-chairs for consideration of in-situ burning is provided in the MSRC application to the RRT for pre-approval in Region VI. The application, submitted in January 1994, includes a review of operational and environmental aspects of in-situ burning and both a Oil Spill Response Checklist for In-situ Burning (see Appendix G) and Operational Checklist: In-situ Burning (see Appendix H).

10.0 Decision-Making for In-Situ Burning

10.1 Introduction

This chapter presents a flowchart for helping spill managers decide where and when to use in-situ burning to deal with oil spills on water. The decision system focuses on three major questions:

1. Will the oil spill ignite and burn given existing spill and environmental conditions?
2. Is a burning operation feasible given available equipment and trained personnel?
3. Do the environmental benefits of the burn outweigh the potential risks from the burn to the public, spill workers, the environment, and property?

The flowchart in Figure 10.1, and the accompanying text, guide users through the issues to reach a “burn” or “no-burn” decision. The flowchart differs from the checklist in Chapter 6 (Section 6.7) simply in that the latter itemizes the factors to consider in preparing for and implementing a burn operation while the flowchart guides the burn/no-burn decision.

10.2 Scope, Limitations and Assumptions

The following are limitations and assumptions used in developing the flowchart and certain of the critical quantitative threshold values.

1. The decision-aid applies to treatment of batch spills (as opposed to continuous discharges) on water.
2. The decision-aid attempts to consider the burning of both boomed parcels of oil and uncontained slicks.
3. In the decision-aid, health and safety thresholds have been established assuming that no more than 1000 m² of slick area are burning at one time.
4. It is assumed that ignition will be accomplished using a standard Heli-torch ignition system charged with a gasoline-based mixture or gasoline/fuel oil mixture.
5. In reality, making decisions concerning the use or non-use of in-situ burning is a two-step process. The first step assesses the feasibility, practicality, and environmental and safety risks of burning with respect to the existing spill scenario. The second step considers whether burning alone or burning in combination with other countermeasures such as mechanical recovery offers the greater potential level of efficiency in reducing the volume of oil on the sea surface and reducing the overall threat to environmental resources while still offering an acceptable level of safety and

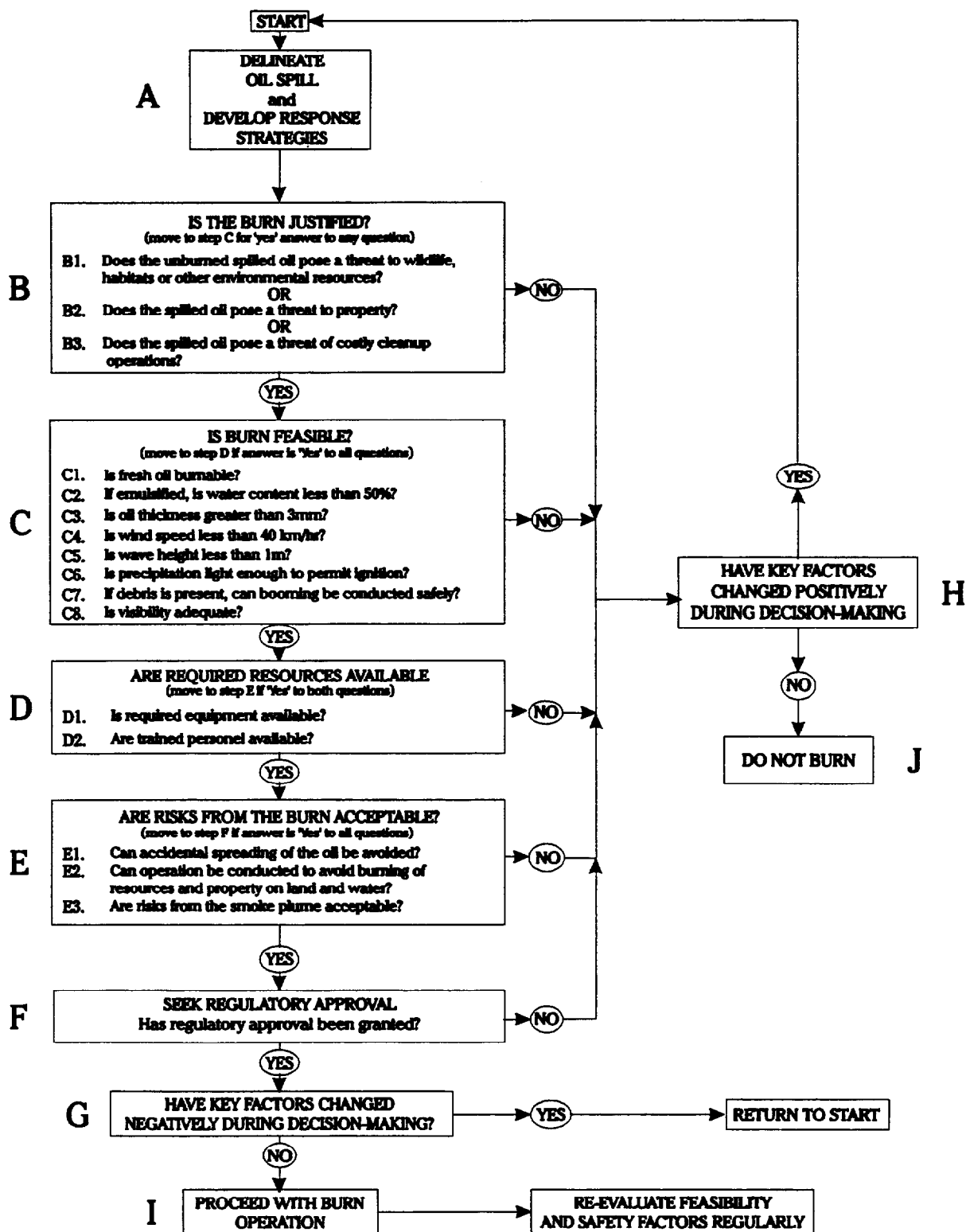


Figure 10.1 Decision tree for in-situ burning of oil spills on water

cost effectiveness. For purposes of this study we have dealt only with the first decision step.

10.3 Decision-Aid System

This section contains the actual decision-aid for in-situ burning of batch spills. It is composed of a decision flowchart (given in Figure 10.1), and the accompanying text. The following lettered and numbered sections refer to corresponding steps in the flowchart in Figure 10.1.

A. DELINEATE OIL SPILL AND DEVELOP RESPONSE STRATEGIES

This initial step calls on the decision-maker to obtain certain specified information on the spill and specify the key elements of the "burn plan" for the operation at hand. Certain of the subsequent decisions will depend on the specifics of the response plan. The decision-maker should specify the operational strategy including requirements of equipment, manpower, logistic support as well as strategies for protecting the health and safety of people and the environment.

B. IS THIS BURN JUSTIFIED?

This step in the decision system specifies the justification for the burn in the present spill scenario. In any scenario there will be certain risks associated with burning (even if they are only risks to the spill workers involved) and there must be clear benefits to be gained from the burn that will justify taking these risks.

There may be several justifications for burning the spilled oil, ranging from environmental protection to minimizing cleanup costs. In the absence of an obvious, compelling need for reducing spill damage or costs, there can be little justification for burning the spill and assuming the risks that burning presents to spill workers and the spill source (e.g., a tanker and its remaining cargo).

In this step (B) one should move to Step C if any of the three questions answers "yes". In all other steps (C, D and E) all questions must be answered "yes" in order to move to the next step.

C. IS THE BURN FEASIBLE?

This section of the decision flow chart deals with conditions that would hinder ignition of slicks. The critical thresholds for variables mentioned in the flow chart are the operational limits for burning oil slicks on water. These thresholds are conditions known to hinder burning under ideal experimental conditions so that if real-world conditions are known to exceed these thresholds, burning is clearly not possible. On the other hand, if conditions for any variable are not known, that variable should not be used to reject burning as a response option.

C1 Is the Spilled Oil of a Burnable Type?

Most crude and refined oils will burn under favorable conditions when spilled.

However, some refined products resist ignition even when fresh. Oils that have been shown to resist ignition under ideal experimental conditions include the following:

1. Bunker A or No. 4 Fuel Oil;
2. Bunker B or No. 5 Fuel Oil;
3. Bunker C or No. 6 Fuel Oil;

If the spilled oil belongs to any of these oil types, burning is not feasible and should not be considered further.

C2 If the Oil is Emulsified, is the Water Content of the Emulsion less than 50%?

While most oils are burnable when fresh, they quickly become more difficult to ignite as they weather on the sea surface. From the perspective of in-situ burning, the most important aspect of weathering is the uptake of water by the oil slick and the formation of stable water-in-oil emulsion. Emulsification occurs quickly in some oils and more slowly in others, but almost all crude oils emulsify to some extent. Under laboratory conditions emulsified oils that contain more than 50% water are difficult to ignite. Because in the real world water-content of oils is difficult to measure, as a rule of thumb one can say that if most of the oil in the slick is visibly heavily emulsified and appears viscous and rusty brown in color, there is little chance of successful ignition. This is true for currently available ignition systems and techniques. New igniting mixtures including emulsion breaking chemicals, ignition promoters and the like should improve the situation.

C3 Is the Oil Thickness Greater than 3 mm?

Thick oil slicks burn readily, but very thin slicks are very difficult to ignite. In laboratory experiments slicks less than 3 mm in thickness are almost impossible to ignite. Operationally, it is currently not possible to measure or predict accurately the thickness of oil slicks. For boomed slicks it is probably inefficient to begin the burning stage of the operation until at least an oil thickness of 5 to 10 cm has been accumulated in the boom. Under these circumstances spill thickness should not be a problem. For unboomed slicks oil thickness will vary widely and the thickness of oil patches will not be known. Under these conditions one can attempt to ignite any patches of thick oil that are visibly thicker than sheen. Computer models may be useful to predict slick thickness for spills of given oil type and spill size. For very large spills that are treated quickly, sufficient slick thickness for burning is likely to exist in the "thick" portion of the spill.

C4 Is the Wind Speed Less than 30 to 40 km/hr?

Burning of oil slicks on water cannot be sustained in high winds. Under laboratory conditions burning cannot be sustained at wind speeds greater than 30 to 40 km/hr. As pointed out below, waves also hinder burning. In the real world winds approaching 30 to 40 km/hr would be accompanied by some wave action which would further interfere with burning. However, for operational purposes the 30 to 40 km/hr threshold for winds is

appropriate for decision-making.

C5 Is the Wave Height less than 0.5 to 1.0 m?

Waves affect burning operations by disrupting flame spreading and affecting booming operations. When slicks are thick and waves are small, the slicks dampen the waves and eliminate most problems. At higher wave heights, however, the waves break up the slicks and disrupt the burn. More important is the effect of waves on the containment boom. Existing types of fire-proof boom are designed to work effectively only at lower sea states (e.g., wave heights less than .25 to .5 m). At higher sea states the booms are ineffective in retaining the burning oil, and small quantities of burning oil may escape from the boom and threaten the spill source, the main body of the slick or other countermeasure operations. In addition, at higher sea states waves may actually damage the fire-proof boom which is usually expensive and in limited supply. Although actual experience is limited, the best available knowledge suggests that burning should not be attempted at wave heights greater than 0.5 to 1.0 m.

C6 Is Precipitation Light Enough to Permit Ignition?

Heavy rain greatly hinders ignition and burning. Therefore ignition should be expected to be successful only in the absence of rain or in light to moderate rain conditions.

C7 If Debris is Present, can Booming Operations be Conducted Safely?

This applies only to boomed burns. Under most circumstances the presence of floating debris will not interfere with burning. However, if the debris threatens to damage the boom or render it ineffective, burning must be suspended if safety is compromised.

C8 Is Visibility Adequate?

This applies to visibility conditions as they affect the safe operation of surface vessels, aircraft and deployment of booms. The safe, coordinated operation of vessels and aircraft requires that visibility exceed certain specified minima. In U.S. coastal and offshore areas, operational ceilings of 150 m or greater are required for safe operation of helicopters. In most U.S. coastal waters safe operation of vessels requires visibilities of at least 1 to 2 km at deck level. Similar visibilities would be required for towing boom in safety.

D. ARE REQUIRED EQUIPMENT AND PERSONNEL AVAILABLE?

This section deals with the feasibility of mounting safe and effective burning operations in terms of equipment and personnel requirements. The feasibility of operating under the existing environmental conditions is dealt with in the previous step.

D1 Is Required Equipment Available?

The equipment required for burning operations is described elsewhere in this report. Equipment required for uncontained oil burning is obviously less than that needed for contained oil burning. The location and availability of necessary equipment will be

determined during pre-spill planning. If certain key pieces of equipment are not available at spill time and replacements cannot be obtained within hours, the burn operation cannot be executed as planned. If a revised, feasible burn plan cannot be developed then burning must be abandoned as an option.

D2 Are Trained Personnel Available?

A safe burning operation will depend on trained and experienced personnel to conduct and manage the operation. If trained personnel are not available, then the risks to spill workers, wildlife, and property are increased and burning should not be attempted.

E. ARE RISKS FROM BURN ACCEPTABLE?

There is always some element of risk associated with the in-situ burning of spilled oil. Decision-making associated with burning depends on whether the environmental advantages of the burn (i.e., the reduced environmental risks due to the reduced amount of oil) outweigh the potential risks associated with the burn. Burning poses some risks to the local human population, spill workers, wildlife and other natural resources, and property. These potential receptors might be either acutely and severely affected by the fire or smoke plume or they might be affected chronically by soot or unburned oil droplets precipitating out of the burn plume. This section of the flowchart addresses the risks of burning in decreasing order of importance.

E1 Can Accidental Spreading of the Oil Fire be Avoided?

For uncontained oil burning the fire may spread to parts of the spill that are as yet unburned and even to the spill source. This is acceptable and even desirable if that is the plan and objective of spill responders. However, for contained burning the goal will usually be to avoid the accidental ignition of oil outside the boomed area and certainly to avoid flashback and ignition of the spill source (which might be, for example, a partially loaded tanker). In the case of boomed burning, if the potential for igniting the spill source cannot be minimized, burning operations cannot be allowed to proceed.

E2 Can Burning be Conducted to Avoid Fire Risk to Resources and Property on Land and on Water?

The risks to humans from fire are immediate and life threatening and of ultimate concern, but the risks from the fire to natural resources (e.g., forests) and property (e.g., marinas, ships, buildings) are very important as well. Clearly, any significant threat from the burn to any of these potential targets is unacceptable and far outweighs any possible environmental benefits that might be derived from the burn. Fortunately, the risk from fire in smaller boomed burns is significant only in the immediate vicinity of the fire itself. However, it is essential to allow for the possible mechanical failure of equipment and the subsequent release of the burning parcel of oil. This is essential because the boom itself will be degraded by the fire. Based on the available experience a minimum safety zone of one kilometer in all directions from the burn should be observed. (The one-kilometer safety margin here would allow the burning slick to extinguish itself or to be extinguished in the

event of boom failure and loss of containment of burning oil.)

E3 Are Risks from the Smoke Plume Acceptable?

The smoke plume poses potential health problems in the area immediately downwind of the burn site. The soot and burn gases pose potential health and safety problems to the public, spill workers, and wildlife. The risks are greatest for particularly sensitive components of the human population, such as persons with respiratory diseases, children and the elderly. The risk is greatest where atmospheric conditions keep the smoke plume at the sea surface or at ground level. Based on the best available information and to be conservative, humans should not be exposed to smoke within 5 km downwind of an offshore burn. (The 5-km distance is based on the results of the simulation in Appendix B. Five kilometers is the approximate distance beyond which average PM concentrations fall below the 150 ppm level.)

If persons are present within 5 km downwind of the burn, then appropriate precautions (notification, cautions) must be taken to protect them from the effects of the smoke plume. If human population centers or major concentration of wildlife occur within 5 km downwind of the burn site, it should be assumed that the burn cannot be conducted in safety. Obviously, precautions must be taken to ensure safety of spill workers under all conditions.

Smoke may pose a significant visibility problem in the immediate vicinity of the spill. This is not of itself a major problem except when smoke plume affects other potentially high risk activities such as high speed motorways or vessel or aircraft operations. The best available information suggests that at least 2 km should be allowed between the burn site and the nearest activity for which adequate visibility is essential. If sensitive spill response activities are taking place within 2 km downwind of a burn, then appropriate precautions must be taken to minimize risks to these operations.

F. SEEK REGULATORY APPROVAL

Regulatory control over in-situ burning may lie with one or more government agencies. A simple, streamlined process for obtaining or granting approval should be established during planning. At the time of a spill, regulatory approval must be obtainable within minutes or at most a very few hours and must require no more than a minimum amount of communication.

G. and H. WILL KEY FACTORS CHANGE WITH TIME?

Certain of the key factors affecting burning may change with time, either negatively (G) or positively (H). Re-evaluate the burn/no-burn decision as critical conditions change.

I. PROCEED WITH BURN OPERATION

At this point of decision-making, all criteria and approval processes have been satisfied and you may proceed with the burn operation. As the operation proceeds, key factors such as slick thickness, freshness of oil, weather, etc. may degrade and prevent oil ignition and burning, forcing a halt to operations. Be prepared for this by periodically reviewing the relevant decision-tree factors. Also, be sure to re-evaluate regularly those factors related to the

safety aspects of the burn.

J. DO NOT BURN

If you have arrived at this point in the decision-tree, at least one critical requirement for in-situ burning can not be satisfied. Proceed to consider other countermeasure alternatives.

11.0 Recommendations

11.1 Introduction

This report provides extensive documentation to support the view that in-situ burning of marine oil spills is a promising countermeasures technique that can be used on selected spills with effectiveness and safety. It is thus recommended that a major effort be initiated to incorporate in-situ burning programs in existing contingency plans and to educate and train both operators and regulators accordingly. Chapter 8 of this report makes very strong ecological and human-health arguments for considering in-situ burning under most marine spill situations. The major constraint to the routine use of the countermeasure is our lack of operational experience and lack of knowledge regarding spill situations where burning can be considered feasible, practical and effective. For example, we remain uncertain about the effect of oil type and emulsification on ignition and burning efficiency, about the practicalities and efficiencies of uncontained oil spill burning, about the cost-benefits of using smoke suppressors such as Ferrocene, and about a great number of other important questions. The objective of this chapter is to identify and discuss all of the major areas of knowledge and technology that should be addressed to advance the safe and effective use of in-situ burning for dealing with marine oil spills.

11.2 Research and Development Recommendations

Recommendations are made regarding studies that should be undertaken to improve the technology and knowledge of in-situ burning. We begin with an identification of information gaps. This is followed by a compilation of fifty-two specific research and development ideas that have been proposed in this study, in previous studies, and in various meetings of researchers over the past five years. Fourteen of the ideas selected by the study team as being the most important are then presented in further detail. Not addressed are the problems of oil spilled under or on a complete ice cover, and burning or incineration techniques used for dealing with the products of an offshore recovery or shoreline cleanup program. These areas were not covered in the report.

11.2.1 Information Gaps

There are two categories of research at issue. The first relates to environmental and regulatory concerns that currently limit the acceptance of in-situ burning as a first-line spill response method. The second relates to technological or operational concerns regarding the feasibility of burning marine oil spills under a range of spill and environmental conditions.

Environmental and Regulatory Concerns: The primary constraint to the use of in-situ burning as an operational tool is concern over the impacts of the byproducts of burning on people and the environment. Until recently, few data existed on the constituents of the smoke and their concentrations, the chemicals of concern in the residue, and the thermal effects of in-situ burning on the underlying water column. The two large offshore burns of contained crude oil that were conducted off Newfoundland in 1993 were the culmination of a multi-year, multi-million dollar research program on these subjects (Fingas *et al.* 1994). It

is believed that the results of this offshore study will do much to fill major data gaps in the three areas mentioned. Nonetheless, regulatory acceptance of in-situ burning will likely continue to be a problem because of concerns over the human health implications of burning. This subject area thus forms the basis for several of the R&D recommendations identified in this chapter. Another regulatory issue that limits in-situ burning as a response tool is the concept that in-situ burning is a second-tier response tool (i.e., skimming first, then burning). Since there is a "window-of-opportunity" for burning that closes after about a day or less, its relegation to a second-tier response can completely negate its effectiveness. Legal, safety and insurance issues associated with in-situ burning, especially near a stricken vessel, are also key limitations on its use as a response tool. These issues are also included in the list of projects identified for future consideration.

Technological and Operational Concerns: The greatest technological constraint to in-situ burning is emulsification. With present-day technology, even thin and highly evaporated oil slicks can be contained, thickened and burned using fire containment booms; however, if the oil emulsifies beyond a certain limit, ignition is not possible. Other external limitations also exist, such as wind speed, sea state, visibility and currents. All of these combine to define a spill-specific "window-of-opportunity" for in-situ burning.

The appropriate equipment that should be deployed on-site for in-situ burning also requires research. The limitations and capabilities of igniters and fire containment booms must be fully researched and understood before in-situ burning can be used with confidence. Finally, there are a number of operational issues that remain unanswered, such as how to coordinate a multi-approach response involving burning, dispersing and skimming so as to maximize oil removal and minimize environmental impact.

11.2.2 Previously Identified R&D Ideas

This section lists specific research and development ideas that have been proposed over the past five years. These were taken from proceedings of the following symposia and workshops:

Alaska Arctic Offshore Oil Spill Response Technology Workshop — Nov/Dec 1988 (Jason 1989)

Workshop to Establish Canadian Marine Oil Spill Research and Development Priorities — March 1990 (Ross and Potter 1990)

Research Needed to Respond to Oil Spills in Ice-Infested Waters — Findings and Recommendations of the U.S. Arctic Research Commission — May 1992 (USARC 1992)

First International Oil Spill R&D forum — June 1992 (TMS 1992)

In addition, papers presented at oil spill conferences dealing with the R&D activities of various organization were reviewed, including those of MSRC (MSRC 1991, Engelhardt 1992 and 1993), MMS (Tennyson 1993), Environment Canada (Fingas 1992), NIST (Evans

1992) and USCG (Jensen and Tebeau 1991). Study team members also contributed their own ideas, as documented in this report.

As a result of the review, 52 R&D ideas evolved. These are listed in Table 11.1. The ideas have been sorted into five categories pertaining to:

- processes,
- technology,
- field trials,
- operational, and
- environmental and human health.

The ideas are not presented in any particular order.

Table 11.1 Compendium of In-Situ Burning R&D Ideas

Category	Idea	Description	Sources
Processes	1. Effects of Emulsification	<ul style="list-style-type: none"> continue R&D to ascertain the processes occurring during burning of w/o emulsions and the limitations imposed by emulsification on ignitability, flame spreading and burning of emulsions, including thermal aspects. 	Jason 1989 USARC 1992 Ross & Potter 1990 Evans 1992 Fingas 1992 Tennyson 1992 Engelhardt 1992, 1993 MSRC 1991 This study
	2. Effects of Currents and Waves	<ul style="list-style-type: none"> study the effects of currents and waves on in-situ burning. 	Ross & Potter 1990 USARC 1992 TMS 1992 MSRC 1991 This study
	3. Effects of Oil Types and Properties	<ul style="list-style-type: none"> study the effects of oil type and properties on the basic processes of in-situ burning. 	USARC 1992 Tennyson 1992
	4. Burning in Broken Ice	<ul style="list-style-type: none"> investigate the effects of broken ice on in-situ burning of oil. 	Jason 1989 Ross & Potter 1990
	5. Uncontained Burning	<ul style="list-style-type: none"> continue research and modeling efforts regarding the ignition and burning of uncontained oil slicks on water. 	Ross & Potter 1990 This study
	6. Scaling Effects	<ul style="list-style-type: none"> conduct test burns with a range of fire sizes and oil types to measure effects of scale on various burn processes. 	Jason 1989 Tennyson 1992
	7. Burning Oil on Mudflats	<ul style="list-style-type: none"> investigate the feasibility of burning oil on mudflats, where no other countermeasures can be used. 	Ross & Potter 1990 Engelhardt 1992
	8. Burning at/or near Shorelines	<ul style="list-style-type: none"> evaluate the possibilities for burning oil at/near certain shorelines, e.g., marsh. 	Fingas 1992
	9. Flame Spreading	<ul style="list-style-type: none"> study the effects of wind, temperature, oil type, thickness, etc. on flame spreading rates over oil slicks and develop suitable models. 	This study

Table 11.1 Compendium of In-Situ Burning R&D Ideas continued

Category	Idea	Description	Sources
Technology	10. Smoke Reduction	<ul style="list-style-type: none"> continue the development of technologies/additives to reduce/eliminate smoke produced by in-situ burning. 	Jason 1989 USARC 1992 Engelhardt 1993
	11. Break and Burn	<ul style="list-style-type: none"> investigate techniques for reducing emulsification in slicks to permit ignition and burning and extend "window-of-opportunity", including emulsion breakers, anti-foaming agents, ignition promoters and combustion promoters. 	Ross & Potter 1990 TMS 1992 Engelhardt 1993 This study
	12. Novel Methods to Enhance In-Situ Burning	<ul style="list-style-type: none"> study ways to increase burn rates and efficiencies, including combustion air increases, instigation of vigorous burning, radiation reflectors, wire mesh media in boom pockets, water injection and combustion promoters. 	Jason 1989 Ross & Potter 1990 TMS 1992
	13. Capabilities and Limitations of Existing Igniters	<ul style="list-style-type: none"> develop a quantitative description of the capabilities and limitations of existing igniter technology as a function of weather, sea state, oil type and emulsification variables. 	USARC 1992 This study
	14. New Fire Proof Boom Designs	<ul style="list-style-type: none"> develop new fire resistant boom technology to improve efficiency and enable operations in higher sea states. 	TMS 1992 Engelhardt 1993 This study
	15. Standardized Testing of Fire Proof Booms	<ul style="list-style-type: none"> quantify the capabilities and limitations of existing fire booms in salt water wave tanks/basins, with fire using standardized test methods. 	Ross & Potter 1990 This study

Table 11.1 Compendium of In-Situ Burning R&D Ideas continued

Category	Idea	Description	Sources
Technology cont'd	16. Igniter Improvements	• continue research into improving the capabilities and reducing the limitations of the Helitorch by studying additives and alternate fuels.	This study
	17. New Igniter Concepts	• research novel igniter techniques.	USARC 1992
	18. Residue recovery	• develop/test potential methods for the recovery at sea of burn residue.	Jason 1989 Ross & Potter 1990 USARC 1992
Field Trials	19. Offshore Fire Proof Boom Trials	• verify mesoscale work on efficiency and develop protocols; sufficient number of trials to determine viability under variable weather and sea conditions; quantify scale rules.	Jason 1989 Ross & Potter 1990 USARC 1992 Evans 1992 Tennyson 1992 TMS 1992
	20. Ignition and Burning of Emulsions	• research the ignition and burning of emulsions of varying water content and weathering to assess capabilities and limitations and scaling rules.	Jason 1989 Ross & Potter 1990 This study
	21. Uncontained Burning	• evaluate the efficacy of burning uncontained oil in the 1 to 10 m ³ size range.	Ross & Potter 1990 This study
	22. Burning in Broken Ice	• conduct a burn in broken ice conditions to determine the efficacy of the technique.	Jason 1989 Ross & Potter 1990
	23. Igniter Tests	• evaluate ignition devices.	Ross & Potter 1990

Table 11.1 Compendium of In-Situ Burning R&D Ideas continued

Category	Idea	Description	Sources
Operational	24. Equipment Deployment Exercises	<ul style="list-style-type: none"> • demonstrate techniques and train end users in the methods employed in in-situ burning; refine procedures; determine limitations imposed by weather and sea conditions. 	USARC 1992 TMS 1992 Engelhardt 1993 This study
	25. Control of Offshore In-Situ Burning	<ul style="list-style-type: none"> • research, develop and/or test techniques of controlling offshore in-situ burns; as a function of pool size; extinguishment techniques. 	Engelhardt 1993 This study
	26. Comparison of Trade-Offs with other Response Techniques	<ul style="list-style-type: none"> • research, document and compare the trade-offs between mechanical, chemical and burning countermeasures. 	USARC 1992
	27. Safety Issues	<ul style="list-style-type: none"> • study the safety issues associated with in-situ burning; develop protocols and procedures for safe operations; institute loss management techniques. 	Jason 1989 Ross & Potter 1990 USCG 1991 This study
	28. Regulatory and Public Education Programs	<ul style="list-style-type: none"> • develop techniques to inform and educate regulators and the public as to the capabilities and limitations and trade-offs associated with in-situ burning; include net environmental benefits analysis and safety aspects. 	Jason 1989 Ross & Potter 1990 USCG 1991 This study
	29. Practicality Assessment	<ul style="list-style-type: none"> • assess the practicality of various burn scenarios vis a vis operational windows; incorporate response time, personnel and equipment availability, staging logistics, oil behavior, etc. for a range of weather and sea conditions. 	Jason 1989

Table 11.1 Compendium of In-Situ Burning R&D Ideas continued

Category	Idea	Description	Sources
Operational cont'd	30. Ignition Procedures	<ul style="list-style-type: none"> • develop procedures for ignition of slicks on water (or ice) in a range of situations; include oil type, weather, sea state, logistics, etc., as variables. 	This study
	31. Large Spill Burning	<ul style="list-style-type: none"> • develop procedures for employing in-situ burning at large spills; include interactions with other response operations. 	Engelhardt 1993
	32. Protocols and Procedures	<ul style="list-style-type: none"> • develop standardized protocols and procedures for the implementation of in-situ burning offshore. 	USCG 1991
	33. Legal, Environmental and Safety Issues	<ul style="list-style-type: none"> • define the legal, environmental and safety issues associated with controlled in-situ burning and develop decision protocol for the O.S.C. 	USCG 1991
	34. Uncontained Burn Issues	<ul style="list-style-type: none"> • as 33 above, but for the situation of ignition, and burning uncontained slicks. 	This study
	35. Decision Making Aids for Extinguishing Vessel Fires	<ul style="list-style-type: none"> • develop decision-making aids for the case of extinguishing an already-burning vessel; incorporate legal, insurance and environmental trade-off aspects. 	This study
	36. Helicopter Safety	<ul style="list-style-type: none"> • assess the safety of operating helicopters in the vicinity of burning operations. 	Ross & Potter 1990

Table 11.1 Compendium of In-Situ Burning R&D Ideas continued

Category	Idea	Description	Sources
Environmental Issues	37. Effects of Low Temperature and Winds	<ul style="list-style-type: none"> ● assess the effects of emissions at low temperatures and a range of wind speeds. 	USARC 1992
	38. Develop Smoke Plume Models	<ul style="list-style-type: none"> ● write and test better computer models to predict air pollution impacts; make existing models simpler for use on personal computers. 	Ross & Potter 1990 Fingas 1992 TMS 1992
	39. Thermal Effects on Water Column	<ul style="list-style-type: none"> ● quantify the thermal effects of in-situ burning on the water column; create mathematical models to predict effects in various situations. 	This study
	40. Burn-of-Opportunity Research	<ul style="list-style-type: none"> ● at accidental oil fires, measure particulate fallout downwind and attempt to measure environmental impacts. 	Fingas 1992 This study
	41. PAH and Metals	<ul style="list-style-type: none"> ● further study of PAH's and metals. 	Fingas 1992 This study
	42. Residue Studies	<ul style="list-style-type: none"> ● study of changes to residue. 	Fingas 1992 This study
	43. Aldehydes and Ketones	<ul style="list-style-type: none"> ● study of aldehydes and ketones. 	Fingas 1992 This study
	44. Particulates and Residue Toxicology	<ul style="list-style-type: none"> ● study the toxicology of particulates and residue. 	Fingas 1992 This study
	45. Emission Assessment Techniques	<ul style="list-style-type: none"> ● develop rapid techniques for assessing emissions in real and trial spills. 	Fingas 1992 This study
	46. Plume Measurement Techniques	<ul style="list-style-type: none"> ● develop rapid plume measurement techniques. 	Fingas 1992 This study
	47. Flux Gases	<ul style="list-style-type: none"> ● assess the flux gases from burns. 	Fingas 1992 This study
	48. Impact Assessment Protocols	<ul style="list-style-type: none"> ● develop impact assessment protocols for spills of opportunity. 	Fingas 1992 This study
	49. Monitoring Techniques	<ul style="list-style-type: none"> ● develop monitoring techniques for in-situ burn response implementation. 	Fingas 1992 This study
	50. Effects of Residue Sinking	<ul style="list-style-type: none"> ● determine the causes, conditions and environmental effects of in-situ burn residue sinking. 	This study

Table 11.1 Compendium of In-Situ Burning R&D Ideas continued

Category	Idea	Description	Sources
Environmental Issues cont'd	51. Burn Consideration Zones	• use present air quality models to develop pre-approved zones for coastal areas.	This study
	52. Burn Risk Model	• develop a fast, transportable, field-simplified risk assessment model for burn screening.	This study

11.2.3 Recommendations for Future R&D

The ideas in Table 11.1 that are considered to be "top priority" were identified as follows. Each member of the study team separately selected his personal "top ten" ideas from the 52 listed. All "top ten" lists were then consolidated into one list of fourteen R&D areas. Several of these areas incorporate more than one R&D idea with a common theme (e.g., "uncontained burning" research is included in ideas #5, 21 and 34 in Table 11.1). Each recommended R&D area is now briefly described; the corresponding R&D idea(s) from Table 11.1 are given for each area. The recommended R&D areas are not listed in any particular order.

Effects of Emulsification (Table 11.1, #1). Although progress has been made recently in understanding the basic processes involved with in-situ burning of emulsions, more needs to be done to quantify the limitations it imposes on:

- ignitability,
- flame spreading,
- burn efficiency, and
- burn rate.

Particular aspects requiring further study are:

- scaling effects,
- parent oil effects,
- sea state effects, and
- the development of a simple "screening" test for a particular oil.

Uncontained Burning (Table 11.1, #'s 5, 21 and 34). Preliminary studies in the mid-1980s

(S.L. Ross and Energetex 1986) indicate that ignition of thick, fresh crude oil slicks that are not contained in booms can result in high removal efficiencies because the air drawn into the fire keeps the slick from spreading. Further research is recommended to:

- determine viability at larger scales,
- explore the capabilities and limitations of the technique,
- validate mathematical models, and
- address the legal, environmental and safety issues associated with uncontained burns.

Flame Spreading (#9). The achievement of high overall removal efficiencies using in-situ burning requires that the flames spread from the ignition source to cover the greatest possible area of the slick. Flame spreading may very well be the limiting factor governing burning practicability. Little work has been done on flame spreading over oil slicks, particularly at larger scales in the field. Research is needed in the areas of:

- effects of oil type and weathering,
- effects of slick thickness,
- environmental and sea state influences, and
- flame spreading promoters or primers.

Break and Burn (#11). This research area offers potential to extend the "window-of-opportunity" for in-situ burning. Emulsion breakers can be applied aurally to an emulsified slick to reduce its water content (e.g., Lunel and Lewis 1993) and perhaps render it ignitable. Some preliminary small-scale testing has been undertaken, but much more is required. Research (both lab-scale and field-scale) is recommended in the areas of:

- scaling emulsion breaker burn testing,
- potential for anti-foaming agents,
- application of ignition and flame spreading promoters, and
- operational aspects.

Fire Control and Safety Issues (#s 25 and 27). The "fire control" part of this R&D area relates specifically to researching, developing and/or testing methods that can be used offshore to:

- extinguish an already burning oil slick or portion thereof (either contained or uncontained), and

- positively control the spread of fire over slicks (particularly near the source of the slick).

The "safety" portion of this R&D area relates to developing and testing procedures for safe, controlled in-situ burning offshore (including fire control). Key areas would involve ignition safety, personnel protection and flame and heat hazards.

Fire-Proof Boom Studies (#s 14 and 15). Many varieties of fire-proof or fire-resistant containment booms are commercially available; each has its capabilities and limitations. Fabric-based booms are relatively lightweight and flexible but may only survive a few hours of exposure to flames, particularly in waves; metallic booms are available that offer excellent fire resistance, but these tend to be heavier, more cumbersome and less flexible than fabric booms. A standardized test protocol for fire proof booms needs to be developed and a suitable test facility needs to be located or developed. Concurrently, research and development of new fire proof boom designs should continue with the objective of developing a lightweight, easy-to-handle, long-life, high-seas product.

Burn-of-Opportunity (#40). One obvious technique for collecting smoke plume data for large oil fires is to respond to accidental oil fires-of-opportunity (such as tank farm fires, tanker fires, etc.) and measure key smoke parameters and any environmental impacts, including human health impacts. This would avoid the costs and regulatory problems of mounting a large experimental burn program. This program would entail developing a rapid response unit (both monitoring equipment and personnel) properly equipped to take advantage of accidental oil fires.

Smoke Reduction (#10). The smoke plume from an in-situ burn is considered a major constraint to the use of the technique as an operational tool. If the smoke could be eliminated, much of the resistance to the use of burning would be reduced. Several studies of the use of Ferrocene and its derivatives as a smoke suppressant have shown promising results (Mitchell and Moir 1992). Continued research on cost-effective additives and application technologies is warranted.

Igniter Tests and Improvements (#s 13, 16 and 23). Some commercially available igniter systems have been extensively tested and others have undergone only limited testing. In order to select the proper igniter for a given spill, it is necessary to develop a standardized series of tests for igniter systems that will quantify their effectiveness as a function of oil type, and weathering, (particularly emulsification), sea state, and environmental conditions.

It is also recommended that the research into extending the capabilities of gelled-gasoline igniter systems, exemplified by the Heli-torch, be continued. The use of alternative fuels (Bech *et al.* 1992) and additives, including emulsion breakers and smoke suppressants, shows promise in lab and small-scale testing as a means of expanding the applicability of this type of igniter system to emulsions. Research into other types of additives, delivery system tests and larger scale testing are all recommended.

Residue Sinking (#50). One existing constraint on the use of in-situ burning is the concern that the residue remaining on the water after the burn will sink and contaminate the sea bottom. Much research and field testing has indicated that this is not likely for most oils;

however, some heavy crudes that have burned at sea are reported to have sunk (Turbini *et al.* 1993, Moller 1992). Research on the likelihood of burn residue from fires of heavy (i.e., high density) crudes sinking, conditions that favor sinking and the potential environmental effects is recommended.

Practicality Assessment (#29). A study is needed to assess the practicality of in-situ burning operations for a range of spill types, spill sizes and environments. Using a scenario approach and realistic response capabilities, in-situ burning would be applied to a large number of spill scenarios and its likely effectiveness in removing oil would be estimated using known mathematical techniques. The equipment requirements, response times, logistical support necessary, cost and removal efficiency would be compared critically with conventional containment and response and dispersant application operations.

Protocols and Procedures for Contained Burning (#32). Some regions of North America (notably Alaska and EPA Region VI - Louisiana and Texas) have made considerable progress in developing pre-approval protocols for offshore in-situ burning, and some response organizations have state-of-the-art in-situ burning response plans in place. Many other areas and response organizations are not as advanced, so continued efforts to develop standardized protocols and procedures for contained in-situ burning (using booms) is recommended. Without clear guidelines on when and how to implement an in-situ burning operation, its operational use is unlikely.

Legal, Environmental and Safety Issues (#33). In order to implement an in-situ burning operation, an On-Scene Commander (OSC) needs to consider the legal, environmental and safety ramifications of the planned burn(s). It is recommended that these be clearly defined and documented and that an easy-to-use decision protocol for the OSC be developed. Some jurisdictions (e.g., Alaska, EPA Region VI) have checklist-type burn application forms that address these issues; these would form a good framework for other jurisdictions.

Regulatory and Public Education Programs (#28). One key stumbling block to the operational use of in-situ burning is the unconsidered fear of the effects of in-situ burning by the general public, special interest groups and some regulatory agencies. It is recommended that methods be devised for educating concerned persons about the capabilities and limitations of burning, potential impacts of the smoke, safety aspects and net environmental benefits.

11.2.4 Conclusion

On the basis of a comprehensive review of in-situ burning as a countermeasures technique for oil spills at sea, and a review of proceedings from past meetings of experts, a list of fourteen ideas for top R&D consideration has been developed. The list should be considered preliminary and open for discussion. The aim in the end is to develop a coordinated R&D program for in-situ burning that leads to the regular acceptance and use of the technique in the overall interests of protecting the environment and human health and safety.

11.3 References to Chapter 11

- Bech, C., P. Sveum and I. Buist. 1992. In-situ burning of emulsions: The effect of varying water content and degree of evaporation. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 547-560.
- Engelhardt, F.R. 1992. The MSRC research and development program. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 261-270.
- Engelhardt, F.R. 1993. The MSRC research and development program: An update on progress. Proceedings of the 1993 International Oil Spill Conference, March 29-April 1, 1993, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 537-540.
- Evans, D. 1992. In-situ burning. NIST studies. Proceedings of the First International Oil Spill R&D Forum. Interagency Coordinating Committee on Oil Pollution Research of the U.S. Government. Washington, D.C. (produced by TMS Inc.) pp. 241-246.
- Fingas, M. 1992. In-situ burning of oil spills: Review and research priorities. Proceedings of the First International Oil Spill R&D Forum. Interagency Coordinating Committee on Oil Pollution Research of the U.S. Government. Washington, D.C. (produced by TMS Inc.) pp. 247-252.
- Fingas, M.F., F. Ackerman, K. Li, P. Lambert, Z. Wang, M.C. Bissonnette, P.R. Campagna, P. Boileau, N. Laroche, P. Jokuty, R. Nelson, R.D. Turpin, M.J. Trespalacios, G. Halley, J. Belanger, J. Paré, N. Vanderkooy, E.J. Tennyson, D. Aurand and R. Hiltabrand. 1994. The Newfoundland offshore burn experiment — NOBE preliminary results of emissions measurement. Proceedings of the Seventeenth Arctic and Marine Oilspill Program Technical Seminar, June 8-10, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 1099-1164.
- Jason, N.H., ed. 1988. Alaska arctic offshore oil spill response technology workshop proceedings. Anchorage, Alaska, November 29-December 1, 1988. NIST. Special Publication 762. National Institute of Standards and Technology, Gaithersburg, MD 20899.
- Jensen, D.S. and P.A. Tebeau. 1991. Coast Guard research and development for the 1990s. Proceedings of the 1991 International Oil Spill Conference, March 4-7, 1991, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 661-665.
- Lunel, T. and A. Lewis. 1993. Oil concentrations below a demulsifier treated slick. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 955-972.

- Mitchell, J.B.A. and M.E. Moir. 1992. Smoke reduction from pool fires using ferrocene and derivatives. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 681-688.
- Moller, T.A. 1992. Recent experience of oil sinking. Proceedings of the Fifteen Arctic and Marine Oil Spill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 11-14.
- MSRC. 1991. Priority topics for research and development in oil spill response. Technical Report Series 91-001. Marine Spill Response Corporation, Washington, D.C. 26 pp.
- Ross, S.L. and S.G. Potter. 1990. Proceedings of a workshop to establish Canadian marine oil spill research and development priorities. Environmental Studies Research Funds, Canadian Department of Energy, Mines and Resources. ESRF publication number 106.
- S.L. Ross Environmental Research Ltd. and Energetex Engineering. 1986. In-situ burning of uncontained oil slicks. Environmental Emergencies Technology Division report EE-60 revised. Environment Canada, Ottawa. pp. 150.
- Tennyson, E. 1993. Results from oil spill response research — an update. Proceedings of the 1993 International Oil Spill Conference, March 29-April 1, 1993, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 541-544.
- TMS (Technology & Management Services, Inc.). 1992. Proceedings of the first international oil spill R&D forum. June 1-4, 1992, McLean, Virginia. Co-sponsored by the U.S. Coast Guard and the International Maritime Organization.
- Turbini, W., E. Fresi and F. Bambacigno. 1993. The *Haven* incident: Lessons learned with particular reference to environmental damages. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 179-183.
- USARC. 1992. Research needed to respond to oil spills in ice-infested waters. U.S. Arctic Research Commission Issue No. 8 — May 1992. Washington, D.C. 20 pp.

12. Consolidated References and Bibliography

- Akita, K. and T. Yumoto. 1965. Heat transfer in small pools and rates of burning of liquid methanol. Tenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA., pp. 943-948.
- Akita, K. 1972. Some problems of flame spread along a liquid surface. Fourteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA., pp. 1075-1083.
- Alaska Clean Seas. 1991. Long duration test burn: 3M 8-inch fire containment boom. ACS Newsletter. Vol (1), No. 1, March 31, 1991. Anchorage.
- Alaska Clean Seas. 1991. Proposed plan for 1992 full-scale in-situ burn test, Beaufort Sea, Alaska. Unpublished proposal.
- Alger, R.S., R.C. Corlett, A.S. Gordon, and F.A. Williams. 1976. Some aspects of structures of turbulent fires. Proc. 1976 Fall Meeting Western States Section Combustion Institute, Lojolla, CA.
- Allen, A.A. and W.G. Nelson. 1981. Oil spill countermeasures in landfast sea ice. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 297-304.
- Allen, A.A. 1986. Alaska Clean Seas survey and analysis of air-deployable igniters. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 353-373.
- Allen, A.A. (Spiltec). 1986. Survey and analysis of air-deployable igniters. Prepared under contract to Shell Western E&P, Inc. for Alaska Clean Seas.
- Allen, A.A. 1987. Test and evaluation of the helitorch for the ignition of oil slicks. Proceedings of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 243-265.
- Allen, A.A. and W. Simpson. 1987. Alaska Clean Seas test and evaluation of fire containment boom. Proceeding of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 187-201.
- Allen, A.A. (Spiltec). 1987. Refinement of aerial ignition systems (test and evaluation of the helitorch for the ignition of oil slicks. Prepared under contract to Shell Western E&P, Inc. for Alaska Clean Seas.

- Allen, A.A. 1988. Comparison of response options for offshore oil spills. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 289-306.
- Allen, A.A. and E.M. Fischer. 1988. Test and evaluation of a new and unique fire containment boom. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 185-199.
- Allen, A.A. 1988. In situ burning. Alaska Arctic Offshore Oil Spill Response Technology. U.S. Government Printing Office, Washington, D.C., NIST report No. SP 762, pp. 11-14.
- Allen, A.A. 1990. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 305-313.
- Allen, A.A. 1990. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. Spill Technology Newsletter vol. 15, no. 2, pp. 1-5.
- Allen, A.A. 1991. Controlled burning of crude oil on water following the grounding of the *Exxon Valdez*. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 213-216.
- Allen, A.A. 1991. In situ burning of spilled oil. Spill Technology Newsletter 16(4):1-12.
- Allen, A.A. 1992. In-situ burning field operations manual. 3M Ceramic Materials Department. St. Paul, MN.
- Allen, A.A. and Ferek, R.J. 1993. Advantages and disadvantages of burning spilled oil. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. p. 765-772.
- Alramadhan, M.A., V.S. Arpaci, and A. Selamet. 1990. Radiation affected liquid fuel burning on water. Combustion Science and Technology 72:233-253.
- American Cancer Society. 1990. Cancer Facts & Figures — 1990. American Cancer Society. Atlanta, GA.
- American Conference of Government Industrial Hygienists. 1993. 1993-94 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Limits. American Conference of Government Industrial Hygienists, Cincinnati, OH. 124 pp.
- Andersen, W.H. 1972. Model of transient ignition to self-sustained burning. Combustion Science and Technology 5(2):75-81.

- Anderson, H.E. 1966. Fire spread and flame shape. *Fire Technology* 4:51-58.
- Anderson, E., E. Howlett, W. Knauss, D. French, M. Spaulding, M. Reed, S. Puckett, T. Isaji, and D. Mendelsohn. 1990. The Alyeska tactical oil spill model. *Mar. Technol. Soc. J.*, vol. 24, no. 4, pp. 33-38.
- Anonymous. 1967. Chemicals vs. crude oil. *Chemical Week* 100(20):49.
- Anonymous. 1968. A product that is an irritant in chemical warfare can also combat ocean oil spills. *Chemical Engineering* 75(26):54.
- Anonymous. 1968. For igniting slicks. *Tanker and Bulk Carrier* 15(6):364.
- Anonymous. 1968. Chemicals to combat ocean petroleum spills keep coming. *Chemical Engineering* 75(11):70.
- Anonymous. 1969. Oil spills can be burned. *Offshore* 29(11):43.
- Anonymous. 1970. Materials applications. *Industrial Research* 12(3):67-68.
- Anonymous. 1970. Oil for burning. *Marine Pollution Bulletin* 1(12):181; 1970.
- Anonymous. 1970. Small cellular glass beads burn off oil spills. *Industrial Research*.
- Anonymous. 1970. Major oil slick burned by Cabot Chemical. *Chemistry and Industry* 16:509.
- Anonymous. 1970. Oil burning beads. *World Oil* 170(2):77.
- Anonymous. 1970. Control of oil slick. *Petroleum Times* 74(1888):26.
- Anonymous. 1970. Burning oil spills. *Science* 168(3930):451.
- Anonymous. 1971. Oil spill technology makes strides. *Environmental Science and Technology* 5(8):674-675.
- Anonymous. 1977. Fire hazards of oil spills on waterways. American Petroleum Institute, Washington, D.C., API Publication No. 2022, 5 p.
- Anonymous. 1979. Economical and environmentally safe burning of heavy oil. *NORSK SKOGINDUSTRI* 33(12):309.
- Anonymous. 1984. Discussion notes - workshop on self help oil spill countermeasures for tankers in remote areas. Toronto, Ontario, Canada, February 28-29.
- Anonymous. 1990. Analysis technique enhances oil spill response optimization. *Offshore* 50(9):34-38.

- Anonymous. 1990. Tanker spills, safety again chief industry environmental worries. *Oil and Gas Journal* 88(25):13-16.
- Anonymous. 1993. Columbian spill threatens water supply. *Oil Spill Intelligence Report*, XVI (34) pp. 4.
- Arctec Canada Ltd. 1977. Novel countermeasures for an arctic offshore well blowout. Report No. EPS-3-EC-77-14: Fisheries and Environment Canada, Ottawa, Ontario. pp. 18-24.
- Askaryan, G.A., E.K. Karlova, R.P. Petrov, and V.B. Studenov. 1974. Evaporation, combustion, and limitation of spreading out of petroleum and other films on water. *USPEKHI FIZICHESKIKH NAUK* 113(4):709-771.
- Atallah, S. and D.S. Allan. 1961. Safe separation distances from liquid fuel fires. *Fire Technology* 7(1):47-56.
- Atallah, S. 1965. Flame heights and burning rates of liquid fuels in open tanks. *Combustion and Flame* 9:203-205.
- Baalman, R.W. and C.W. Dotson, editors. 1980. Burning of oil spills. Pacific Northwest Laboratory annual report for 1979 to the DOE Assistant Secretary for Environment, pp. 31-33.
- Babrauskas, V. 1983. Estimating large pool fire burning rates. *Fire Technology* 19(4):251-261.
- Babrauskas, V. and G. Mulholland. 1987. Smoke and soot data determinations in the cone calorimeter - Mathematical modelling of fires. American Society for Testing and Materials, Philadelphia, PA., ASTM STP 983, pp. 83-104.
- Babrauskas, V. 1988. Burning rates. *The SFPE Handbook of Fire Protection Engineering*. pp. 2.1-2.15.
- Bakan, S., A. Chlond, U. Cusbach, J. Feichter, H. Graf, H. Grassl, K. Hasselmann, I. Kirchner, M. Latif, E. Roeckner, R. Sausen, V. Schlese, D. Schriever, I. Schult, U. Schumann, F. Sielmann, and W. Welke. 1991. Climate response to smoke from the burning oil wells in Kuwait, *Nature*, 351, 367-371.
- Barber, F.G. 1970. Oil spills in ice: some cleanup options. *Arctic* 23(4):285-286.
- Battelle. 1979. Combustion: An oil spill mitigation tool. Report for U.S. Department of Energy, Contract No. EY-76-C-06-1830. U.S. Department of Energy, Washington, D.C.

- Bayliss, R. and R. Spoltman. 1981. The wreck of the *Lee Wang Zin*. Proceedings of the 1981 Oil Spill Conference, March 2-5, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 221-226.
- Bech, C. P. Sveum, and I.A. Buist. 1992. In situ burning of emulsions: The effects of varying water content and degree of evaporation. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 547-559.
- Bech, C., P. Sveum, and I. Buist. 1993. The effect of wind, ice and waves on the in-situ burning of emulsions and aged oils. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 735-748.
- Beckett, C.J. 1979. The grounding of the *Imperial St. Clair* — a case history of contending with oil in ice. Proceedings of the 1979 Oil Spill Conference, March 19-22, New Orleans, Louisiana. American Petroleum Institute, Washington, D.C. pp. 371-375.
- Belicek, K. and J. Overall. 1976. Some aspects of weathering and burning of crude oil in a water-and-ice environment. Arctic Petroleum Operators Association, Calgary, Alta., APOA Project 107, 34 p.
- Bellier, P. and G. Massart. 1979. The *Amoco Cadiz* oil spill clean-up operations - an overview of the organization and control. Proceedings of the 1979 Oil Spill Conference, March 19-22, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 141-146.
- Belore, R.C. and C. Seeley. 1990. Air jet atomization and burning of oil slicks. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 289-304.
- Benner, B.A. Jr., N.P. Bryner, S.A. Wise, G.W. Mulholland, R.C. Lao, and M.F. Fingas. 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. *Environmental Sciences and Technology* 24:1418-1427.
- Benner, B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, and R. Lao. 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. Govt Reports Announcements & Index (GRA&I), Issue 01, 1991.
- Benner, B.A., N.P. Bryner, S.A. Wise, G.W. Mulholland, D.D. Evans, M.F. Fingas, and K. Li. 1991. Emissions of polycyclic aromatic hydrocarbons from the combustion of crude oil on water. *Spill Technology Newsletter* 16(1).

- Bennett, J.A., I.R. McAllister, L. Pertile, and D. McQuillan. 1982. Removal of stranded oil from remote beaches by in situ combustion. Bennett Environmental Consultants Ltd., Vancouver, B.C., Report No. BEC-8703, pp. 131.
- Beynon, L.R., *et al.* 1971. Dealing with major oil spills at sea. Journal of the Institute of Petroleum (London) pp. 187-193.
- Beynon, L.R. 1980. Combatting oil spills in the marine environment. Available from BPS Exhib. Ltd., London, England., Technical Session M, pp. 21-25.
- Blackshear, P.L. and K.A. Murty. 1967. Some effects of size, orientation, and fuel molecular weight on the burning of fuel-soaked wicks. Eleventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA., pp. 545-552.
- Blinov, V.I. and G.N. Khudiakov. 1959. Certain laws governing diffusive burning of liquids. Fire Research Abstracts and Review. Vol 1(1), pp. 41-44.
- Blinov, V.I. and G.N. Khudiakov. 1961. Diffusion burning of liquids. U.S. Army Research and Development Laboratories Translation T-1490 -c 63-15670.
- Blokker, P.C. 1964. Spreading and evaporation of petroleum on water. Proceedings of the 4th International Harbour Conference, Antwerp, Belgium.
- Bobra, M.A., P.I. Kawamura, M.F. Fingas, and D. Velicogna. 1987. Laboratory and tank test evaluation of elastol. Proceedings of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 223-242.
- Bobra, M. 1990. A Study of the formation of water-in-oil emulsions. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 87-117.
- Bobra, M. and S. Callaghan. 1990. A catalogue of crude oil and product properties: Environment Canada, Environmental Protection Directorate Unpublished Report EE-125, Ottawa, 542 pp.
- Bobra, M. 1991. Water-in-oil Emulsification: A Physicochemical Study. Proceedings of the 1991 International Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 483-488.
- Bobra, M. 1992. Photolysis of Petroleum. Environment Canada Environmental Emergencies publication EE-131, Ottawa, Ontario K1A 0H3.
- Borst, M. 1983. GEMENG lightweight fireproof boom: oil containment testing at OHMSETT. Environment Canada, Ottawa, Ontario, Report No. EPS 4-EP-83-5, 18 p.

- Bowker, R.R. 1991. The environmental impact of the Gulf War; *Ecologist*, Jul-Aug 91, v 21, n 4, p 166(6).
- Brander-Smith, D., D.P. Therrien and J. Tobin. 1990. Protecting our waters. Public Review Panel on Tanker Safety and Marine Spills Response Capability. Final Report, September 1990. Minister of Supply and Services Canada 1990. Catalogue No. EN21-91/1990 E.
- Brown, H.M. and R.H. Goodman. 1986. In situ burning of oil in ice leads. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 245-256.
- Brown, H.M. and R.H. Goodman. 1987. In situ burning of oil in experimental ice leads. Environment Canada, Ottawa, Ontario, Environmental Studies Revolving Funds Report No. 064, 33 p.
- Brown, V.M. 1991. Radical environmentalism, the new approach. The removal of oil as a primary goal of oil spill cleanup operations. Proceedings of the 7th Symposium on Coastal and Ocean Management. American Society of Civil Engineers, New York, NY., pp. 301-314.
- Brzustowski, T.A. and E.C. Sommer Jr. 1973. Predicting radiant heating from flames. Mid Year Meeting of the API, Philadelphia, PA.
- Brzustowski, T.A., S.R. Gollahalli, M.P. Gupta, M. Kaptein, and H.F. Sullivan. 1975. Radiant heating from flares. ASME Paper 75-HT-4.
- Brzustowski, T. 1977. Plume burning experiment. Second Report, January 14.
- Brzustowski, T.A. 1979. A model for predicting the shapes and lengths of turbulent diffusion flames over an industrial. 22nd Canadian Chemical Engineering Conference, Toronto, Ontario.
- Brzustowski, T.A. and E.M. Twardus. 1982. A study of the burning of a slick of crude oil on water. Nineteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA., pp. 847-854.
- Brzustowski, T.A. 1985. A study of the burning of unconfined oil slicks. Transactions of the Canadian Society for Mechanical Engineers 9(2):192-199.
- Buist, I.A. and I.R. McAllister. 1981. Dome Petroleum's fireproof boom — development and testing to date. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 479-497.

- Buist, I., W. Pistruzak and D. Dickins. 1981. Dome Petroleum's oil and gas under sea ice study. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 647-686.
- Buist, I.A., W.M. Pistruzak, and D.F. Dickins. 1981. Dome Petroleum's oil and gas undersea ice study. Spill Technology Newsletter, May-Jun 81, v6, n3, p. 120-147.
- Buist, I and S. Potter. 1982. Sub-sea containment: COOSRA research to date. Proceedings of the Fifth Arctic and Marine Oilspill Program Technical Seminar, June 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 129-150.
- Buist, I.A., R.C. Belore, and L.B. Solsberg. 1983. Countermeasures for a major oil spill from a tanker in arctic waters. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 168-189.
- Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy, and I.R. McAllister. 1983. The development and testing of a fireproof boom. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, June 14-16, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 70-84.
- Buist, I.A., S.G. Potter, and D.F. Dickins. 1983. Fate and behaviour of water-in-oil emulsions in ice. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, June 14-16, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 263-279.
- Buist, I.A., R.C. Belore, and L.B. Solsberg. 1983. Behaviour of and response to a major oil spill from a tanker in arctic waters. Spill Technology Newsletter 8(3):50-77.
- Buist, I.A. and E.M. Twardus. 1984. In situ burning of uncontained oil slicks. Proceedings of the Seventh Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 128-154.
- Buist, I.A. and D.F. Dickins. 1984. Oil and gas under sea ice - final report. pp. 22-41.
- Buist, I.A. and E.M. Twardus. 1985. Burning unconfined oil slicks: large scale tests and modelling. Proceedings of the Eighth Arctic and Marine Oilspill Program Technical Seminar, June 18-20, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 103-129.
- Buist, I.A. and I. Bjerkelund. 1986. Oil in pack ice: preliminary results of three experimental spills. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 379-397.

- Buist, I.A. 1987. A preliminary feasibility study of in situ burning of spreading oil slicks. Proceedings of the 1987 Oil Spill Conference, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 359-367.
- Buist, I.A. and D.F. Dickins. 1987. Experimental spills of crude oil in pack ice. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 373-382.
- Buist I.A., S. Potter, D. Mackay, and M. Charles. 1989. Laboratory studies on the behavior and cleanup of waxy crude oil spills. Proceedings of the 1989 Oil Spill Conference, February 13-16, San Antonio, Texas. American Petroleum Institute, Washington, D.C. pp. 105-113.
- Buist, I.A. 1989. Disposal of spilled hibernia crude oils and emulsions - in situ burning and the "Swirlfire" burner. Proceedings of the Twelfth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 245-277.
- Burgess, D.S., J. Grumer, and H.G. Wolfhand. 1961. Burning rates of liquid fuels in large and small open trays. The Use of Models in Fire Research. National Research Council, Washington, D.C.
- Burgess, D.S., A. Strasser, and J. Grumer. 1961. Diffusive burning of liquid fuels in open trays. Fire Research Abstracts and Reviews 3(3):177-192.
- Burgess, D. and J. Grumer. 1962. Comments on "The burning rate of liquid fuels from open trays by natural convection. Fire Research Abstracts and Reviews 4(3):236-238.
- Burgess, D.S. and M. Hertzberg. 1974. Radiation from pool flames. Heat transfer in flames. John Wiley & Sons, New York, NY., pp. 413-430.
- Burgoyne, J.H. and L.L. Katan. 1947. Fires in open tanks of petroleum products: some fundamental aspects. Journal of the Institute of Petroleum Technologists 33(1):158-191.
- Burns, R.C. 1988. Cleanup and containment of a diesel fuel spill to a sensitive water body at a remote site under extreme winter conditions. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 209-220.
- Cabioc'h, F. 1993. Last French experiments in order to evaluate the burning possibilities of three water-in-oil emulsions. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario.

- Calderbank, A. 1989. The Occurrence and Significance of Bound Pesticide Residues in Soil. *In* Review of Environmental Contamination and Toxicology 108: 71-103. Springer-Verlag. New York.
- Callahan, M., M. Slimak, N. Gabel, I. May, C. Fowler, R. Freed, P. Jennings, R. Durfee, F. Whitmore, B. Maestri, M. Mabey, B. Holt and C. Gould. 1979. Water-Related Environmental Fate of 129 Priority Pollutants. Chapter 97. EPA 440/4-79-029a.
- Campagna, P.R. and A. Humphrey. 1992. Air sampling and monitoring at the Kuwait oil well fires. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 575-592.
- Campbell, D.M. 1993. Shetland oil spill. *Br. Med. J.* 306:519.
- Canguard Consulting Ltd. 1980. Preliminary evaluation and testing of ultrasonic transducers in acoustic oil collection and burning.
- Caron, P. (Department of Civil Engineering and Applied Mechanics). 1988. Atomization methods for burning oil spills. McGill University, Montreal, Quebec., 29 p.
- Carrier, G., F. Fendell, and J. Mitchell. 1992. In situ burning via towed boom of oil spilled at sea. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 659-680.
- Casarett, L.J. and J. Doull. 1991. Toxicology: The Basic Science of Poisons. 4th ed. Pergamon Press.
- Castellucci, N.T., *et al.* 1972. Process for burning a combustible liquid using cellular ceramic nodules. U.S. Patent 3661497.
- Chamberlain, G. 1989. Technology tackles the oil spill. *Design News* 45(12):90-95.
- Chen, E.C. (United States Coast Guard). 1972. Arctic winter oil spill test. Report for Environment Canada, Inland Waters Directorate, Environment Canada, Ottawa, Ontario, pp. 1-20.
- Christie, B. 1993. Shetland Oil spill prompts health checks on islanders. *Br. Med. J.* 306:230.
- Clark, R.C. and W.D. MacLeod. 1977. Impacts, transport mechanisms and observed concentration of petroleum in the marine environment. *In* D.C. Malius (ed). Effects of petroleum on arctic and subarctic marine environments and organisms. Vol. 1. Nature and fate of petroleum. Academic Press, Inc. New York, N.Y., pp. 91-223.

- Clement Associates. 1988. Comparative Potency Approach for Estimating the Cancer Risk Associated with Exposure to Mixtures of Polycyclic Aromatic Hydrocarbons. Interim Final Report. EPA Contract No. 68-02-4403.
- Cochrane, H. 1971. Process for burning oil spills. U.S. Patent Office: Official Gazette 882(3):1204.
- Cofer, W.R. III, R.K. Stevens, E.L. Winstead, J.P. Pinto, D.I. Sebacher, M.Y. Abdulraheem, M. Al-Sahafi, M.A. Mazurek, R.A. Rasmussen, D.R. Cahoon, and J.S. Levine. 1992. Kuwaiti oil fires: Compositions of source smoke. *Journal of Geophysical Research*, Vol. 97, No. D13, pages 14,521-14,525.
- Comfort, G., B. Menon, and W. Purves. (Arctec Canada Ltd). 1979. The feasibility of pneumatic and water spray barriers as fireproof oilslick containment devices. *Spill Technology Newsletter* 4:93-110.
- Comfort, G., B. Menon, and P. Noble. 1979. Feasibility of air and water spray barriers for the collection, concentration and in situ burning of spilled oil. AMOP Technical Seminar Preprints. Environment Canada, Ottawa, Ontario, p 13.
- Comfort, G. (Fleet Technology Ltd.). 1989. Tests to evaluate the effect of a waterjet barrier on the burning efficiency of a floating oil slick. Environment Canada Report EE-112, Environment Canada, Ottawa, Ontario.
- Comfort, G., B. Menon, and W.F. Purves. 1980. Feasibility of water spray barriers as fireproof oilslick containment devices. Inst. Electr. Electron. Eng. Inc., New York, NY.
- Comfort, G. and M. Punt. 1989. Oil burning tests conducted in the presence of a high pressure waterjet barrier. Proceedings of the Twelfth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 227-243.
- Costantinides, G. and G. Arich. 1967. Non-hydrocarbon compounds in petroleum. *In*: WHO, 1989.
- Coupal, B. 1972. Use of peat moss in controlled combustion technique. Environment Canada, Ottawa, Ontario, Environment Canada Report No. EPS 4-EE-72-1, 32 p.
- Coupal, B. 1976. Controlled combustion tests carried out near Rimouski. Environment Canada Report EPS-4-EC-76-2. Environment Canada, Ottawa, Ontario.
- Couture, J.E.G. and P.A. Twardawa. 1982. Peripheral-burning incendiary device. Canadian Patent 1,132,355.
- Curzon, F. and B. Ahlborn. 1978. Oil removal system using acoustical radiation. Unpublished report to Environment Canada. Ottawa.

- Cutter Information Corp. 1992. The international oil spill control directory. Eleventh Edition 1991-92. Cutter Information Corp. Arlington, MA.
- Cutter Information Corp. 1993. The international oil spill control directory. Twelfth Edition. Cutter Information Corp. Arlington, MA.
- D-Atri, B. and T. King. 1993. Flicking your Bic at twenty-five below (or: The Atigun Pass Diesel Spill project). Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 669-678.
- Daling, P.S. and P.J. Brandvik. 1988. "A study of the formation and stability of water-in-oil emulsions". Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 153-170.
- Danenberger, E.P. 1991. Oil spill contingency planning for OCS operations. Proceedings of the 7th Symposium on Coastal and Ocean Management. ASCE, New York, NY., pp. 472-484.
- Day, T., D. MacKay, S. Nadeau, and R. Thurier. 1978. Characteristics of smoke from in situ crude oil fires. Proceedings of the AMOP Technical Seminar, March 15-17, Edmonton, Alta. Environment Canada, Ottawa, Ontario, pp. 179-189.
- Day, T., D. Mackay, S. Nadeau, and R. Thurier. 1979. Emissions from in situ burning of crude oil in the arctic. *Water, Air and Soil Pollution* 11(2):139-152.
- Day, T., D. Mackay, S. Nadeau, and R. Thurier. 1979. Characteristics of atmospheric emissions from an in-situ crude oil fire. *Environ. Canada Technol. Develop. Report EPS 4-EC-79-1*. 79 p.
- Dayan, A. and C.L. Tien. 1974. Radiant heating from a cylindrical fire column. *Combustion Science and Technology* 9(1):41-47.
- Delaurier, P.C., S. Martin, B. Morson, and B. Baxter. 1977. The physical and chemical behavior of the bouchard no. 65 oil spill in the ice covered Beaufort sea. NOAA OCSEAP Report.
- DeLauze, H.G. and S.A. Comex. 1978. Removing heavy crude from a sunken tanker. *Ocean Industry* 13(2):37-40.
- Delvigne, G.A.L. 1985. Experiments on natural and chemical dispersion of oil in laboratory and field circumstances. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C.

- Delvigne, G.A.L. 1987. Droplet size distribution of naturally dispersed oil. In Kuiper, J. and W.J. Van den Brink (eds). *Fate and Effects of Oil in Marine Ecosystems*. Martinus Nijhoff Publ., Dordrecht, Netherlands, pp. 29-40.
- deRis, J. 1979. Fire radiation - a review. Seventeenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA., pp. 1003-1016.
- Det norske Veritas. 1979. Tanker oil spill analysis study. Technical report for Canadian Marine Drilling Limited. Det norske Veritas Ship Division.
- Dewling, R.T. 1969. Chemical treatment of oil spills. Proceedings of the 1969 Joint Conference on the Prevention and Control of Oil Spills, December 15-17, New York, NY. American Petroleum Institute, Washington, D.C. pp. 217-222.
- Dickins, D.F. 1979. Air deployable oil spill igniter tests - Yellowknife. Arctic Petroleum Operators Association Project 164.
- Dickins, D.F., I.A. Buist, and W.M. Pistruzak. 1981. Dome Petroleum's study of oil and gas under sea ice. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 183-190.
- Diederichsen, J., A.R. Hall, and P.T. Hinde. 1972. Ignition and combustion in situ of oil from wrecked tankers: small scale burning tests. NTIS Report No. AD-784,988. Rocket Propulsion Establishment, Wescott, England.
- Diederichsen, J., A.R. Hall, P.T. Hinde, and A.T. Jeffs. 1973. Oil burning rates in partly vented tanks: application to disposal of wrecked oil tanker cargoes. *Journal of the Institute of Petroleum* 59(567):98-105.
- Diederichsen, J., A.R. Hall, and A.T. Jeffs. 1973. The burning of oil in wrecked tankers: large scale burning tests. Rocket Propulsion Establishment, Wescott, England.
- Dome Petroleum Ltd. 1981. Fire proof boom development — OHMSETT trials. Dome Petroleum Ltd., Calgary, Alberta., 27 p.
- Dome Petroleum Ltd. 1981. Oil and gas under sea ice. Final report volume one. Report to COOSRA. Calgary, AB.
- Dome Petroleum Ltd., Esso Resources Canada Ltd., and Gulf Canada Resources Inc. 1982. Beaufort Sea - Mackenzie Delta environmental impact statement - volume 6: accidental spills. pp. 5.1-9.1
- Dome Petroleum Ltd. 1982. Fate and behavior of water-in-oil emulsions in ice. Report to COOSRA. Calgary, Alberta. 55p.
- Dome Petroleum Ltd. 1983. Fireproof boom field testing. COOSRA Report. Dome Petroleum Ltd., Calgary, Alta.

- Doodier, J.L. and R.J. Siclari, R.J. 1981. Combustion: an oil spill mitigation tool. Phase II: the burning of the *M/T Burmah Agate*. U.S. Government Printing Office, Washington, D.C., U.S. Department of Energy Report DOE/TIC-11471. 134 p.
- Dowty, B.J., J.W. Brown, F.N. Stone, J. Lake, and J.L. Laseta. 1981. GC-MS analysis of volatile organics from atmospheres impacted by the *Amoco Cadiz* oil spill. In *Amoco Cadiz: Fates and Effects of the Oil Spill*. Proc. Int. Symp., Centre Oceanog. de Bretagne, Brest, France, 19-22 November 1979. Centre Nationale Pour Exploitation des Oceans. Paris, pp. 13-22.
- Duerden, F.C. 1975. Spill in Portugal: a report of the *Jakob Maersk* incident. Environmental impact and assessment. Environment Canada, Ottawa, Ontario, Report No. EPS-8-EC-76-1. 32 p.
- Eggleston, L.A., W.R. Herrera, and M.D. Pish. 1975. The effect of turbulent waters on the nature and extinguishment of oil spill fires. Proceedings of the Fourth International Symposium on the Transportation of Hazardous Cargoes by Sea and Inland Waters, NTIS Report No. AD/A-023505.
- Eisler, R. 1987. Polycyclic Aromatic Hydrocarbon Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review. U.S. Fish and Wildlife Service. Biological Report 85(1.11).
- Energetex Engineering. 1977. Ignition and burning of crude oil on water pools and under arctic spring time conditions. Arctic Petroleum Operators Association Project 141. 70 p. APOA, Calgary, Alta.
- Energetex Engineering. 1978. Testing of air-deployable incendiary devices for igniting oil on water. Environment Canada, Ottawa, Ontario, Report No. EPS-4-EC-78-11, 98 p.
- Energetex Engineering. 1979. A review of oil slick combustion promoters. Environment Canada, Ottawa, Ontario. Environment Canada Report EPS-3-EC-79-8, 48 p.
- Energetex Engineering. 1980. A study to evaluate the combustibility and other physical and chemical properties of aged oils and emulsions. Report to Environment Canada, Ottawa.
- Energetex Engineering. 1981. Burning of crude oil under wind herding conditions. Report prepared for Canadian Marine Drilling Ltd.
- Energetex Engineering. 1981. Arctic field trials of the DREV/AMOP incendiary devices. Environment Canada, Ottawa, Ontario. Report EE-17, 25 p.
- Energetex Engineering. 1981. In situ combustion: an oil spill countermeasure for arctic shorelines. Report for Environment Canada. Environment Canada, Ottawa, Ontario.

- Energetex Engineering. 1981. Subsea containment study. Phase II - turbulent burning. Report prepared under the sponsorship of COOSRA.
- Energetex Engineering. 1982. Environmental testing of Dome air-deployable igniter. Final report prepared for Dome Petroleum Ltd., 28 p.
- Energetex Engineering. 1982. Improvement of air-deployable oil slick igniters. Arctic Petroleum Operators Association Project 165. APOA, Calgary, Alta.
- Engelhardt, F.R. 1993. The MSRC research and development program: An update on progress. Proceedings of the 1993 International Oil Spill Conference, March 29-April 1, 1993, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 537-540.
- Evans, D., H. Baum, B. McCaffrey, G. Mulholland, M. Harkleroad, and W. Manders. 1986. Combustion of oil on water. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 301-336.
- Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1987. Environmental effects of oil spill combustion. Proceedings of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 91-130.
- Evans, D.D. 1988. Combustion of oil spills on water. Technology Assessment and Research Program for Offshore Minerals Operations; OCS Study MMS 88-0057. pp. 169-179.
- Evans, D.D. 1988. In situ burning of oil spills: Appendix B - case histories of attempts to use burning. Alaska Arctic Offshore Oilspill Response Technology Workshop Proceedings. pp. 77-81.
- Evans, D.D. 1988. In situ burning of oil spills. Alaska Arctic Offshore Oil Spill Response Technology. U.S. Government Printing Office, Washington, D.C., Report NIST SP 762, pp. 47-55.
- Evans, D.D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1988. Burning, smoke production, and smoke dispersion from oil spill combustion. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 41-87.
- Evans, D., G. Mulholland, D. Gross, H. Baum, W. Walton, and K. Saito. 1988. Burning, smoke production, and smoke dispersion from oil spill combustion. NISTIR 89-4091, (U.S. Dept. of Commerce, National Institute of Standards and Techn.) 57 p.

- Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1988. Environment effects of oil spill combustion. Govt Reports Announcements & Index (GRA&I), Issue 02, 1989.
- Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1989. Generation and dispersal of smoke from oil spill Combustion. Proceedings of the 1989 Oil Spill Conference, February 13-16, San Antonio, Texas. American Petroleum Institute. Washington, D.C. pp. 181-186.
- Evans, D., H. Baum, G. Mulholland, N. Bryner, and G. Forney. 1989. Smoke plumes from crude oil burns. Proceedings of the Twelfth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario pp. 1-22.
- Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito. 1989. Smoke production and smoke dispersion from Oil spill combustion. NISTIR report in preparation.
- Evans, D. 1989. Burning, smoke production, and smoke dispersion from oil spill combustion. National Institute of Standards and Technology, Gaithersburg, MD., 51 p.
- Evans, D., W. Walton, H. Baum, R. Lawson and R. Rehm. 1990. Measurement of large scale oil spill burns. Govt Reports Announcements & Index (GRA&I), Issue 22, 1990.
- Evans, D., W. Walton, H. Baum, R. Lawson, R. Rehm, R. Harris, and A. Ghoniem. 1990. Measurement of large scale oil spill burns. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 1-38.
- Evans, D.D., G.W. Mulholland, J.R. Lawson, E.J. Tennyson, P.A. Tebeau, M.F. Fingas, and J.R. Gould. 1991. Burning of oil spills. Proceedings of the 1991 Oilspill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 677-680.
- Evans, D., W. Walton, H. Baum, G. Mulholland, J. Lawson, H. Koseki, and A. Ghoniem. 1991. Smoke emission from burning crude oil. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 421-449.
- Evans, D.D. and E.J. Tennyson. 1991. In situ burning: a promising oil spill response strategy. Proceedings of the Seventh Symposium on Coastal and Ocean Management, Long Beach, CA.

- Evans, D., W. Walton, H. Baum, K.A. Notarianni, J.R. Lawson, H.C. Tang, K.R. Keydel, R.G. Rehm, D. Madrzykowski, and R.H. Zile. 1992. In-situ burning of oil spills: Mesoscale experiments. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 593-657.
- Evans, D. 1992. In-situ burning. NIST studies. Proceedings of the First International Oil Spill R&D Forum. Interagency Coordinating Committee on Oil Pollution Research of the U.S. Government. Washington, D.C. (produced by TMS Inc.) pp. 241-246.
- Ewing, H. 1979. Devices to contain oil for in-situ burning. Spill Technology Newsletter. Vol 4(3). May-June 1979. Environment Canada, Ottawa. pg 175.
- Exxon. 1983. Oil Spill Cleanup Manual; Volume II. Exxon Corporation.
- Exxon. 1990. Valdez oil spill technology. Exxon Production Research Company.
- Falk, H.L., P. Kotin and S. Thompson. 1964. Inhibition of carcinogenesis: The effect of polycyclic hydrocarbons and related compounds. Arch. Environ. Health 9: 169-179.
- Ferek, R.J., P.V. Hobbs, J.A. Herring, K.K. Laursen, R.E. Weiss, and R.A. Rasmussen. 1992. Chemical composition of emissions from the Kuwait oil fires. Jour. Geophys. Research, v. 97 (D13); p. 14483-14489.
- Fingas, M.F., W.S. Duval, and G.B. Stevenson. 1978. The basics of oil spill cleanup. Environment Canada, Ottawa, Ontario, 155 p.
- Fingas, M.F. 1979. The Basics of Oil Spill Cleanup. Environmental Canada.
- Fingas, M. and N. Laroche. 1990. An introduction to in-situ burning of oil spills. Spill Technology Newsletter, Dec 90, v15, n4, p. 1-9.
- Fingas, M. and N. Laroche. 1991. An introduction to in-situ burning of oil spills. Spill Technology Newsletter 15(4):1-11.
- Fingas, M. 1992. In-situ burning of oil spills: Review and research priorities. Proceedings of the First International Oil Spill R&D Forum. Interagency Coordinating Committee on Oil Pollution Research of the U.S. Government. Washington, D.C. (produced by TMS Inc.) pp. 247-252.
- Fingas, M.F., K. Li, F. Ackerman, P.R. Campagna, R.D. Turpin, S.J. Getty, M.F. Soleki, M.J. Trespalacios, J. Pare, M.C. Fissonnette, and E.J. Tennyson. 1993. Emissions from Mesoscale in-situ oil fires: The Mobile 1991 and 1992 tests. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. p. 749-821.

- Fingas, M.F., F. Ackerman, K. Li, P. Lambert, Z. Wang, M.C. Bissonnette, P.R. Campagna, P. Boileau, N. Laroche, P. Jokuty, R. Nelson, R.D. Turpin, M.J. Trespalacios, G. Halley, J. Belanger, J. Paré, N. Vanderkooy, E.J. Tennyson, D. Aurand and R. Hiltabrand. 1994. The Newfoundland offshore burn experiment — NOBE preliminary results of emissions measurement. Proceedings of the Seventeenth Arctic and Marine Oilspill Program Technical Seminar, June 8-10, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 1099-1164.
- Fons, W.L. 1961. Rate of combustion from free surfaces of liquid hydrocarbons. *Combustion and Flame* 5:283-287.
- Ford, W.L. 1970. Report of the scientific coordination team to the head of the task force Operation Oil. Ministry of Transport, Ottawa, Ontario. Report of the Task Force-Operation Oil (Cleanup of the ARROW Oil Spill in Chedabucto Bay) II:1-104.
- Forest Service, U.S. Department of Agriculture. Operating guidelines: Gelled-Fuel Helitorch. U.S. Department of Agriculture, Missoula, Montana. 21 p.
- Franken, P., D. Perry, R. Randt, R. Petersen, and C. Thorpe. 1992. Combustive management of oil spills — Final report. University of Arizona.
- Fraser, J.P. 1991. Initial environmental evaluation — oil burning experiment offshore southern Louisiana. Unpublished proposal.
- Freedman, B. 1989. *Environmental Ecology: the Impacts of Pollution and Other Stresses on Ecosystem Structure and Function*. Academic Press, Inc., San Diego, CA.
- Frieberger, A. and J.M. Byers. 1971. Burning agents for oil spill cleanup. Proceedings of the 1971 Conference on Prevention and Control of Oil Spills, June 15-17, Washington, D.C. American Petroleum Institute, Washington, D.C. pp. 245-251.
- Frish, M.B., M.A. DeFaccio, P.E. Nebolsine, and G.A. Simons. 1985. Laser ignition of arctic marine oil spills. Proceedings of the 8th AMOP Technical Seminar, June 18-20, Edmonton, Alta. Environment Canada, Ottawa, Ontario, pp. 166-275.
- Frish, M.B., G.A. Simons, M.A. DeFaccio, and P.E. Nebolsine. 1985. Laser ignition of oil spills; Phase I: Concept Development. Final Technical Report. Physical Sciences Inc., Andover, MA.
- Frish, M., P. Nebolsine, M. DeFaccio, H. Scholaert, W. Kung, and J. Wong. 1986. Laser ignition of arctic oil spills — engineering design. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 203-221.

- Frish, M.B., P.E. Nebolsine, and M.A. Defaccio. 1987. Laser ignition of oil spills. Proceedings of SPIE - The International Society for Optical Engineering, 709:110-117, SPIE, Bellingham, WA.
- Frish, M., V. Gauthier, J. Frank, and P. Nebolsine. 1988. Laser Ignition of Oil Spills: Telescope assembly and testing. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario, pp. 277-287.
- Frish, M.B. 1988. Helicopter-borne laser ignition of oil spills. Technology Assessment and Research Program for Offshore Minerals Operations. OCS Study MMS 88-0057.
- Frish, M., V. Gauthier, T. Frank, and P. Nebolsine. 1989. Laser ignition of oil spills: telescope assembly and testing. Environment Canada, Ottawa. Environment Canada report EE-113.
- Frish, M.B., M.A. DeFaccio, P.E. Nebolsine, A.M. Nawwar, and D. Howard. Laser ignition of oil spills; Phase II: outdoor demonstration. Final Technical Report, Physical Sciences Inc., Andover MA and Arctec Canada Ltd., Kanata, Ontario.
- Gainer, J.G., W.J. Logan, and D. Mackay. 1977. Sixth Arctic Environmental Workshop. Publication EE6.
- Georghiou, P.E., and P.E. Sheppard. 1982. A study of the mutagenicity of residue resulting from the burning of crude oil. Environment Canada, Ottawa, Ontario, 34p
- Glaeser, J.L. and G.P. Vance. 1971. A study of the behavior of oil spills in the Arctic. U.S.C.G. Report CG-D-53-74. Washington.
- Glassman, I., and J.G. Hansel. 1968. Some thoughts and experiments on liquid fuel spreading, steady burning and ignitability. Fire Research Abstracts and Reviews 10(3):217-234.
- Glassman, I., J.G. Hansel, and T. Eklund. 1969. Hydrodynamic effects in the flame spreading, ignitability and steady burning of liquid fuels. Combustion and Flame 13:99-101.
- Glosten Associates, Inc., D.F. Dickins Associates Ltd., and S.L. Ross Environmental Research Ltd. 1991. Conceptual design for a 144' x 60' x 11' Arctic environment incinerator barge. Report to Shell Western E&P, Anchorage, AK.
- Godin, G.H.F., G.M.L. Bringer Quertier. 1967. Process for recovering, destroying or displacing a petroleum product on the surface of a liquid. Patent No. FR 1556960.
- Golden, P.C. 1974. Oil removal techniques in an arctic environment. MTS Journal 8(8):38-43.

- Gollahalli, S.R., and H.F. Sullivan. 1973. Liquid pool fires (a review). Research Report No. 23. Department of Mechanical Engineering, University of Waterloo.
- Gooding, R.M. 1971. Oil pollution on Wake Island from the Tankers R.C. Stones NOAA/NMF's Spec. Sci. Rep. (Fish): 636:12 pp.
- Goon, D. 1991. Oral Bioavailability of "Aged" Soil-Adsorbed Benzo(a)pyrene (BaP) in Rates. Society of Toxicology Annual Meeting Abstracts #1356.
- Gostintsev, Y.A., N.P. Kopylov, V.V. Lararev, M.A. Motin, Y.V. Shatskikh, and A.F. Solodovnik. 1984. Burning of petroleum on the surface of water (large scale experiment). Combustion, Explosion and Shock Waves 19(4):401-404.
- Grimmer *et al.* 1991. Relevance of polycyclic aromatic hydrocarbons as environmental carcinogens. Jour. Analyt. Chem., v. 339; p. 792-795.
- Groves, A.D. 1986. Multiple-burst vehicle kill probability model where the probability of igniting spilled oil. Army Material Systems Analysis Activity Report. 96 p.
- Gundlach, E.R. and M.O. Hayes. 1971. Vulnerability of coastal environments to oil spill impacts, Mar. Tech. Soc. J. 12 18-27.
- Haaktela, I. 1970. Oil spills off Finland. Marine Pollution Bulletin 1(1):19-20.
- Hägglund, B. and L. Persson. 1976. The heat radiation from petroleum fires, FOA report C 20126-D6(A3) Stockholm.
- Hall, A.R. 1973. Pool burning. Oxidation and Combustion Reviews 6:169-225.
- Hann, R.W. Jr. 1977. Fate of oil from the supertanker *Metula*. Proceedings of the 1977 Oil Spill Conference, March 8-10, New Orleans, Louisiana. American Petroleum Institute, Washington, D.C. pp. 465-468.
- Hardy and Associates, Ltd. 1981. Preliminary assessment of certain beach cleanup techniques. Environment Canada, Ottawa, Ontario. Report No. EPS-4-EC-81-1, 57 p.
- Hayward-Walker, A., D.L. Ducey, J.R. Gould and A.B. Nordvik. 1993. Formation and breaking of water-in-oil emulsions: Workshop proceedings, June 14-15, Kananaskis, AB. MSRC Technical Report Series 93-018. Marine Spill Response Corporation, Washington, D.C.
- Health and Environmental Sciences Department. 1985. Oil spill cleanup: options for minimizing adverse ecological impacts. API Publication No. 4435. American Petroleum Institute, Washington, D.C.

- Heskestad, G. 1983. Luminous height of turbulent diffusion flames. *Fire safety journal*, 5, pp. 103-108.
- Heskestad, G. 1988. Fire plumes. *The SFPE Handbook of Fire Protection Engineering*. National Fire Protection Association, Quincy, MA. pp. 1.107-115.
- Hillman, S.O., and R.V. Shafer. 1983. ABSORB: a three year update in arctic spill response. *Proceedings of the 1983 Oil Spill Conference*, February 28 - March 3, San Antonio, Texas. American Petroleum Institute, Washington, D.C. pp. 219-226.
- Hillman, S.O. 1985. Arctic spill response improvements: a 1985 review of arctic research and development. *Proceedings of the 1985 Oil Spill Conference*, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 411-414.
- Hillstrom, W.W. 1971. Ignition and combustion of unconfined liquid fuels. *Combustion Science and Technology* 3(4):179-186.
- Horn, S.A. and P. Neal. 1981. The *Atlantic Empress* sinking — a large spill without environmental disaster. *Proceedings of the 1981 Oil Spill Conference*, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 429-435.
- Hossain, K. and D. MacKay. 1981. A study of the combustibility of weathered crude oils and water-in-oil emulsions. Environment Canada, Ottawa, Ontario. Environment Canada Report EE-12. 43 p.
- Hottel, H.C. 1959. Certain laws governing diffusive burning of liquids. *Fire Research Abstracts and Reviews* 1(1):41-44.
- Houston, B.J. 1968. Investigation of materials and methods for use in removing surface layers of oil on water. Report No. AD-732221. 27 p.
- Huchnall, D.J. 1985. *Chemistry of hydrocarbon combustion*. London: Chapman and Hall Ltd. pp. 1-128.
- Hume, H.R., I.A. Buist, D. Betts, and R. Goodman. 1983. Arctic marine oil spill research. *Cold Regions Science and Technology* 7:313-341.
- IKU (Institutt for kontinentalsokkelundersøkelser og petroleumsteknologi A/S). 1991. Characterization and prediction of the weathering properties of oils at sea — a manual for the oils investigated in the DIWO Project. DIWO-report no. 16.
- Industry Task Group. 1983. Oil spill response in the Arctic. Part 2. Field demonstrations in broken ice. Industry Task Force comprised of Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company, U.S.A., and Amoco Production Company, Anchorage, Alaska.

- Ivanov, V.M. and P.I. Nefedov. 1965. Experimental investigation of the combustion process on natural and emulsified Fuels. NASA Technical Translation TT F-258.
- Jacobsson, M. 1993. The *Rio Orinoco* and *the Haven* — Two major cases from a legal point of view. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 663-666.
- Jason, N.H., ed. 1988. Alaska arctic offshore oil spill response technology workshop proceedings. Anchorage, Alaska, November 29-December 1, 1988. NIST. Special Publication 762. National Institute of Standards and Technology, Gaithersburg, MD 20899.
- Jason, N.J. 1989. Alaska arctic offshore oil spill response technology - workshop proceedings. NIST SP 762, U.S. Government Printing Office, Washington, D.C.
- Jeffrey, P.G. 1973. Large-scale experiments on the spreading of oil at sea and its disappearance by natural factors. Proceedings of the 1973 Conference on Prevention and Control of Oil Spills, March 13-15, Washington, D.C. American Petroleum Institute, Washington, D.C. pp. 469-474.
- Jensen, D.S. and P.A. Tebeau. 1991. Coast Guard research and development for the 1990s. Proceedings of the 1991 International Oil Spill Conference, March 4-7, 1991, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 661-665.
- Jerbo, A. 1973. Two types of oil spills in Swedish inland waters — Tests of new materials, ideas and methods. Proceedings of the 1973 Conference on Prevention and Control of Oil Spills, March 13-15, Washington, D.C. American Petroleum Institute, Washington, D.C. p. 559.
- Jordan, R.E. and J.R. Payne. 1980. Fate and weathering of petroleum spills in the marine environment. Ann Arbor Science Publ. Ann Arbor, MN.
- Kana, T.E., E. Thompson, and R. Pavia. 1981. *Burmah Agate*: chronology and containment operations. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 131-138.
- Kanury, A.M. 1988. Ignition of liquid fuels. SFPE Handbook of Fire Protection Engineering. National Fire Protection Association, Quincy, MA. pp. 1.315-1.325.
- Koblanski, J.N. 1981. Oil spill removal in the marine environment utilizing acoustic energy. Journal of Canadian Petroleum Technology 20(3):92-96.
- Koblanski, J.N. 1981. Method and apparatus for atomizing and burning liquid hydrocarbons floating on water. U.S. Patent No. 4,308,006.

- Koblanski, J.N. 1983. An acoustical method of burning and collecting oil spills on cold open water surfaces. Proceedings of the 1983 Oil Spill Conference, February 28 - March 3, San Antonio, Texas. American Petroleum Institute, Washington, D.C. pp. 25-28.
- Koblanski, J.N. 1985. Design improvements in a sonic burner for the in situ combustion of oil spills. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. p643.
- Koblanski, J.N. (Ocean Ecology Ltd.). 1986. Apparatus to remove oil slicks. Patent No. US 4576569, 21 p.
- Koblanski, J.N. (Ocean Ecology Ltd.). 1987. Method of removing an oil slick by atomizing and burning. U.S. Patent No. US 4669972, 30 p.
- Koops, W. 1985. The *Katina* oil spill 1982: combating operations at sea. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C.
- Koseki, H. and G.W. Mulholland. 1991. The effect of diameter on the burning of crude oil pool fires. *Fire Technology* 27(1):54-65.
- Koseki, H. 1993. Thermography research for radiation measurement of an oil spill fire. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 833-842.
- Kretschmer, D. and J. Odgers. 1985. Combustibility and incineration of beaufort crude/seawater emulsions. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 19-23.
- Laisk, E. 1976. Feasibility of oil slick removal from seawater using power lasers. *Environmental Science and Technology* 10(8):814-815.
- Lait, G.R. and S.J. Muraro. 1977. The P.F.R.C. aerial ignition system, Mark II. Fisheries and Environment Canada, Ottawa, Ontario.
- Laperriere, F. 1985. A lightweight and low cost fireproof boom. *Spill Technology Newsletter* 10:26-33.
- Laperriere, F. 1985. High pressure waterjet barrier trial in norman wells. *Spill Technology Newsletter*.

- Laskin, S.M., M. Kushner and R.T. Drew. 1970. Studies in pulmonary carcinogenesis. In M. G. Hanna *et al.*, eds. Inhalation Carcinogenesis. AEC Symposium Series No. 18. Washington, D.C.: U.S. Atomic Energy Commission.
- Laursen, K.K., R.J. Ferek, P.V. Hobbs, and R.A. Rasmussen. 1992. Emission factors for particles, elemental carbon, and trace gases from the Kuwait oil fires. *Jour. Geophys. Research*, v. 97 (D13); p. 14491-14497.
- Lee, R.F. 1980. Processes affecting the fate of oil in the sea. In Geyer, R.A. (ed). *Marine Environmental Pollution 1 Hydrocarbons*. Elsevier. New York, N.Y., pp. 337-351.
- Leveille, T.P. 1991. The *Mega Borg* fire and oil spill: a case study. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 273-278.
- Lewis, E.L. 1976. Oil in sea ice. Beaufort Sea Project Overview Report. Department of the Environment, Victoria, B.C.
- Li, K., T. Caron, M. Landriault, J.R. Pare, and M. Fingas. 1992. Measurement of volatiles, semi-volatiles and heavy metals in an oil burn test. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 561-573.
- Lichtenthaler, R.G. and P.S. Daling. 1985. Aerial application of dispersants — comparison of slick behavior of chemically treated vs non-treated slicks. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 471-478.
- Lippson, A.J. and R.L. Lippson. 1984. *Life in Chesapeake Bay*. John Hopkins University Press. Baltimore, Maryland.
- Lipski, C. 1986. Study of in-situ combustion of oil spills. Environment Canada, Ottawa, Ontario. Report to the Environmental Emergencies Technology Division, 24 p.
- Little, Arthur D. (Inc.). 1969. Combatting pollution created by oil spills - volume one: methods. NTIS Report No. AD 969 935, U.S. Coast Guard, Washington, D.C.
- Logan, W.J. 1975. Oil spill countermeasures for the Beaufort sea. Proceedings of the 1975 Oil Spill Conference, March 25-27, San Francisco, California. American Petroleum Institute, Washington, D.C.
- Logan, W.J., D.E. Thornton, and S.L. Ross. 1976. A review of oil spill countermeasures. Beaufort Sea Project Technical Report No. 31. Environment Canada, Ottawa, Ontario.

- Logan, W.J., D.E. Thornton, and S.L. Ross. 1976. Oil spill countermeasures for the southern Beaufort sea: appendix. Beaufort Sea Technical Report No. 31b. Department of the Environment, Victoria, BC.
- Lunel, T. and A. Lewis. 1993. Oil concentrations below a demulsifier treated slick. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 955-972.
- Mackay, D., K. Hossain, and A. Kisil (Institute of Environmental Studies). 1979. Research in oil, gas and ice at the University of Toronto. University of Toronto, Toronto, Ontario. pp. 27-31.
- Mackay, D., I.A. Buist, R. Mascarenhas, and S. Paterson. 1980. Oil spill processes and models. Department of Chemical Engineering, University of Toronto, Toronto, Ontario, Environmental Protection Service Publication No. EE-8.
- Mackay, D. 1981. Fate and behavior of oil spills. In J.B. Sprague *et al.* (eds). Oil and dispersants in Canadian seas. Environmental Protection Services, Ottawa, Canada., p.7-27.
- Mackay, D. 1984. The fate and behaviour of oil in cold climates. Department of Chemical Engineering and Applied Chemistry. Report to Environment Canada, Ottawa.
- Mackay, D. and A. Chau. 1986. The effectiveness of chemical dispersants: a discussion of laboratory and field test results. DOOS — seminar, November 10-12, 1986. Trondheim, Norway.
- Mackey, A.L. 1985. In situ combustion of oil spills utilizing acoustic energy. Report for Environment Canada, Environmental Emergencies Technology Division. Environment Canada, Ottawa, Ontario.
- Mackinven, R., J.G. Hansel, and I. Glassman. 1970. Influence of laboratory parameters on flame spread across liquid Fuels. Combustion Science and Technology 1(4):293-306.
- Marcinowski, H.J. 1970. Recent results of methods for combating acute oil pollution of the sea and coastal waters. Stichting CONCAWE Report 2(28).
- Marsh, G.D., L.A. Schultz, and F.W. DeBord. 1979. Cold regions spill response. Proceedings of the 1979 Oil Spill Conference, March 19-22, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 355-358.
- Martec Ltd. 1984. Report on the environmental program associated with the blowout at Shell *et al.* Uniacke G-72. Unpublished report prepared for Shell Resources Canada Ltd., Dartmouth, Nova Scotia, Canada.

- Massie, L.C., A.P. Ward, J.M. Davies, and P.R. Mackie. 1985. The effects of oil exploration and production in the northern North Sea. Part 1. The levels of hydrocarbons in water and sediments in selected areas, 1978-1981. *Mar. Environ. Res.*; vol. 15, no. 3, pp. 165-213.
- Maybourn, R. 1971. The work of the IP working group on the burning of oil. *Journal of the Institute of Petroleum* 57:12-16.
- McAlevy III, R.F. and R.S. Magee. 1968. The mechanism of flame spreading over the surface of the igniting condensed-phase materials. Twelfth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA, pp. 215-227.
- McAllister Engineering Ltd. 1979. Development and testing of a "quickie" fire resistant oil containment boom. Report to Canadian Marine Drilling, Dome Petroleum Ltd.
- McAllister, I.R. and I.A. Buist. 1980. Fireproof boom development. Phase III - prototype construction and testing. Report for Dome Petroleum Ltd.
- McAllister, I.R. and I.A. Buist. 1981. Dome Petroleum's fireproof boom — development and testing to date. Proceedings of the Fourth Arctic Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario.
- McAuliffe, C.D., D.E. Fitzgerald, B.L. Steelman, J.P. Ray, W.R. Leek, and C.D. Barker. 1981. The 1979 southern California dispersant treated research oil spills. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 269-282.
- McCaffrey, B.J. and G. Heskestad. 1976. A robust bidirectional low-velocity probe for flame and fire application. *Combustion and Flame* 26:125-127.
- McCaffrey, B.J. 1983. Momentum implications for buoyant diffusion flames. *Combustion and Flame* 52:149-167.
- McCaffrey, B.J. 1988. Flame height. *The SFPE Handbook of Fire Protection Engineering*; Quincy, MA: National Fire Protection Association. pp. 1.298-1.305.
- McConnell, E.E., G.W. Lucier, R.C. Lumbaugh, P.W. Albro, D.J. Harvan, J.R. Hass and M.W. Harris. 1984. Dioxin in Soil: Bioavailability After Ingestion by Rats and Guinea Pigs. *Science* 223:1077-1079.
- McGibbon, G., R.G. Gisher, I.G. Meldrum, and A.J. Plomer. 1982. Further developments in oil spill solidification. Proceedings of the Fifth Arctic and Marine Oilspill Program Technical Seminar, June 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 199-216.

- McGuire, J.H. 1968. Heat transfer by radiation. Fire Research Special Report No. 2. H.M. Stationery Office, London.
- McKendrick, J.D. and W.M. Mitchell. 1978. Effects of burning crude oil spilled onto six habitat types in Alaska. *Arctic* v. 31 (3), p. 277-295.
- McLeod, W.R. and D.L. McLeod. 1972. Measures to combat offshore Arctic oil spills. Preprints — 1972 Offshore Technology Conference, pp. 141-162.
- McManus, S. 1993. Personal communication, fax of 15/11/93 re test results for fire boom. Kepner Plastics Fabricators Inc. Torrance, CA.
- McMinn, T.J. 1973. Crude oil behavior on Arctic winter ice. U.S. Coast Guard Project 734108. Washington, D.C. NTIS AD-754, 261.
- McMinn, T.J. and P. Golden. 1973. Behavioral characteristics and cleanup techniques of north slope crude oil in an Arctic environment. Proceedings of the 1973 Oil Spill Conference, March 13-15, Washington, D.C. American Petroleum Institute, Washington, D.C. pp. 263-276.
- Meijs, F.H., L.J. Schmit Jongbloed, and H.J. Tadema. 1969. New methods for combatting oil slicks. Proceedings of the Joint Conference on Prevention and Control of Oil Spills, December 15-17, New York, NY. American Petroleum Institute, Washington, D.C. pp. 263-269.
- Meikle, K. 1981. An oil slick igniter for remote areas. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 617-621.
- Meikle, K.M. 1981. Incendiary device for oil slick ignition. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 499-513.
- Meikle, K.M. 1983. An effective low-cost fireproof boom. Proceedings of the 1983 Oil Spill Conference, February 28 — March 3, San Antonio, Texas. American Petroleum Institute, Washington, D.C. pp. 39-42.
- Meikle, K.M., H. Whittaker, and F. Laperriere. 1985. Experimental high pressure waterjet barrier. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C.
- Meikle, K.M. 1989. The arctic and marine oilspill program - AMOP. Proceedings of the Alaska Arctic Offshore Oil Spill Response Technology Workshop. pp. 117-131.
- Menez, J.R., F. Berthou, D. Picart, and C. Richie. 1978. Impacts of the oil spill (*Amoco Cadiz*) on human biology. *Penn. Ar. Bed.* 94:367-378.

- Milne, A. and R.H. Harinveaux. 1977. Crude oil in cold water, the Beaufort sea and the search for oil. Environment Canada, Ottawa, Ontario.
- Milne, A.R. and R.H. Harinveaux. 1978. Crude oil in cold water. Ministry of Supply and Services, Canada. 119p.
- Mitchell, J.B.A. and J.M. Miller. 1989. Studies of the effects of metallic and gaseous additives in the control of soot formation in pool fires. Combustion and Flame 75:45-55.
- Mitchell, J.B.A. 1990. The effectiveness of ferrocene in reducing smoke emission from burning crude oil. Proceedings of the Thirteenth Arctic and Marine Oilspill Program Technical Seminar, June 6-8, Edmonton, Alberta. Environment, Canada, Ottawa, Ontario. pp. 75-85.
- Mitchell, J.B.A. 1990. The use of additives to control smoke emission from the burning of crude oil. Report No. II for Esso Resources Canada Ltd.
- Mitchell, J.B.A. (Department of Physics). 1991. A review of emission factors from the combustion of various fuels. University of Western Ontario, London, Ontario.
- Mitchell, J.B.A. 1991. Smoke reduction from burning crude oil using ferrocene and its derivatives. Combustion and Flame 86:179-184.
- Mitchell, J.B.A. 1991. Smoke reduction from burning crude oil using ferrocene and its derivatives. Spill Technology Newsletter 15(4):11-19.
- Mitchell, J.B.A. and E. Janssen. 1991. The use of additives for smoke reduction from burning pool fires. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 391-397.
- Mitchell, J.B.A. and M.E. Moir. 1992. Smoke reduction from pool fires using ferrocene and derivatives. Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 681-689.
- Modak, A.T. 1981. The burning of large pool fires. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta Georgia. American Petroleum Institute, Washington, D.C.
- Moir, M.E., S. Charbonneau and J.B.A. Mitchell. 1993. Soot reduction chemicals for in-situ burning. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 761-764.

- Moldan, A.G.S. and L.F. Jackson *et al.* 1985. Some aspects of the Castillo de Bellver oil spill. *Marine Pollution Bulletin* 16(3): p. 97-102.
- Moller, T.H., H.D. Parker, and J.A. Nichols. 1987. Comparative costs of oil spill cleanup techniques. *Proceedings of the 1987 Oil Spill Conference*, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 123-127.
- Moller, T.H. 1992. Recent experience of oil sinking. *Proceedings of the Fifteenth Arctic and Marine Oilspill Program Technical Seminar*, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 11-14.
- Moorhouse, J. 1982. Scaling criteria for pool fires derived from large-scale experiments. *I. Chem. Sym.* 71. pp. 165-179.
- Morson, B.J., S.O. Hillman, and W.F. Gusey. 1982. Alaskan Beaufort sea oil spill response considerations manual. *Proceedings of the Fifth Arctic and Marine Oilspill Program Technical Seminar*, June 15-17, Edmonton, Alberta. Environment Canada, Ottawa. Ontario. pp. 297-310.
- MSRC. 1991. Priority topics for research and development in oil spill response. *Technical Report Series 91-001*. Marine Spill Response Corporation, Washington, D.C. 26 pp.
- Muden, K. and P. Croce. 1988. Fire hazard calculations for large open hydrocarbon fires. *SFPE Handbook of Fire Protection Engineering*. Nat. Fire Protection Association, Quincy, MA. pp. 2.45-2.87.
- Mulholland, G.W., N.P. Bryner, L.K. Ives, C.F. Rogers, J.G. Hudson, and J. Hallett. In press. Effect of cloud processing on the optical properties of smoke. *NATURE*.
- Muller-Dethlefs, K. and A.F. Schlader. 1976. The effect of steam on flame temperature burning velocity and carbon formation in hydrocarbon flames. *Combustion and Flame* 27(2):201-215.
- Murad, R.J., J. Lamendola, H. Isoda, and M. Summerfield. 1970. A study of some factors influencing the ignition of a liquid fuel pool. *Combustion and Flame* 15(3):289-298.
- Murty, K.A. 1988. Ignition of liquid fuels. *The SFPE Handbook of Fire Protection Engineering*, Quincy, MA: National Fire Protection Association. pp. 1.315-1.325.
- Nadeau, J.S. and D. Mackay. 1978. Evaporation rates of complex hydrocarbon mixtures under environmental conditions. *Spill Technology Newsletter*, Canadian Environmental Protection Service, Volume 3(2). p.42-55.

- Nakata, K., S. Kanamaki, and T. Kojima. 1991. Numerical model development for oil spill dispersion into the marine environment. IN: Hydraulic Engineering. Proceedings of the 1991 National Conference. American Society of Civil Engineers, New York. 1991. p 644-649.
- National Academy of Sciences (NAS). 1972. Biologic Effects of Atmospheric Pollutants: Particulate Polycyclic Organic Matter. Washington, D.C. NAS.
- Natl. Inst. Oceanogr., Reg. Cent., Versova. 1985. Investigations on oil patches around M.T. Lajpatrai Bombay Harbour. Mahasagar., vol. 18, no. 4, p. 511-516.
- National Research Council (U.S.). 1985. Oil in the Sea: Impacts, fate and effects. National Academy Press, Washington, D.C., 601 pp.
- National Research Council of Canada. 1983. Polycyclic aromatic hydrocarbons in the aquatic environment: Formation, sources fate and effects on aquatic biota. Associate Committee on Scientific Criteria for Environmental Quality, NRCC No. 18981, National Research Council of Canada, Ottawa, Canada.
- The National Response Team. 1989. The *Exxon Valdez* oil spill. A report to the President [United States] from S.K. Skinner, Secretary, Department of Transportation, and W.V. Reilly, Administrator, Environmental Protection Agency, 37 pp.
- Nazka, M.A. and R.J. Crookes. 1984. Effect of water content on pollutant formation in a burning spray of water-in-diesel fuel emulsion. Twentieth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 2001-2010.
- Neff, J.M. 1979. Polycyclic Aromatic Hydrocarbons in the Aquatic Environment: Sources Fates and Biologic Effects. Applied Science Publ. Ltd., London. In: Eisler, 1987.
- Neff, J.M. and J. W. Anderson. 1981. Response of Marine Animals to Petroleum and Specific Petroleum Hydrocarbons. Halsted Press, New York.
- Nelson, W.G. and A.A. Allen. 1982. The physical interaction and cleanup of crude oil with slush and solid first year Sea ice. Proceedings of the Fifth Arctic and Marine Oilspill Program Technical Seminar, June 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 37-58.
- Nikolaychuk, J. and D.E. Thornton. 1976. Technique for burning oil safely where recovery is not feasible. Report to PROSCARAC.
- NOBE Newsletter. September 1993. Environment Canada, Ottawa.
- NORCOR Engineering and Research Ltd. 1974. Investigations of the oil spill at Riviere St. Paul, P.Q. Technical report for Gulf Oil Canada Ltd. Gulf Oil Canada Ltd., Yellowknife, N.W.T. 34 p.

- NORCOR Engineering and Research Ltd. 1975. The interaction of crude oil with arctic sea ice - Beaufort Sea Project. Environment Canada, Ottawa, Ontario. pp. 143-144.
- OSIR (Oil Spill Intelligence Report). Published weekly by Cutter Information Corp., 37 Broadway, Arlington, MA 02174-5539.
- Oenbring, A.R. 1980. Flare design are current methods too conservative? Hydrocarbon processing. May 1980. pp. 124-129.
- Owens, E.H. and K. Trudel. 1985. Oil spill countermeasures for low-energy shorelines in Canada. Environment Canada, Report EE-73.
- Pagni, P.J. 1991. Fire modeling. Grant Report. Summaries of BFRL Fire Research Program In-house Projects and Grants. Gaithersburg, MD. NIST pp. 57-60.
- Pallister, J. 1987. Oil spill contingency measures for the arctic offshore: research and practices. A.P.O.A. Review. Arctic Petroleum Operators Assoc., Calgary, Alta. p11.
- Pertile, L. 1986. In situ combustion of stranded oil on remote shorelines. Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, June 10-12, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 237-244.
- Petty, S.E. 1983. Combustion of crude oil on water. Fire Safety Journal 5:123-134.
- Pipkin, O.A. and C.M. Sliepcevich. 1964. Effect of wind on buoyant diffusion flames. Ind. & Eng. Chem. Fundamentals, (3), No. 2, p 147.
- Pistruzak, W.M. 1981. Dome Petroleum's oil spill research development program for the arctic. Proceedings of the 1981 Oil Spill Conference, March 2-5, Atlanta, Georgia. American Petroleum Institute, Washington, D.C. pp. 173-181.
- Pistruzak, W.M. 1983. Oil spills state-of-the-art review. Twelfth Annual Arctic Environmental Workshop: "Issues of the 80's". Canadian Petroleum Association, Calgary, Alta.
- Pistruzak, W.M. and E.M. Twardus. 1983. Air deployable oil slick igniter. Canadian Patent No. CA1196510. 11 p.
- Poklis, A. and C.D. Burkett. 1977. Gasoline sniffing: a review. Clinical Toxicol. II(1):35-41.
- Politzer, I.R., I.R. DeLeon, and J.L. Lasetar. 1985. Impact on human health of petroleum in the marine environment. Report prepared for the American Petroleum Institute, Washington, D.C. 162 pp.

- Pope, P., A.A. Allen, and W.G. Nelson. 1985. Assessment of three surface collecting agents during temperate and Arctic conditions. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 199-202.
- Potter, S.G. and L.B. Solsberg. 1986. Countermeasures for dealing with spills of viscous waxy crude oils. Environment Canada, Ottawa, Ontario. Canadian Environmental Studies Revolving Funds Report No. 058, 70 p.
- Purves, W.F. (Arctec Canada Ltd.). 1977. Techniques for igniting and burning oil on arctic ice. Report of DSS Contract No. 02SS-KE204-6-EP20. Environment Canada, Ottawa, Ontario.
- Purves, W. 1978. Design and development of equipment to aid in the burning of oil on water. Proceedings of the First Arctic and Marine Oilspill Program Technical Seminar, March 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p190.
- Purves, W.F. and A. Daoust. 1978. Booms for in situ burning of oil spills. Report to Environment Canada, Ottawa.
- Purves, W.F. 1979. The use of promoters for burning oil on water. Spill Technology Newsletter 4(4):230-231.
- Putnam, A.A. 1965. A model study of wind blown free-burning fires. Tenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 1039-1046.
- Quam, H.A. 1976. Techniques for burning oil in front of a deflection boom and conditions where fire safety Permits. Canadian Petroleum Association, Calgary, Alta.
- Quintiere, J.G. 1988. Surface flame spread. The SFPE Handbook of Fire Protection Engineering, Quincy, MA: National Fire Protection Association. pp. 1.360-1.367.
- Rainio, K., R.R. Linko, and L. Ruotsila. 1986. Polycyclic aromatic hydrocarbons in mussel and fish from the Finnish Archipelago Sea. Bull. Environ. Contam. Toxicol., vol. 37, no. 3, p. 337-343.
- Raloff, J. 1993. Burning issues: Is torching the most benign way to clear oil spilled at sea? Science News 144 (14):220-223 (October 2, 1993)
- Ramsier, R.O., G.S. Gantcheff, and L. Colby. 1973. Oil spill at Deception Bay. Scientific Series No. 29. 60 p.
- Rao, U.R., M.G. Chandrasekhar, K. Radhakrishnan, V. Jayaraman, P.S. Desai, P.K. Pal, and P.C. Joshi. 1991. Environmental impacts of the Persian Gulf oil spill and oil-fire smoke. CURR. SCI., vol. 60, no. 8, pp. 486-492.

- Roberts, D. 1978. Development of oil spill burning equipment. Proceedings of the First Arctic and Marine Oilspill Program Technical Seminar, March 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 191-193.
- Roberts, D., and D.K.T. Chu. 1978. Development of oil spill burning equipment. Report by Bennett Pollution Control to Environment Canada, Ottawa.
- Roberts, D. 1979. Development of oil spill burning equipment. Proceedings of the AMOP Technical Seminar, March 7-9, Edmonton, Alta. Environment Canada, Ottawa, Ontario. pp. 191-193.
- Robertson, I., J.R. McDonald, N.S. Robertson and L.B. Solsberg. 1976. The *Urquiola* Oil Spill, La Coruña, Spain. Spill Technology Newsletter, May-June 1976, Canadian Department of the Environment, Environmental Protection Service, Ottawa, Ontario.
- Robertson, I. 1991. Operational examples of in-situ burning: Lessons from the burning of two recent diesel spills on the B.C. coast. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 411-419.
- Robinson, F.J.L. 1979. Treating oil spillages. Great Britain Patent No. GB 2078355A.
- Ross, S.L., C.W. Ross, F. Lepine, and E.K. Langtry. 1979. Ixtoc I Blowout. Spill Technology Newsletter 4(4):245-256.
- Ross, S.L. 1980. Oil spill countermeasures in offshore production. Proceedings of the Ninth Environmental Workshop on Offshore Hydrocarbon Development. Arctic Institute of North America, University of Calgary, Calgary, Alta. pp. 372-397.
- Ross, S.L. 1981. Development of countermeasures for oil spills in Canadian arctic waters. London, England: Graham & Trotman Ltd. pp. 377-399.
- Ross, S.L. 1985. An overview of physical and chemical processes in open water. In Duval, W.S. (ed). A review of the biological fate and effects of oil in cold marine environments. Unpubl. Rep. by ESL Environmental Sciences limited, S.L. Ross Environmental Research Ltd., and Arctic Laboratories Limited for Canada, Environmental Protection Service, Edmonton., pp. 5-12.
- Ross, S.L. and S.G. Potter. 1990. Proceedings of a workshop to establish Canadian marine oil spill research and development priorities. Environmental Studies Research Funds, Canadian Department of Energy, Mines and Resources. ESRF publication number 106.

- Ruby, C.H., L.G. Ward, I.A. Fischer, and P.J. Brown. 1978. Buzzards Bay oil spill — an arctic analogue. International Conference on Ports and Ocean Engineering under Arctic Conditions (POAC '77), 4th Conference, St. John's, Newfoundland, 1977, Volume 2.
- Salooja, K.C. 1972. Burner fuel additives. *Journal of the Institute of Fuel* 45(371):37-42.
- Saunders, H.L., J.F. Grassle and G.R. Hampson. 1972. The West Falmouth Oil Spill. I. Biology. Tech Rep. Woods Hole Oceanogr. Inst. (72-80): 48 pp.
- Schatzberg, P. and K.V. Nagy. 1971. Sorbents for oil spill removal. Proceedings of the 1971 Oil Spill Conference, June 15-17, Washington, D.C. American Petroleum Institute, Washington, D.C. pp. 221-233.
- Schneider, D. 1993. Oil Spill Has Long-Term Effects. *Water, Environ. Technol.* September, 1993.
- Schrier, E. and C. Eidam. 1979. Cleanup efficiency of a fuel oil spill in cold weather. Proceedings of the 1979 Oil Spill Conference, March 19-22, Los Angeles, California. American Petroleum Institute, Washington, D.C. pp. 419-427.
- Schulze, R. 1990. Spill response trade-offs in a very large spill. Proceedings of the 1990 Conference on Oil Spills Management and Legislative Implications. American Society of Civil Engineers, New York, NY. pp. 232-239.
- Schulze, R. 1993. World catalog of oil spill response products: fourth edition. Robert Schulze Environmental Consultant, Inc. Elkridge, MD.
- Seeger, P.G. 1974. On the combustion and heat transfer in fires of liquid fuels in tanks. *Heat Transfer in Fires*. Washington, D.C.: Scripta Book Company. pp. 95-126.
- Seeger, P.G. 1974. Heat transfer by radiation from fires of liquid fuels in tanks. *Heat Transfer in Flames*. New York, NY: John Wiley and Sons. pp. 431-439.
- Shafer, R.V. 1987. Alaska Clean Seas: meeting response needs for 1987 and beyond. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 145-149.
- Shafer, R.V. 1987. Continuing the program: Alaska Clean Seas research, development and engineering. Proceedings of the Tenth Arctic and Marine Oilspill Program Technical Seminar, June 9-11, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 407-422.
- Sharratt, M. and M. Butler. 1992. Toxicological effect of oil smoke. In, *The Environmental and Health Impacts of the Kuwaiti Oil Fires*, Proc. of and International Symposium, Oct. 1991. Birmingham, England; p. 51-56.

- Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company USA, and Amoco Production Company. 1983. Oil spill response in the arctic, part 1: an assessment of containment, recovery, and disposal practices.
- Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company USA, and Amoco Production Company. 1983. Oil spill response in the arctic, part 2: field demonstration in broken ice.
- Shell Oil Company, Sohio Alaska Petroleum Company, Exxon Company USA, and Amoco Production Company. 1984. Oil spill response in the arctic, part 3: Technical documentation.
- Sheppard, E.P. and P.E. Georgiou. 1981. The mutagenicity of Prudhoe Bay crude oil and its burn residues. Proceedings of the Fourth Arctic and Marine Oilspill Program Technical Seminar, June 16-18, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. p. 195-213.
- Sheppard, E.P., R.A. Wills, and P.E. Georgiou. 1983. The mutagenicity of a Prudhoe Bay crude oil and its residues from an experimental in situ burn. *Env Research*, v30, n2, p. 427-442.
- Shokri, M. and C.L. Beyler. 1989. Radiation from large pool fires. *Journal of Fire Protection Engineering* 1(4):141-150.
- Shu, H., D. Paustenbach, F.J. Murray, L. Marple, B. Brunck, D. Dei Rossi and P. Teitlebaum. 1988. Bioavailability of Soil-Bound TCDD: Oral Bioavailability in the Rat. *Fundam. Appl. Toxicol.* 10:648-654.
- SINTEF and S.L. Ross. 1993. In-situ burning of water-in-oil emulsions. Draft report to NOFO. Stavanger, Norway.
- Sirignano, W.A. and I. Glassman. 1970. Flame spreading above liquid fuels: surface-tension driven flows. *Combustion Science and Technology* 1:307-312.
- Siron, R., E. Pelletier, and C. Brochu. 1991. Suivi d'une contamination petroliere accidentelle dans l'estuaire moyen du Saint-Laurent: Le cas de l'Ile-aux-Grues (Results of an accidental oil spill in the St. Lawrence middle Estuary: The Ile-aux-Grues case). *Water Pollut. Res. J. Can.*; vol. 26, no. 1, p. 61-86.
- Skinner, S.K. and W.K. Reilly. The *Exxon Valdez* oil spill — a report to the President. The National Response Team. Washington, D.C.
- S.L. Ross Environmental Research Ltd. 1981. Air deployable igniters: the feasibility of their use for an oil blowout in the southern Beaufort sea. Report prepared for Dome Petroleum Ltd.

- S.L. Ross Environmental Research Ltd. 1982. Oil spill countermeasures for a major spill from a vessel in Canadian arctic waters. Environment Canada, Ottawa, Ontario. Report to Environment Canada. 89 p.
- S.L. Ross Environmental Research Ltd. 1983. A study of on-board self-help oil spill countermeasures for arctic tankers. Report to Environment Canada. Environment Canada, Ottawa, Ontario.
- S.L. Ross Environmental Research Ltd. 1983. Evaluation of industry's oil spill countermeasures capabilities in broken ice conditions in the Alaskan Beaufort Sea. Report to Alaska Department of Environmental Conservation. Juneau, AK.
- S.L. Ross Environmental Research Ltd. 1984. Hibernia oil spills and their control. Report for Mobil Oil Canada Ltd., St. John's, Newfoundland. 381 p.
- S.L. Ross Environmental Research Ltd. 1984. Igniter requirements for a major oil spill from a vessel in the Canadian arctic. Environmental Emergencies Technology Division Report EE-56. Environment Canada, Ottawa, Ontario.
- S.L. Ross Environmental Research Ltd. and Energetex Engineering. 1986. Decision-making aids for igniting or extinguishing well blowouts to minimize environmental impacts. Environmental Studies Revolving Funds Report Number 051. 95 p.
- S.L. Ross Environmental Research Ltd. and Energetex Engineering. 1986. In-situ burning of uncontained oil slicks. Environmental Emergencies Technology Division report EE-60 revised. Environment Canada, Ottawa. pp. 150.
- S.L. Ross Environmental Research Limited. 1986. An experimental study of oil spill treating agents that inhibit emulsification and promote dispersion. Environment Canada, Environmental Protection Directorate, Report EE-87, Ottawa.
- S.L. Ross Environmental Research Ltd. and DF Dickins Associates Ltd. 1987. Field research spills to investigate the physical and chemical fate of oil in pack ice. Environmental Studies Revolving Funds Report No. 062. 95 p.
- S.L. Ross Environmental Research Ltd. 1988. A study of equipment and techniques to dispose of oily materials from Spill cleanups. Report to the Canadian Coast Guard.
- S.L. Ross Environmental Research Ltd. and Mackay Environmental Research Ltd. 1988. Laboratory studies of the behavior and fate of waxy crude oil spills. Environmental Studies Research Funds, Report 084, Ottawa.
- S.L. Ross Environmental Research Ltd. 1989. Disposal of spilled Hibernia crude oils and emulsions: In-situ burning and the "Swirlfire" burner. Report to Canadian Coast Guard, Ottawa.

- S.L. Ross Environmental Research Ltd. 1993. The risk of tainting in flatfish stocks during offshore oil spills. Environment Studies Research Funds Report No. 121. Calgary, 48 pp.
- Smith, J.W. 1969. United Kingdom Ministry of Technology work on oil pollution. Proceedings of the Joint Conference on Prevention and Control of Oil Spills, December 15-17, New York, NY. pp. 27-40.
- Smith, J.W., editor. 1983. The control of oil pollution. Graham & Trotman Ltd., London., pp. 157-171.
- Smith, N.K. and A. Diaz. 1985. In-place burning of crude oil in broken ice — 1985 testing at OHMSETT. Proceedings of the Eighth Arctic and Marine Oilspill Program Technical Seminar, June 18-20, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 176-191.
- Smith, N.K. and A. Diaz. 1985. In-place burning of Prudhoe Bay oil in broken ice. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, CA. American Petroleum Institute, Washington, D.C. pp. 405-409.
- Smith, N.K. and A. Diaz. 1987. In-place burning of crude oils in broken ice. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 383-387.
- Solsberg, L. and R.C. Belore. 1982. An operational evaluation of the prototype Gemeng lightweight fire proof boom. Report to Canadian Coast Guard and Environment Canada, Ottawa.
- Solsberg, L. 1983. A catalog of oil spill containment barriers. Environment Canada report EPS 9/SP/1. Environment Canada, Ottawa.
- Spalding, D.B., Comments by D. Burgess and J. Grumer. 1964. The burning rate of liquid fuel from open trays by natural convection. Fire Research Abstracts and Reviews 4:234-238.
- Sparlin, D.D. 1972. Promotion of burning of oil slicks with particulate, foamed alkali metal silicates. U.S. Patent Office Official Gazette 903(3):960.
- Spiltec. 1986. Test and evaluation of fire containment boom. Report to Alaska Clean Seas, Anchorage, AK.
- Spiltec. 1987. Refinement of aerial ignition systems, (test and evaluation of the Heli-torch for the ignition of oil slicks). Report to Alaska Clean Seas, Anchorage, Alaska.
- Steward, F.R. 1964. Linear flame heights for various fuels. Combustion and Flame 8:171-178.

- Steward, F.R. 1970. Prediction of the height of turbulent buoyant diffusion flames. *Combustion Science and Technology* 2(4):203-212.
- Stoker, S.W. 1992. Biological conditions in Prince William Sound, Alaska following the Valdez oil spill: 1989-1992. Prepared by Beringian Resources, Arthur D. Little, Inc., Cook Inlet Fisheries Consultants, Woodward-Clyde Consultants. September 1992.
- Stone, R. 1991. Icy inferno: researchers plan oil blaze in arctic. *Science* 253(5025):1203-1204.
- Strobel, C.J., J.H. Gentile, S.C. Schimmel, R.S. Carr, J.W. Williams, and D.A.F. Redford. 1988. Proposed biological testing methods for the United States incineration-at-sea research program. *MAR. POLLUT. BULL.*, vol. 19, no. 11B, pp. 605-610.
- Summerfield, M. 1993. Radiative exposure of oil spills on seas or rivers. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pg 849.
- Sveum, P. and C. Bech. Oil in snow; spreading, weathering and in-situ burning. SINTEF - report STF90099. 84 p.
- Sveum, P., C. Bech, and M. Thommasen. 1991. Burning of oil in snow: experiments and implementation in a Norsk Hydro Drilling contingency plan. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, June 12-14, Vancouver, British Columbia. Environment Canada, Ottawa, Ontario. pp. 399-412.
- Swift, W.H., C.J. Touhill, and P.L. Peterson. 1968. Oil spillage control. *Chemical Engineering Progress Symposium Series* 65(97):265-273.
- Swiss, J.J., D.J. Smrke, D.J., and W.M. Pistruzak. 1985. Unique disposal techniques for arctic oil spill response. Proceedings of the 1985 Oil Spill Conference, February 25-28, Los Angeles, CA. American Petroleum Institute. pp. 395-398.
- Tam, W.K. and W.F. Purves (Institute of Electrical Electronic Engineers, Inc.). 1980. An experimental evaluation of oil spill combustion promoters. pp. 415-421.
- Tam, W.K. and W. F. Purves. 1980. Experimental evaluation of oil spill combustion promoters. Proceedings of the Oceans '80 International Forum on Ocean Engineering in the 80's. IEEE, Piscataway, NJ. pp. 415-421.
- Tebbens, B.D., J.F. Thomas and M. Mukai. 1966. Fate of arenes incorporated with airborne soot. *Amer. Ind. Hyg. Assoc. J.* 27:415-422.

- Telford, A. and D.E. Thornton. 1978. Oilspill workshop. Seventh Arctic Environmental Workshop. Institute for Environmental Studies, University of Toronto, Toronto, Ontario. pp. 102-116.
- Tennyson, E.J. 1989. Arctic aspects of the technology assessment and research program of the Minerals Management Service. Proceedings of the Alaska Arctic Offshore Oil Spill Response Technology Workshop. pp. 111-116.
- Tennyson, E. 1990. Results from selected oil spill response research by the Minerals Management Service. *Marine Technology Society Journal* 24(4):27-32.
- Tennyson, E. 1993. Results from oil spill response research — an update. Proceedings of the 1993 International Oil Spill Conference, March 29-April 1, 1993, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 541-544.
- Thomas, J.F., M. Mukai and B.D. Tebbens. 1968. Fate of airborne benzo(a)pyrene. *Environ. Sci. Tech.* 2:33-39.
- Thomas, P.H. 1963. The size of flames from natural fires. Ninth Symposium (International) on Combustion. Academic Press, New York, NY. pp. 844-859.
- Thompson, C.H., G.W. Dawson, and J.L. Goodier. 1980. Combustion: an oil spill mitigation tool. 2:561-588. US Department of Energy, Reston, VA.
- Thornton, D.E., S.L. Ross, W.J. Logan, and C.W. Ross. 1977. Arctic offshore oil spill countermeasures with emphasis on an oil and gas blowout in the Beaufort Sea. Proceedings of the 1977 Oil Spill Conference, March 8-10, New Orleans, Louisiana. American Petroleum Institute, Washington, D.C. pp. 313-319.
- Thornton, D.E. 1979. In situ burning. *Spill Technology Newsletter* 4(3):162-168.
- Tidmarsh, W.G., R. Ernst, R. Ackman, and T. Farquharson. 1986. Tainting of fishery resources. *Environmental Studies Research Funds* No. 021.
- Tien, C.L., K.Y. Lee, and A.J. Stretton. 1988. Radiation heat transfer. *The SFPE Handbook of Fire Protection Engineering*; Quincy, MA: National Fire Protection Association. pp. 1.92-1.105.
- TMS (Technology & Management Services, Inc.). 1992. Proceedings of the first international oil spill R&D forum. June 1-4, 1992, McLean, Virginia. Co-sponsored by the U.S. Coast Guard and the International Maritime Organization.
- Tokarz, R.D. 1979. Apparatus to facilitate burning of a layer of oil, particularly oil spills. U.S. Patent No. US 4154684. 6 p.

- Torrance, K.E. and R.L. Mahajan. 1974. Fire spread over liquid fuels: liquid phase Parameters. Fifteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. pp. 281-287.
- Turbini, W., E. Fresi and F. Bambacigno. 1993. The *Haven* Incident: Lessons learned with particular reference to environmental damages. Proceedings of the 1993 Oil Spill Conference, March 29-April 1, Tampa, Florida. American Petroleum Institute, Washington, D.C. pp. 179-183.
- Twardawa, P. and G. Couture. 1980. Incendiary devices for the in situ burning of oil spills. Proceedings of the Third Arctic and Marine Oilspill Program Technical Seminar, June 3-5, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 281-289.
- Twardawa, P. and G. Couture. 1982. Incendiary device for the in-situ combustion of crude oil slicks. DND DREV report 4282/83. Environment Canada, Ottawa.
- Twardus, E.M. 1978. Development and evaluation of continuously-burning wicking devices for burning oil slicks. Proceedings of the First Arctic and Marine Oilspill Program Technical Seminar, March 15-17, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 164-178.
- Twardus, E.M. 1978. Evaluation of air-deployable incendiary devices for the ignition of oil on water. Proceedings of the AMOP Technical Seminar, March 15-17, Edmonton, Alta. Environment Canada, Ottawa, Ontario. pp. 143-163.
- Twardus, E.M. 1980. In situ combustion: an oil spill countermeasure for arctic shorelines. Proceedings of the Third Arctic and Marine Oilspill Program Technical Seminar, June 3-5, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 385-401.
- Twardus, E.M. 1980. A study to evaluate the combustibility and other physical and chemical properties of aged oils and emulsions. Report to Environmental Impact Control Directorate, Environmental Protection Service. Environment Canada, Ottawa, Ontario. pp. 1-169.
- Twardus, E.M. and T.A. Brzustowski. 1981. The burning of crude oil spilled on water. *Archivum Combustionis* 1(1/2):49-60.
- USARC. 1992. Research needed to respond to oil spills in ice-infested waters. U.S. Arctic Research Commission Issue No. 8 — May 1992. Washington, D.C. 20 pp.
- U.S. Congress, Office of Technology Assessment. 1990. Coping with an oiled sea: an analysis of oil spill response technology. Report No. PB-90-219973/XAB OTA-BP-0-6382. U.S. Government Printing Office, Washington, D.C.
- U.S. Environmental Protection Agency (EPA). 1980. Ambient water quality criteria for polyaromatic hydrocarbons. EPA 440/5-80-069.

- U.S. EPA. 1989a. Risk Assessment Guidance for Superfund. Volume 1: Human Health Evaluation Manual. EPA/540/1-89/002.
- U.S. EPA. 1989b. Exposure Factors Handbook. EPA 600/8-89/043.
- U.S. EPA. 1991a. Human Health Evaluation Manual, Supplemental Guidance: "Standard Default Exposure Factors." OSWER Directive.
- U.S. EPA. 1991b. Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions. OSWER Directive 9355.0-30.
- U.S. EPA. 1993. Health Effects Assessment Summary Tables (HEAST). Environmental Criteria and Assessment Office. Cincinnati, OH.
- U.S. EPA. Integrated Risk Information System (IRIS). On-line database.
- van Oudenhoven, J.A.C.M., M. Angles, A. De Roocker, R.P. Kelly, W.L. Loudon, and J.K. Rudd. 1980. Disposal techniques for spilt oil. CONCAWE Report.
- Varanasi, U. (Ed.) 1989. Metabolism of Polycyclic Aromatic Hydrocarbons in the Aquatic Environment. CRC Press, Inc., Boca Raton, FL.
- Various. 1958. Literature of the combustion of petroleum. American Chemical Society, Washington, D.C.
- Wakamiya, W., S.E. Petty, A. Boiarski, and A. Putnam (Pacific Northwest Laboratory). 1982. Combustion of oils on water: an experimental program. U.S. Department of Energy Report No. NBM/1002. U.S. Department of Energy, Washington, D.C. 95 p.
- Walker, A.H. and L.J. Field. 1991. Subsistence fisheries and the *Exxon Valdez*: Human health concerns. Proceedings of the 1991 Oil Spill Conference, March 4-7, San Diego, California. American Petroleum Institute, Washington, D.C. pp. 441-446.
- Walton, W.D., D.D. Evans, K.D. McGratton, H.R. Baum, W.H. Twilley, D. Madrzykowski, A.D. Putorti, R.G. Rehm, H. Koseki and E.J. Tennyson. 1993. In-situ burning of oil spills: Mesoscale experiments and analysis. Proceedings of the Sixteenth Arctic and Marine Oilspill Program Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp. 679-734.
- Wardley-Smith, J. 1971. Oil pollution: causes and cures. *Engineering* 211(6):644-648.
- Waterworth, M.D. 1987. The laser ignition device and its application to oil spills. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 369-372.

- Welker, J.R. and C.M. Sliepcevich. 1966. Bending of wind blown flames from liquid pools. *Fire Technology* 2:127-135.
- Welker, J.R. and C.M. Sliepcevich. 1966. Burning rates and heat transfer from wind-blown flames. *Fire Technology* 2(3):211-218.
- White, I.C. and J.A. Nichols. 1983. The cost of oil spills. Proceedings of the 1983 Oil Spill Conference, February 28 - March 3, San Antonio, TX. American Petroleum Institute, Washington, D.C. pp. 541-544.
- Whittaker, H. 1987. Laser ignition of oil spills. Proceedings of the 1987 Oil Spill Conference, April 6-9, Baltimore, Maryland. American Petroleum Institute, Washington, D.C. pp. 389-394.
- Wichman, I.S. 1985. A preliminary analysis of oil-slick combustion. US Dept. of Commerce, Gaithersburg, MD. Report No. NBSIR-85/3266 to Minerals Management Service, Department of the Interior. 20 p.
- Williams, R.E. and T.S. Cooke. 1985. Feasibility of using a bubble barrier for the containment/incineration of spilled Oil. Proceedings of the Eighth Arctic and Marine Oilspill Program Technical Seminar, June 18-20, Edmonton, Alberta. Environment Canada, Ottawa, Ontario. pp. 212-227.
- Wise, S.A., B.A. Benner, S.N. Chesler, L.R. Hilpert, C.R. Vogt, and W.E. May. 1986. Characterization of the polycyclic aromatic hydrocarbons from two standard reference burns. *Analytical Chemistry* 58:3068.
- Woodyard, D. 1970. Oil slick destroyed by burning. *Engineering* 209(5433):629.
- World Health Organization. 1982. Environmental Health Criteria 20. Selected petroleum products, WHO, Geneva, Switzerland.
- World Health Organization (WHO). 1989. IARC monographs on the evaluation of carcinogenic risks to humans. Occupational exposures in petroleum refining: Crude oil and major petroleum fuels. International Agency for Research on Cancer. Vol. 45. Lyon, France.
- Yamaguchi, T. and K. Wakasa. 1986. Oil pool fire experiment. First International Symposium on Fire Safety Science. Hemisphere Publishing Co. pp. 911-918.
- Yumoto, T. 1971. Heat transfer from flame to fuel surface in large pool fires. *Combustion and Flame* 17:108-110.
- Yumoto, T. 1977. Fire spread between two oil tanks. *Journal of Fire and Flammability* 8(4):494-505.

Zieserl, E. 1979. Hydrocarbon ingestion and poisoning: Comprehensive Therapy, 5, 35-42.

Appendix A

State of Alaska

Burn Plan Approval Guidelines

State of Alaska Burn Plan Approval Guidelines

Section III-F of the Alaska Air Quality Control Plan lists the requirements for obtaining written approval to open burn. The applicant is required to submit a burn plan addressing eleven smoke control concerns. The following guidelines are recommended for Departmental approval of burn plans:

1. Location and inclusive dates considered for fires to the extent possible. The plan should state the expected duration the fire would be allowed or expected to burn.
2. The location of all sensitive population centers ground travel routes, airport or other activities that should not be impacted by smoke.
3. Where the weather forecasts will be obtained and how they will be used to prevent smoke problems.
4. How weather changes will be monitored and what will be done to reduce or mitigate smoke impacts if unfavorable weather should occur after ignition.
5. What the considerations are for visibility impacts.
6. How coordination with air quality authorities having jurisdiction will be accomplished.
7. The procedures that will be used to coordinate with other concerned agencies such as the FAA, State Troopers, military, adjacent land managers, etc.
8. How the public will be informed prior to, during and after the burning.
9. What will be done within reason to reduce the duration of the active fire phase and smoldering phase.
10. What will be done to validate predicted smoke dispersal conditions such as a test fire, smoke bomb, etc.
11. For fires other than fire fighter training, and evaluation of alternatives to open burning, demonstrating open burning is the only feasible alternative.

OIL SPILL RESPONSE CHECKLIST: IN SITU BURNING

I. SPILL DATA (TO BE COMPLETED BY PARTY RESPONDING TO SPILL)

A. Circumstances (circle appropriate response(s))

1. Collision
2. Grounding
3. Fire/Explosion
4. Source still burning (circle one: yes/no)
5. Blowout
6. Other (specify):_____

B. Time and date of incident:

C. Spill Location:

1. Latitude: _____; Longitude: _____
2. Distance (in miles) to nearest land:_____
3. Distance (in miles) and direction to nearest town/village:_____

D. Product released:

E. Estimated volume of product released:

F. Total volume of product potentially released:

G. Status of release (circle one):

1. Continuous
2. Intermittent
3. One time only - now stopped

If release is continuous or intermittent, specify rate of release (in gallons or barrels), if possible:

H. Estimated water surface covered (in square miles):

II. SPILLED OIL CHARACTERISTICS (TO BE COMPLETED BY PARTY RESPONDING TO SPILL)

(Circle choice in each of A-E or provide the required information)

	Product I: Alaska North Slope	Product II: Cook Inlet Crude	Product III: Chevron Residual	Other Product:
A. Specific gravity	SG .8954 @ 70°F API 25.7-27.5	SG .8398-.8499 @ 70°F API 35-37	SG .975 @ 50°F API 15.5	
B. Viscosity:	174 Cst @ 60°F	37.2 Cst @ 100°F	1000 Cst @ 50°F	
C. Pour Point:	0°F	-15°F	60°F	
D. Volatility (flash point)	-20° to -30°F	-20°F to -30°F	150°F	
E. Easily forms emulsion?	Yes	No	No	

If already emulsified, circle one:

- Light emulsion (0-20%)
- Moderate emulsion (20-50%)
- Heavy emulsion (more than 50%)
- Unknown

F. Debris present? If so, specify amount and type:

G. Other relevant information (e.g., composition, persistence):

III. WEATHER AND WATER CONDITIONS: AT TIME AND LOCATION OF SPILL (TO BE COMPLETED BY PARTY RESPONDING TO SPILL)

A. Air temperature:

B. Water temperature:

C. Wind speed:

D. Wind direction:

E. Tidal state (circle one):

1. Slack tide
2. Incoming (flood)
3. Outgoing (ebb)

- F. Dominant current (net drift)
 - 1. Speed:
 - 2. Direction:
- G. Sea conditions (e.g. flat, choppy, waves - specify wave heights):
- H. Water depth:
- I. Ice present? If so, estimate percent coverage:
- J. Other special considerations (e.g. visibility, rip tides, whirlpools, eddies):

IV. WEATHER AND WATER CONDITIONS FORECAST: FROM TIME OF SPILL (TO BE COMPLETED BY SCIENTIFIC SUPPORT COORDINATOR)

- A. Wind speed
 - 1. 24-hour projection:
 - 2. 48-hour projection:
- B. Wind direction
 - 1. 24-hour projection:
 - 2. 48-hour projection:
- C. Sea conditions (e.g. flat, choppy, waves - specify wave heights)
 - 1. 24-hour projection:
 - 2. 48-hour projection:

D. Tidal Information

	Cycle	First	Second	Third
1. Time of maximum ebb tide:				
2. Speed of maximum ebb tide (knots):				
3. Direction of maximum ebb tide:				
4. Height of maximum ebb tide:				
5. Time of slack tide before flood tide:				
6. Time of maximum flood tide:				
7. Speed of maximum flood tide (knots):				
8. Direction of maximum flood tide:				
9. Height of maximum flood tide:				
10. Time of slack tide before ebb tide:				

E. Dominant current (net drift)

1. Speed:
2. Direction:

**V. PREDICTED OIL BEHAVIOR: UNTREATED/UNBURNED OIL
FORECAST (TO BE COMPLETED BY PARTY RESPONDING TO SPILL
AND SCIENTIFIC SUPPORT COORDINATOR)**

A. Party responding to spill

1. Estimated trajectory referenced to geographic features:
2. Trajectory method used:
3. Expected area(s) and time(s) of land fall:
4. Estimate percent dispersed and evaporated within first 24 hours:

B. Scientific Support Coordinator

1. Estimated trajectory referenced to geographic features:
2. Expected area(s) and time(s) of land fall:
3. Estimated percent dispersed and evaporated within first 24 hours:

VI. PROPOSED BURNING PLAN (TO BE COMPLETED BY PARTY RESPONDING TO SPILL)

- A. Location of proposed burn in reference to source:
- B. Location of proposed burn in reference to nearest ignitable oil slick or slicks:
- C. Location of proposed burn in reference to nearest land:
- D. Risk of accidental (secondary) fires:
- E. Risk of reducing visibility at nearby airstrip(s) and airport(s):
- F. Distance to, and location and type (e.g. fishing cap, village) of nearest human habitation:
- G. If approval to conduct in situ burning is received, identify method(s) to be used to notify residents in areas within the potential smoke plume trajectory, prior to igniting the oil:
- H. Type of igniter proposed for use:
- I. Helicopter operations approved by FAA for aerial ignition (circle one);
 - 1. Aerial ignition not required
 - 2. Awaiting verification
 - 3. Yes (specify company and helicopter):
- J. Type of burning promoters to be used, if any:
- K. Type of wicking agents to be used, if any:
- L. Proposed application method for:
 - 1. Igniter:
 - 2. Burning promoter:
 - 3. Wicking agents:
- M. Method of oil containment, if any:
- N. Location of oil containment relative to source:

- O. Proposed burning strategy (circle appropriate responses):
1. Immediate ignition at or near source
 2. Ignition away from source after containment and movement to safe location
 3. Ignition of uncontained slick(s) at a safe distance
 4. Possible need for multiple ignition attempts
- P. Estimated amount of oil to be burned:
- Q. Estimated duration of burn:
- R. Estimated smoke plume trajectory:
- S. Method for collecting burned oil residue:
- T. Status of Alaska Department of Environmental Conservation burning permit (circle one):
1. Obtained (specify date _____, time _____, authorization signature _____)
 2. Planning to submit request (specify date _____, time _____)
 3. Awaiting approval (specify date _____, time _____ submitted, and to whom _____)
 4. Permit not required

VII. RESOURCES AT RISK: (TO BE COMPLETED BY RESOURCE AGENCIES)

A. Location and type of habitats already affected	
1. Pelagic:	
2. Shoreline:	
a. Exposed, rocky shores	
b. Exposed, wave-cut platforms	
c. Fine-grained sand beaches	
d. Coarse sand beaches	
e. Exposed tidal flats	
f. Mixed sand and gravel beaches	
g. Gravel beaches	
h. Sheltered rocky shores	
i. Sheltered tidal flats	
j. Marshes	

B. Location and type of biological resources already affected	
1. Endangered/threatened species:	
2. Marine mammals:	
3. Birds:	
4. Fish:	
5. Invertebrates:	
6. Marine plants:	

C. Location and type of human resources already affected	
1. Commercial facilities and enterprises:	
2. Public facilities and enterprises:	
3. Cultural resources:	

D. Location and type of resources of special significance already affected	
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E. Location and type of habitats potentially affected	Untreated/Unburned Spill	Burned Oil
1. Pelagic:		
2. Shoreline:		
a. Exposed, rocky shores		
b. Exposed, wave-cut platforms		
c. Fine-grained sand beaches		
d. Coarse sand beaches		
e. Exposed tidal flats		
f. Mixed sand and gravel beaches		
g. Gravel beaches		
h. Sheltered rocky shores		
i. Sheltered tidal flats		
j. Marshes		

F. Location and type of biological resources potentially affected	Untreated/Unburned Spill	Burned Oil
1. Endangered/threatened species:		
2. Marine mammals:		
3. Birds:		
4. Fish:		
5. Invertebrates:		
6. Marine plants:		

G. Location and type of human resources potentially affected	Untreated/Unburned Spill	Burned Oil
1. Commercial facilities and enterprises		
2. Public facilities and enterprises:		
3. Cultural resources		

H. Location and type of resources of special significance potentially affected	Untreated/Unburned Spill	Burned Oil
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VIII. OCS's AND RRT's EVALUATION OF THE CONSEQUENCES OF BURNING (TO BE COMPLETED, IF APPLICABLE, BY FEDERAL ON-SCENE COORDINATOR AND ALASKA REGIONAL RESPONSE TEAM)

- A. Has mechanical clean-up been fully evaluated?
- B. Has dispersant use been fully evaluated?
- C. Have the type and magnitude of potential air-quality impacts (such as inhalation, fall-out, and visual impacts) been fully evaluated?
- D. How will burning alter the extent of environmental impacts?
 - 1. Habitats:
 - 2. Biological resources:
 - 3. Human resources:
 - 4. Other resources of special significance:

IX. OCS's DECISION REGARDING BURNING (TO BE COMPLETED BY, IF APPLICABLE, FEDERAL ON-SCENE COORDINATOR)

- A. Do not burn
- B. Burn in limited or selected areas (describe)
- C. Burn to the maximum extent possible.

NOTE: If the OSC approves in-situ burning, prior to initiating the burn, the OSC must attempt to notify residents in areas within the potential smoke plume trajectory.

Appendix B

Air Dispersion Modeling for Project

Air dispersion modeling of the behavior of the smoke plume from a burning oil slick was conducted using the EPA model SCREEN2. The SCREEN2 model uses a steady state Gaussian plume equation that incorporates source-related factors and meteorological factors to estimate pollutant concentrations in the air at locations downwind from continuous sources. The model assumes that the pollutant does not undergo any chemical reactions, and that no other removal processes, such as wet or dry deposition, act on the plume during its transport from the source. SCREEN2 results are often characterized as worst-case estimates of pollutant concentration because of these assumptions.

SCREEN2 can perform all of the single source, short-term calculations in the "Screening Procedures for Estimating the Air Quality Impact of Stationary Sources (Revised)" (EPA 1992), including estimating maximum ground-level concentrations and the distance to the maximum.

SCREEN2 allows the user to specify point, flare, or area sources. Another analysis was examined in choosing which mode should be used for analysis of dispersion of pollutants from an in-situ burn of crude oil. Comparisons of the National Institute of Standards and Technology (NIST) Large Eddy Simulation (LES) model predictions of dispersion agreed with measurements from experimental burn tests (Evans *et al.* 1992). A comparison between predictions from the NIST LES model and the SCREEN2 model was also conducted. According to Evans *et al.* (1992), while none of the SCREEN2 options are exactly suited to predictions of large pool fires, the flare option agreed most closely with the LES simulation and experimental data from actual burn studies. SCREEN2 was originally designed for modeling smoke plumes generated by low-energy, low-buoyancy fires, however, it may be used for high energy fires as found in crude oil fires, if a realistic value for the heat release rate is used.

Plumes are considered nonbuoyant in models of area sources. The plume from an oil fire is thermally buoyant, and the flare option in SCREEN2 treats the plume as a buoyant plume. Thus, the flare option in SCREEN2 was selected for estimating the concentration of pollutants with distance from a crude oil burn because it corresponds more closely with test data and the LES model simulation, and treats the plume as a buoyant plume.

SCREEN2 was used to examine a range of stability classes and wind speeds to identify the "worst-case" meteorological conditions, i.e., the combination of wind speed and stability that results in the maximum ground level concentrations. The wind speed and stability class combinations are given in Table B.1. Table B.1 includes some cases that may not be considered standard stability class/wind speed combinations, namely E with 1 m/s, and F with 4 m/s. The combination of E and 1 m/s is often excluded because the algorithm developed by Turner (1964) to determine stability class from routine National Weather Service (NWS) observations excludes cases of E stability from wind speeds less than 4 knots (2 m/s). The combination of E and 1 m/s is included in SCREEN2 because it is a valid combination that could appear in a data set using on-site meteorological data with another stability class method. A wind speed of 6 knots (the highest speed of F stability in Turner's scheme) measured at a typical NWS anemometer height of 20 feet (6.1 meters) corresponds to a 10-meter wind speed of 4 m/s under F stability. Therefore the combination of F and 4 m/s has been included.

Table B.1 Combinations of Wind Speed and Stability Class Used in SCREEN2 Model Runs

Stability Class	Wind Speed at 10 Meters Above Ground								
	1	2	3	4	5	8	10	15	20
A	*	*	*						
B	*	*	*	*	*				
C	*	*	*	*	*	*	*		
D	*	*	*	*	*	*	*	*	*
E	*	*	*	*	*				
F	*	*	*	*					

When the full meteorology mode is used, SCREEN2 evaluates all wind speed and stability combinations and presents the meteorological conditions that produce the maximum concentration of the pollutant at specified distances. The model also identifies the overall maximum pollutant concentration, and the location and meteorological conditions that produced the maximum.

The plume from an oil fire would be thermally buoyant due to the intense heat associated with the fire. Methods to estimate plume rise are incorporated into the SCREEN2 model, using the flare option. The model calculates plume rise to determine the effective release height used, and is based on the heat released during burning. The effective heat release is determined from the total heat release, which is calculated by multiplying the heat of combustion of crude oil by the mass of crude oil lost during burning.

A set of simple equations is used to determine the total heat release and the effective heat release for burning crude oil. Evans *et al.* (1992) recommends that the average burn rate of crude oil is 0.045 kg/s/m². For the circumstance examined here, it is assumed that 1000 barrels (159 m³) of oil is burned per hour. (This may be a worst case for predicting emissions impacts. Burning smaller oil pools controlled by fire-proof boom would reduce emissions and plume dispersion.) The area of the fire is 757 m² (159 m³/hr of oil burned x 1 hr/60 min x 1 min/3.5 x 10⁻³ m rate of oil regression). Multiplying the average burn rate by the area of the fire results in an average burn rate of 34.965 kg/s. This value is used as the mass of crude oil loss in calculating the total heat release rate.

The heat of combustion of oil is assumed to be 41.9 MJ/kg (Evans *et al.* 1992). Multiplying the heat of combustion by the mass of crude oil loss results in the total heat release.

$$41.9 \text{ MJ/kg} \times 34.065 \text{ kg/s} = 1427.3 \text{ MJ/s, total heat release}$$

To determine the convective heat release, the total heat release is multiplied by 45% (Evans *et al.* 1992), which equals 642.15 MJ/s. Converting 642.15 MJ/s to kcalories/s, results in 153,477 kcal/s. The convective heat release is the effective heat release for the model analysis.

The SCREEN2 model run is attached to this appendix. The source was modeled as an unitized emission rate of 1 g/s. The results for receptors along the plume from 100 m to 50 km were then multiplied by the emission factors for pollutants of concern shown in Table B.2. The emission factors are based on field observations by Ferek (1992) and Allen (1993). For averaging periods greater than one hour, the unitized concentration was multiplied by the following factors as recommended in the EPA Screening Procedures (1992) document.

Averaging Time	Multiplying Factor
3 hours	0.9
8 hours	0.7
24 hours	0.4

The final pollutant concentration results are presented in Table B.3, along with the percent of applicable U.S. National Ambient Air Quality Standard (NAAQS) for short-term concentrations (1 to 24 hour averaging times).

TABLE B-2
SUMMARY OF AIR QUALITY EMISSION RATES

Pollutant	Emission Factor g/kg	Emission Rate g/s
SO ₂	20.00	742
NO _X	6.10	226.3
CO ₂	2700.00	100170
CO	1.75	64.9
VOC	0.28	10.4
PAH	0.00	0
TSP	100.00	3710

ASSUMPTIONS:

Density of Oil is 840 kg/m³

158.9 m³/hr burned

which equals 37.1 kg/s

Table B-3 SCREEN Modeling Results MSRC In-Situ Burn Risk Assessment

XXQ (ug/m3)	DWN WIND DIST (m)	WIND SPEED	PG	STABILITY	SO2 1-HR	SO2 24-HR	% SO2 NAAQS 1-HR	% SO2 NAAQS 24-HR	NOX 1-HR	NOX 24-HR	CO2 1-HR	CO2 24-HR	CO 1-HR	% CO NAAQS 1-HR	CO 8-HR	% CO NAAQS 8-HR	TSP 1-HR	TSP 24-HR	% TSP NAAQS 24-HR
0.001	100	1	5	5	0.67	0.60	0.0	0.27	0.1	0.20	0.08	90.15	36.06	0.06	0.04	0.0	3.34	1.34	0.9
0.011	200	1	5	5	8.46	7.61	0.9	3.38	2.38	1.03	1141.94	456.78	0.74	0.52	0.0	42.29	16.92	11.3	
0.012	300	1	5	5	8.76	7.88	1.0	3.50	2.67	1.07	1182.01	472.80	0.77	0.54	0.0	43.78	17.51	11.7	
0.012	400	1	5	5	8.76	7.88	1.0	3.50	2.67	1.07	1182.01	472.80	0.77	0.54	0.0	43.78	17.51	11.7	
0.012	500	1	5	5	8.90	8.01	0.6	3.56	2.72	1.09	1202.04	480.82	0.78	0.55	0.0	44.52	17.81	11.9	
0.012	600	1	5	5	9.13	8.21	0.6	3.65	2.78	1.11	1232.09	492.84	0.80	0.56	0.0	45.63	18.25	12.2	
0.013	700	1	5	5	9.35	8.41	0.6	3.74	2.85	1.14	1262.14	504.86	0.82	0.57	0.0	46.75	18.70	12.5	
0.013	800	1	5	5	9.55	8.59	0.7	3.82	2.92	1.17	1292.19	516.88	0.84	0.59	0.0	47.86	19.14	12.8	
0.013	900	1	5	5	9.79	8.81	0.7	3.92	3.01	1.19	1322.24	528.90	0.86	0.60	0.0	48.97	19.59	13.1	
0.034	1000	3	1	5	25.52	22.97	1.8	10.21	7.78	3.11	3445.85	1378.34	2.23	1.56	0.0	127.62	51.05	34.0	
0.083	1100	3	1	5	61.44	55.29	4.3	24.58	18.74	7.50	8294.08	3317.63	5.37	3.76	0.0	307.19	122.84	81.9	
0.137	1200	3	1	5	101.63	91.49	7.0	40.66	31.00	12.40	13723.29	5499.32	8.49	6.22	0.1	504.27	203.31	135.5	
0.181	1300	3	1	5	134.30	120.87	9.3	53.72	40.96	16.38	18130.77	7252.31	11.75	8.22	0.1	671.51	268.60	179.1	
0.207	1400	3	1	5	153.22	137.90	10.6	61.29	46.33	18.69	20685.11	8274.04	13.40	9.38	0.1	766.12	306.45	204.3	
0.217	1500	3	1	5	160.72	144.65	11.1	64.29	49.02	19.61	21696.82	8678.73	14.06	9.84	0.1	800.99	321.43	214.3	
0.216	1600	3	1	5	160.20	144.18	11.1	64.08	48.86	19.54	21628.70	8610.68	14.01	9.81	0.1	800.99	320.40	213.6	
0.210	1700	3	1	5	155.60	140.04	10.8	62.24	47.46	18.98	21005.65	8492.26	13.61	9.53	0.1	777.99	311.19	207.5	
0.202	1800	3	1	5	149.59	134.63	10.4	59.83	45.62	18.25	20194.27	8077.71	13.08	9.16	0.1	747.94	299.17	199.4	
0.193	1900	3	1	5	143.50	129.15	9.9	57.40	43.77	17.51	19372.88	7749.15	12.55	8.79	0.1	717.51	287.01	191.3	
0.186	2000	3	1	5	137.79	124.01	9.5	55.12	42.02	16.81	18601.57	7400.63	12.03	8.44	0.1	684.95	275.58	183.7	
0.179	2100	3	1	5	132.60	119.34	9.2	53.04	40.44	16.18	17900.38	7160.15	11.60	8.12	0.1	662.98	265.19	176.8	
0.172	2200	3	1	5	127.77	115.00	8.8	51.11	38.97	15.59	17249.27	6899.71	11.18	7.82	0.1	634.84	255.54	170.4	
0.166	2300	3	1	5	119.17	107.25	8.2	47.67	37.61	15.04	16648.25	6659.30	10.79	7.55	0.1	616.60	246.64	164.4	
0.161	2400	3	1	5	115.38	103.84	8.0	46.15	36.34	14.54	16087.30	6434.92	10.42	7.30	0.1	591.83	238.33	158.9	
0.156	2500	3	1	5	111.58	100.84	8.0	44.15	35.19	14.08	15576.44	6230.57	10.09	7.06	0.1	576.91	230.76	153.8	
0.151	2600	3	1	5	111.82	100.64	7.7	44.73	34.10	13.64	15095.62	6038.25	9.78	6.85	0.1	559.10	223.64	149.1	
0.146	2700	3	1	5	108.48	97.63	7.5	43.39	33.09	13.23	14644.85	5847.94	9.49	6.64	0.1	542.40	216.96	144.6	
0.143	2800	3	1	5	105.88	95.30	7.3	42.35	32.29	12.92	14294.26	5717.70	9.26	6.48	0.1	529.42	211.77	141.2	
0.140	2900	3	1	5	103.81	93.43	7.2	41.52	31.66	12.66	14013.78	5605.51	9.08	6.36	0.1	519.03	207.61	138.4	
0.137	3000	3	1	5	101.73	91.56	7.0	40.69	31.03	12.41	13733.31	5493.32	8.90	6.23	0.1	504.64	203.46	135.6	
0.125	3500	3	1	5	92.45	83.21	6.4	36.98	28.20	11.28	12481.18	4992.47	8.09	5.66	0.1	462.27	184.91	123.3	
0.114	4000	3	1	5	84.66	76.20	5.9	33.86	25.82	10.33	11429.40	4571.76	7.41	5.18	0.1	421.31	169.32	112.9	
0.105	4500	3	1	5	78.06	70.25	5.4	31.22	23.81	9.52	10537.88	4215.15	6.83	4.78	0.0	390.29	156.12	104.1	
0.098	5000	3	1	5	72.42	65.18	5.0	28.97	22.09	8.83	9776.59	3910.64	6.33	4.43	0.0	362.10	144.84	96.6	
0.093	5500	3	2	5	68.78	61.91	4.8	27.51	20.98	8.39	9285.76	3714.30	6.02	4.21	0.0	343.92	137.57	91.7	
0.095	6000	3	2	5	70.19	63.17	4.9	28.08	21.41	8.56	9476.08	3780.43	6.14	4.30	0.0	350.97	140.39	93.6	
0.094	6500	3	2	5	69.97	62.97	4.8	27.99	21.34	8.34	9446.03	3778.41	6.12	4.28	0.0	349.85	139.94	93.3	
0.093	7000	3	2	5	68.71	61.84	4.8	27.48	21.48	8.38	9275.74	3710.30	6.01	4.21	0.0	343.55	137.42	91.6	
0.090	7500	3	2	5	66.71	60.04	4.6	26.68	20.34	8.14	9005.28	3602.11	5.83	4.08	0.0	332.03	128.81	88.9	
0.087	8000	3	2	5	64.41	57.97	4.5	25.76	19.64	7.86	8694.76	3477.90	5.63	3.94	0.0	320.79	123.91	82.6	
0.084	8500	3	2	5	61.96	55.76	4.3	24.78	18.90	7.56	8364.20	3345.68	5.42	3.79	0.0	309.79	119.02	79.3	
0.080	9000	3	2	5	59.51	53.56	4.1	23.80	18.15	7.26	8033.63	3213.45	5.20	3.64	0.0	297.54	114.27	76.2	
0.077	9500	3	2	5	57.13	51.42	4.0	22.85	17.43	6.97	7713.09	3085.24	5.00	3.50	0.0	285.67	109.82	73.2	
0.074	10000	3	2	5	54.91	49.42	3.8	21.96	16.75	6.70	7412.58	2965.03	4.80	3.36	0.0	274.54	105.82	70.0	
0.061	15000	3	3	5	45.11	40.60	3.1	18.05	13.76	5.30	6090.34	2436.13	3.95	2.76	0.0	225.57	90.23	60.2	
0.067	20000	3	5	5	48.79	44.81	3.4	19.92	15.18	6.07	6721.41	2688.56	4.35	3.05	0.0	248.94	99.58	66.4	
0.069	25000	2.5	5	5	50.83	45.74	3.5	20.33	15.50	6.20	6861.65	2744.66	4.45	3.11	0.0	254.14	101.65	67.8	
0.070	30000	2	5	5	51.64	46.48	3.6	20.66	15.75	6.30	6971.83	2788.73	4.52	3.16	0.0	258.22	103.29	68.9	
0.071	40000	1.5	5	5	52.53	47.28	3.6	21.01	16.02	6.41	7092.04	2836.81	4.59	3.22	0.0	262.67	105.07	70.0	
0.069	50000	1	5	5	51.05	45.94	3.5	20.42	15.57	6.23	6891.70	2756.68	4.47	3.13	0.0	255.25	102.10	68.1	
Maximum Concentration																			
0.217	1539	3	1	5	161.24	145.11	11.2	64.49	49.17	19.67	21.766.94	8706.78	14.10	9.87	0.1	806.18	322.47	215.0	

Maximum Concentration
 NAAQS
 SO2 1-HR 1300
 SO2 24-HR 365
 CO 1-HR 40000
 CO 8-HR 10000
 TSP 24-HR 150

Table B-4 Output of SCREEN2 model

SIMPLE TERRAIN INPUTS:

```

SOURCE TYPE           =      FLARE
EMISSION RATE (G/S)   =      1.00000
FLARE STACK HEIGHT (M) =      .0000
TOT HEAT RLS (CAL/S)  =      .153477E+09
RECEPTOR HEIGHT (M) =      .0000
URBAN/RURAL OPTION    =      RURAL
EFF RELEASE HEIGHT (M) =      37.3159
BUILDING HEIGHT (M)   =      .0000
MIN HORIZ BLDG DIM (M) =      .0000
MAX HORIZ BLDG DIM (M) =      .0000
  
```

BUOY. FLUX = 2544.698 M**4/S**3; MOM. FLUX = 1551.704 M**4/S**2.

*** FULL METEOROLOGY ***

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*****
*** SCREEN AUTOMATED DISTANCES ***
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*** TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
100.	.9325E-03	5	1.0	1.6	10000.0	385.31	85.03	84.88	NO
200.	.1136E-01	5	1.0	1.6	10000.0	385.31	100.11	99.62	NO
300.	.1157E-01	5	1.0	1.6	10000.0	385.31	100.85	99.81	NO
400.	.1180E-01	5	1.0	1.6	10000.0	385.31	101.83	100.01	NO
500.	.1204E-01	5	1.0	1.6	10000.0	385.31	103.03	100.25	NO
600.	.1231E-01	5	1.0	1.6	10000.0	385.31	104.43	100.51	NO
700.	.1260E-01	5	1.0	1.6	10000.0	385.31	106.01	100.79	NO
800.	.1291E-01	5	1.0	1.6	10000.0	385.31	107.76	101.09	NO
900.	.1324E-01	5	1.0	1.6	10000.0	385.31	109.67	101.41	NO
1000.	.3439E-01	1	3.0	3.3	1338.6	1337.64	282.05	491.91	NO
1100.	.8282E-01	1	3.0	3.3	1338.6	1337.64	303.97	590.95	NO
1200.	.1370	1	3.0	3.3	1338.6	1337.64	325.50	701.12	NO
1300.	.1805	1	3.0	3.3	1338.6	1337.64	346.70	822.49	NO
1400.	.2065	1	3.0	3.3	1338.6	1337.64	367.59	955.12	NO
1500.	.2166	1	3.0	3.3	1338.6	1337.64	388.20	1099.08	NO
1600.	.2159	1	3.0	3.3	1338.6	1337.64	408.54	1254.45	NO
1700.	.2097	1	3.0	3.3	1338.6	1337.64	428.65	1421.27	NO
1800.	.2016	1	3.0	3.3	1338.6	1337.64	448.54	1599.61	NO
1900.	.1934	1	3.0	3.3	1338.6	1337.64	468.22	1789.55	NO
2000.	.1857	1	3.0	3.3	1338.6	1337.64	487.71	1991.12	NO
2100.	.1787	1	3.0	3.3	1338.6	1337.64	507.01	2204.40	NO
2200.	.1722	1	3.0	3.3	1338.6	1337.64	526.14	2429.44	NO
2300.	.1662	1	3.0	3.3	1338.6	1337.64	545.11	2666.30	NO
2400.	.1606	1	3.0	3.3	1338.6	1337.64	563.93	2915.03	NO
2500.	.1555	1	3.0	3.3	1338.6	1337.64	582.60	3175.69	NO
2600.	.1507	1	3.0	3.3	1338.6	1337.64	601.13	3448.32	NO

Table B-4 Output of SCREEN2 model (continued)

2700.	.1462	1	3.0	3.3	1338.6	1337.64	619.53	3732.98	NO
2800.	.1427	1	3.0	3.3	1338.6	1337.64	634.64	4029.22	NO
2900.	.1399	1	3.0	3.3	1338.6	1337.64	647.65	4337.34	NO
3000.	.1371	1	3.0	3.3	1338.6	1337.64	660.72	4657.72	NO
3500.	.1246	1	3.0	3.3	1338.6	1337.64	726.80	5000.00	NO
4000.	.1141	1	3.0	3.3	1338.6	1337.64	793.66	5000.00	NO
4500.	.1052	1	3.0	3.3	1338.6	1337.64	860.87	5000.00	NO
5000.	.9761E-01	1	3.0	3.3	1338.6	1337.64	928.15	5000.00	NO
5500.	.9272E-01	2	3.5	3.8	1152.9	1151.88	766.61	777.57	NO
6000.	.9457E-01	2	3.5	3.8	1152.9	1151.88	817.11	842.89	NO
6500.	.9430E-01	2	3.5	3.8	1152.9	1151.88	867.57	909.62	NO
7000.	.9257E-01	2	3.5	3.8	1152.9	1151.88	917.94	977.55	NO
7500.	.8993E-01	2	3.5	3.8	1152.9	1151.88	968.17	1046.52	NO
8000.	.8682E-01	2	3.5	3.8	1152.9	1151.88	1018.23	1116.42	NO
8500.	.8351E-01	2	3.5	3.8	1152.9	1151.88	1068.10	1187.14	NO
9000.	.8021E-01	2	3.5	3.8	1152.9	1151.88	1117.76	1258.59	NO
9500.	.7703E-01	2	3.5	3.8	1152.9	1151.88	1167.21	1330.72	NO
10000.	.7402E-01	2	3.5	3.8	1152.9	1151.88	1216.43	1403.45	NO
15000.	.6084E-01	3	3.5	4.0	1120.0	1108.71	1214.22	789.61	NO
20000.	.6710E-01	5	3.0	4.8	10000.0	278.60	755.47	129.23	NO
25000.	.6852E-01	5	2.5	4.0	10000.0	293.72	918.59	139.63	NO
30000.	.6957E-01	5	2.0	3.2	10000.0	313.52	1077.44	149.79	NO
40000.	.7080E-01	5	1.5	2.4	10000.0	341.32	1384.45	166.34	NO
50000.	.6879E-01	5	1.0	1.6	10000.0	385.31	1680.66	181.25	NO

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 100. M:

1539.	.2173	1	3.0	3.3	1338.6	1337.64	395.96	1156.78	NO
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DWASH= MEANS NO CALC MADE (CONC = 0.0)
 DWASH=NO MEANS NO BUILDING DOWNWASH USED
 DWASH=HS MEANS HUBER-SNYDER DOWNWASH USED
 DWASH=SS MEANS SCHULMAN-SCIRE DOWNWASH USED
 DWASH=NA MEANS DOWNWASH NOT APPLICABLE, $X < 3 \times LB$

 *** SUMMARY OF SCREEN MODEL RESULTS ***

CALCULATION PROCEDURE	MAX CONC (UG/M**3)	DIST TO MAX (M)	TERRAIN HT (M)
SIMPLE TERRAIN	.2173	1539.	0.

 ** REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS **

References to Appendix B

- Allen, A.A. and R.J. Ferek. 1993. Advantages and Disadvantages of Burning Spilled Oil. Proc. 1993 Oil Spill conference, Tampa, Florida.
- Briggs, G.A. 1975. Plume Risk Predictions. In: Lectures on Air Pollution and Environmental Impact Analysis, Haugen, D.A. (ed.), American Meteorological Society, Boston, MA, pp. 59-111.
- Ferek, R.J., P.V. Hobbs, J.A. Herring, K.K. Laursen, R.E. Weiss and R.A. Rasmussen. 1992. Chemical Composition of emissions from the Kuwait oil fires. Jour. Geophys. Res. 97 (D13):14483-14489.
- Turner, D.B. 1964. A Diffusion Model for an Urban Area. Journal of Applied Meteorology, 3, 83-91.
- Turner, D.B. 1970. Workbook of Atmospheric Dispersion Estimates. Revised, Sixth printing, Jan. 1973. Office of Air Programs Publication No. AP-26.
- U.S. Environmental Protection Agency. 1992. Screening Procedures for Estimating the Air Quality Impact of Stationary Sources — Draft for Public Comment. EPA-450/4-88-010. U.S. Environmental Protection Agency, Research Triangle Park, NC.

Appendix C

MSRC In-Situ Burning Study Regulatory Permits Questionnaire

**MSRC IN-SITU BURNING STUDY
REGULATORY PERMITS QUESTIONNAIRE
1992**

Woodward-Clyde Consultants (WCC), jointly with S. L. Ross and Spiltec, are preparing a study of "The Role of Burning in Oil Spill Countermeasure Technology" sponsored by the Marine Spill Response Corporation (MSRC). This study is constrained to oil spills in marine environments found in the contiguous U.S.. As part of this program, WCC is compiling a list of permit requirements and procedures that must be considered or obtained for (1) actual use of in-situ burning of a spill on water or (2) on site burning of oil collected during a spill response. Of particular interest are:

- What is required for use of in-situ burning during spill response?
- What are the requirements or limitations for the use of burning additives?
- What are the air quality permitting requirements?

Contacts are being made at federal, regional, and state levels to gain this information. Your assistance with this process is greatly appreciated.

1. Exactly what permits are required? For how long is the permit valid?
2. Which permit is critical?
3. What sort of timeline can be anticipated for the permit review process?
4. To whom does a permit get submitted and who specifically reviews the permit?
5. Are there any permit applications or steps that can be done pre-spill to streamline the approval process?
6. Are there any pre-operational and/or operational monitoring requirements needed for permitting?
7. Is there any guidance documentation to accompany the application(s)?
8. Are there specific actions/programs being taken regarding the use of in-situ burning for marine spill response? If so, what are they?

**MSRC IN-SITU BURNING STUDY
REGULATORY PERMITS QUESTIONNAIRE
1993**

Woodward-Clyde Consultants (WCC), jointly with S. L. Ross and SpilTec, are completing a study of "The Role of Burning in Oil Spill Countermeasure Technology" sponsored by the Marine Spill Response Corporation (MSRC). This study is constrained to oil spills in marine environments found in the contiguous U.S.. As part of this program, we hope to compile the latest information on permit requirements and procedures that must be considered or obtained for (1) actual use of in-situ burning of a spill on water or (2) on site burning of oil collected during a spill response. Of particular interest are:

- **What is required for use of in-situ burning during spill response?**
- **What are the requirements or limitations for the use of burning additives?**
- **What are the air quality permitting requirements?**

We appreciate your review of our synopsis of the regulatory status on a state-by-state basis. Please check the attached table for accuracies or lacking information. Your help is appreciated in advancing our general knowledge and ability to use appropriate countermeasures for spill response. Other questions that are of interest include:

1. Are there any permit applications or steps that can be done pre-spill to streamline the approval process?
2. Has in-situ burning been approved during recent drills or exercises? What key conditions lead to a yes or no decision?
3. Is there any guidance documentation to accompany the application(s)?
4. Are there specific off-limit areas, areas to be considered, or approved areas in your region?

Appendix D

Mobile, Alabama, MSO Application Process and Authorization Form for In-Situ Burning

ACTION

The action required for Coast Guard OSC will fall into 4 stages:

- Feasibility Assessment
- Implementation
- Supervision
- Monitoring

Feasibility Assessment. Complete the *MSO In-Situ Burning Action Guide*. This will entail extensive amounts of research and phone work to complete.

Implementation. Will undoubtedly be the most challenging for the Coast Guard OSC once he receives permission from the RRT to proceed. He will have to:

1. Aid every conceivable party with logistics
2. Implement site safety plan
3. Address possible maritime community and public concerns (ie, NOTAMS, safety zones)
4. Address possible public affairs matters
5. Initiate cost documentation if federalized

Supervision. Coast Guard OSC's will continue in their transitional role of supervising just as they would in a standard mechanical cleanup. The main concerns are:

1. Continue cost documentation if federalized
2. Site safety for O/S personnel, ie, scientific community, contractor, other government entities
3. Safety of maritime community and public
4. Continue solving logistical problems
5. Ensure efficiency of action taken

Monitoring. Monitoring may, or may not be requested by the RRT. Unlike bioremediation and dispersants, *in-situ* burning deals with much shorter time frames and poses significant logistical problems for monitoring. If it is determined by the RRT that this is a burn of

opportunity for collecting scientific data on *in-situ* emissions, then you will still be concerned with:

1. Maintaining site safety for O/S personnel
2. Safety of maritime community and public
3. Final cost documentation if federalized
4. Ongoing public affairs matters

IN-SITU BURNING AUTHORIZATION FORM

A. DETAILS OF THE SPILL

(INFORMATION TO BE PROVIDED AT TIME OF SPILL BY SPILLER (IF KNOWN), HIS AGENT, OR BY THE OSC)

1. SPILL DATA

- a. Circumstances (fire, grounding, collision, transfer, etc.)

- b. Location of spill (report all available details)

Distance and direction from nearest port or land mass

Latitude and Longitude _____

Block (give reference) _____

- c. Time and date of spill _____

- d. Potentially responsible party _____

Name of company _____

Address _____

Individual to contact _____

Telephone _____

- e. Product spilled (the name or type of product spilled may be useful in establishing answers requested in Sections A.2 and A.3, below)

Type of product (crude oil or refined product) _____

Name of crude or product (if known) _____

Volume released (if known) _____

- f. Type of release (instantaneous, continuous, intermittent, belching, etc.)

g. Total potential volume of release (if still leaking) _____

h. Expected poll radius (CHRIS Manual, MacIntosh, SSC, etc.) _____

2. PROPERTIES OF THE SPILLED OIL (IF KNOWN) (MSDS, CHRIS, COMPANY TRADE INFORMATION, ETC.)

a. Specific gravity or API gravity _____

b. Viscosity, cp. _____ at temperature, °F _____

c. Pour point, °F _____

d. Sulfur content, %w _____

B. SPILL TRAJECTORY AND WEATHER (INFORMATION TO BE PROVIDED AT TIME OF SPILL BY NOAA).

(NOTE: Some of this information may be available from the spiller, the OSC, or other interested parties.)

1. Weather conditions and forecast:

- a. Air temperature _____
- b. Wind speed _____
- c. Wind direction _____
- d. Visibility (in miles) _____

2. Sea Conditions and Forecast:

- a. Wave height, ft. _____
- b. Swell height, ft. _____
- c. Water depth, ft. _____

3. Currents - Tidal and Longshore

Tidal

Longshore

- a. Speed, knots _____
- b. Direction _____
- c. Speed, knots _____
- d. Direction _____

4. Oil spill trajectory information - forecasts should be made for at least 48 hours and preferably 96 or 120 hours.

a. Surface trajectory forecast

Expected position of center of spill (e.g., latitude and longitude coordinates) on

Day 1 _____ Day 4 _____
 Day 2 _____ Day 5 _____
 Day 3 _____

NOTE: The leading edge of the spill may be as much as one to five miles in advance (downwind) of the center of the spill, depending on spill size, time, and wind speed.

Expected landfall (when, where, and how much) _____

What will be the effects on above if the winds change?

What will be effect on above if the currents change?

5. Spreading, weathering, dispersion

- a. Surface area of slick (see Table B.5.a in Subpart H of the Region 6 Regional Contingency Plan) at end of:

Day 1 _____ Day 4 _____

Day 2 _____ Day 5 _____

Day 3 _____

- b. Amount lost by weathering, % (See Table B.5.b in Subpart H of the Region 6 Regional Contingency Plan) at end of:

Day 1 _____ Day 4 _____

Day 2 _____ Day 5 _____

Day 3 _____

- c. Is emulsion (mousse) formation expected? (Use Table B.5.c in Subpart H or the Region 6 Regional Contingency Plan to determine whether or not mousse formation should be expected.)
-

Immediately or after weathering? (See Table B.5.c in Subpart H of the Region 6 Regional Contingency Plan.)

C. DETAILS OF IN-SITU BURNING PLAN

(INFORMATION TO BE PROVIDED AT TIME OF SPILL BY SPILLER (IF KNOWN), HIS AGENT OR BY THE OSC)

1. In-Situ Burning Method to be used (see Pre-Action Considerations)

(x) Appropriate Scenario

() Scenario A - Open Water, Containment Needed

() Scenario B - Open Water, Oil of Sufficient Thickness, No
Containment Needed

() Scenario C - Oil Contained by Physical or Natural Barriers

Exact Details of In-Situ Burn Proposed: _____

2. Type of ignition device

Available from: Name _____

Address _____

Telephone _____

3. Method to deliver ignition device (vessel, helo, etc.)

Available from: Name _____

Address _____

Telephone _____

4. Amount and type of fire retardant boom

Available from: Name _____

Address _____

Telephone _____

5. Vessels to be used to tow fire retardant boom

Available from: Name _____

Address _____

Telephone _____

6. Time (in hours) needed for transport to the spill site

7. Does a pre-approved in-situ burn plan exist?

Appendix E

USCG Commandant — Questions on In-Situ Burning for RRTs

U.S. Department
of Transportation

United States
Coast Guard



Commandant
U.S. Coast Guard

2100 Second Street S.W.
Washington, DC 20593-0001
Staff Symbol: (G-MEP-2)
Phone. (202) 267-0436

16450

JUN 19 1992

From: Commandant
To: Distribution

Subj: QUESTIONS ON IN-SITU BURNING FOR RRT'S

1. For the past several years, the U.S. Coast Guard and the U.S. Minerals Management Service have been supporting the concerns noted by the Regional Response Teams associated with the lack of scientific data needed to assist in decisions regarding the use of dispersants or in-situ burning. Regarding the issue of "in-situ" burning, the Coast, MMS and others, have supported laboratory testing and actual meso-scale burning experiments. We also jointly submitted a request to the Environmental Protection Agency (EPA) for a permit to discharge oil into the Gulf of Mexico for an open-water in-situ burn in the summer of 1993. As this test is critical to the future use of this technology, I request you assist us in our application by responding to the questions below. We will need your input when responding to anticipated questions from the EPA as it considers whether to issue the requested permit.

2. Since the mid 1980's the USCG and MMS have been working to advance our understanding of the in-situ burning technology. Our efforts have followed a three phase approach to furthering our information; 1) laboratory testing, 2) large meso-scale testing, and 3) actual at-sea burn tests. The first two phases are complete and initial data indicates that in-situ burning may be successful without concerns for health, air quality, or the environment. We are currently awaiting the necessary permits to conduct Phase 3 tests in two locations involving both cold and warm water environments. Additional information on these phases can be found in the enclosed materials.

3. The agencies interested in supporting this test to gather scientific data include Environment Canada, the U.S. and Canadian petroleum industries, MMS, the National Institute of Standards and Testing, National Oceanic and Atmospheric Administration, and the USCG. We believe it is essential to prove whether this technology is a viable removal option so that RRTs may have sufficient confidence to approve its use and the private sector may invest the capital necessary to stockpile appropriate equipment. The data gathered will allow for informed decisions regarding potential trade-offs between air quality, water quality, and shoreline/critical habitat impacts. We recognize that this information will be most useful

16450

SUBJ: QUESTIONS ON IN-SITU BURNING FOR RRT'S

to On-Scene Coordinators in the coastal areas; however, a significant amount of the data should provide some basis for inland response decisions as well.

4. In addition to the efforts noted above, we recently came very close to obtaining the necessary permit to conduct a test burn of an intentional spill in the Beaufort Sea off the North Slope of Alaska. This burn was spearheaded by an Alaska cleanup cooperative, Alaska Clean Seas, and was sponsored by the Coast Guard. Throughout the planning evolution, the support for this burn proposal from the Alaska RRT was outstanding. Its support of this proposed test burn clearly demonstrates its proactive leadership and commitment to the advancement of response technologies. I am pleased to note that we also have strong indications of support from the Region VI RRT regarding the proposed Gulf of Mexico burn. The willingness of these RRTs to support the advancement of removal technologies is most appropriate and very encouraging.

5. Congress has been disappointed with the lack of research and development progress through the late 1970's and into the late 1980's. One result was the establishment of the Interagency Coordinating Committee on Oil Pollution Research required by Title VII of the Oil Pollution Act of 1990 (OPA). The Coast Guard and MMS intend to respond to the spirit of OPA by aggressively pushing the development of alternative response and treatment technologies as much as possible. You can help us greatly in our efforts by providing your insight and comments on the following questions:

A) Do you believe that, if provided the results of the first two phases of this research effort, you would you be able to make a reasonably sound decision regarding when and if to use in-situ burning within your region?

B) Should we pursue full scale testing (including intentional spills) to acquire conclusive evidence of the operational viability and environmental acceptability of this technology?

C) If such tests are permitted, conducted, and show positive results, would you consider a "pre-approval" process for your region?

D) What additional information, if any, do you need to seriously consider in-situ burning in your region?

RESEARCH ON IN-SITU BURNING FOR OIL SPILL RESPONSE

Burning of oil on water is believed to be a potentially useful tool for response to major oil spills--large amounts of oil can be removed rapidly from the water surface under a wide variety of environmental conditions. Drawbacks to this technique include production of smoke and possible production of gaseous air contaminants.

Under sponsorship of a variety of agencies including the U.S. Minerals Management Service, the U.S. Coast Guard, Environment Canada, and both U.S. and Canadian industry, a major research program has been under way for the past several years to evaluate the technology of in-situ burning of spilled oil and to examine the environmental trade-offs. To date, this research program has involved (1) laboratory tests at NIST to study the combustion processes and to measure and characterize the combustion products both chemically and physically and (2) large mesoscale tests at the U.S. Coast Guard burn test facility in Mobile Bay to extend the laboratory-scale tests at NIST.

Results from the laboratory scale tests have been reported in proceedings of the 1989 and 1991 Oil Spill Conferences and in the proceedings of the 1991 Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. The laboratory tests indicate that substantial amounts of soot may be produced from in-situ burning (e.g., five to ten percent or perhaps more), but undesirable combustion products such as polynuclear aromatic hydrocarbons (PAHs) may not be produced.

Results from the mesoscale tests have not yet been analyzed fully; the first publications from this series of tests are expected to be presented at the AMOP Technical Seminar in June, 1992. Although full analysis of the meso-scale test data is not yet available, preliminary inspection of the raw data suggests that in-situ burning should not have severe adverse impacts. As hoped by the proponents of in-situ burning, it appears from this preliminary inspection of the data that:

- There may be a substantial reduction in the total quantity of polynuclear aromatic hydrocarbons (PAHs) from the amounts originally present in the oil,
- There is no production of objectionable oxygenated compounds such as dioxins, dibenzofurans, acrolein, etc., and
- The smoke which is produced rapidly becomes sufficiently diffuse that surface-level impacts of soot appear minor and limited to the near vicinity down-wind from the fire.

Please note that these tentative conclusions need further study and verification before they can be relied upon. One of the major reasons for proposing to conduct full-scale at-sea burn tests is to

ENCLOSURE(1)

provide additional data to support and extend the laboratory and meso-scale test results.

The next phase of this research program will be to conduct tests at sea, using a fire resistant boom to contain the burning oil. The at-sea tests will involve tests off Newfoundland in cool waters and tests in the Gulf of Mexico in relatively warm waters. The Gulf of Mexico tests will involve one burn test in which the amount of oil which is burned is about the size of the largest burn at Mobile and two burns which are about six times larger. The largest burns will each involve about 25,000 gallons of crude oil.

The tests at NIST and in Mobile Bay were designed to learn more about the combustion products which are formed, where they may go, and what are their ecological consequences. In planning these tests, it has been our intention to provide a progression from laboratory scale tests, through mesoscale, to full scale. The full-scale tests will extend the laboratory and meso-scale test results to larger size and will incorporate the effects of wave action, interaction of the burning oil with the containment (fire-resistant) boom, and movement of the burning oil over the water surface. The measurement techniques which were used in the meso-scale tests will also be used during the at-sea tests to study quantity, composition, and distribution of the smoke and gaseous combustion products. In addition to study of the ecological consequences of burning, we expect that the full-scale at-sea tests will provide information which will enable us to improve our ability to conduct controlled in-situ burning safely and efficiently at the time of an actual spill event.

The equipment layout for the at-sea tests is indicated in the attached sketch and plans for chemical and biological tests are shown in another attachment.

In addition to our present research program, the following research has been accomplished in the last 10-15 years: (a) tests of ignition devices by Environment Canada, (b) development of fire-resistant booms and testing of these booms in open-air tanks, (c) tests of burning emulsions and burning of oil in broken ice at the EPA OHMSETT facility, (d) one case in which in-situ burning (i.e., controlled burning using a fire-resistant boom for containment) was used in an actual spill event (the Exxon Valdez spill), (e) one field test off Norway to demonstrate the feasibility of in-situ burning, (f) tests by Esso Resources, Canada of chemical smoke suppression, and (g) research in Norway of improved means to ignite emulsions and weathered oils.

Research on ignition of oil on water, emulsified oil, and oil on ice is under way in Norway. Esso Resources in Canada is sponsoring additional work on smoke suppression. And Alaska Clean Seas has made application to the EPA for permission to discharge oil into the Beaufort Sea to conduct additional research on burning oil at sea, with special emphasis on durability of the 3M Fire Boom.

IN-SITU BURNING QUESTIONNAIRE

REGIONAL RESPONSE TEAMS I & II

The following is a questionnaire designed to address the questions asked in the attached document. Please complete this form and return it in the envelope provided at your earliest convenience. Thank you.

1. Do you believe that , if provided the results of the first two phases of this research effort [outlined in the attached document], you would be able to make a reasonably sound decision regarding when and if to use in-situ burning within your region?

☐ YES

☐ NO

2. Should we pursue full scale testing (including intentional spills) to acquire conclusive evidence of the operational viability and environmental acceptability of this [in-situ burning] technology?

☐ YES

☐ NO

3. If such test are permitted, conducted, and show positive results, would you consider a "pre-approval" process for your region?

☐ YES

☐ NO

4. What additional information, if any, do you need to seriously consider in-situ burning in your region?

Name:	_____	
Agency:	_____	
Region:	One <input type="checkbox"/>	Two <input type="checkbox"/>

Appendix F

Regional Summaries Regarding State and Federal Government Contracts and Policies on In-Situ Burning

Region I

RRT Agencies & Contacts

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
USCG - MSO Portland, ME	Steve Wishman (Pollution Response Officer)	(207) 780-3251
USCG - MSO Providence, RI	J.S. Sisitsky	(401) 528-5335
USCG - MSO Long Island, CT	Moeller (Marine Environmental Protection Officer)	(203) 468-4464
RRT Coordinator	Bruce Blackman (Acting Coordinator)	(617) 223-8243

MAINE

Department of Pollution Prevention

Oil & Hazardous Materials Cindy Bertocci (207) 287-2651

Summary - (USCG MSO Portland, ME)

There is currently no pre-approval procedure for in-situ burning, and no permitting process. Requests for approval for in-situ burning would be taken for consideration on a case by case basis. Input from several groups/agencies (COTP, USCG, State agencies, NOAA, RRT) would be necessary for approval to be granted. To date, no guidelines have been written to assist planners. A burn was approved and conducted in an onshore, wetlands spill during late March 1993. The USCG and NOAA were actively involved.

MASSACHUSETTS

Environmental Protection

Haz. Waste-Waste Site Cleanup Phil Mallard (617) 292-5851
FAX (617) 556-1049

CONNECTICUT

Department of Environmental Conservation

Oil & Chemical Spill Division Don Burton (203) 566-4633
FAX (203) 566-4924

Summary - (USCG MSO Long Island)

The issue of in-situ burning of an oil spill has not yet come up in Long Island Sound, according to the Coast Guard Marine Environmental Protection Chief.

RHODE ISLAND

Department of Environmental Management

Division of Water Resources Dave Shelding (401) 277-3961
FAX (401) 521-4230

Summary - (USCG MSO Providence, RI)

There are no permits or any guidance concerning permits at this time. The Coast Guard is, however, soliciting input from all of its districts concerning creation of a "pre-approval" process. Implementation of a "pre-approval" process would be contingent upon positive results from studies currently being conducted by the Coast Guard.

Region II

RRT Agencies & Contacts

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
USCG MSO New York, NY Pollution Response Unit		(212) 668-7917 668-7920

No approval process in place. Very unlikely inside of approximately 10-15 miles.

NEW JERSEY

Summary -

No policy on in-situ burning is in place at this time; it is not likely that in-situ burning will be a response option in New Jersey state waters in the near future. Most discussion currently focused on options and considerations for use dispersants.

NEW YORK

Dept of Environmental Quality	Koon Tang	(718) 482-4949 FAX (718) 482-4954
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Summary -

No policy on in-situ burning is in place at this time.

Region III

RRT Agencies & Contacts

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
USCG MSO Baltimore	LT Cindy Stowe	(410) 962-5121
USCG MSO Philadelphia	CDR Jack Reed	(215) 271-4880

General Region III Issues: (USCG MSO Philadelphia)

In-situ burning will probably only be an option in deep waters, not in state waters. Policies for approval of in-situ burns will be similar to dispersants policies. The RRT gave simulated approval for a test burn during a 1991 drill.

MARYLAND

Oil Control	Rick Collins	(410) 631-3324 FAX (410) 631-3321
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Summary -

No policy on in-situ burning is in place at this time; in-situ burning will possibly be a response option in Maryland state waters in the near future, however, burning in Chesapeake Bay will probably not be an option.

DELAWARE

Summary -

No policy on in-situ burning is in place at this time; in-situ burning will possibly be a response option in Delaware state waters in the near future, however, burning in Delaware Bay will probably not be an option.

VIRGINIA

Department of Waste Management	Brett Burdick	(804) 225-2667 FAX (804) 225-3753
Water Board - Headquarters	John Godfrey	(804) 527-5121 FAX (804) 527-5311

Summary -

No policy on in-situ burning is in place at this time; it is not likely that in-situ burning will be a response option in Virginia state waters in the near future.

Region IV

RRT Agencies & Contacts

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
USCG MSO Savannah	LTJG J.A. Simmerman	(912) 652-4371
NOAA SSC - EPA Region IV	Gary Vandenburg	(305) 530-7931

NORTH CAROLINA

Department of the Environment, Health and Natural Resources
Water Resources Division Dianne Wilburn (919) 733-5291

Summary -

Region IV RRT is currently developing a regional policy. They have had a recent meeting on the subject of in-situ burning and have asked state representatives to comment on a draft policy (February 1993). North Carolina has sent the draft policy to state air pollution control experts for review and comment. They will probably decide on in-situ burning on a case-by-case basis, rather than having a pre-approval process. State waters extend to 3 miles offshore; in-situ burning will probably be restricted to greater than 3 miles offshore.

SOUTH CAROLINA

Department of Health and Environmental Control
Solid and Hazardous Waste Ron Kinney (803) 734-5189

Summary -

Region IV RRT is currently developing a regional policy. They have had a recent meeting on the subject of in-situ burning and have asked state representatives to comment on a draft policy (February 1993). South Carolina has sent a letter to the RRT stating that they intend to make all decisions concerning in-situ burning on a case-by-case basis.

GEORGIA

Summary - (USCG MSO Savannah)

Currently no procedures have been written/implemented for in-situ burning. Revisions to the Savannah Local Contingency Plan (LCP) based on OPA 90 are expected July 1993.

FLORIDA

Department of Natural Resources Carolann Bowen (904) 488-2974
Dept. of Environmental Regulation Greg Lee (904) 488-0190

Summary - (Dept. of Natural Resources)

Currently there are no specific procedures for obtaining approval to use in-situ burning. The decision to use in-situ burning would be a joint decision by RRT members (e.g. DNR, DER, NOAA SSC, USCG).

Greg Lee (DER) - In certain offshore situations, approval for in-situ burning as a response option is likely. However, there are no permitting or pre-approval processes in place in Florida at this time. The DER and air permitting agencies are in the process of jointly developing a policy for emergency burning approval. Special issues in Florida include the storage and transfer of oil in highly populated areas and high concentrations of elderly people who may have higher sensitivity to certain air pollutants. Public perceptions and public education will probably be important in the process of developing in-situ burning policy. State is reviewing pre-approval process adopted by Region VI.

Region VI

RRT Agencies & Contacts

Note: Since the 1992 canvassing of RRTs and MSOs, Region VI has developed a pre-approval process for in-situ burning that allows the On-Scene Commander to determine the adequacy for burning under prescribed conditions. The RRT, in general, endorses burning as a countermeasure as indicated in Section 1. Burning can be used at the discretion of the FOSC/SOSC for spills outside of 3 nm, except over hard banks or coral reefs, and not within 7 nm of Grande Isle, La.

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
USCG MSO Corpus Christi	LTJG Suzanne Thurn (Chief, Marine Environmental Response)	(512) 888-3162
USCG MSO Houston	LTJG John Francis	(713) 671-5121
USCG MSO Galveston	Lt. Commander Salveson	
USCG MSO Mobile	Chief Lecain	

ALABAMA

Dept of Environmental Management	(205) 479-2336
----------------------------------	----------------

Summary - (USCG MSO Mobile, AL)

There is general guidance concerning in-situ burning, and a formal pre-approval process is expected. For approval to burn a spill, there would need to be input from the Captain Of The Port, EPA, and the Regional Response Team (in state waters). For experimental burns, however, a permit is required and can be obtained.

Limitations in this area would be primarily related to the availability of equipment (e.g. fire-proof boom).

MISSISSIPPI

Bureau of Pollution Control	Robert Rogers	(601) 961-5171
		(Emergency Services Coordinator)

Summary -
(see *Alabama summary*)

LOUISIANA

Department of Environmental Quality

State Oil Spill Coordinator	Roland Guidry	(504) 922-3230
	Tim Hebert	

Summary - (Tim Hebert, Deputy State Oil Spill Coordinator)

Every Louisiana State agency has endorsed in-situ burning as an appropriate method of spill response. RRT favors in-situ burning but cannot provide pre-approval for

burns because of the potential need for Federal Coastal Zone Consistency Determination and EIAs (Environmental Impact Assessments). RRT has final approval authority for in-situ burning; however, they may relegate this authority to the state Oil Spill Office, which is governed by all state resource trustees and the state police. State resource trustees in Louisiana are:

- Department of Environmental Quality
- Wildlife and Fisheries
- Department of Natural Resources (wetlands, coastal zone)
- Department of Health and Human Services (DHH) (water intakes)

Monitoring is an important issue in Louisiana; i.e. how will monitoring be done?, who will conduct/oversee monitoring?, when and where will monitoring be conducted? All of these questions must be addressed.

USCG MSO New Orleans maintains a form for obtaining a permit to use in-situ burning on a spill. However, pre-application does not constitute pre-approval.

TEXAS

Texas Air Control Board

Summary -

In-situ burning is covered under the Federal Clean Air Act and the State Laws contained in 31 Texas Administrative Code. Although no permit is necessary for burning spilled oil, approval from the Texas Air Control Board is required. Restrictions to the conduct of outdoor burning and the notification procedures are described in the Texas Air Control Board Rules, Chapters 101 and 111.

The RRT has developed a pre-approval checklist in an effort to speed up the process of using in-situ burning. At the present time, the use of in-situ burning during a spill response must be approved on a case-by-case basis through the RRT for areas inshore of 3 nm; however, the state recognizes burning as a valuable countermeasure that should be considered, even in areas such as Galveston Bay.

It is expected that approval could be granted within 24-48 hours or faster during an emergency. Limitations in this area would be physical limitations (i.e. location of spill), weather conditions, and availability of equipment. No specific limitations are placed on burning except for the use of burning agents to facilitate burning. No specific written documentation is required by the Coast Guard district.

Region IX

RRT Agencies & Contacts

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
EPA Region IX	Kathleen Shimmin	(415) 744-2280 Fax (415) 744-1796
USCG District 11	Capt. Casmir	
California Dept. of Fish & Game	Don Lollock	

CALIFORNIA

Summary - (Notes from In-situ Burning Workshop, 21-22 May 1991)

California law currently prohibits in-situ burning. However, in 1990, the RRT gave its simulated approval to use in-situ burning during an exercise. A workshop was held in May 1991 to discuss in-situ burning and find out what efforts are needed to facilitate a legislative change in California that would permit in-situ burning.

Issues and concerns which were raised at the In-Situ Burning Workshop (21-22 May 1991) included:

- What is the limiting size (volume) to initiate a burn?
 - What state agency will handle burning decision?
 - Will decision be made by a single individual or a group?
 - Issues involving State vs. Federal waters
 - Safety of the individual(s) associated with the burn
 - Monitoring - how? by what agency or group? when? where?
 - Local fire departments and police should be involved in pre-planning
 - Legality of burns in California
 - Future research needed?
 - Factors needed in a permit - what items are needed for pre-approval?
 - How will Air Quality Control Districts and Air Resources Boards mesh into the Federal representation on the RRT?
 - Plume modelling - during a spill? or just run in advance for planning purposes?
 - How overwhelming does the evidence need to be to support the decision to go with a burn?
 - Meteorology
 - Best Possible Technology Available

Major considerations are: volume handling capacity of the system; windows of opportunity; relative impact on the environment; and logistics.

California Air Quality Management Districts:

Legal concerns: Liability for burns
 Responsibility
 local and State Laws involved
(all of these issues to be addressed for each District)

Definition of emissions e.g. 2nd day formations, volatilization, combined effects.

Information exchange

Burn protocol: i.e. what time of day to burn, what type(s) of oil, weather conditions, wind, 2nd day particulates and acids produced.

Identification of operational constraints

Air Resources Board Summary:

Local decision making - need for legislative changes

Data on burn impacts - including comparative aspects (burn vs. no burn), and emission factors

The State has adopted a checklist and application form for submitting a request to burn. This information is contained in the Area Contingency Plans.

Region X

RRT Agencies & Contacts

<u>Agency</u>	<u>Contact</u>	<u>Phone no.</u>
USCG MSO Puget Sound	LT Craig Petersen	(206) 286-5540
		FAX (206) 286-5544
USCG MSO Portland		

WASHINGTON

Washington Dept of Ecology	Lin Bernhardt	(206) 438-7254
Washington Office of Marine Safety	Joel Green	(206) 664-9125

Summary - (USCG MSO Puget Sound)

In-situ burning is regulated by the Washington State Department of Ecology (Ecology). Ecology has published interim policy guidelines regarding the use of in-situ burning in the Washington State Master Oil and Hazardous Substance Spill Contingency Plan (Appendix C). According to these guidelines, in-situ burning would not be approved within Puget Sound except west of Low Point (Port Angeles). Burning would be considered an option (on a case by case basis) at spill locations at least 20 miles from the nearest land. Guidelines for the use of chemical burning agents are being developed by Region X. Any use of such chemicals at the present time must be approved by the EPA and State RRT Representatives. Currently, there is no process for obtaining a permit to burn an oil spill. The State Master Plan, Appendix C lists procedures to be followed in the event that a burn/no burn decision is appropriate.

OREGON

Summary - (Oregon State Oil and Hazardous Materials Contingency Plan)

In-situ burning is regulated by the Oregon Department of Environmental Quality (DEQ) and requires DEQ approval. According to the State Contingency Plan, in-situ burning would ordinarily be allowed only in offshore areas, and would usually be considered only if it was away from human populations.

Appendix G

Region VI - Oil Spill Response Checklist for In-Situ Burning

OIL SPILL RESPONSE CHECKLIST: IN-SITU BURNING

The following checklist is provided as a summary of important information to be considered by the Federal On-Scene Coordinator (FOSC) in reviewing any request to conduct in-situ burning in response to an offshore oil spill in the Gulf of Mexico.

1. SPILL DATA (To be completed by Responding Party and submitted to FOSC)

- A. Name of incident: _____
- B. Date and time of incident: Month/Day/Year _____, Time _____
- C. Incident: Grounding _____ Transfer Operations _____ Collision _____
Blowout _____ Pipeline Rupture _____ Explosion _____ Other _____
- D. Did spill source ignite? Yes _____ No _____
Is source still burning? Yes _____ No _____
- E. Spill Location: Latitude _____ Longitude _____
- F. Distance (in naut. miles) and direction to nearest land: _____
- G. Product(s) released: _____
- H. Product(s) easily emulsified? Yes _____ No _____ Uncertain _____
- I. Product(s) already emulsified upon release? No _____
Light emulsion (0-20%) _____ Moderate emulsion (21-50%) _____
Heavy emulsion (>51%) _____ Unknown _____
- J. Estimated volume(s) of product released: _____ gals _____ bbls _____
_____ gals _____ bbls _____
- K. Estimated volume(s) of product that could still be released:
_____ gals _____ bbls _____
_____ gals _____ bbls _____
- L. Release status: Continuous _____ Estimated Rate _____
Intermittent _____ Estimated Rate _____
One time only ("batch" spill); flow now stopped _____
- M. Estimated area of spill:
Approx. Date/Time _____ Surface Area _____ Sq. Miles (Stat _____ Naut. _____)
Approx. Date/Time _____ Surface Area _____ Sq. Miles (Stat _____ Naut. _____)
Approx. Date/Time _____ Surface Area _____ Sq. Miles (Stat _____ Naut. _____)

2. WEATHER AND WATER CONDITIONS AT TIME & LOCATION OF SPILL
(To be completed by responding party and submitted to FOSC)

- A. Temperature: Air ____ (deg. F) Water ____ (deg. F)
- B. Weather: Clear ____ Partly Cloudy ____ Heavy Overcast ____
Rain ____ (heavy ____ moderate ____ light ____)
Fog ____ (type & amount at spill source ____)
(type & amount at burn site ____)
- C. Tidal Condition: Slack Tide ____ Incoming (flood) ____ Outgoing (ebb) ____
- D. Dominant Surface Current (net drift):
Speed ____ (knots)
Direction (to) ____ (True compass heading)
- E. Wind Speed: ____ knots Wind Direction (from) ____
- F. Expected transition time between on-shore & off-shore breeze ____
- G. Sea State: Flat Calm ____ Light Wind-Chop ____
Wind-Waves: <1 ft ____ 1-3 ft ____ >3 ft ____
Swell (est. height in ft) ____
- H. Water Depth (feet): 0-3 ____ 4-10 ____ 11-30 ____ 31-99 ____ >100 ____
- I. Other Considerations:
General Visibility ____
Rip Tides/Eddies ____
Floating Debris ____
Submerged Hazards ____

Notes: See Section IV for weather and water conditions forecast (to be completed by NOAA Scientific Support Coordinator (SSC)).

See Section V for predicted oil behavior (to be completed by NOAA SSC).

Responding party has option of also submitting information on predicted oil behavior to FOSC.

3. PROPOSED BURNING PLAN (To be completed by party responding to spill)

- A. Location of proposed burn with respect to spill source: _____
- B. Location of proposed burn with respect to nearest ignitable oil slick(s): _____

- C. Location of proposed burn with respect to nearest land: _____

- D. Location of proposed burn with respect to commercial fishing activity, vessel traffic lanes, drilling rigs and/or other marine activities/facilities: _____

- E. Risk of accidental (secondary) fires: _____

- F. Risk of reducing visibility at nearby airstrip(s) or airport(s) _____

- G. Distance to, location and type of nearest population center(s) (e.g., recreational site, town, city, etc.): _____
- H. Methods that will be used (prior to ignition) to notify residents in areas where smoke could conceivably drift into or over such areas: _____

- I. Type of igniter proposed for use: _____
- J. Helicopter(s) needed to deploy igniters? No ____ Yes ____
Name of company and type of helicopter to be used: _____

FAA approval already granted to company for use of igniter:
Yes _____ No _____

Awaiting FAA approval or verification of prior approval ____.
- K. Burning promoters or wicking agents proposed for use?
Yes ____ No ____
If yes, give type and amount: _____
- L. Describe proposed method of deployment for:
Igniter(s): _____
Burning Promoter(s): _____
Wicking Agent(s): _____
- M. Describe method for oil containment, if any: _____

- N. Proposed location of oil containment relative to spill source: _____

- O. Proposed burning strategy:
____ Immediate ignition at or near source
____ Ignition away from source after containment and movement to safe location
____ Ignition of uncontained slick(s) at a safe distance
____ Controlled burning in boom or natural collection site at/near shore
____ Possible need for multiple ignition attempts
- P. Estimated amount of oil to be burned: _____

- Q. Estimated duration of each burn: _____.
Total possible burn period: _____
- R. Estimated smoke plume trajectory: _____

- S. Method for collecting burned oil residue: _____

- T. Proposed storage & disposal of burned oil residue: _____

4. WEATHER AND WATER CONDITION FORECAST FROM TIME OF SPILL
(To be completed by NOAA SSC)

- A. Wind Speed (knots):
24-hour projection: _____
48-hour projection: _____
- B. Wind Direction (from):
24-hour projection: _____
48-hour projection: _____
- C. Sea Conditions:
24-hour projection:
Flat Calm ____ Light Wind-Chop ____
Wind-Waves: <1 ft ____ 1-3 ft ____ >3 ft ____
Swell (est. height in ft) _____
- 48-hour projection:
Flat Calm ____ Light Wind-Chop ____
Wind-Waves: <1 ft ____ 1-3 ft ____ >3 ft ____
Swell (est. height in ft) _____
- D. Tidal Information:
Date ____ High (time/height)____/____ Low (time/height)____/____
Date ____ High (time/height)____/____ Low (time/height)____/____
Date ____ High (time/height)____/____ Low (time/height)____/____

Date ____ High (time/height)____/____ Low (time/height)____/____

- E. Predicted Dominant Current (net drift):
Speed (knots): _____ Direction (to): _____

5. PREDICTED OIL BEHAVIOR (To be completed by NOAA SSC)

A. Unburned Oil Forecast:

Estimated trajectory (attach sketch if necessary):

B. Expected area(s) and time(s) of land fall:

Location _____	Date/Time _____
Location _____	Date/Time _____
Location _____	Date/Time _____
Location _____	Date/Time _____

C. Estimated percent naturally dispersed and evaporated:

Within first 12 hours: _____
Within first 24 hours: _____
Within first 48 hours: _____

6. RESOURCES AT RISK (To be completed by resource agencies)

A. Habitats

Sheltered Tidal Flats
Coastal Marshes
Etc.

B. Biological Resources -

Are marine mammals, turtles, or concentrations of birds noted in the burn area.?

Yes _____ No _____

Endangered/Threatened Species

Non-Endangered/Threatened Species

C. Historic and Archaeological Resources

D. Commercial Harvest Areas

7. FEDERAL ON-SCENE COORDINATOR'S EVALUATION OF RESPONSE OPTIONS (To be completed by FOSC)

A. Is in-situ burning likely to result in the elimination of significant volumes of spilled oil?

Yes _____ No _____

- B. Will the use of in-situ burning interfere with (or in any way reduce the effectiveness of) mechanical recovery and/or dispersant application?
Yes _____ No _____

If yes, do the potential benefits of burning outweigh the potential reductions in effectiveness of mechanical/dispersant use?

Yes _____ No _____

- C. Can in-situ burning be used safely, and with an anticipated overall reduction in environmental impact (compared with the decision not to burn)?

8. FEDERAL ON-SCENE COORDINATOR'S DECISION REGARDING IN-SITU BURNING (To be completed by FOSC)

- A. _____ Do not conduct in-situ burn
- B. _____ In-situ burn may be conducted in limited or selected areas
- C. _____ In-Situ burn may be conducted as requested

Note: If the FOSC approves of in-situ burning, residents in areas within the potential smoke plume trajectory must be notified prior to initiating the burn.

Signature of FOSC: _____

Printed Name of FOSC: _____

Time and Date of Decision: _____

Appendix H

Region VI - Operational Checklist: In-Situ Burning

The following list is provided as a condensed "checklist" of critical conditions, concepts or pieces of equipment that should be considered prior to the initiation of an in-situ burn at sea.

Approval and Notification Considerations:

- _____ Approval "checklist" completed and submitted to federal and state RRT and FOSC.
- _____ Any other burn plan or permit and approval requests completed and submitted to appropriate agencies.
- _____ All approvals received from federal, state and local organizations
- _____ U.S. Coast Guard notified regarding Notice To Mariners for proposed burn time and locations in which no unauthorized vessels would be allowed.
- _____ FAA notified regarding Notice To Aviators for proposed burn time and locations in which no unauthorized aircraft would be allowed.
- _____ Local public radio and television announcements of intent to burn, along with information on estimated times, duration of burn(s), potentially affected areas, possible health effects, and unauthorized zones for public use.
- _____ State or local emergency services groups on standby for any possible assistance in notifying or evacuating certain populations.

Oil and Environmental Conditions:

- _____ Oil type and condition -- sufficiently combustible (thickness, evaporation, emulsification) under existing weather conditions.
- _____ Visibility -- suitable for vessels and aircraft in carrying out burn. Consideration given to number of daylight hours left to initiate burn.
- _____ Wind and waves -- suitable for oil collection, ignition and sustained combustion. General wind, speed and direction, and atmospheric mixing (now and predicted) acceptable to initiate and sustain burn.

Location, Timing and Compatibility of Response:

- _____ Proposed burn site(s) properly located with respect to population centers and other sensitive natural resources.
- _____ Sufficient time available to mobilize response personnel, transport and deploy equipment, ignite and complete burn(s).
- _____ Timing and conditions appropriate for consideration of night-time burn(s). Possibility of night-time oil collection with burns initiated at daybreak.
- _____ Burning operations safe and practical in light of spill status (ignited versus non-ignited, proximity to shore).
- _____ Burning safe and practical in light of vessel traffic lanes.
- _____ Burning safe and practical in light of spill source stabilization efforts.
- _____ Burning safe and practical in light of any personnel evacuation efforts.
- _____ Burning compatible with mechanical cleanup operations.
- _____ Burning compatible with dispersant application techniques.
- _____ Burning compatible with shoreline protection & cleanup activities.

Personnel Requirements:

- _____ All personnel trained and qualified for burning operations.
- _____ All personnel briefed and familiar with burn plan.
- _____ Full response team(s) and supervisor(s) for vessels on location or enroute.
- _____ Pilot and support personnel for aerial support functions on location or enroute (e.g., reconnaissance, Heli-torch operations).
- _____ Backup Fire Control Team on location or enroute.
- _____ Everyone has protective clothing, respirators, flotation devices, etc.

Vessel Requirements:

- _____ Two fire-containment booms towing vessels available for each U-configuration.
- _____ One fire control vessel available for each burn region. More than one vessel possibly needed should individual burns be widely separated.
- _____ Backup support vessel(s) as needed for personnel transport; refuelling operations; recovery and storage of burn residue; transport, deployment and recovery of fire-containment booms, boom towing vessels.

Aircraft Requirements:

- _____ Helicopter(s) as appropriate for number of burns anticipated, modes of ignition to be employed, and distances to be covered from staging area(s) to assigned region(s) of coverage.
- _____ Fixed-wing aircraft as appropriate to supplement helicopter operations involving oil reconnaissance missions, direction of vessels to collection sites, monitoring of smoke plume trajectories, etc.

Fire-containment booms and Igniter Requirements:

- _____ Inspected and ready-to-deploy fire containment boom (typically 500 ft to 1,000 ft per U-configuration), along with long tow lines (typically 500 ft to 800 ft per tow vessel), towing bridles, and anchoring systems as appropriate.
- _____ Backup fire containment boom (500 ft to 1,000 ft per U-configuration), along with additional lengths of boom for any modes of deployment (e.g., containment at spill source, deflection booming into designated nearshore burn sites, exclusion booming).
- _____ Inspected and ready-to-deploy Heli-torch(es) as needed for any aerial ignition activities (backup drums available for rapid turn-around).
- _____ Batch mixers for gelling large quantities of fuel mix for Heli-torch(es) if necessary (backup fuel supplies such as gasoline, diesel or crude oil, and gelling mix).
- _____ Supply of hand-held igniters (at least 10 per vessel and helicopter) for potential use (backup supply of at least 200 igniters or a means of acquiring or constructing additional units on short notice).

Communications Requirements:

- _____ Dedicated radio links (and equipment) with specific frequencies for air-to-air and air-to-surface communications.
- _____ Dedicated radio links (and equipment) with specific frequencies for vessel-to-vessel and vessel-to-command communications.
- _____ Repeater stations as appropriate for distant or blocked communication paths.

Fire Safety Considerations:

- _____ Possible use of dedicated personnel and vessels with vapor emission monitoring equipment (explosimeter).
- _____ Backup fire fighting vessels, if necessary, for unique situations involving a burning spill source and/or unusual potential exposures of personnel/vessels to burning oil.
- _____ Small fire fighting packages (extinguishers, monitors, foam, etc.) aboard the boom towing boats for backup use in the event of an emergency on or near one of the response vessels.
- _____ An explosimeter on each vessel involved in burning operations.

