ALASKA ARCTIC OFFSHORE OIL SPILL RESPONSE TECHNOLOGY

WORKSHOP PROCEEDINGS

Anchorage, Alaska
November 29 - December 1, 1988
Nora H. Jason, Editor

Sponsored by Minerals Management Service, U.S. Department of Interior

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Alaska Arctic Offshore Oil Spill Response Technology Workshop Proceedings

Anchorage, Alaska, November 29–December 1, 1988

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EXECUTIVE SUMMARY

Alaska Arctic Offshore Oil Spill Response Technology Workshop
Anchorage, Alaska
November 29-December 1, 1988

The objective of the Workshop was to provide a public forum to describe existing research programs, to identify future research needs and priorities to improve and to advance Arctic oil spill response capabilities, to present discussions of the state-of-the-art for all aspects of oil spill response under Arctic conditions and to provide information for the refinement of the existing Minerals Management Service (MMS) Technology Assessment and Research Program. The National Institute of Standards and Technology (NIST) served as the Workshop Coordinator on behalf of the MMS.

To achieve the Workshop objective, Keynote Speakers presented the current state-of-the-art in the following areas: Mechanical Containment and Recovery; Chemical Treatment; In-Situ Burning; Readiness. These presentations were followed by the status of several on-going efforts: the Technology Assessment and Research Program, the OHMSETT (Oil and Hazardous Materials Simulated Environmental Test Tank) Program, the Arctic and Marine Oil Spill Program, the Alaska Clean Seas Research and Development Program and the Norwegian Oil Spill Response (NOFO) Program.

After the Keynote Speakers' presentations in the general session, five Panels were formed from Workshop attendees and chaired by selected experts. The topical area for each Panel was the same as the above state-of-the-art papers. The goal of each Panel was to establish research needs and priorities within their area of expertise. Discussions by these Panels lead to recommendations of future research needs and testing and evaluating new techniques in specific environments representative of the Chukchi and Beaufort Seas. The major recommendations were:

- Large-scale tests (i.e., field tests) are necessary to replicate and validate innovations or to validate small-scale tests, to investigate the refinement of field measurement technique, to study the ignition and sustained combustion of emulsified oil measurements, and to investigate of the recovery of burn residue;

- small-scale tests (i.e., laboratory or test tank tests) are necessary to better understand a problem prior to large-scale testing, to investigate the ignition and sustained combustion of floating emulsified oil layers, to validate emissions from burning oils and other common air pollutants;

- research should be considered to improve current capabilities of recovering oil adhering to ice, and improving disposal techniques for oil-covered peat and other beach materials;

- chemical treating agents should be considered as a primary response tool in contingency planning, research is needed in such areas as biodegradability, toxicity, to quantify the amount of treating agent, to investigate their effectiveness in different water temperatures, to adapt existing technology to the Arctic environment;

- research on in-situ burning, e.g., oil spill burns in open water and broken ice are needed to measure burning rate, smoke emission, movement, and particulate deposition; techniques for recovering the burn residue from the water should be examined; laboratory investigations are needed to assess the feasibility of burning different oil-water emulsions and develop new techniques for burning enhancement; to address public concerns an analysis of the relative significance of oil spill burn emissions to other ordinary sources such as fireplaces, forest fires, and automobile engines was recommended;

- alternative techniques are necessary for acceptable disposal techniques, research is needed in such areas as incineration, landfilling, treatment products to solidify oil, investigation of injection/reinjection techniques into a pipeline or disposal well;

- remote sensing capabilities should be improved in the areas of reliably measuring the oil slick thickness, detecting oil in the presence of ice, and detecting sunken oil concentrations.

Although there may appear to be an overlap within individual Panel summaries, the combined research priorities and technological needs present a comprehensive view of the current Alaska Arctic offshore oil spill response technology. Recommendations for projects of a more administrative nature, e.g., a manual of transportation, logistics and support, are noted in individual Panel summaries. For more detailed information about each Panel, the reader is encouraged to review one or more Panel summaries of interest.

The Panel recommendations represent the combined input of the attendees and may serve as a working document for the MMS to refine their existing research programs.

Workshop on

ALASKA ARCTIC OFFSHORE OIL SPILL RESPONSE TECHNOLOGY

Sheraton Anchorage Hotel, Anchorage, Alaska
November 29-December 1, 1988

November 29

9 AM-12 Noon Registration at Sheraton Anchorage Hotel
9 AM-12 Noon Panel Chairmen Caucus

1:00 PM Welcome
1:15 PM Introduction by *Dr. David D. Evans*, Workshop Chairman, National Institute of Standards and Technology
1:30 PM *H. W. Lichte*, Keynote Speaker, Mechanical Containment and Recovery
2:00 PM *M. F. Fingas*, Keynote Speaker, Chemical Treatment

2:30 PM Coffee Break

3:15 PM *Dr. David D. Evans*, Keynote Speaker, In-Situ Burning
3:45 PM *Cdr. Dennis Rome*, US Coast Guard, Keynote Speaker, Readiness
4:30 PM Announcements; News Items

Adjourn for the day

November 30

7:30 AM-8:30 AM Registration

8:30 AM *Edward Tennyson*, Technology Assessment and Research Program, and the OHMSETT Program, Mineral Management Services
9:00 AM *Kenneth Meikle*, Arctic and Marine Oil Spill Program
9:30 AM *James J. Swiss*, Canadian Environmental Science Revolving Fund

10:00 AM Coffee break

10:30 AM *Richard V. Shafer*, Alaskan Clean Seas Research & Development Program
11:00 AM *Odd B. Angelvik*, NOFO Program

11:30 AM Break for lunch

November 30 (continued)

1:00 PM Participants will divide into five panels:
- Mechanical Containment - *H. W. Lichte*, Chairman
- Mechanical Recovery - *Sharon O. Hillman*, Chairwoman
- Chemical Treatment - *M. F. Fingas*, Chairman
- Is-Situ Burning - *Alan A. Allen*, Chairman
- Readiness - *Cdr. Dennis Rome*, Chairman

3:45 PM Coffee break

4:00 PM Workshop Chairmen will present 10 minute summaries of their progress

5:00 PM Announcements; News Items

Adjourn for the day

December 1

9:00 AM Workshop reconvenes and Panels resume discussions

10:30 AM Coffee break

11:00 AM Panels reconvene

1:00 PM Luncheon break

2:00 PM Individual panel presentations and discussion

4:00 PM Closing comments by Workshop Chairman
Panel Chairmen submit their written summaries

4:30 PM Workshop closes

INTRODUCTION

The Alaska Arctic Offshore Oil Spill Response Technology Workshop was held in Anchorage, Alaska, from November 29-December 1, 1988. The objective of the Workshop was to provide a public forum to describe existing research programs, to identify future research needs and priorities to improve and to advance Arctic oil spill response capabilities, to present discussions of the state-of-the-art for all aspects of oil spill response under Arctic conditions and to provide information for the refinement of the existing Minerals Management Service (MMS) Technology Assessment and Research Program. The National Institute of Standards and Technology (NIST) served as the Workshop Coordinator on behalf of the MMS.

To solicit public comments and recommendations on questions and issues relating to Arctic oil spill response capabilities, a Federal Register notice was published on July 25, 1988. Comments were sent to the MMS Reston Headquarters Office and Alaska OCS Region Office and, in turn, these comments were sent to the Panel Chairpersons so that the issues and recommendations would be addressed during the Panel sessions. A second Federal Register notice appeared on November 9, 1988 to announce the location and date of the Workshop.

To achieve the Workshop objective, Keynote Speakers presented the current state-of-the-art in the following areas: Mechanical Containment and Recovery; Chemical Treatment; In-Situ Burning; Readiness. These presentations were followed by the status of several on-going efforts: the Technology Assessment and Research Program, the OHMSETT (Oil and Hazardous Materials Simulated Environmental Test Tank) facility studies, the Arctic and Marine Oil Spill Program, the Alaska Clean Seas Research and Development, the Norwegian Oil Spill Response Organization. The next phase was for experts in the areas of Mechanical Containment, Mechanical Recovery, Chemical Treatment, In-Situ Burning and Readiness to lead the discussions and to summarize their Panel recommendations. The individual papers and recommendations of the Panels follow this Introduction.

This proceedings is the official transmittal of workshop information and recommendations to the sponsor, Minerals Management Service, Department of the Interior. It reflects the combined input of the workshop participants.

The statements and conclusions in this report are those of the authors and do not necessarily reflect the views of the National Institute of Standards and Technology.

IN-SITU BURNING PANEL

Attendees:

A. Allan, Chair
D. Dickins, Recorder
I. Buist
D. Evans
K. Saito
O. Angelvik
G. Schultz
F. Henicke
J. Pearce
L. Ethelbah
A. Sheets
R. Campbell
J. Stanger
W. Matumeck
P. Devenis

Introduction

A broad range of topics were identified and considered by the Panel. Out of this list of topics (for complete list, see "Topic Areas Discussed during Panel Session"), the key considerations were categories under two primary headings: Acceptability and Technology of Burning. Factors related to the "acceptability" of burning as a viable option were considered: products of combustion; perceived level of "control" during burning; proximity to people, equipment and biota; and perceived level of success. Factors related to the "technology" of in-situ burning also were addressed. Such factors included: methods of enhancing the burning process; refinement of ignition concepts and the various types of equipment available; refinement of the fire containment boom and the relationship and compatibility of in-situ burning with other response options.

Research Priorities

1. Field tests - Large oil volumes
   a. Offshore, open-water tests to gain experience and to refine field measurement techniques involving burning oil;
   b. scaling (i.e., <u>burn size</u>) with respect to burn rates, intensity of burn, nature and amount of smoke and burn residue, fallout, etc.;
   c. offshore, moving, broken ice tests to examine the above parameters and to evaluate fate and behavior of oil released into a variety of broken ice conditions;
   d. feasibility of igniting and sustaining combustion of emulsified oils;
   e. feasibility of recovering burn residue.

2. Laboratory work
   a. Thermal requirements for burning and breaking down various water-in-oil emulsions (i.e., different oil types and percentages of water);
   b. feasibility of igniting and sustaining combustion of floating emulsified oil layers;
   c. procedures/equipment for enhanced burning (e.g., air and/or water injection);
   d. comparative evaluation of emissions from the burning of various oils and other common air pollutant sources.

3. Studies
   a. Relative significance of burning versus other emission sources (e.g., fireplaces, forest fires, automotive engines, industrial smoke stacks);
   b. assessment of practical burning scenarios and strategies for arctic in-situ burning (or "operational windows"). Factors such as response time, personnel/equipment availability, staging location, etc., also should be investigated;
   c. development of public and government education programs with respect to safety, environmental impact and procedures for in-situ burning;
   d. assessment of requirements for permits to establish both simplified and practical means of conducting realistic offshore field tests.

Low Priority Items

Devices for burning oil off the water. Open burning as a slick is far more efficient in processing large volumes of oil quickly (ca. 0.07/gal/ft2/min) than is burning through a floating device--the floating burner may clean up the burn (less smoke), but it will likely be slower and introduce additional hardware and operational constraints that can become sources for "breakdown", extra cost, complexity in planning, deployment and maintenance, etc. Burning in remote areas (even with a lot of smoke) should be kept simple, dependable and adaptable to a broad range of environmental conditions.

Additional research on melt pools (over solid ice) should be of low priority based on accomplishments to date. An exception would be the fate, behavior and combustibility of oil spilled into or beneath ice conditions typical of the late-season Chukchi Region. Differences in ice/water conditions in the Chukchi may significantly influence the timing and deployment of burning systems and techniques.

Subsea containment/burning systems. Well studied, these ideas (e.g., Sombrero) are too big, costly and difficult to deploy and to maintain to consider for further research and development at this time.

Laser ignition. Suggest no additional research on this technique in light of current proven ignition concepts.

Additional Concepts

A wire mesh medium may be used in the apex of the fire containment boom to reduce entrainment and splashover, to heat the water and to introduce oxygen through vaporization and/or atomization at the oil/water surface during burn and radiate the heat back into the fire. This technique may also reduce smoke.

Radiation reflectors may be used along side of and/or on top of a fire containment boom to heat the oil and to enhance burning.

Topic Areas Discussing During Panel Session

1. Products of combustion;
2. potential for buring under different environmental conditions;
3. government regulations, guidelines and checklists;
4. methods of enhancing burning;
5. feasibility of igniting/burning emulsions, weathered oils, etc.;
6. refinement of existing ignition concepts/equipment;
7. refinement of combustion processes;
8. importance of burn size on burn rate, efficiency, products of combustion, nature and amount of burning residue, etc.;
9. equipment storage and deployment concepts;
10. recovery/elimination of burn residue;
11. reignition of unburned oil/burn residue;
12. overlap/interaction with other spill response options;
13. equipment testing procedures;
14. refinement of existing fire containment systems;
15. feasibility of igniting and maintaining combustion over subsea blowout (with and without ice);
16. safety considerations involving spill ignition procedures and deployment of fire containment boom;
17. strategy/planning considertions involving in-situ burning;
18. incineration techniques;
19. methods for igniting and sustaining combustion of oil in tankers;
20. procedures for handling and deploying igniters;
21. relative significance of burning versus other activities involving air emissions;
22. thermal radiation effects upon animals, humans and equipment;
23. assessment of practical scenarios invoving in-situ burning.

In-Situ Burning of Oil Spills

David D. Evans
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Introduction

Response to oil spills, regardless of location, includes considerations of oil containment, recovery, disposal and the logistics of delivering response equipment. In Arctic waters changing ice conditions during freeze-up to solid ice cover and the reverse process of ice break-up provide an extreme range of conditions for operation of oil spill response equipment. In general, the logistics of equipment movement and the efficiency of oil recovery and disposal varies substantially for response techniques and equipment as the percentage of ice-cover in the water changes.

In-situ burning has a broad range of applicability in Arctic areas as the effectiveness is not hampered by ice conditions. A relative comparison of in-situ burning and on-site incineration to other response techniques was summarized in chart form by an oil industry task group [1] and is reproduced in Appendix A of this paper. This chart rates the applicability of burning as "good" over the entire range of conditions evaluated. Experimental burns of oil in ice leads (channels of water through ice) conducted by Brown and Goodman [2] and Smith and Diaz [3] have shown that removal efficiencies typically better than 50% and, in some cases, over 90% are possible. In tests in which oil pools were free to spread during burning, Buist and Twardus [4] report consumptions of 70 - 90%.

Burning has been used in response to accidental oil spills with varying success. In most cases, these spills resulted from accidents involving tankers or barges. Case histories of several accidents and results from large controlled burned tests prior to 1979 [5] are provided in Appendix B. One example of successful burning under emergency conditions was the 1977 Buzzards Bay, Massachusetts, spill in which 40% of the 5000 gallon fuel oil spilled was removed by burning from the water containing floating ice.

The use of burning to remove oil from the water produces a trade-off that must be evaluated by local authorities. As oil is removed from the water by burning, the atmosphere receives the products of the combustion. Research continues to clarify the effectiveness of the burning process and the characteristics of the combustion products thereby increasing the amount of information that can be used by local authorities to aid in their spill response decisions. This research also provides experience with oil spill combustion techniques.

This paper presents previous research and discussion of in-situ oil spill burning. Sources of research applicable to oil spill combustion are identified and the current understanding is summarized. Reproductions of information, particularly summaries of findings, from the research literature are included for the convenience of the reader. The rudiments of oil spill combustion are discussed to provide a basis for decisions about the applicability of the broad range of available research in liquid fuel combustion to the particular problems of oil spill combustion in Arctic regions.

Previous Research

A comprehensive resource document providing a wide range of technical information about oil spill burning is the 1979 U.S. Department of Energy (DOE) report, Combustion: An Oil Spill Mitigation Tool [5]. This report supplied an extensive review of research work available at the time of publication and an extensive discussion of issues associated with in-situ burning of oil spills. Appendix C of this report is largely drawn from the bibliography provided in the DOE report. This Appendix gives sources and abstracts of research closely associated with oil spill combustion in the Arctic. The applicable research in this area comes from national and international sources: academic, government, and industry.

In the DOE report, oil spill combustion is discussed in terms of the three broad categories of fuels instead of individual fuel properties. The three categories are determined based on ease of burning. The operational evaluation of ease of burning is determined by the combustion properties of the hydrocarbon compounds making up the crude oil mixture. A simple energy balance for a unit mass of fuel is used to determine a Net Energy which is defined as the difference between energy input to the fuel surface largely by radiation from the flame, and the energy necessary to evaporate the liquid fuel. This relationship is:

$$\text{Net Energy} = 0.02\Delta H_{comb} - \Delta H_{evap} - C_p\,(T_{bp} - T_{amb})$$

where ΔH represents enthalpy change, C_p represents the specific heat of the fuel at constant pressure, and T represents temperature. The first term on the right-hand-side of the equation, $0.02\Delta H_{comb}$, represents an assumed energy input to the fuel surface from flame radiation equal to 2% of the heat of combustion of the fuel. The second term, ΔH_{evap}, represents the energy needed to evaporate the liquid fuel at its boiling temperature. The third term, $C_p(T_{bp} - T_{amb})$, represents the energy required to heat the fuel from its initial ambient temperature, T_{amb}, to the boiling point temperature, T_{bp}. Three categories of fuel result from this analysis depending on whether the Net Energy is much greater than zero, approximately zero or much less than zero. These correspond to categories 1, 2, and 3 fuels respectively.

Crude oils which are mixtures of hydrocarbon compounds do not have well-defined boiling point temperatures or latent heats of evaporation. For crude oils or other mixtures of hydrocarbons, "breakeven points" in the distillation of the fuel are determined. At the breakeven point the Net Energy is zero. The crude oils are placed in categories according to the following:

Category 1: greater than 67% of the mixture by volume has positive Net Energy

Category 2: greater than 40% but less than 67% of the mixture by volume has positive Net Energy

Category 3: less than 40% (below 30%) of the mixture by volume has positive Net Energy

This provides a structure to begin to generalize results of research that often use different oils. In general, Category 1 fuels can be expected to burn easily under most conditions. Category 2 fuels can be expected to burn under some conditions. Category 3 fuels would not be expected to sustain burning without combustion promoters. The categories for various oil products and crude oils are given in table 1 based on an evaluation using an ambient temperature of 4.4°C [5].

As indicated by the analysis above, the fraction of energy released that can be recaptured by the burning surface is important in determining the ability to burn oil spills. Placement of oil within the three categories as described above was done based on 2% of the energy released returning to the surface of the burning oil. If the radiant heat captured by the oil can be increased by an additional 1% of the energy released, substantially more oils could sustain combustion [5].

The effects of variation in oil thickness on the water, ambient temperature, exposure time prior to burning, and wind velocity on the combustibility of an oil in all three categories are shown in figures 1 through 4 as presented in the 1979 DOE report [5]. Results show that in 1979 oil thickness below 3 mm were considered generally not burnable as were any spill subject to winds greater than 5 m/s. Research and development in the technology of oil burning since then has shown that improvements can be made that increase the range of known combustible conditions. Burning of oil spills involves the processes of ignition, flame spread, pool burning, and extinction. Major findings of recent studies are presented below.

Ignition

Buist and Twardus [4] studied the process of oil slick ignition during the development of pyrotechnic igniters. They concluded that next to igniting the entire surface, the most efficient ignition technique is to ignite the periphery of the slick. The resulting flame spreads outward with the burning oil spread and inward aided by the fire induced air flow. Figure 5 shows the results of their research for both maximum time delay before ignition and number of igniters needed based on a 3 m spacing based on initial spill volume. The maximum ignition delay time increases with the 0.5 power of spill volume and the number of igniters with the 0.45 power of spill volume.

There are four principal igniter devices that have been used and studied for oil spill ignition.

1. Environmental Protection Service (EPS) Igniter, (Pyroid Igniter)
   The unit contains a pyrotechnic device held between two layers of material that provides flotation (fig. 6). The 2 kg. igniter is 25 cm. square with a height of 13 cm. It is activated by pulling on a firing pin which strikes a primer cap. A 25-second delay is provided to permit manual tossing of the igniter and settling on the oil slick surface. The flame from the edge of the igniter lasts for 2 minutes [6].

2. <u>Dome Igniter</u>
This device consists of a wire-mesh basket filled with solid propellant and gelled kerosene suspended between two metal floats (fig. 7). The 0.5 kg. igniter measures approximately 30 cm x 18 cm x 11 cm. An electric ignition system starts the 25 cm long fuse wire which provides 45 seconds of delay before ignition. The solid propellant burns for about 10 seconds to ignite the gelled kerosene in the wire-mesh basket. The total burn time is 10 minutes [6].

3. <u>Laser Ignition of Oil Spills (LIOS)</u>
Two coupled lasers potentially can be used from a helicopter to heat and ignite oil spills. A laboratory system has been demonstrated to ignite crude oil pools. Actual helicopter mounted equipment, as pictured in figure 8, has not been built. The process of ignition is illustrated in figure 9. A continuous-wave (CW) carbon dioxide laser heats a portion of the oil surface to the flashpoint temperature. A more intense but smaller focused pulse laser beam provides the energy in the gases above the warm oil spot to initiate flaming. The system under design will be capable of igniting oil pools from a hover altitude of 20 m with an aiming angle of 0 - 49 degrees corresponding to 0 - 23 m travel distance along the ground [7].

4. <u>Helitorch Igniter</u>
The Helitorch is a proven igniter system commonly used by the forest services for controlled burning during fire-control operations. The system (fig. 10) releases burning gelled gasoline globules from a tank system weighing 243 kg. that can be suspended by cables below the helicopter and controlled from the cockpit. Typical burning globules ignited and released from the unit at heights of 18 m or less range from 60 - 120 ml and have burning times of 4 - 6 minutes [8].

<u>Flame Spread</u>

Each of the igniters above provides for oil ignition in the immediate area around the device. Flame spread from this position eventually involves the entire slick. Buist and Twardus [9] investigated both oil spread on water and flame spread on oil. They found that burning oil did not spread on water faster nor farther than cold oil. Only in the case of diesel fuel at wind speeds less than 1 m/s did the flame spread not keep up with the spread of oil. Figure 11 shows test results for aged Alberta Sweet Mix Blend (ASMB) crude oil in a 0.25 m/s counterflow wind velocity.

<u>Burn Efficiency, Oil Burn Residue</u>

The consumption of the oil spill by burning is of course the primary issue of interest. The efficiency of the burn is the percentage of the original oil that is removed by burning. Some oil residue remains in the water from all burns, as the flame is always quenched by heat losses to the water surface when the oil layer is thin. Thus the burn efficiency is limited naturally below 100%. Burn efficiencies and oil residue data from 1 m and 2 m diameter oil pool fires [9] and spills in water channel between ice blocks (fig. 12) [3] are presented in tables 2 and 3 respectively. Burn efficiencies greater than 90% were obtained in the confined pool fires and 79% for the oil burned in ice channels. Based on experiments and analysis of unconfined oil slick burns, Buist and Twardus [4] proposed an equation for rough estimates of burn efficiency that used only initial spill volume (V_s) as:

$$\text{Burn efficiency} = (1 - 1/3\ V_s^{-1/5}) \times 100\%$$

Measured burn efficiencies from small and large scale unconfined burns (fig. 13) are compared with calculated burn efficiencies using a more complete model in figure 14 [4]. Two assumed velocities of the burning induced surface current (U_c) are shown. The induced surface current acts to limit oil slick spread.

Demonstration of Oil Spill Response Capabilities

An example of the continuing industrial research activity in Arctic oil spill burning is the cooperative work of four major oil companies operating in Alaska. In response to concerns of oil industry regulatory agencies about existing technical capabilities to clean-up oil spills in broken-ice conditions in the Alaskan Beaufort Sea, demonstration tests of oil spill response techniques and equipment were performed in 1983. These tests form the basis of an industry demonstration that allows for drilling in the Alaskan Beaufort Sea under Tier 2 regulations. Tier 2 permits unrestricted drilling with exception of locations outside the barrier islands during the fall bowhead whale migration. Six different tasks were addressed in the study, three of which dealt directly with oil spill combustion. These tests are typical of many efforts to evaluate equipment and response techniques and are included in this paper for that reason. Test descriptions and results were:

1. In-situ burning of crude oil in the presence of scattered ice.

   The in-situ burning of up to 288 gallons of fresh Prudhoe Bay crude oil was demonstrated in four separate tests in an onshore pit at Prudhoe Bay. The results of the four tests demonstrated that: 1) cold waters and ice can be beneficial in limiting the initial spread of oil; 2) the oil slicks are ignitible using helicopter deployment of igniters; 3) the oil slicks can be burned, even in scattered ice conditions, with consumption efficiencies of 55 - 85%; and 4) the unburned oil and burned oil residue can be removed using conventional oil sorbent materials [10].

2. Burning of oil in a containment boom.

   The in-situ burning of crude oil was demonstrated in an onshore pit at Prudhoe Bay. In these tests the burning oil was contained within an 2.4 m diameter area by a fire containment boom for the 10 minutes necessary to consume the initial 25 mm thick layer. In the second burn test, oil was replenished at a rate of 2.5 gallons per minute, providing a continuous burn. In this test the boom became submerged on the downwind side after 45 minutes allowing burning oil to escape. Burn efficiencies of 90% and 95% were measured [10].

3. Deployment of a fire containment boom in the lee of a drilling island.

   More than 500 feet of fire containment boom was positioned in a fixed containment mode in the lee of an offshore drilling island. The boom encountered moving broken ice (4 to 7 oktas) for more than 24 hours. A helicopter was used to transport and deploy 240 feet of wet boom in moving broken ice (up to 3 oktas). The boom drifted freely for 2 days. In both cases the boom survived the handling and ice exposures [10].

This same oil industry task group prepared reports assessing the state-of-the-art of oil spill response techniques for the Arctic [11]. Subsequent to that publication, the task group prepared a practical guide to oil spill response techniques that presents technical information about the relative effectiveness of method under conditions found in the Alaskan Beaufort Sea [1]. Guidance also is provided on logistical and manpower requirements, as well as recovery rates and efficiencies. Appendix A contains a chart giving the relative effectiveness of in-situ burning to other response techniques and copies of two technical information sections from this reference -- In-situ Burning with Natural Containment, and In-situ Burning with Fire Containment Boom.

Many of the oil spill research activities involving combustion, like those discussed above, are conducted in outdoor test facilities. Often these permit large and realistic tests but these tests are often susceptible to uncontrolled effects of weather. Large scale fire test facilities offer protected and instrumented spaces in which realistic size burns can be conducted under controlled conditions. Measurements from these research burns provide the best basis for understanding oil spill combustion. Results and understanding generated through controlled measurement in these specialized facilities usually can be generalized to conditions that occur in actual oil spill combustion situations. It is for this reason that the Center for Fire Research at the National Institute of Standards and Technology (NIST) [formally known as the National Bureau of Standards (NBS)] was asked to examine the technology of oil spill combustion under support from the Minerals Management Service, U.S. Department of the Interior. Starting in 1984, measurements and calculations were performed to understand the burning behavior of crude oil spills on water, the physical and chemical properties of the smoke produced in the burning, and the dynamics of the smoke plume flow.

An important result of these studies was an evaluation of polynuclear aromatic hydrocarbon (PAH) content of the crude oil, the smoke produced by burning the oil on water, and the residual oil left in the water after combustion. The question of what effect combustion of oil that contains PAH compounds would have on the net amount of these compounds remaining in the burn residue and carried in the smoke is important to analyze fully the consequences of the combustion. Measurements of PAH compounds were performed by both NIST and Environment Canada on samples collected from 0.6 m diameter pool burns performed in the NIST large scale fire test facility. These measurements showed that:

1. The PAH concentration in the burn residue was equal to that of the original oil [12].

2. The total PAH content of the smoke was equal to or less than the mass of PAH compounds in the oil that was consumed in the combustion depending on the burning conditions [12,13].

3. In cases where the total mass of PAH compounds in the oil burned and in the smoke were the same, the distribution of PAH compounds in the smoke was shifted towards larger molecular weight species [13].

Based on these measurements, it appears that the total PAH content of the environment remains the same or is reduced by combustion of the crude oil spills on water.

Dynamics of oil spill combustion

The burning process for crude oil on water exhibits two distinct burning regimes. Initially the oil layer burns in a quiescent pool. For most crude oils the surface temperature of the vaporizing liquid is greater than the boiling point temperature of the water on which the oil is floating. As fuel is consumed the oil layer is heated in depth and is reduced in thickness. The thinner oil layer also allows more radiation from the flame to penetrate to the water layer. Both of these processes eventually produce boiling in the supporting water layer under the oil. At the onset of water boiling, there is a rapid transition to a much more intense burning. Boiling water churns the oil layer throwing water and oil droplets into the flame. The energy release rate and oil consumption rate increase from two to four times the pre-boiling rate. A secondary effect of the vigorous burning is that some water is injected into the flame. It is known from engine emissions studies that water injection into hydrocarbon flames reduces the smoke production [14]. Measurements during the burning of crude oil have shown that when the burning entered the vigorous burning regime, the smoke emission per unit fuel mass loss decreased by a factor of five [13].

Figure 15 shows mass loss rate histories for Alberta Sweet Blend Mix crude oil fires with initial thickness from 2 - 10 mm [13]. The thicker layers demonstrate clearly the two burning regimes. With regard to crude oil consumption, figure 15 shows that for the 2 mm and 3 mm thick layers of oil burned, approximately 65% of the oil burned was consumed during the vigorous burning period. Only 33% of the thicker 10 mm layer was consumed during a vigorous burning period. As smoke production during the vigorous burning period is substantially less per unit fuel mass consumed, the burning of the thinner slicks should produce less total smoke emission per mass of crude oil consumed.

The mass loss rate histories shown in figure 15 also demonstrate the rapid natural extinction of the oil spill fire. At some point in the combustion, heat losses to the supporting water layer or mixing process due to churning of the oil layer by boiling water reduces the oil layer temperature sufficiently to prevent evaporation of the crude oil necessary to sustain burning. The flame is extinguished leaving an oil burn residue on the water. This residue is generally depleted in low temperature volatiles compared to the original oil. Referring to the classification systems for ease of burning, a Category 2 crude oil may produce a Category 3 burn residue.

Closing

Despite the ability to describe the burning process, quantitative predictions of burning rates, transition to vigorous burning caused by boiling of the supporting water layer, and flame extinction conditions are not possible at this time. Measurements show that vigorous crude oil burning associated with boiling of the water supporting layer produces less smoke per unit mass of oil consumed and this smoke carries less total PAH species content than the oil burned. Thicker oil layers generally are easier to ignite and burn but thinner layers that induce boiling in the water are relatively cleaner burning.

All controlled research burns, equipment evaluation tests, and efforts to utilize combustion in response to spills increases the collective experience with the technique. This effort has improved the technology well beyond the expectations of 10 years ago. Hopefully, future efforts can continue this trend.

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Table 1 Oil Products and Crude Oils by Combustibility Category [5]

CATEGORY NUMBER 1

Oil products	Crude Oils	
Motor Fuel Antiknock	Attaka, E. Kalimantan, Indonesia	Pennington, Nigeria
Compounds with Lead Alkyls	Tembungo, Malaysia	Melabin, E. Kalimantan, Indonesia
Gasoline and Flash Feed Stocks	Seppinggan, E. Kalimantan, Indonesia	Qua Iboe, Nigeria
Jet Fuel No. 3	Poleng, Java, Indonesia	Hassi Messaoud blend, Algeria
Coal Tar	Labyan Light, (Samarang) Sabah, Malaysia	Beryl, U.K.
Kerosene and JR No. 1	Es Sidar, Libya	Bonny light, Nigeria
Jet Fuel No. 5	Serei light, Brunei	Arabian light (berri), Saudi Arabia
Fuel Oil No. 1 and 1D		Mubarek, Sharjah, UAE

CATEGORY NUMBER 2

Oil Products	Crude Oils	
Asphalt	Escravos, Nigeria	Brega, Libya
Jet Fuel No. 4	Trinidad blend, Trinidad Tobago	Murban, Abu Dhabi
Gas Oil	Bekapi, El Kalimantan, Indonesia	Arzew blend, Algeria
Fuel Oil No. 4	Arjuna, Java, Indonesia	Umm Shalf, Abu Dhabi
Fuel Oil No. 2 and 2D	Zakum, Abu Dhabi	Wallo export mix, West Irian, Indonesia
Fuel Oil No. 5	Hout, Neutral Zone	Qatar (Duckham), Qatar
Bunker C	Thistle, U.K.	Kerindingan, E. Kalimantan, Indonesia
	Basrah, Iraq	Zueitina, Libya
	Badak, E. Kalimantan Indonesia	North Rumaila, Iran
	Mubarras, Abu Dhabi	Tyumen, USSR

Table 1 (continued)

CATEGORY NUMBER 2

Oil Products	Crude Oils	
	Statfjord, Normany	Cinta, Indonesia
	Qatar Marine, Qatar	Ninian, U.K.
	El Bundug, Abu Dhabi	Reforma (Cactus Reforma, Isthmus) Mexico
	Sassan, Iran	Iranian Light, Iran
	Piper, U.K.	Arabian Light, Saudi Arabia
	Montrose, U.K.	Strip Blend 27.1 API, Iran
	Forcados blend, Nigeria	Iranian Heavy, Iran
	Zarzaitine, Algeria	Romashkinskaya, USSR
	Ekofisk, Norway	Bunju, E. Kalimantan, Indonesia
	Forties, U.K.	Lagomedio, Venezuela
	Rostam, Iran	Dubai, Dubai
	Bai Hassan, Janbur, Iraq	Bonny Medium, Nigeria
	Kirkuk, Iraq	Tarakan (Pamusian) E. Kalimantan, Indonesia
	Bu-Attifel, Libya	Ecuador (Oriente), Ecuador
	Handil, E. Kalimantan, Indonesia	Cabinda, Cabinda, Angola
	Darius, Iran	North Slope, USA
	Oman, Oman	Mandji, Gabon
	Sarir, Libya	
	Gulf of Suez Blend Egypt	
	Kuwait Crude, Kuwait	

Table 1 (continued)

CATEGORY NUMBER 2

Oil Products	Crude Oils	
	Arabian Medium (Zuhof), Saudi Arabia	Ratawi, Neutral Zone
	Fereidoon Bled, Iran	Minas (Sumatran Light) Samatra, Indonesia
	Arabian Medium Saudi Arabia	Burgan (Wafra) Neutral Zone
	Ekhabinskaya, USSR	Anguille, Gabon
	Amna (High Pour), Libya	Taching, China (PRC)
	Arabian Heavy, Saudi Arabia (Safaniya and Khafi)	

CATEGORY 3

Oil Products	Crude Oils	
Castor Oil	Gamha, Gabon	Jatibarang, Jaba, Indonesia
Spray Oil	Eocene, Neutral Zone	Klamono, Irian, Java Indonesia
Rosin Oil	Emeraude, Congo Brazzaville	Duri, Indonesia
Diesel Oil	Cyras, Iran	Boscan, Venezuela
	Bachequero, 16.8°API (Bachequero Heavy), Venezuela	

Table 2

Confined Pool Crude Oil Burn Test [9]

Oil Type	Oil Volume (1)	Pool Dia. (m)	Initial Oil Thickness (mm)	Residue Volume (1)	Residue Thickness (mm)	Burning Time (min)	Regression Burning Rate (mm/min)	Burn Efficiency+ %
ASMB	4	1	5.0	0.7	0.9	2:20	1.8	82
ASMB	6	1	7.6	0.85	1.1	3:15	2.0	86
ASMB	8	1	10.1	0.95	1.2	4:50	1.84	88
ASMB	10	1	12.7	0.95	1.2	6:40	1.7	90
ASMB	12	1	15.3	1.0	1.27	8:35	1.65	92
ASMB	16	1	20.3	1.0	1.27	11:42	1.63	94
ASMB	16	1	20.3	0.8	1.0	9:30	2.0	95
ASMB	17	1	21.6	0.8	1.0	10:00	2.0	95
ASMB	20	1	25.47	1.0	1.27	14:00	1.72	95
ASMB	32	1	40.7	0.9	1.15	19:00	2.0	97
Diesel	6	1	7.6	1.1	1.4	3:50	1.6*	82
Diesel	12	1	15.3	1.6	2.0	7:15	1.8*	87
Diesel	20	1	25.47	0.9	1.15	11:50	2.0	95
Diesel	12	2	3.8	4.2	1.33	2:20	1.0*	65
Diesel	20	2	6.36	4.1	1.3	3:00	1.68*	79
ASMB	10	2	3.18	1.7	0.54	1:35	1.74	83
ASMB	14.7	2	4.67	2.3	0.73	2:00	1.97	84
ASMB	20	2	6.36	2.7	0.859	2:19	2.39	86

*Residue emulsified

+(Oil Volume - Residue Volume/Oil Volume) x 100%

ASMB Alberta Sweet Mix Blend Crude Oil

Table 3 Test Results - Oil Burned on Water with Ice Cover [3]

Test No.	Test Fluid Description	Fluid Volume (liters)	Ice Coverage* (%)	Ignition/Burn Time (min:sec/min:sec)	Air Temp (C)	Water Temp (C)	Wind Speed (m/s)	Burn Efficiency (%)
1	Fresh Prudhoe Bay crude	35.6	76-81	0:15/11:31	5	4	2	72.4 ± 2.3
1R	Fresh Prudhoe Bay crude	29.0	84-86	0:15/24:03	-6	0	8	62.5 ± 3.8
1R2	Fresh Prudhoe Bay crude	35.6	82-89	0:06/13:45	-1	0	2	58.3 ± 2.4
4	Sparged Prudhoe Bay Bay crude. Flash Point: 24C	35.6	75-84	0:15/15:50	-3	0	4	79.1 ± 2.2
5A	Emulsion 18% Bay water/82% fresh Prudhoe Bay crude	35.6	81-86	1st 0:17/2:30 2nd 0:21/15:45 3rd None**/33:04	4	0	6	9.6 ± 2.7
6A	Sparged Prudhoe Bay crude. Flash Point: 40C	35.6	75-80	0:13/9:21	7	0	6	61.9 ± 2.3
7A	Emulsion 8% Bay water/92% fresh Prudhoe Bay crude	35.6	79-85	1st 0:11/25:27 2nd 0:15/11:05 3rd 0:07/5:10	4	0	7	34.7 ± 2.5
8A	Sparged Prudhoe Bay crude. Flash point: 40C	35.6	78-84	0:07/8:07	-1	0	< 2	68.3 ± 2.3
9A	Fresh Amauligak crude	35.6	82-88	0:07/16:32	3	5	4	62.9 ± 2.4
10A	Sparged Amauligak crude. Flash Point: 38C	35.6	82-83	0:08/27:15	11	7	1	68.3 ± 2.4
11A	Emulsion-9% Bay water 91% fresh Amauligak crude	35.6	76-80	1st 0:08/21:32 2nd 0:10/4:58 3rd 0:43/17:11	12	7	5	51.7 ± 2.5

* Range based on average ice coverage measurement ± standard deviation of measurements. Magnitude of range indirectly indicative of ambient light levels which affect the quality of video recording.

** 3rd igniter placed while 2nd still ongoing.

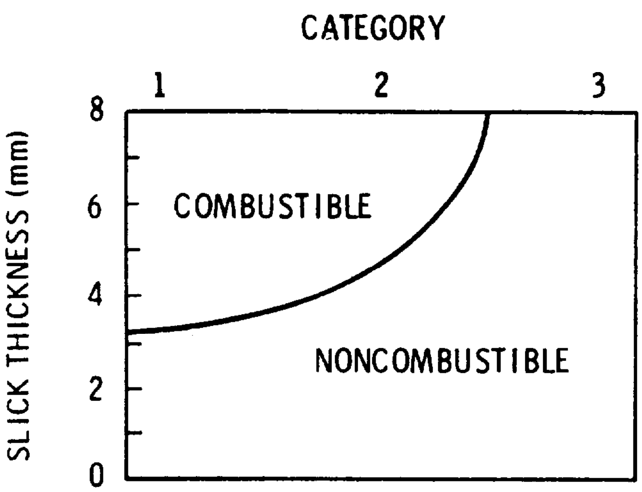


Figure 1 Effect of Oil Layer Thickness on Combustibility [5]

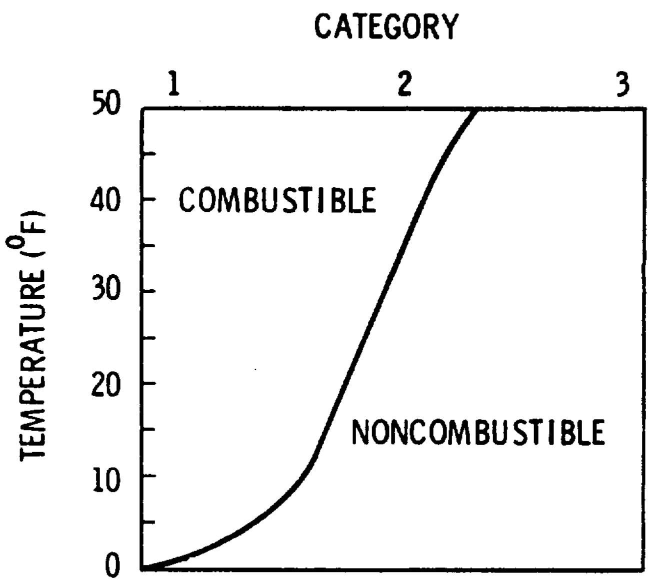


Figure 2 Effect of Ambient Temperature on Combustibility [5]

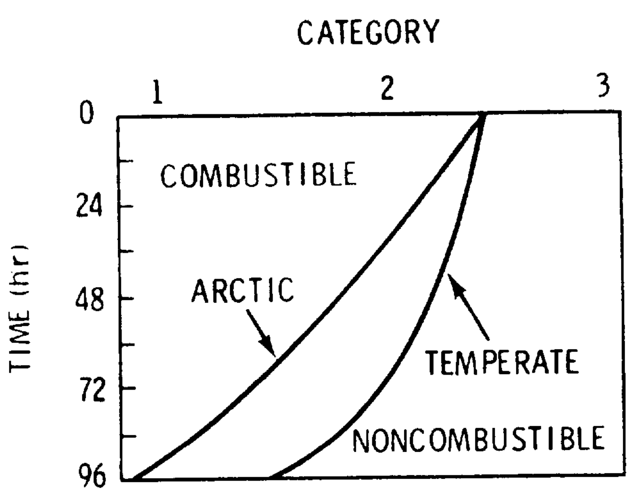


Figure 3 Effect of Time Delay on Combustibility [5]

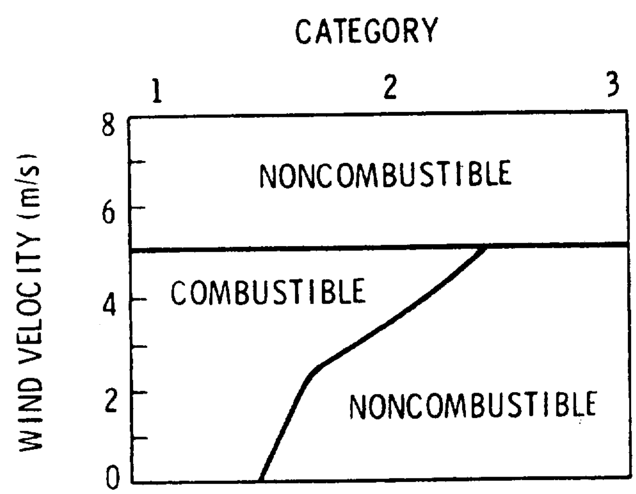


Figure 4 Effect of Wind Velocity on Combustibility [5]

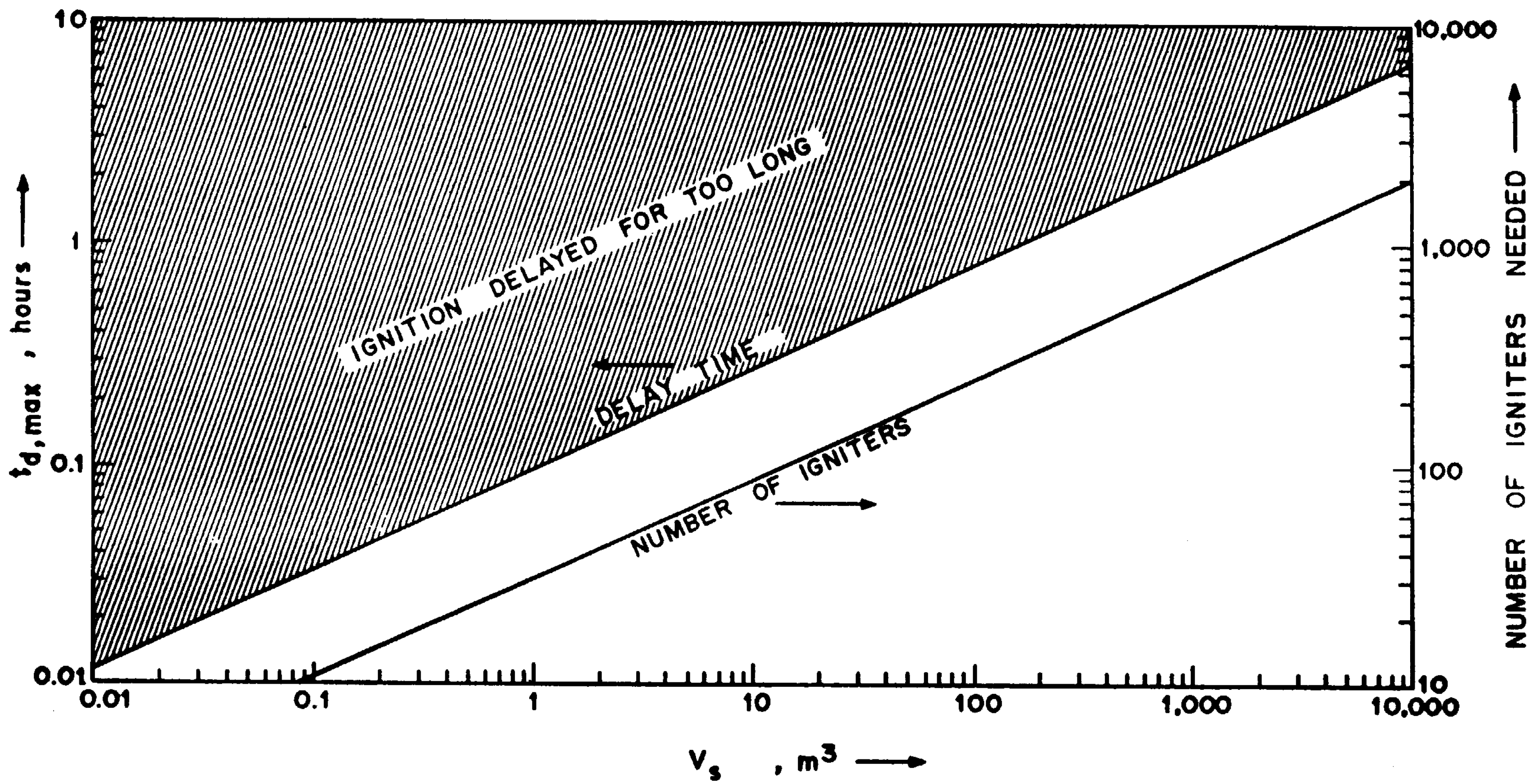
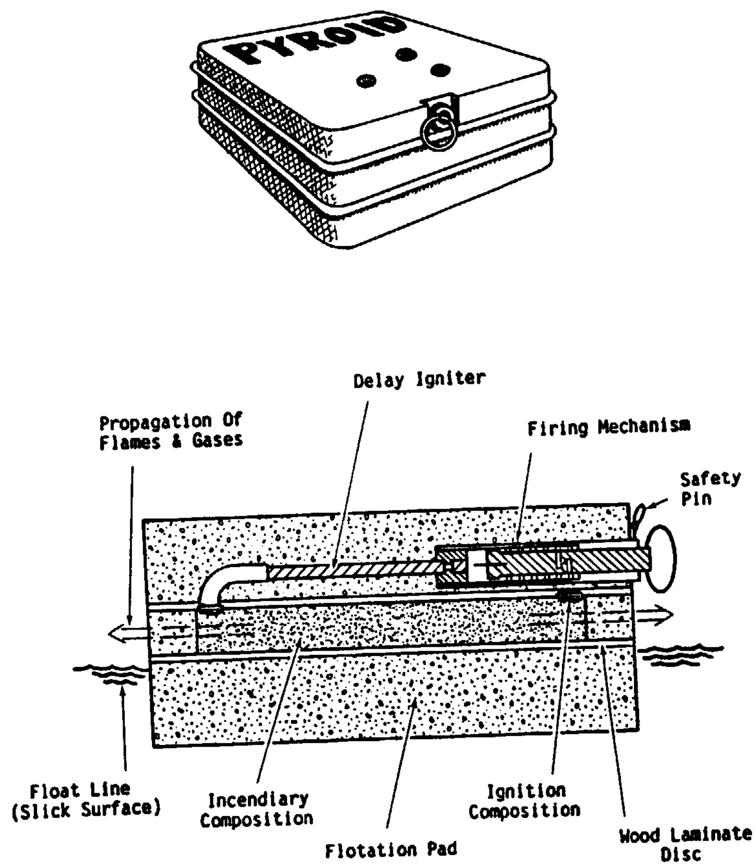


Figure 5 Maximum permissible ignition delay time and the number of igniters required at that time as a function of spill volume [4].



After: Twardawa & Couture, 1983.

Figure 6 Environmental Protection Service (EPS) igniter showing internal firing mechanism and pyrotechnic components [6].

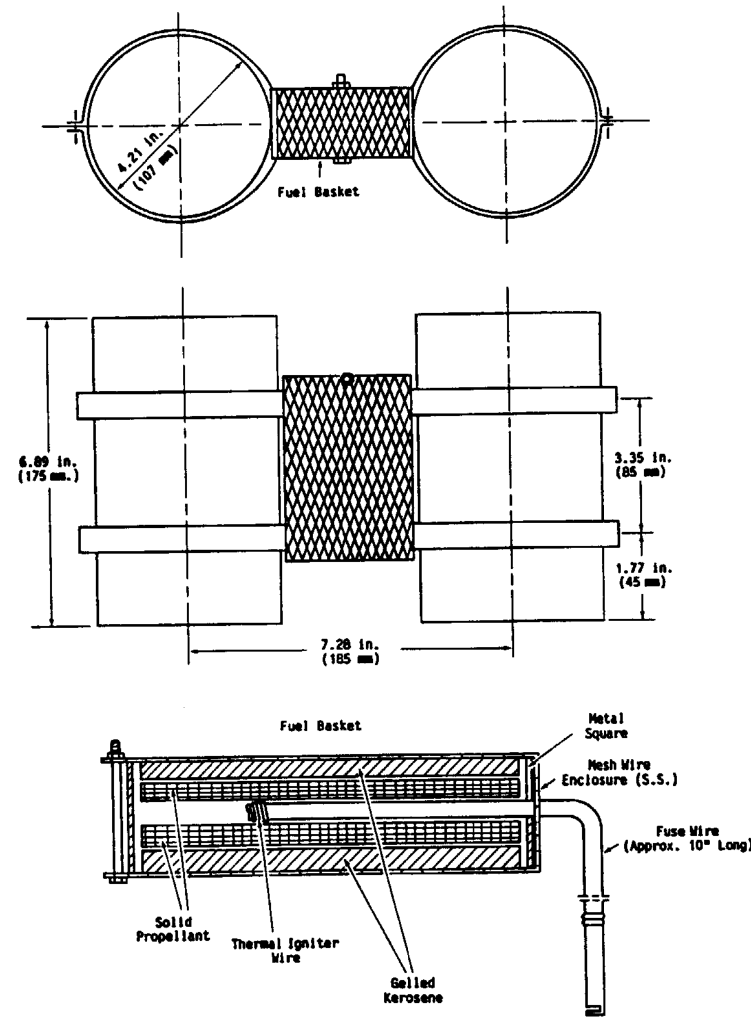


Figure 7 Basic design and internal components of the Dome igniter [6]

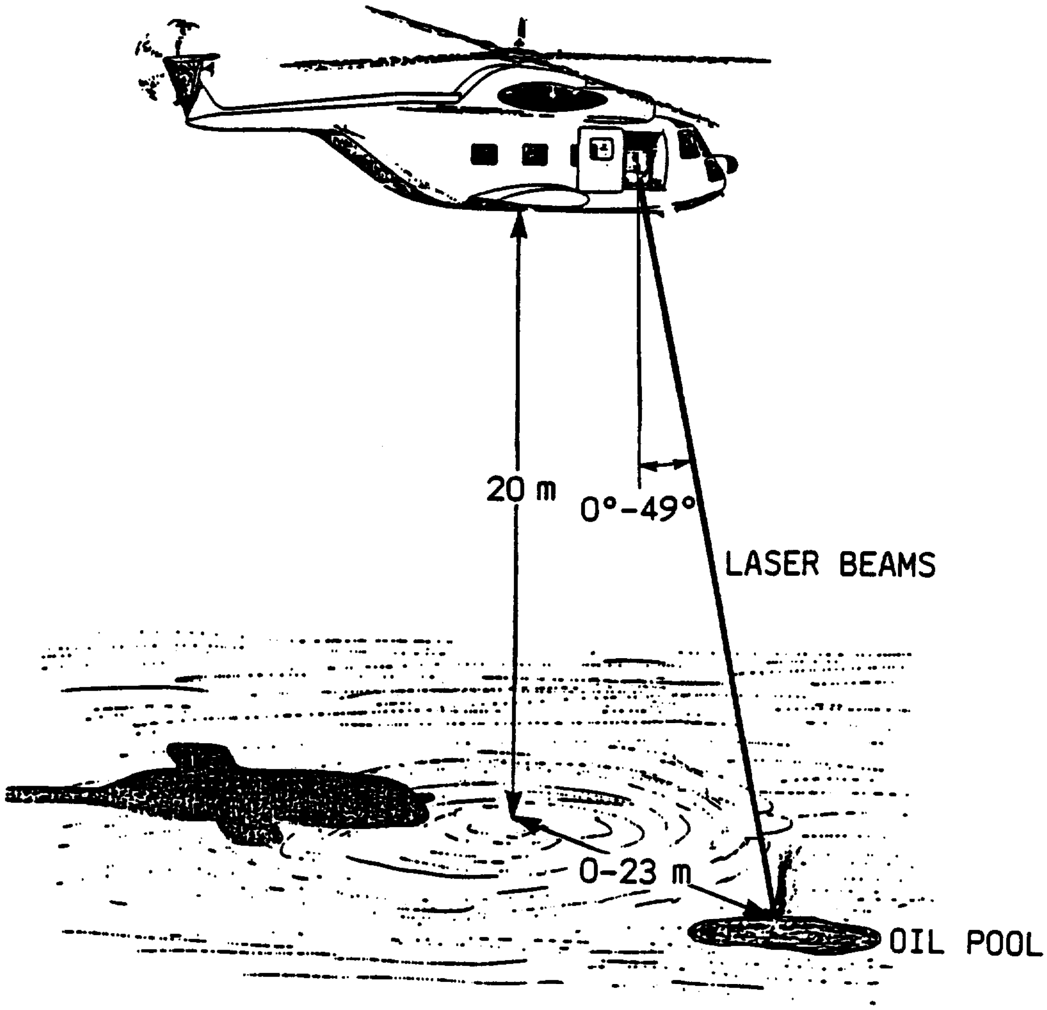


Figure 8 Illustration of airborne LIOS system [7]

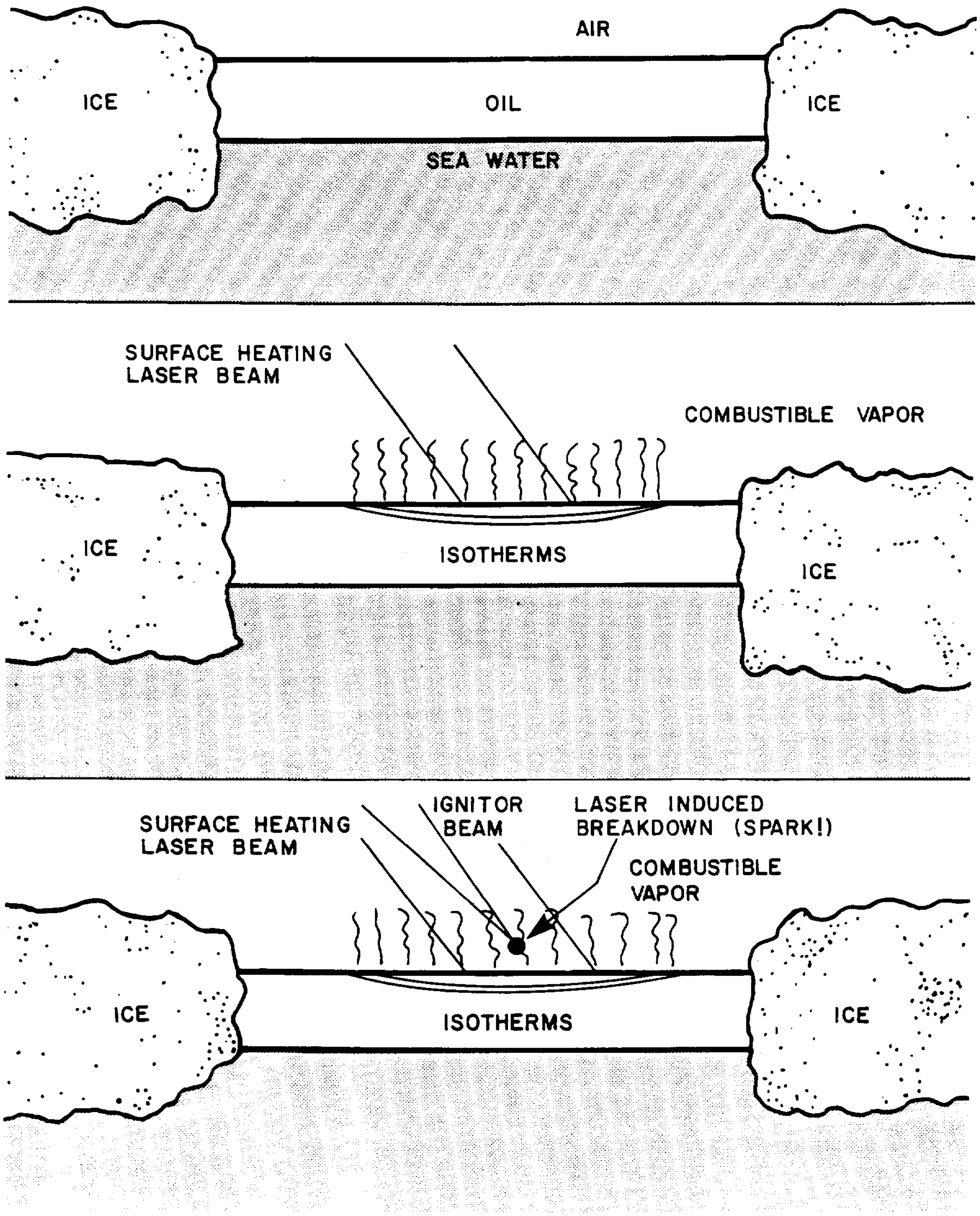


Figure 9 Process of oil spill ignition using LIOS [7]

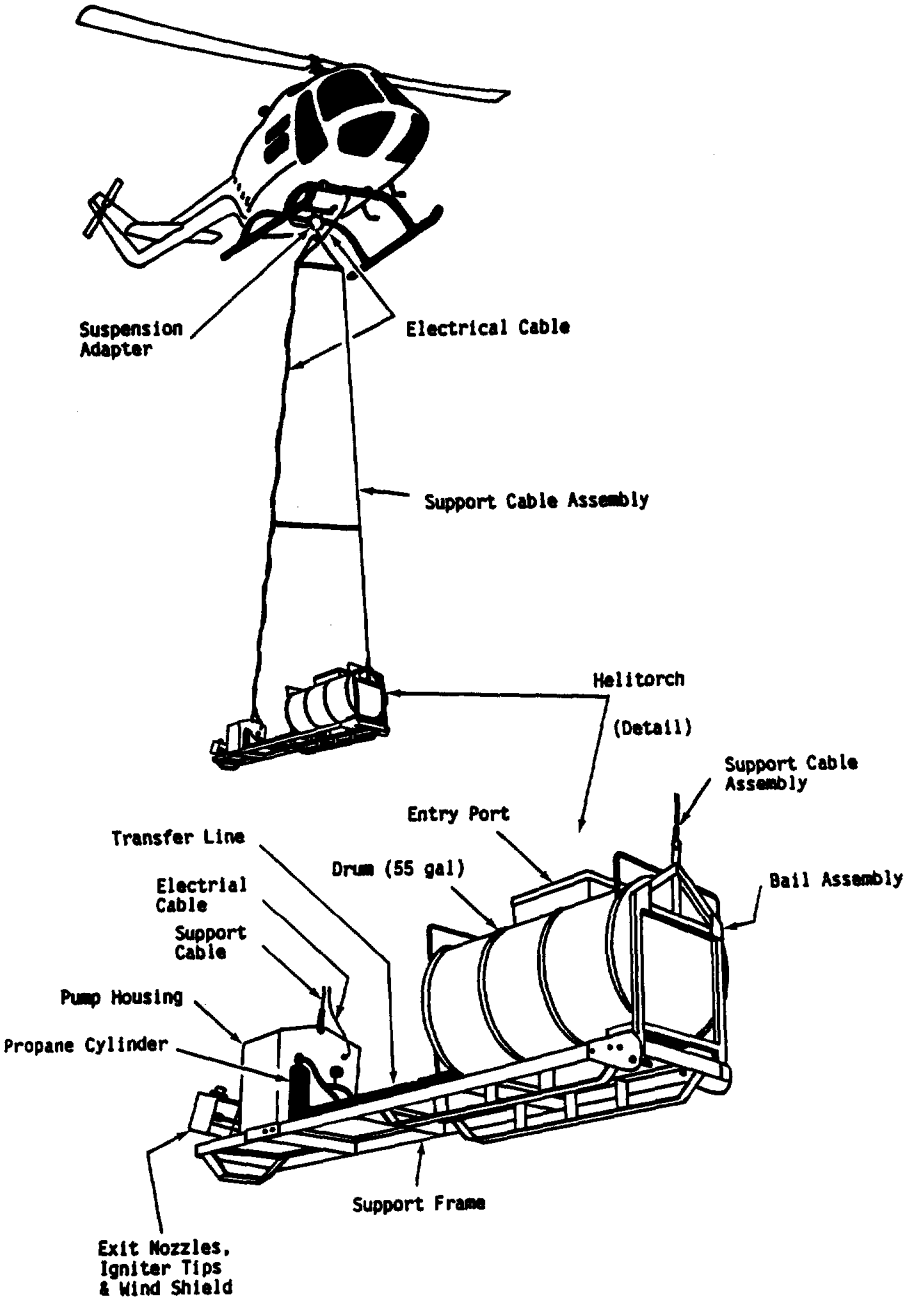


Figure 10 Helitorch igniter system [8]

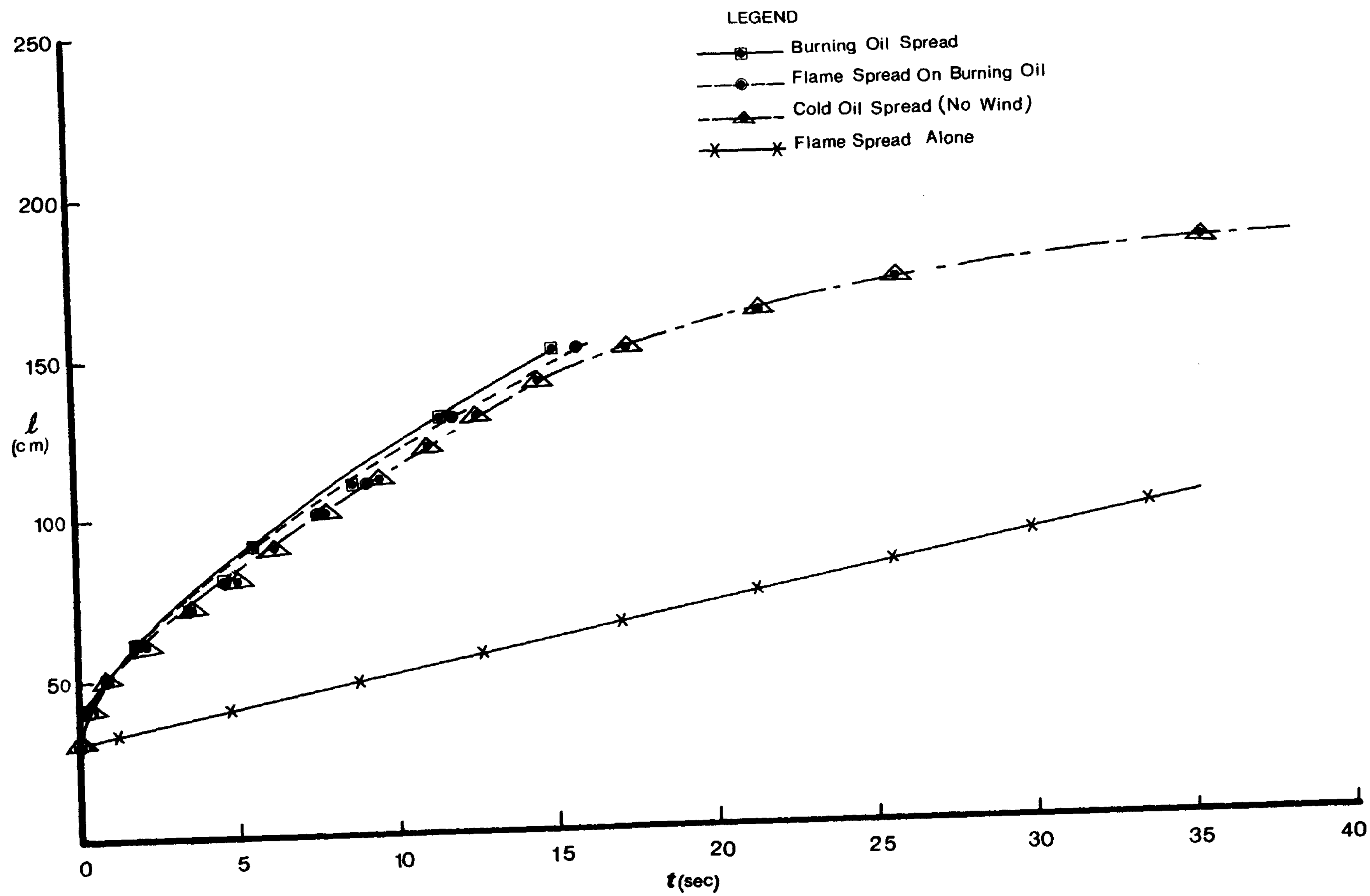


Figure 11 Oil and flame spreading (4 hour aged ASMB at 0.25 m/s wind speed) [9]

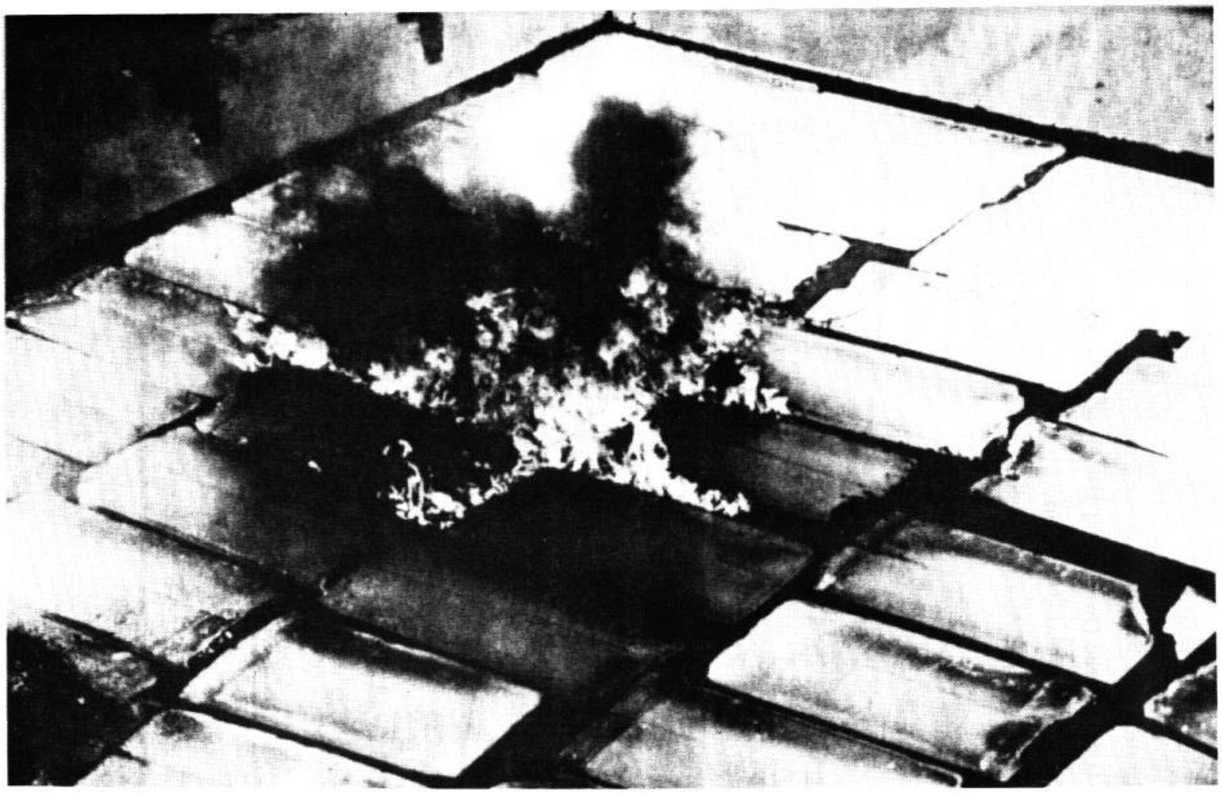


Figure 12 Demonstrating the burnability of an emulsion of 92% Prudhoe Bay crude oil and 8% bay water in tests at OHMSETT [3]

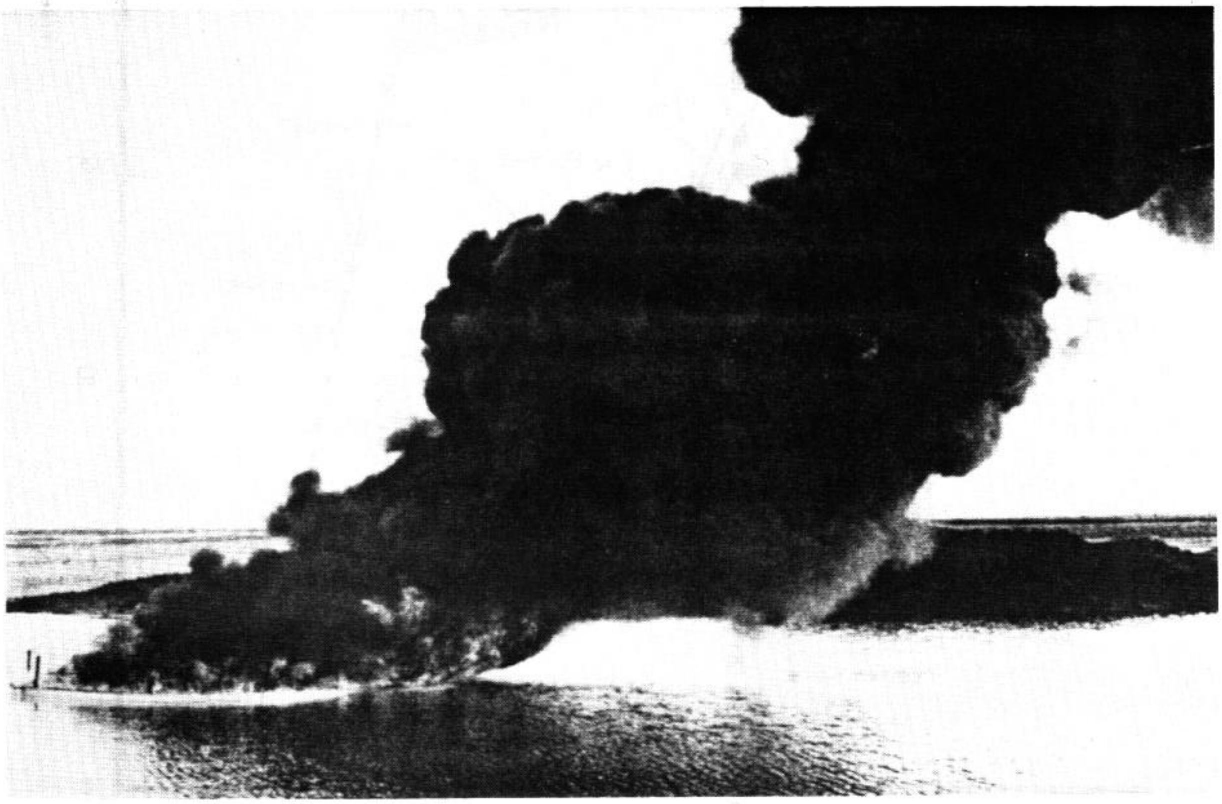


Figure 13 Large scale burn tests near Prudhoe Bay, Alaska [4]

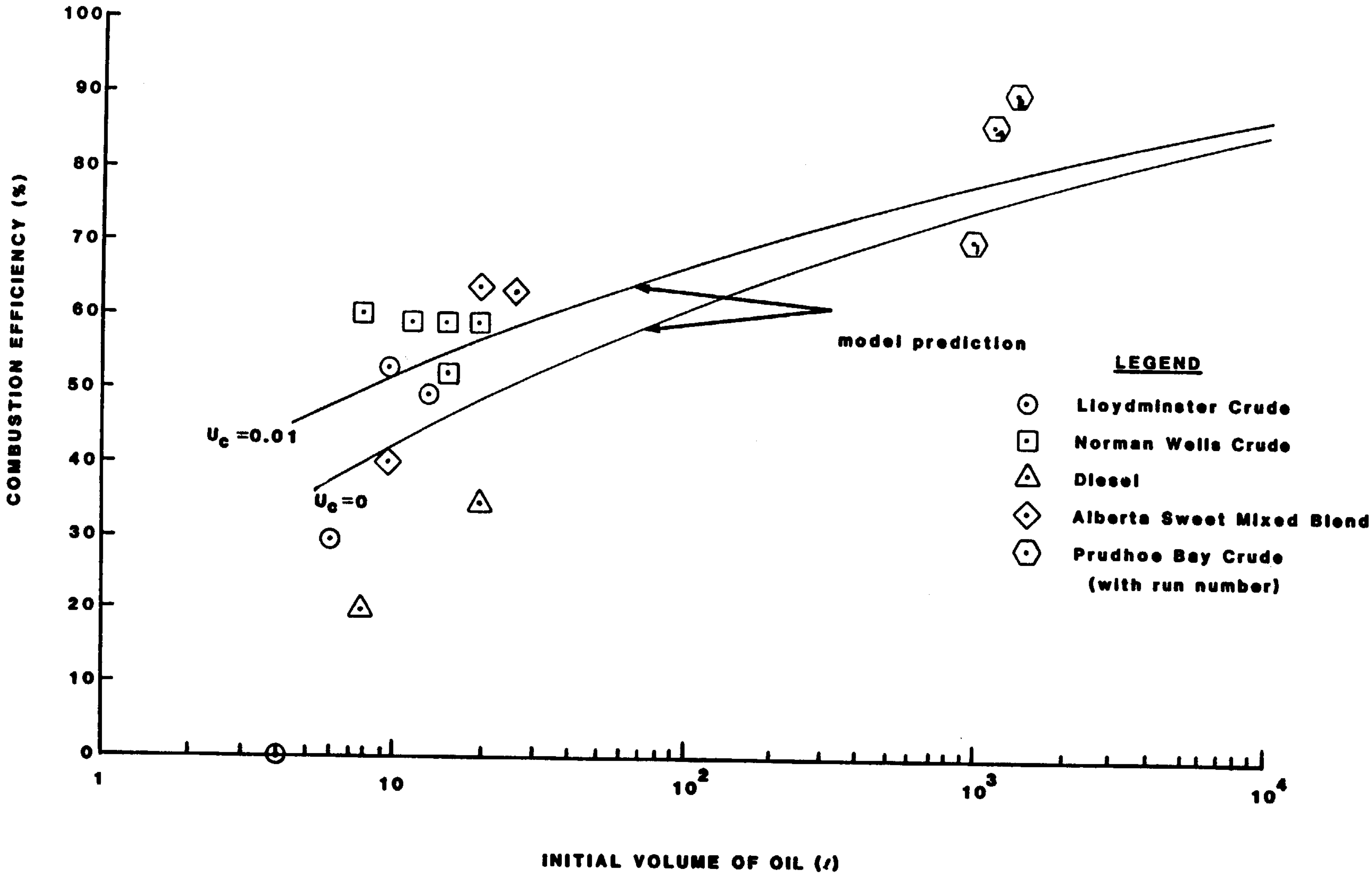


Figure 14 Oil spill combustion efficiency assuming instantaneous ignition [4].

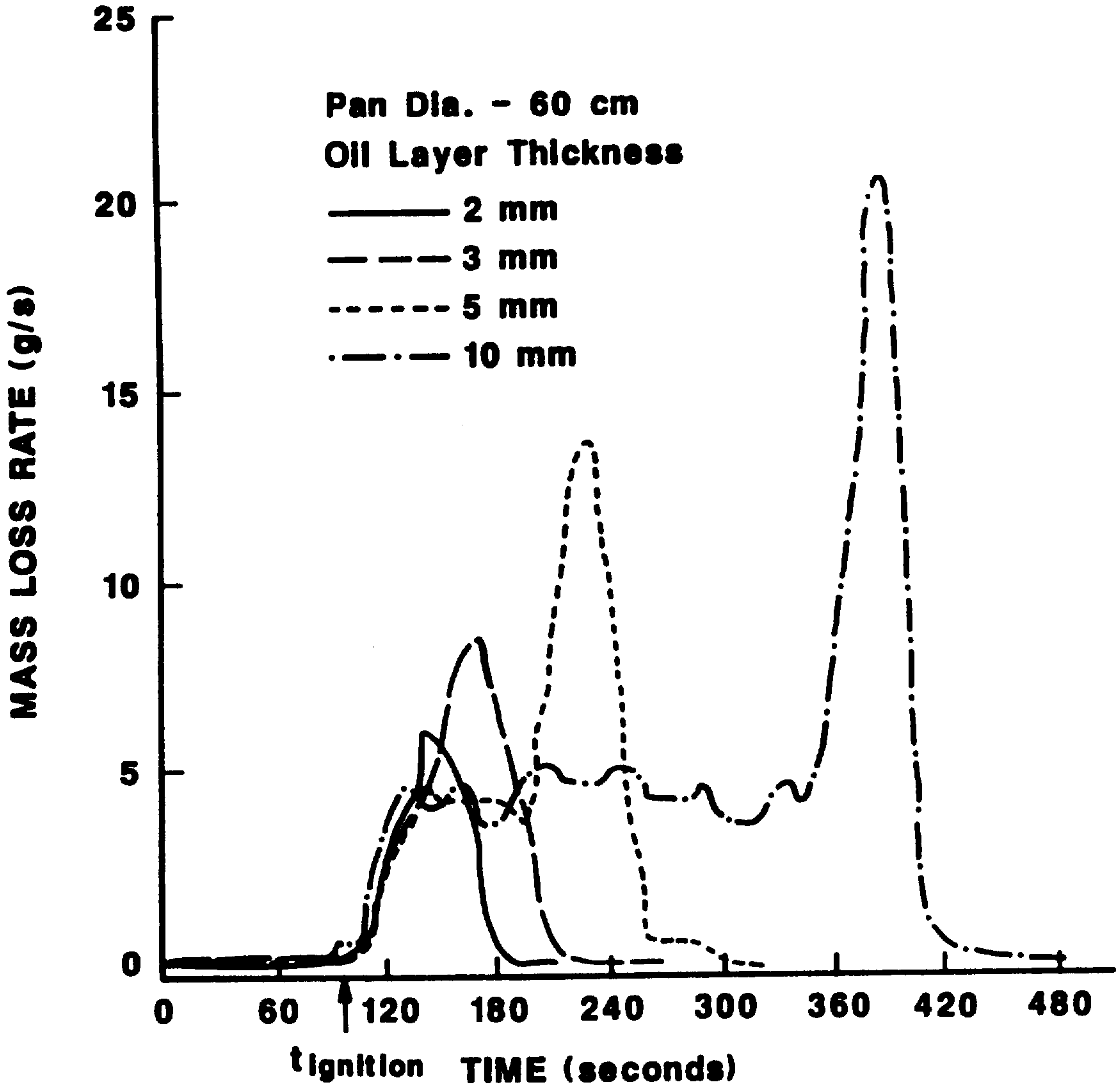


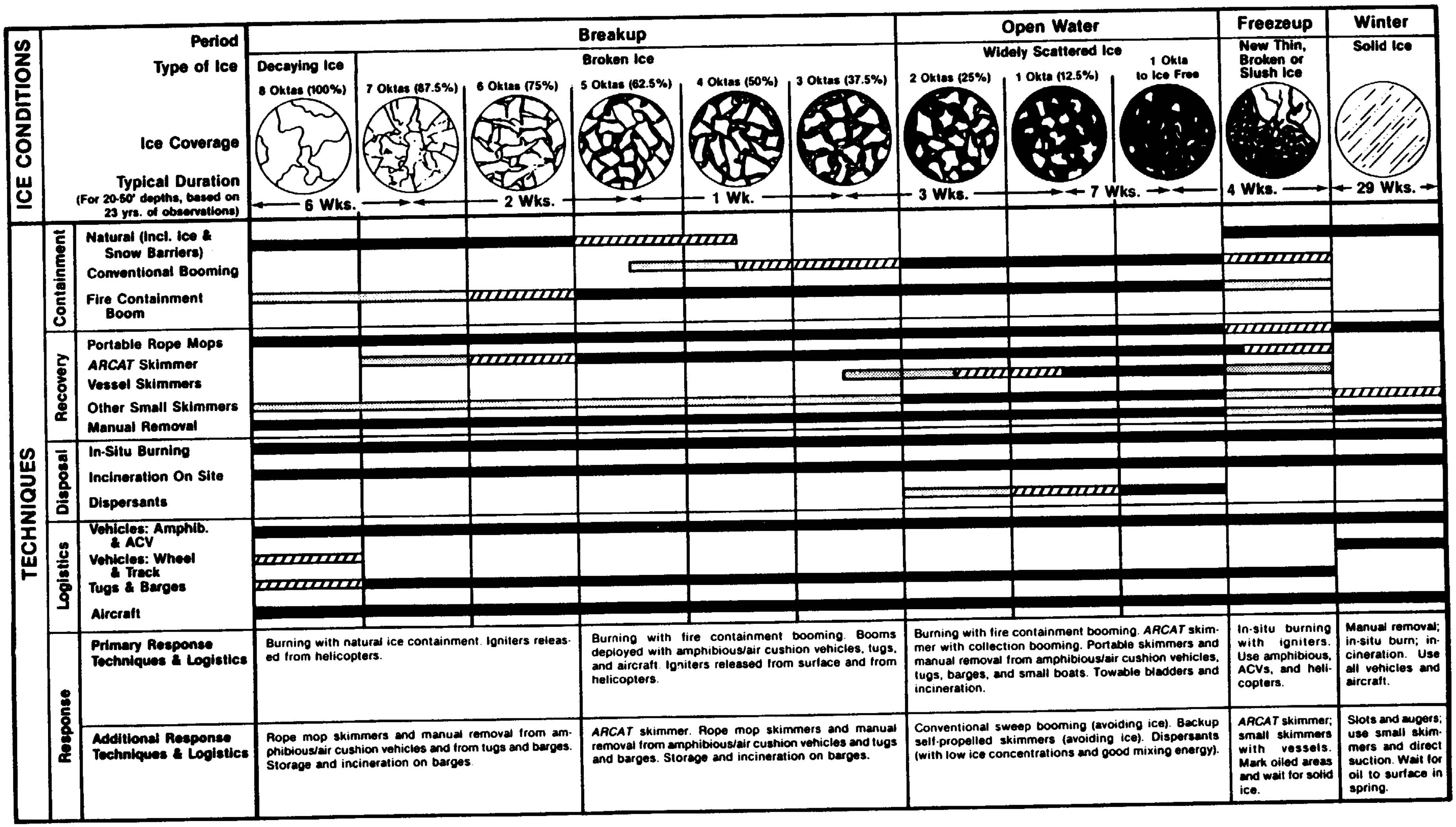
Figure 15 Effect of oil layer thickness on the mass loss rate history during burning

Appendix A

Applicability and Effectiveness of Burning as an Oil Spill Response Technique

Reproduced with permission from reference 1:

Oil Spill Response in The Arctic, Part 3: Technical Documentation, research administered by Shell Western E&P, Inc., Sohio Alaska Petroleum Company, Amoco Production Company, 1984.

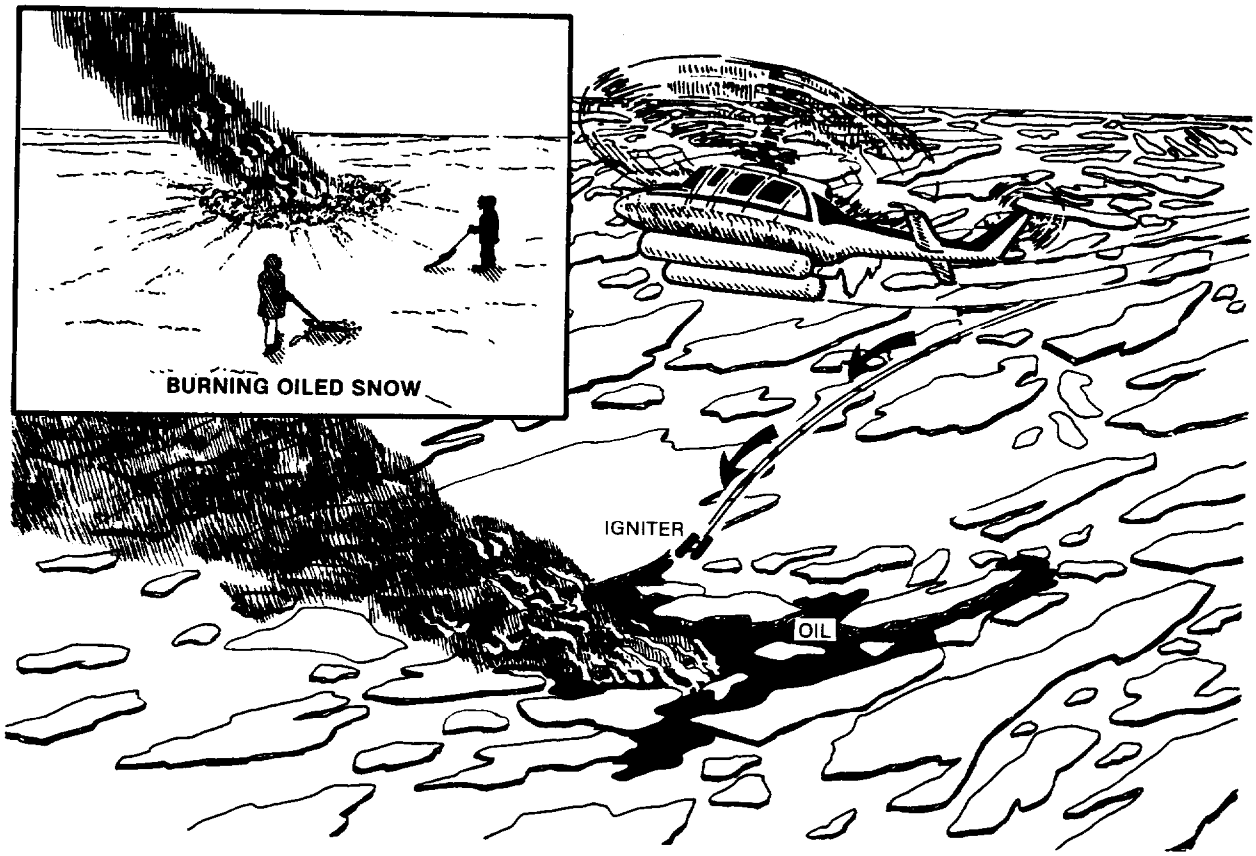


APPLICABILITY OF ARCTIC OIL SPILL RESPONSE TECHNIQUES

Good / Fair/Limited / Has Potential

NOTE: This chart is an updated version of the industry Task Group's applicability chart and is not to be confused with previous versions dated March 1983 and August 1983. This latest chart contains several revisions based on the demonstrations conducted by industry in the summer of 1983 and on subsequent evaluations by the Task Group.

IN-SITU BURNING WITH NATURAL CONTAINMENT



DESCRIPTION

Under the influence of wind, oil will tend to drift with a greater speed (and at times a different direction) than individual ice pieces. Oil released in a broken ice field, however, can be herded by natural effects into concentrations that can support in-situ burning. Oil will tend to accumulate in leads and cracks, it can be herded by the wind and be concentrated in or against tightly packed ice fields, and it can accumulate against the windward sides of large floes. Oil entrained in solid ice during the winter can migrate to the surface during the spring melt and accumulate in melt pools on the ice surface. In each of these modes of concentration, oil can be ignited by air-deployable igniters dropped from helicopters or, in some cases, from surface craft. Aerial monitoring of oil concentrations is essential to ensure that the heaviest and freshest oil is ignited as soon as possible. The proper government permits must be obtained for any burning of oil or oily debris.

APPLICABILITY

LOCATION			SURFACE CONDITION			
AT/NEAR SOURCE	BETWEEN SOURCE & SHORELINE	AT/NEAR SHORELINE	SOLID ICE	DECAYING ICE	PARTIAL/THIN ICE COVER	OPEN WATER
Good	Good	Good	Good	Good	Good	Fair/Limited

Good · Fair/Limited · Has Potential · N/A Not Applicable

IN-SITU BURNING WITH NATURAL CONTAINMENT

PERSONNEL

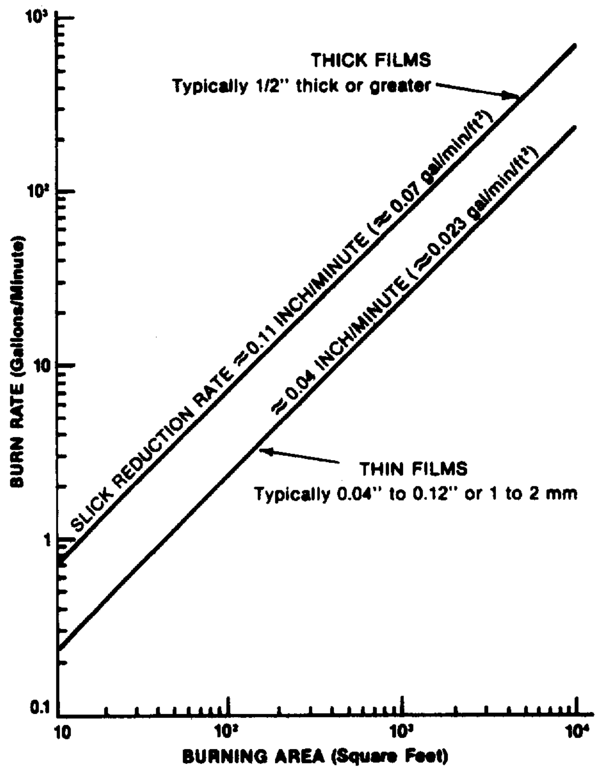
Personnel requirements minimal, normally involving 1 or 2 people for ignition/monitoring teams. Nature and distribution of individual oil pools will dictate the total number of ignition/monitoring teams.

EQUIPMENT

Helicopter(s)
Igniters (several per oil pool as backup)

PHYSICAL PARAMETERS

IN-SITU BURN RATE



- Monitor oil and weather conditions — allow wind to herd oil into concentrations (in leads or melt pools; against large floes, gravel islands, etc.).
- The thicker the initial layer of oil prior to ignition, the smaller the percentage of burn residue.
- Winds can increase the burn rate; however, higher winds will not appreciably improve the burn efficiency.
- Winds in excess of 20 mi/hr (≈37 km/hr) will make ignition very difficult and hamper combustion through excessive cooling of the fire.
- In-situ burning of oil/water emulsions is not normally practical.
- Aged, emulsified crude oil (>1 to 2 weeks exposure) can usually be burned but is difficult to ignite.
- Minimum thicknesses for ignition:
  ≈0.04 in. (1 mm) for fresh oil
  ≈0.12 in. (3 mm) for aged oil

NOTE: Use a burn rate of 0.11 in./min for thick oil concentrations (≥ 0.5 in.).

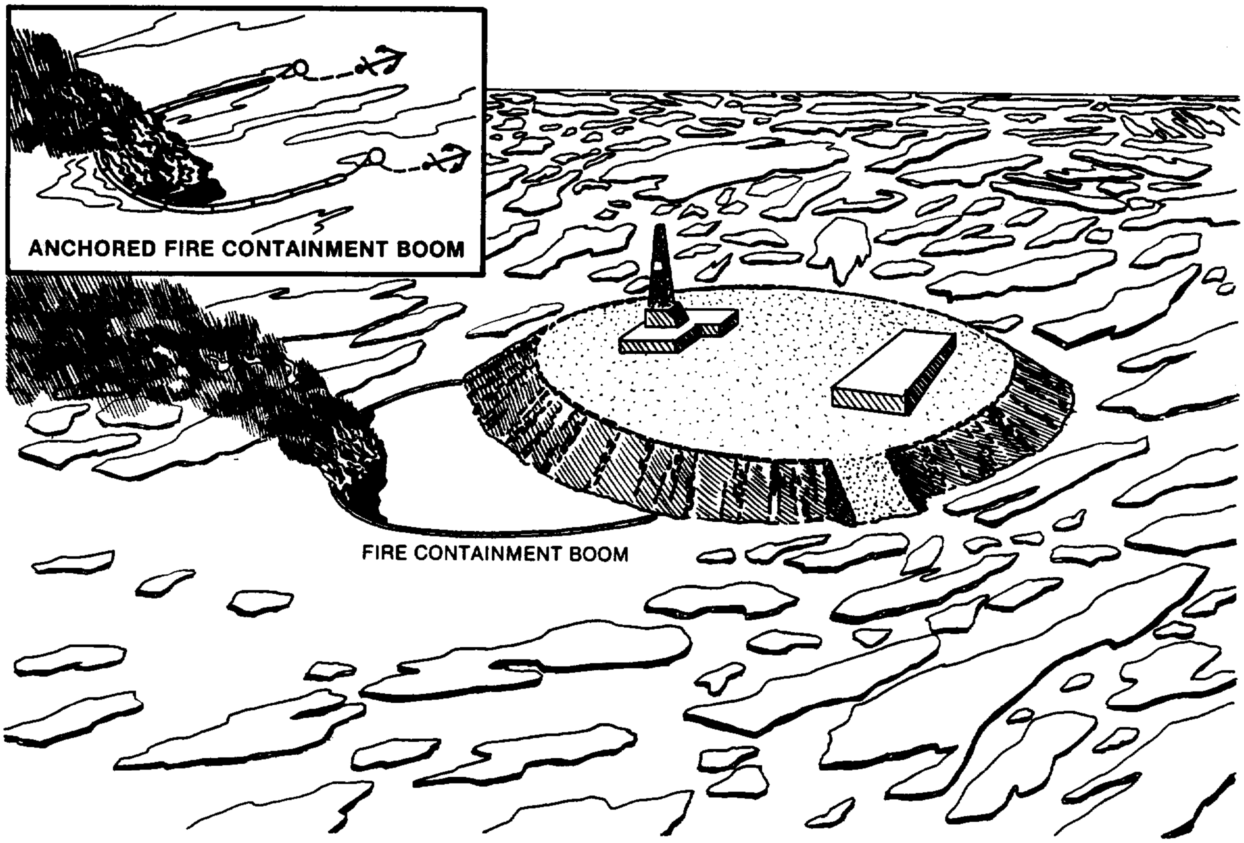
CONVERSION FACTORS

1 gal/min = 1.43 bbl/hr = 34.3 bbl/day
1 ft² = 2.296 x 10^{-5} acres = 9.29 x 10^{-2} m²
Oil at 0.1 in. thick = 41,400 bbl/mi² = 64.7 bbl/acre = 0.062 gal/ft²

RELATED TECHNIQUES

In-Situ Burning with Fire Containment Boom

IN-SITU BURNING WITH FIRE CONTAINMENT BOOM



DESCRIPTION

Fire containment boom can be used in several ways to provide concentrations of oil for in-situ burning. Two boats can tow the boom in a U-configuration to collect oil, and then the boom can be set adrift or anchored while the oil is ignited and burned in place. Fire containment boom can also be deployed in a free-drift mode among broken ice pieces by helicopters, air-cushion vehicles, or tugs to enhance natural wind-herding of oil for subsequent ignition.

If a blowout on a drilling island is ignited during heavy ice conditions, burning in the lee of the island can be enhanced with the use of fire containment boom. The magnitude of the blowout and the intensity of the burn will determine whether or not it is feasible or safe to deploy the boom in the lee of the island. Small-boat operations and/or boom maintenance by personnel on foot must not be attempted unless it is possible to avoid contact with the oil and to remain at a safe distance from all burning and potentially ignitable vapors and materials. Deployment of the boom with self-anchoring shoreline connections may be necessary using helicopters without ground support. Multiple or replacement booms would be deployed in the same way. The proper government permits must be obtained for any burning of oil or oily debris.

APPLICABILITY

LOCATION			SURFACE CONDITION			
			N/A			
AT/NEAR SOURCE	BETWEEN SOURCE & SHORELINE	AT/NEAR SHORELINE	SOLID ICE	DECAYING ICE	PARTIAL/THIN ICE COVER	OPEN WATER

Good Fair/Limited Has Potential N/A Not Applicable

IN-SITU BURNING WITH FIRE CONTAINMENT BOOM

PERSONNEL

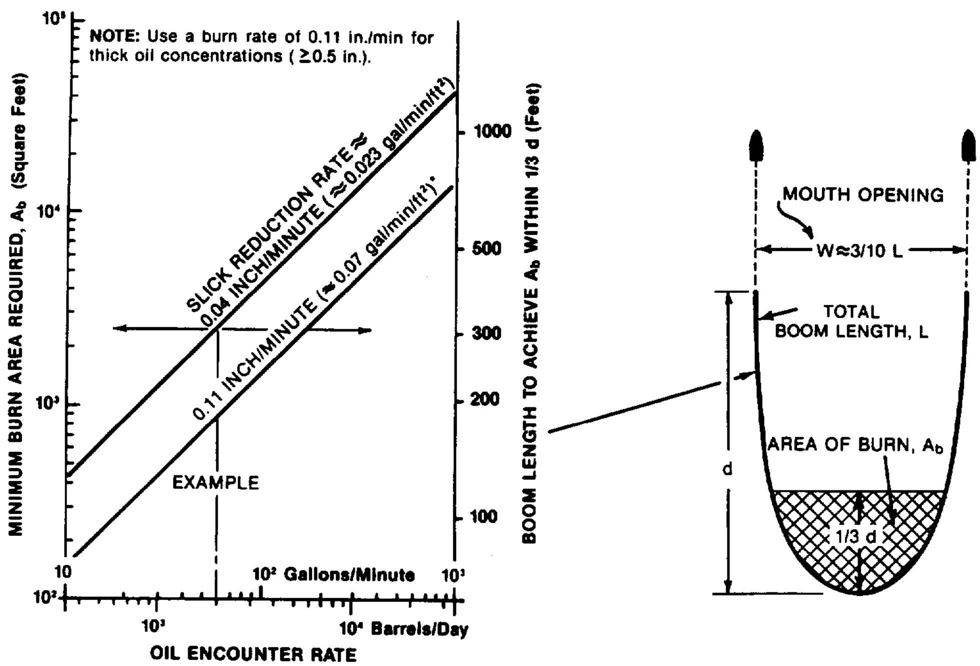
If fire containment boom is towed, a minimum of 1 operator and 1 crewman required per tow vessel. Boom deployment mode, nature of spill source, and variability of winds and currents will dictate the manning requirements during burn. Aerial spotter personnel may be needed for optimum positioning of the containment boom.

EQUIPMENT

Towboats
Fire containment boom (typically 200 to 400 ft)
Igniters, line, floats, anchors, etc.
Spotter aircraft

PHYSICAL PARAMETERS

BURN AREA/BOOM LENGTH VS. ENCOUNTER RATE



EXAMPLE: A U-boom configuration positioned downstream of a 2,000 bbl/day spill source would require a boom length of between 200 and 300 ft in order to provide the 2,500 sq ft needed for in-situ burning within the downstream third (1/3 d) of the boom area. The suggested mouth opening (W) in this example would be 90 ft. W could be increased, of course, depending on the approaching oil, the sea state, winds, and the desired burn concentration.

CONVERSION FACTORS

1 gal/min = 1.43 bbl/hr = 34.3 bbl/day
1 ft² = 2.296 x 10^{-5} acres = 9.29 x 10^{-2} m²
Oil at 0.1 in. thick = 41,400 bbl/mi² = 64.7 bbl/acre = 0.062 gal/ft²

RELATED TECHNIQUES

Containment Using Towed Boom Configurations
In-Situ Burning with Natural Containment

Appendix B

Case Histories of Attempts to Use Burning in Response to an Oil Spill

Reproduced from reference 5:

Thompson, C.H., Dawson, G.W., and Goodier, J.L., Combustion: An Oil Spill Mitigation Tool, U.S. Department of Energy, DOE/EV-1830-1, National Technical Information Service, Springfield, VA 22161, August 1979.

TORREY CANYON (March 1967)

Burning of the TORREY CANYON cargo was attempted after the ship had broken up. Attempts were made to light small oil slicks believed to be reasonably thick, using "oxygen tiles" (a pyrotechnic device containing sodium chlorate to provide an oxygen-rich flame). These attempts were unsuccessful probably because the highly flammable volatile fraction of the crude oil had already evaporated. Sodium chlorate devices were successful in igniting crude oil exuding from the ship. Bombing of the tanker with 1000-lb high explosive bombs produced fire in the tanker and in some surrounding patches. Aviation kerosene was jettisoned to feed the fires. Napalm bombs were also used to start fires. Approximately 160,000 lb of high explosives, 10,000 gallons of aviation kerosene, 3,000 gallons of napalm and several rockets were used in the burning operations.

ARROW (February 1970)

This Liberian-registered tanker spilled 16,000 tons of Venezuelan Bunker C fuel oil after it went aground in Chedabucto Bay, Nova Scotia. Environmental conditions at the time of the spill were: water temperature 0°C to 1°C; air temperature much lower, wind 40 to 50 mph, severe wave conditions and 100-foot water depth. A burn action was initiated using a wicking agent, "Seabeads." The product was used successfully on beaches and on isolated slicks in 1°C to 2°C water. Part of the spill was burned by using two drums of fresh oil and igniting them with "Kontax." Onshore oil deposits were ignited with napalm and a flame thrower and burned well.

OTHELLO AND KATELYSIA (March 1970)

Following a collision in Tralhavet Bay, Sweden, between 60,000 and 100,000 tons of Bunker C oil was trapped in packed ice. The extremely low water temperature excluded the use of dispersants, absorbents, and containment booms and this resulted in a decision to burn the oil. Following application from a tug boat of a combustion promoting chemical (Cab-O-Sil ST-2-O) a large quantity of the spilled oil was ignited and burned. The Cab-O-Sil chemical, now known as Tull-A-Nox 500, is a wicking agent composed of fine particles of fumed silica, surface treated with a silicone coating to render it hydrophobic.

The oil that was trapped in the ice was later burned after the thaw when the ice and oil separated. Some heavily contaminated ice was recovered with a grab bucket dredge and contained in barges until the ice thawed and the oil naturally separated and could be readily recovered.

U.S. COAST GUARD OIL SPILL TESTS (SUMMER 1970)

At Point Barrow, Alaska, the USCG conducted oil burning tests using 55 gallons of North slope crude for each test. Fresh and 6-day old crudes were ignited and burned well both on water and on ice. No difference in ignition and burning was noted when either glass beads or fumed silica burning agents were used. Environment conditions during the tests were: ice temperature, 0.3°C; water temperature, 1°C to 2°C; air temperature, 1°C to 4.8°C.

DECEPTION BAY, QUEBEC (June 1970)

Oil and gasoline that escaped from five bulk storage tanks damaged by a slush ice avalanche was burned in the Western Hudson Strait. This involved oil on ice and oil contained by near shore ice. The remaining oil was pumped onto the ice from the water and burned. All of the ice was eventually cleaned up by repeated burn actions.

ARGO MERCHANT (December 1976)

In this marine casualty, which occurred about 29 nautical miles southeast of Nantucket Island, Massachusetts, the USCG first attempted to burn the oil slick on December 27, 1976. Isolated boxes of Tull-A-Nox 500 charged with fuel were dropped from a helicopter and ignited with a timed thermite grenade. The isolated boxes burned but because of the lack of dispersal of the wicking agent, flame spread was not sustained and the burn was unsuccessful.

On December 31, 1976, at 1538 hours (16 days, 8.38 hours at the initial grounding of the vessel) an attempt was made to burn another slick originating from the stricken vessel. This slick was 90 ft by 120 ft in dimension, was elliptical in shape, of heavy tarry consistency, and 6 to 10 in. thick. The slick contained much debris such as 2 x 4s and other building material. As the vessel maneuvered alongside the slick the patch was broken up into several smaller patches. The Tull-A-Nox wicking agent was left in 11 plastic bags and was thrown on the slick near the center of a smaller 30 ft by 60 ft oil pancake. Some bags burst open on impact. Others were torn open with birdshot from a 12 gauge shotgun. In spite of the wicking agents advertised affinity for oil, its bulk density of 3 lb per cubic feet (comparable ash) allowed the wind to blow approximately 95% of it off the slick. As a result of the high loss rate of the initial 66 lb of wicking agent an additional 66 lb was charged with JP-4 and disbursed along the edge of the slick. It was very obvious at this stage that a continuous coating over the oil slick could not be obtained with the technique available. Sufficient wicking agent was dispersed to theoretically provide a 1/2 in. coating over the 30 x 60 ft oil pancake had 100% of it remained on the slick. Fifty-five gallons of JP-4 fuel were used to prime the slick.

Three cotton sheets were soaked in JP-4 and distributed on the slick. One was ignited using 30 minute railroad flares, and burned for 4 minutes. The heat source was insufficient to ignite the primer which was being mixed with water from the turbulence of the vessel. Unsuccessful attempts were made to ignite a wider region with flares. The demonstration was called off at this point.

The tests were deemed unsuccessful for the following reasons:

1. unable to disperse wicking agent without excessive loss (approximately 90%)
2. unable to main continuity of slick due to vessel propulsion turbulence
3. unable to sustain initial burn.

A total of 220 lb of wicking agent and 55 gallons of JP-4 aircraft fuel were expended on the burn test. The weather conditions during both burns were:

December 27, 1976 - winds 295 T/35 knots; seas 280 T/8 feet, barometer 29.58, visibility 2 miles with snow, air temperature 28 F.

December 31, 1976 - winds 350 T/5 feet, air temperature 30 F, visibility 3 miles and snowing.

BARGE B-65 (January 1977)

When this barge grounded in Buzzards Bay, Massachusetts, on January 31, 1977, two spills of No. 2 fuel oil, one of 10,000 gallons near the shore line and the other 5000 gallons were spilled offshore near the Cleveland Ledge Light. An attempt was made to burn the offshore spill that was crescent moon shaped and interwoven with floating ice. Sixty-six pounds of Tull-A-NOX 500 mixed with 12 gallons of kerosene, were dropped onto the slick from a helicopter flying at an elevation of 15 feet above sea level. Each bag of wicking agent was ignited by a 3 minute time delayed thermite fuse. Thirty minutes after ignition, forty-four pounds of wicking agent were dropped onto the spill. The oil ignited around each bag of wicking agent and two windblown flames ignited the surface slick for a distance of 35 ft from the ignition source. Some 2000 gallons of oil were burned in the response action.

AMOCO CADIZ

This incident posed a tremendous cleanup problem. Observers on scene indicated that burning was considered, but there was opposition expressed by local vegetable farmers.

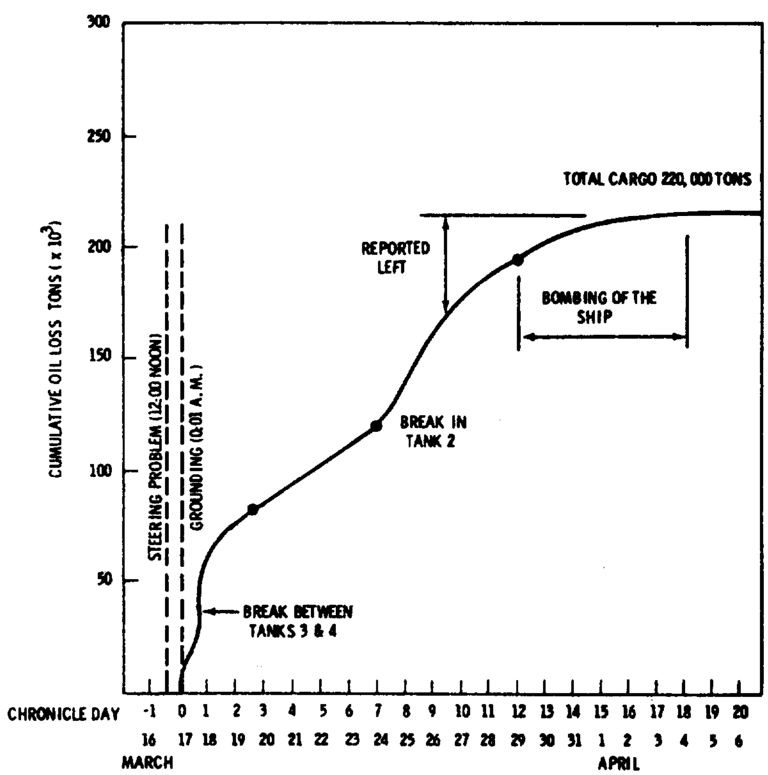


FIGURE B.1. Estimated Cumulative Oil Release from Amoco Cadiz Spill

Source: NOAA/EPA Preliminary Scientific Report, p. 233 Amoco Cadiz.

Those who were not in favor the burn because of soot fallout and tainting of crops found their crops tainted anyway by the intense hydrocarbon fumes moving inland from the contaminated shores. In time the ship was attacked by depth charges. Figure B.1 illustrates the events and shows the use of explosives on the ship. The intent of these bombing attempts was not to cause in situ burning, but are of interest to know that in 12 days the vessel was definitely regarded as a total loss and burning could then have been attempted without owner, etc. objectives. The owner was attempting throughout the incident's early days to locate pyrotechnic specialists.

NOTE: Comment

The evaluation of in situ burning also included consideration of the minimum amount of freeboard available (due to sea state) which rendered the opening of side vents unlikely. The paradox of the "last resort option" which burning is often considered is negated by conditions such as this. Burning without side vents has not been demonstrated, but may be practical when prevailing coastline winds create differential pressure at the deck surface. No responsible person can advise this last resort tactic without additional experience (after M.P. Holdsworth, August 24, 1978, personal communication).

KONTAX BURN TESTS

Successful oil burning was reported by the Dutch Government from tests conducted on July 1, 1969. These tests were conducted 25 miles at sea and on a beach. The tests were conducted on oil floating at sea simulating that resulting from a vessel collision. Studies were designed to ignite and burn confined oil floating at sea, to ignite and burn fresh and 12 hour weathered oil on a sandy beach. The oils involved were heavy and light Arabian crudes and test quantities ranged from 300 liters to 10 tons. The igniter material KONTAX was used in 25 kg plastic bagged form. The bags, being perforated on deck, were immediately tossed into the oil slick and upon contact with seawater caused extensive burning in the confined oil slick.

A 10 ton slick which was approximately 2,000 m^2, 0.5 cm thick and free fixation was created. The Kontax was jettisoned into the slick and spontaneous combustion began with very heavy smoke. Flames were reported by Dutch observers to be 15 to 20 meters high and convection currents were very strong to the point that nonburning oil was drawn to the fire. Estimates of 99% to 90% reduction of this slick were noted. Details of weather and sea state were given. Ignition of oil on the beach was successful even when the oil was deliberately mixed into the wet beach sand. By evaluating the Dutch report and the manufacturer's literature, it would appear that a ratio of 1:100 KONTAX to oil by weight is an appropriate combustion promoter addition.

Appendix C

Bibliography of Studies Relevant to Oil Spill Burning

The majority of citations are taken from the bibliographies in references 5 and 11:

Thompson, C.H., Dawson, G.W., and Goodier, J.L., Combustion: An Oil Spill Mitigation Tool, U.S. Department of Energy, DOE/EV-1830-1, National Technical Information Service, Springfield, VA 22161, August 1979.

and

Oil Spill Response in the Arctic, Part 1: An Assessment of Containment, Recovery, and Disposal Techniques, draft report prepared by Industrial Task Group representing Amoco Production Company, Exxon Company USA, Shell Oil Company, Sohio Alaska Petroleum Company, April 1983

Affens, W.A. 1967. Flammability Properties of Hydrocarbon Fuels. Part 3. Flammability of Hydrocarbon Solutions in Air. Naval Research Laboratory, NRL Report 6617.

Equations have been derived which make it possible to predict overall flammability properties of mixtures from the properties of the individual components.

Allen, A. and Simpson, W. 1986 "Alaska Clean Seas and Evaluation of Fire Containment Boom", Proceedings of the Ninth Annual Arctic and Marine Oilspill Program - Technical Seminar, Edmonton, Canada, June 10-12, 1986.

Four fire containment booms have been tested and evaluated for their resistance to fire during 24-hr. exposures to burning crude oil. Seven individual burn tests were conducted. The performance of each boom was documented on videotape, and temperature profiles were recorded for each thermocouple. The results of these tests are summarized along with an overall assessment of each system's physical and operational strengths and weaknesses. Included is a summary of several tests conducted to evaluate the oil-holding capacity and wave-riding characteristics of each boom. These tests were conducted with an without an oil stimulant in waves up to 0.6 m (2 ft) in height and with currents of 0.2 m/sec to 0.6 m/sec (0.4 kt to 1.2 kt).

Arthur D. Little, Inc. 1969. Combating Pollution Created by Oil Spills. Report to the Department of Transportation. NTIS AD 696 635.

The types, use, and effectiveness of wicking agents for oil slick burning are discussed. Slicks should be thicker than 1/4", freshly spilled, and in relatively calm water for successful burning.

Berridge, S.A. et al. 1968. "The Properties of Persistent Oils at Sea." Institute of Petroleum Journal, 54 (539):300.

This paper discusses physical, chemical, and biological processes on oil spills. Evaporation is the major process, biological degradation is insignificant. Mixing affects the extent and rate of removal. Burning agents on ice pool slicks did not affect burning rate, but changed the residue. Average burning rates were 3-5 gal/min, with thicker slicks burning faster.

Blinov, V.I. and Khudyakov, G.N. 1957. "Certain Laws Governing Diffusive Burning of Liquids," Institute of Energetics of the Academy of Sciences, USSR, Academia Nauk, SSSR, Doklady, 113:1094-1098.

This paper on the natural burning of liquid petroleum products in pans is especially significant because of the wide range of pan size covered (0.37 cm to 22.0 m) which was sufficient to block out clearly the various burning regimes. Liquid burning rates and flame heights were measured. Flame shapes also varied with pan size.

Blokker, P.C. "Spreading and Evaporation of Petroleum Products on Water." 4th International Harbor Conference.

Based on lab-scale experiments and physical deductions, a procedure was developed to calculate the rate of spreading and evaporation of oil spillage on water. Due to the cooling effect of the water, fire risks are present with only very volatile oils (gasoline, crude oil). Quantitative methods are described.

Blumer, M. 1972. "Oil Contamination and the Living Resources of the Sea." Marine Pollution and Sea Life. FAO, Fishing News (Books) Ltd. London, England.

Oil spill countermeasures - detergents, dispersants, mechanical removal and containment, biological degradation, and combustion are compared. Oil burning using wicks or oxidants is more attractive than sinking. Combustion promoters are necessary for complete oxidation.

Brown, H.M. and Goodman, R.H. 1986 "In Situ Burning of Oil in Ice Leads", Proceedings of the Ninth Annual Arctic and Marine Oilspill Program - Technical Seminar, Edmonton, Canada, June 10-12, 1986.

A series of experiments was carried out at the Esso Research ice basin in Calgary, Canada to evaluate the critical parameters of burning oil in ice leads. This may be a useful spill cleanup technique in the Arctic under certain conditions. Twenty-five test burns of Norman Wells crude were carried out to study the effect of wind herding, oil weathering, oil thickness, and lead geometry on burning efficiencies. Burning efficiencies of up to 90% were measured where moderate winds herded the oil into long narrow leads. Burning in other lead geometries was less efficient as was burning in the presence of brash ice. Weathering of the oil up to 20% did not significantly effect the burns.

Brzustowski, T.A. 1985. "Study of the Burning of Unconfined Oil Slicks", Transactions of the Canadian Society for Mechanical Engineers, v 9, n 4, p. 192-199.

A model is developed here to described the spreading and burning of an unconfined oil slick on water. In the model, the air flow into the flame induces a surface current on the water surrounding the slick. The current is directed inward toward the slick and inhibits its spread. It may be as high as 0.01 m/s, independent of slick size. The combustion efficiency (fraction of spilled oil burned) is calculated as a function of the volume of oil spilled (from 10^{-2} m^3 to 10^4 m^3) and of the time delay between the occurrence of the spill and the ignition of the slick. The slick cannot be ignited and will not continue burning if it is thinner than about 0.8 mm. It turns out that the combustion efficiency increases with increasing spill volume, and decreases with increasing delay time. There is a critical delay time beyond which combustion is quite uncertain. That critical delay depends only on the spill volume. In hours, it is of the order of 1/10 of the square root of the spill volume in m^3.

Brzustowski, T.A. and Twardus, E. M. 1982 "Study of the Burning of a Slick of Crude Oil on Water", Proceedings - 19th Symposium (Int'l) on Combustion in Haifa, Israel, August 8-13, 1982, Combustion Publication Institute, Pittsburgh, PA, p. 847-854.

Observations of the burning of a slick of fresh crude oil on water, including photographs taken from underneath the slick, have shown that the combustion is very violent for much of the burning time, with burning drops of oil ejected from the flame. At the same time, the slick is violently disturbed and considerable flame radiation is transmitted through it. The violent combustion appears to be the result mainly of eruptive vaporization of the light fractions of the crude. A simple model of oil slick burning is presented. It is one-dimensional and quasi-steady, and does not include liquid-phase processes. It does incorporate heat loss to the water substrate, initial absorption of radiation, decreasing as the slick burns, and the effect of wind on flame tilt and radiation heat feedback to the slick. The model predicts the minimum thickness for ignition, the unburned residue, the burning time, and the effect of wind on all three quantities.

Burgess, D. S., Strasser, A. and Grumer, J. 1961. "Diffusion Burning of Liquid Fuels in Open Trays," Fire Research Abstracts and Reviews, 3: 177-192.
This paper supports Blinov's and Khudyakov's findings that the burning rate above large pools is determined by the rate of radiative feedback from the flame to the pool of liquid. The paper also describes the effects of fuel temperature and wind on burning rate and suggests that burning rate may be predicted from the heat of vaporization and combustion of the fuel.

Castellucci, N.T. et al. 1972. Process for Burning a Combustible Liquid Using Cellular Ceramic Nodules. U.S. Patent 3661497.
Cellular ceramic nodules are spread on a combustible liquid and act as a wicking agent to sustain combustion.

Chemical Week, "Swedes Solve Oil Spill". April 15, 1970, p. 25.
Oil spilled from the tanker Othello was successfully burned using Cab-O-Sil ST-2-O. Because of the coldness of the waters and formation of ice-packs, use of dispersants, absorbents, or containment booms was impossible. Adding kerosene did not enhance burning.

Coupal, B. 1976. Controlled Combustion Tests Carried Out Near Rimouski. Environmental Protection Service, EPS-4-EC-76-2.
Combustion of oil (Ceuta Crude and Bunker C) on water with peat moss as a wicking agent and diesel fuel as a promoter was effective. Combustion efficiencies of up to 85% were achieved. Ocean burning tests are planned to include wave and current effects.

Day, T., Mackay, D., Nadeau, S. and Thurier, R. 1978. Emissions from In-Situ Burning of Crude Oil in the Arctic. Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada.
A postulated scenario defines the amounts of oil released, the size and number of burnable oil pools, and duration of burning. Estimates of soot, CO, SO_2, and metals emissions are based on literature and experiments. Downwind concentrations of combustion products are calculated using conventional plume dispersion equations with superposition of plumes in time and space from a number of burning pools.

Day, T., Mackay, D., Naudeau, S., and Thurier, R. 1978. Characteristics of Atmospheric Emissions From an In-Situ Crude Oil Fire, A Report Submitted to the Environmental Canada Environmental Protection Service in fulfillment of DSS Contract No. KE-204-7-EP 126.
Oil combustion characteristics relating to emissions, Arctic atmospheric conditions, effect on smoke plume dispersion, and possible oil compositions are discussed. Emission behavior during cleanup can be treated as a set of "unit burns". Soot, SO_2, CO_2, CO, hydrocarbon, and metal concentrations can be calculated with this dispersion model.

Eidam, C.L. 1975. "The Casco Bay Oil Spill: Problems of Cleanup and Disposal." Conference on Oil Spill Control and Prevention, API, Washington, DC.

Clean up for a 100,000 gal oil spill in semi-arctic conditions centered on removal from the vessel, the boomed area, and the bay. Rocky shorelines were cleaned with high pressure hot water hoses. Beach sand and oil soaked debris were burned and the residue buried.

Energetex Engineering. 1978. Combustion Promoters. Interim Report, Prepared for the Environmental Protection Service, Department of Fisheries and Environment, Canada.

This report describes combustion promoters and their past use and effectiveness for in-situ burning of oil slicks. The materials described are classified according to their effects on the oil layer. Detailed information on properties, cost, and availability is also discussed.

Energetex Engineering. 1978. Testing of Air-Deployable Incendiary Devices for Igniting Oil on Water. Draft Report available from R&D Division, Environmental Branch, Environmental Protection Service, Department of Fisheries and Environment, Canada. To be published.

Field studies document the definite feasibility of using air deployable incendiary devices to ignite contained pools of oil. Crude oil (Norman Wells) 3 and 10 mm thickness burned when solid propellant, solid fuel and Kontax igniters were either static or air dropped (11.5 m) using chemical, electrical, or fusewire starters. Advantages and limitations for each system are given along with future research recommendations and a concise theoretical explanation of hydrocarbon pool burning.

Energetex Engineering. 1978. Development of a Continuously Burning Wicking Device for Burning Oil Slicks. Draft Report available from R&D Division, Environmental Emergency Branch, Environmental Protection Service. Department of Fisheries and Environment, Canada.

A portable oil slick burner was designed, built, and tested using a wicking system and a gaseous fuel to be used on Arctic oil spills. Test model was designed to operate at one half U.S. gallons per hour and incorporated drip-feed wicking, time delay ignition, and water cooling barriers to affect heat transfer. It is reported that the units can be built for about $400.00.

Environmental Protection Agency. 1971. "Oil Pollution Control Technology." EPA Training Manual. NTIS PB 258600, p. 15-6.

Commercially available burning agents are tabulated. Wood and other debris caught in an oil slick are not too effective as wicking agents to start or sustain a fire. Oil can be burned if suitably thick, 5 mm.

Environmental Quality Systems. 1972. Waste Oil Recovery Practices. Maryland Environmental Service. p. 29.

Tabulated data of crude oil characteristics and analytical breakdown are compiled. API gravity, sulfur content, initial and end boiling points, and viscosity data are included. Data is also given for contaminated beach samples.

Evans, D., Baum, H., McCaffrey, B., Mulholland, G., Harkleroad, M., and Manders, W. 1986 Combustion of Oil on Water, NBSIR 86-3420, US National Technical Information Service, Springfield, VA 22161.

This report contains the results of measurements performed on both 0.4 m and 0.6 m diameter pool fires produced by burning a layer of Prudhoe Bay crude oil supported by a thermally deep layer of water. Both steady and vigorous burning caused by boiling of the water sublayer were observed. The measured energy release rate for steady burning was about 640 kW/m^2. The emission rate, the size distribution, and specific extinction coefficient were measured for the smoke aerosol produced by the fires. Data were also obtained on the structure of the smoke aerosol by electron microscopy and on emission of CO and CO_2. Analysis of the crude oil burn residue indicated selected depletion of the short chain alkanes and cyclo alkanes when compared to the fresh oil.

Evans, D., Mulholland, G., Gross, D., Baum, H., and Saito, K. 1988. Environment Effects of Oil Spill Combustion, NISTIR 88-3822, US National Technical Information Service, Springfield, VA 22161.

Experimentation and analysis have been performed to quantify the combustion of crude oil on water. The burning behavior of three crude oils -- Alberta Sweet, La Rosa, and Murban, were studied using 1.2 m diameter pool burns. In smaller 0.6 m diameter pool fires using Alberta Sweet, combustion products were collected for extensive chemical analysis. This analysis showed that about 10% of the crude oil was converted to smoke in the combustion process. The CO concentration was a factor of 25 lower than the primary gaseous product CO_2, and the emission of NO and NO_x were less than one thousandth the concentration of CO_2. The PAH content of the smoke was enriched in the larger molecular weight species in comparison with the original fuel. A methodology was developed with which the downwind dispersal of smoke generated by one or more oil spill fires in close proximity may be predicted. Initial results that demonstrate the capability of the analysis are presented.

Freiberger, A. 1971. "Burning Agents for Oil Spill Cleanup." Prevention and Control of Oil Spills, API, Washington, DC, p. 245.

Currently available commercial burning agents are described with documented field test results and case studies. Containment is necessary for efficient burning. Primary effort is in developing igniters for the applied burning agents and reducing air pollution effects. Floating incinerators to contain, ignite, and reduce emissions from oil spills are currently being studied.

Gainer, G. and Mackay, D. 1976. "Burning of Oil," The Impact of Oil on the Freshwater Environment, Proceedings of a Workshop on Canadian Research Priorities, Publication No. EE2 of the Institute of Environment Studies, University of Toronto, Oct. 20-22.

A burner has been field tested that burns oil-contaminated materials like straw, moss, or wood. On ice, snow, or saturated ground, burning oil causes little environmental damage. This talk mainly outlined research needs in oil burning.

Gilmore, G.A. 1970. Analysis of Oil Spills and Control Materials, API, Marine Management Service, Washington, DC.

This contains a brief description of Cab-O-Sil Pyraxon application as combustion promoters. Burning is a viable option where temporary air pollution is not a significant problem and there is no fire danger to the surrounding environment.

Glaeser, J.L. and Vance, G.P. 1971. A Study of the Behavior of Oil Spills in the Arctic, Coast Guard Report. NTIS AD 717 142.
This Arctic study includes data on spreading behavior of crude oil on ice and water surfaces, interaction of oil and ice, aging characteristics of oil, and effectiveness of burning and absorption for removal. Ninety to ninety-eight percent removal was achieved without burning agents at a rate of 4.5 gal/min.

Glotin, B. 1969. "The Disposal of Oil Produced During Offshore Well Tests on Wildcats Without Facilities," Offshore Technology Conference, Paper No. 1084, 2:133.
An oil-burning device has been developed for burning polluted oil on a drilling barge. Offshore well tests then can be conducted where no other oil disposal capacity exists. The burner is designed to protect the platform from the heat given off during combustion.

Hall, A.R. 1972. Pool Burning: A Review. Rocket Propulsion Establishment Technical Report 72/11.
This review covers literature on fundamental aspects of the combustion of liquid fuel at a free surface, including 1) influence of atmospheric conditions, fuel properties, container diameter, and partial venting on burning characteristics; 2) temperature distribution in the liquid; 3) heat transfer from flame to liquid; and 4) effect of water on burning.

Haroy Associates. 1978. A Preliminary Assessment of Beach Cleanup Techniques: A Quasi-Laboratory Assessment. Draft Report available from R&D Division, Environment Emergency Branch, Environmental Protection Service, Department of Fisheries and Environment, Canada.
This study evaluated the effectiveness of burning and sorbent techniques for cleaning off oil contaminated beaches in northern regions. The type of burn achieved, depth of penetration of oil, and amount of residue left were determined. Crude oils were used on fine gravel, sandy and mud flat beach soils. Twelve conclusions given relate to adequacy of burn being dependent upon an oil's ability to maintain a surface film as it penetrates the soil and reflooding to bring oil to surface was observed as not effective.

Hellman, H. and Marcinoroski, H.J. 1972. Experiments on Combating Accidental Release of Oil. Marine Pollution and Sea Life, FAO. Fishing News (Books) Ltd. London, England.
Emulsifiers and dispersant chemicals are generally not recommended because of pronounced toxic effects on marine life. Burning provides a viable option where the air pollution concerns are not as significant as water-land pollution. An alkali-metal carbide mixture enhances oil burning.

Herschmiller, D.W. and Revel, R.D. 1974. "Terrestrial Spillage of Oil in the Arctic," Water-1974: I. Industrial Wastewater Treatment, AIChE Symposium Series, Vol. 70.
Based on selected ecological considerations and environmental parameters, the applicability of oil spill technology to Arctic spills is presented. Contingency plans are developed. Burning is viewed as a fast, low cost alternative. Research needs are discussed.

Hillstrom, W.H. 1970. Ignition and Combustion of Unconfined Liquid Fuel on Water. Ballistic Research Laboratory Project No. 1T061101A91A. NTIS AD716578.

Activated carbon is used to enhance burning by forming an aggregated structure within the fuel lens and acting as a wick to draw the oil to the surface. A dose of 3-25% by weight was effective for different oils. Spreading coefficients for crude oil components are tabulated.

Holdsworth, M.P. 1968. "Control of Accidental Oil Spillage at Sea," Pollution Prevention, The Institute of Petroleum, The Elsevier Publishing Co., Ltd., London.

The author overviews ways to minimize tanker spillage and means of controlling oil spilled on the sea surface. The burning of both unrecoverable cargo in-situ and oil on the sea surface are briefly discussed. The author concludes that the burning alternatives are impractical.

Jerbo, A. Clearance of Oil from Frozen Rivers and Lakes, presented at the British Petroleum Arctic Conference.

The paper dealt with the methods used in Sweden to combat oil spills. Oil adsorbents, trawl nets, oil booms, and burning were mentioned. All compounds in oil do not burn; the residue may be more harmful than the oil itself. Phenols may be formed by combustion.

Koblanski, J. 1985. "Design Improvements in a Sonic Burner for the In Situ Combustion of Oil Spills", Proceedings - 1985 Oil Spill Conference (Prevention, Behavior, Control, Cleanup), Los Angeles, CA February 25-28 1985, API, Washington DC, p. 643.

Design improvements have been made in the Ocean Ecology sonic burner for removing oil slicks in situ. These improvements result in an increase in combustion efficiency, better control of the burn, and rapid ignition in extremely cold air and water. Automation and remote control have also been incorporated. Analysis of total input and output of the burner greatly aided in these improvements. Design was further modified to accommodate a fireproof boom. This small draft boom of superior design is extremely suitable for the Ocean Ecology system of in-situ burning. The results show that such viscous oils as No. 6 fuel oil can be easily combusted in areas as cold as the Beaufort Sea.

Kretschmer, D. and Odgers, J. 1985. "Combustibility and Incineration of Beaufort Crude/Seawater Emulsions", Proceedings - 1985 Oil Spill Conference (Prevention, Behavior, Control, Cleanup), Los Angeles, CA February 25-28 1985, API, Washington, DC, p. 19-23.

The use of certain incinerator to dispose of materials recovered from an oil spill was investigated for the Alaskan Beaufort Sea Oilspill Response Body (ABSORB). A series of combustion experiments was conducted in a prototype incinerator. Combustion rates, emissions, and temperatures were monitored during the experiments. Operating variables investigated included air flow rate, direction of air into the combustion chamber, waste feed rate, water spray over the combustion zone, and the slant of the combustion chamber's front wall.

Kruk, K.F. 1983. "Air Curtain Incineration Tests", Proceeding - 1983 Oil Spill Conference (Prevention, Behavior, Control, Cleanup), San Antonio, TX, February 28 - March 3, 1983, API, Washington, DC, p. 33-38.
The prototype incinerator (10'x10'x14') was able to burn pure oil, emulsions, and oil debris at "practical rates with low emissions" (p. 38). The system, which will be helicopter-transportable and capable of being field-assembled in less than one day, performed well at combustion rates exceeding 600 barrels per day. Oil with 20% to 30% water burned most efficiently.

Lamp'l, H.J. 1969. "Beach Cleanup." Prevention and Control of Oil Spills. API, Washington, DC, p. 229.
State-of-the-art beach cleanup is discussed briefly. Physical removal methods are most acceptable, as detergent or dispersant chemicals further contaminate the beach and in-situ burning is stated to be impractical. Future projects include portable incineration systems and froth flotation techniques.

"Licking the Oil Slick", 1970. Mech. Eng., v 92, n 6, p. 51.
The Cabot Corporation in Boston has developed a silica compound that can be applied in dry powder form to floating slicks. The chemical acts as a wick,drawing up oil by capillary action, insulating it from the lower temperature water, thus permitting combustion. Up to 98% of slick can be thus burned. The remaining 2% forms a hard floating crust that can be easily collected. The chemical has no known toxic effect on marine life or shore birds.

Logan, W.J. 1976. "EEB Activities in Arctic Oil Spill Countermeasures." Spill Technology Newsletter, I(4):15.
The feasibility of in situ burning to remedy oil spillage problems in the Southern Beaufort Sea is considered. Conventional equipment (i.e., booms and skimmers) can be used only in calm and light wind and wave conditions with less than 10% ice infestation. Burning can remove 90% of the oil without promoters and studies are underway to determine what substances may ease cleanup of burnt residues.

Lowthian, J.W. 1977. "Oil Spill Cleanup in the Beaufort Sea - Another Viewpoint." Spill Technology Newsletter, II(3):33.
The probability of a successful, complete burn is low because of the expected film thickness and the current state of ignition technology. The logistics of delivering igniters to many areas are also a problem.

Mackay, D., Day, T., Nadeau, S., and Thurier, R. 1979. "Emissions from In Situ Burning of Crude Oil in the Arctic", Water, Air, and Soil Pollution, 11(2), p. 139-152.
The effects of oil spill burning on air quality in the Beaufort Sea region of the Arctic are discussed. A scenario is postulated defining the amounts of oil released, the size and number of burnable oil pools, and the duration of the burning period. Estimates are made of the likely emissions of soot, CO, SO2 and metals based on literature and some experimental work. Assumptions are made about plume rise and dispersion which permit downwind concentrations of emissions to be calculated and compared with air quality on objectives. Although the calculated concentrations may contain significant error because of the many assumptions, the data demonstrate that concentrations of SO2 and CO will be acceptably low; concentrations of soot and metals will often be undesirably high within 10 km of the fires, but will

be acceptably low at greater distances. Burning may be a method of substantially reducing the adverse environmental impact of oil spills in the Arctic.

Magnus, G. 1959. "Tests on Combustion Velocity of Liquid Fuels and Temperature Distribution in Flames and Beneath Surface of the Burning Liquid." (International Symposium on) the Use of Models in Fire Research, sponsored by The Committee on Fire Research, The Fire Research Conference, National Academy of Sciences, Washington, D.C., Nov. 9-10.

Tank fires of various sizes were studied. Effects of wind velocity, air temperature, humidity, and barometric pressure were noted. The specific burning rate of the liquid fuels was found to increase with surface area. Flame temperatures were measured within the tanks and were found to vary with liquid level and fire size.

Masliyah, J.H. and F.R. Steward. 1969. "Radiative Heat Transfer from a Turbulent Diffusion Buoyant Flame with Mixing Controlled Combustion," Flame, 13:613-625.

A mathematical model of a turbulent buoyant diffusion flame is used to calculate the radiative emission from the flame. Burning rates of a liquid fuel can be predicted from the radiative heat flux.

Maybourn, R. 1971. "The Work of the IP Working Group on the Burning of Oil," Journal of the Institute of Petroleum, 57(553).

This group concentrated mainly on problems associated with burning oil in situ in a tanker and on the sea surface. An igniter is necessary to start the burning. Residues of 15% or more of the original quantity of oil will remain.

Mayo, F. 1968. "Dealing with Oil Pollution on Water and Shores", Pollution Prevention, The Institute of Petroleum, The Elsevier Publishing Co. Ltd., London.

The paper discusses the proved methods of dealing with oil on inshore waters: dispersion, absorption, entrainment, and removal with mechanical devices. Burning does not seem to be effective unless suitable catalysts or oxidants can be developed.

McLean, A.Y. 1972. "The Behavior of Oil Spilled in a Cold Water Environment," Offshore Technology Conference, paper #1522, 2:129.

This paper deals with the way oil interacts with the cold water environment and the effect of these interactions on clean-up techniques.

McMinn, T.J. and Golden, P. 1973. "Behavioral Characteristics and Cleanup Techniques of North Slope Crude Oil in an Arctic Winter Environment." Prevention and Control of Oil Spills, API, Washington, DC, p. 263.

This paper deals with the physical fate and behavior of crude oil (spreading, aging, interactions with environment, effectiveness of cleanup) when spilled on ice and snow. Oil can be easily ignited with kerosene-soaked rags on snow and ice if the spill has not been snowed upon. Burning agents had no effect. Oil burning on ice is more successful than on snow (95% vs 80%).

McMinn, T.J. 1973. Crude Oil Behavior on Arctic Winter Ice, United States Coast Guard Project 734108. Washington, D.C. NTIS AD-754, 261.

The burning of oil on ice and snow is discussed. Under conditions of limited snowfall and wind velocity below 14 knots, 80% of spilled petroleum can be burned without promoters. Three burning agents, silicate beads, asbestos powder, and powdered calcium carbonate were determined to be of no benefit in Arctic burning conditions. If Arctic oil is not removed, it will become sandwiched in the ice cover only to thaw in the summer months.

Meikle, K.M. 1977. "Design and Development of Equipment to Aid in the Burning of Oil on Water", Spill Technology Newsletter, Sept/Oct 1977.

Two equipment ideas have been suggested to aid ignition, containment, and support of oil combustion on water. One is a buoyant net which would trap oil in its mesh, allowing it to be contained, ignited and burned in the net's openings. The other is a lightweight fireproof boom to contain the oil. Both could be used simultaneously.

Menagie, H.M. 1970. Kontax Burning Experiments, Water Control Division - Hook of Holland, Ministerie van Buitenlandsezaken Afdeling Vertalingen.

Kontax is a chemical that ignites spontaneously when spread on water. Both beach and open water burn testing results are reported here.

Modak, A.T. 1978. "Radiation From Products of Combustion," prepared for Factory Mutual Research, FMRC J.I OAOE6.Bu-1, RC 78-BT-28, October 1978. Presented at the Eastern Section Meeting of the Combustion Institute, Miami Beach FL., Nov. 29, 30 and Dec. 1.

This report presents simplified calculations and a computer program for radiative energy transfer in fires. Radiation from soot particles, carbon dioxide, and water vapor is the primary form of heat transfer in large fires. The radiative properties of these components exhibit very rapid variations with respect to the wavelength of radiation. These simplified calculations agree well with the more detailed and exact spectral calculations.

O'Rourke, C. 1976. "Oil Spill Cleanup in the Beaufort Sea." Spill Technology Newsletter, I(6):12.

This report by Canmar, a Canadian oil drilling firm, discusses contingency plans in the event of an oil well blowout. Ignition of the plume and containment of the burning oil is a primary cleanup measure. Non-emulsified heavy oils burn readily without promoters in the Arctic waters. Studies are underway to improve ignition techniques and fireproof booming.

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.

Both point and area-source flames and line fires were exposed to cross winds to study free-burning fire modeling. With point and area-source flames, the flame height decreased slowly when initially exposed to the cross wind but decreased rapidly when the cross wind velocity increased. Experimental observations were related to the Froude number.

Ross, S.L. 1975. "Oil Spill Technology Development in Canada," Conference on Prevention and Control of Oil Spills, API, p. 329.

The organization and activity of the Canadian Environmental Emergency Branch is detailed. Burning is considered a promising option of cleanup of oil spills, particularly in Arctic conditions. Canadian spillage data is tabulated for the years 1971-73.

Smith, C.L. and MacIntyre, W. 1971. "Initial Aging of Fuel Oil Films of Sea Water," Prevention and Control of Oil Spills Conference Proceedings, API, Washington, DC, p. 457.

Evaporation and dissolution are the main mechanism of initial weathering. Rates of evaporation and relative importance of evaporation and dissolution for oil components are reported. During initial weathering, the rate of evaporation (by weight) is proportional to the percentage of volatile components.

Smith, N. K. and Diaz, A. 1985. "In-place Burning of Prudhoe Bay Oil in Broken Ice", Proceedings - 1985 Oil Spill Conference (Prevention, Behavior, Control, Cleanup), Los Angeles, CA February 25-28 1985, API, Washington, DC, p. 405-409.

Small-scale and large-scale experiments were performed at the U.S. Environment Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility to explore the range of conditions in which oil slicks of Prudhoe Bay crude can be burned in broken ice and to determine the efficiencies of such burns. In laboratory experiments, the minimum slick thickness supporting combustion was found to be 2.5 mm on brackish water at temperature from 2 Degree to 6.5 Degree C. Four burn tests were performed in the OHMSETT tank with varying ice cover, volume of oil, and wave conditions. Study results are reported.

Struzeski, E.J. 1969. "Chemical Treatment of Oil Spills." Prevention and Control of Oil Spills, API, Washington, DC, p. 217.

The latest technical information is presented on the applicability and effectiveness of the chemicals and materials available for preventing and controlling oil spills. Special emphasis is on absorbing and gelling oil on the surface sinking oil, and burning it on open waters and shorelines. Burning is attractive and inexpensive for slicks thicker than 3 mm. FWPCA testing in 1969 is discussed.

Tam, W.K. and Purves, W.F. 1980. "Experimental Evaluation of Oil Spill Combustion Promoters", IEEE, Piscataway, NJ, p. 415-421.

Three petroleum fractions were burned floating on water in confined and unconfined layers, at two thicknesses and in various wave and ice conditions. Ten promoter materials were screened in an effort to improve the ease of ignition and the completeness of the burns. The test results continue to suggest that in-situ burning is a promising oil spill response technique.

Thornton, D.E. 1977. "Testing of Air-Deployable Incendiary Devices for Ignition on Water," Spill Technology Newsletter, Sept/Oct.

Incendiary devices and wicking agents are being developed for burning all spills on ice and snow.

Tom, G., and Purves, W.F. 1979. An Experimental Evaluation of Spill Burning Promoters. Draft Report available from R&D Division, Environmental Emergency Branch, Environmental Protection Service, Department of Fisheries and Environment, Canada.

A total of 395 combustion experiments were conducted in outdoor tanks during the winter of 1978. The program covered ten combustion promoters, three types of oil and two oil thicknesses. The ignition method was proved inadequate for Bunker C oil. Aged crude oils were burned both on water, in the presence of slush ice, in waves and under unconfined conditions. Test results continue to commend that in-situ burning is a promising method of disposing of Arctic oil spills. .

Tully, P.R. 1969. "Removal of Floating Oil Slicks by the Controlled Combustion Technique, Oil on the Sea," Proceedings of a Symposium on Oil Pollution of the Sea, Sponsored by MIT and Woods Hole, Cambridge, Mass.

Cab-O-Sil is recommended as an effective wicking agent that contains oil burning to a specified area. Burning with fumed silica (Cab-O-Sil) is effective with slicks down to 2 mm thick.

Twardus, E.M. 1979. A Study to Evaluate the Combustibility and Other Physical and Chemical Properties of Aged Oils. Draft Report available from R&D Division, Environmental Emergency Branch, Environment Protection Service, Department of Fisheries and Environment, Canada. DSS File No. 03SS, KE204-8-1011.

Oil aging and the formation of water in oil emulsions were studied in Arctic spring conditions using Bunker C, marine diesel, and six crude oils. The igniter systems used demonstrated that these oils could be burned if oil thickness were 3-6 mm up to 4 weeks after release, except Bunker C which needed 10 mm combustion of without emulsions was reported possible, 20% water easily ignited with higher water content being harder to ignite, but once fully developed, combustion of w/o emulsion was very intense except for w/o emulsions which tended to foam.

Vaux, W.G., Weeks, S.A. and Walukas, D.J. 1971. "Oil Spill Treatment with Composted Domestic Refuse," Prevention and Control of Oil Spills, API, Washington, DC, p. 305.

The use of compost made from domestic refuse as a sorbent and combustion promoter is discussed. The material is readily available but only moderately effective. Burning is discouraged because of the sooty smoke and incomplete combustion.

Walkup. P.C. 1970. Oil Spill Treating Agents: Test Procedures: Status and Recommendations, Battelle, Pacific Northwest Laboratories.

This section discusses evaluation techniques and comparison parameters for combustion promoters. Surface disturbances, application techniques, product type, temperature and size of spill must all be addressed in a complete analysis. The dosage ratio, completeness of burning and residue removal, as well as flame stability are factors to be considered.

Warren Springs Laboratory. 1976. "UK Oil Clearance Techniques and Equipment", Petroleum Times, April 30, 1976.

This article briefly overviews burning, sinking, absorbing, physical containment, and dispersing as oil spill mitigation techniques. Burning oil on water is considered to be generally ineffective. More attention is focused on dispersants, both on water and land.

Water Quality Laboratory. 1969. Chemical Treatment of Oil Slicks. Edison, New Jersey. NTIS PB 185947.

The effectiveness and potential pollution effects of chemicals and other materials used to disperse, sink, burn, or otherwise dissipate oil slicks are discussed. Burning is inexpensive and appears feasible using proper wicking agents which increase burning surface area and insulation from the water heat sink. Controlling the burning oil mass, ensuing air pollution, and disposal of residue appear to preclude the use of this course of action except in those situations where the oil is sufficiently distant from the shore and off-shore facilities.

Water Quality Office, EPA. 1970. Feasibility Analysis of Incinerator Systems for Restoration of Oil Contaminated Beaches, 15080 DXE 11/70. B5.

This article recommends using a three-stage rotary furnace to cleanse beach sands. A cost analysis is included. This report includes oil-water-sand thermodynamic data and spill experience. Burning oil pools and residues in coastal areas by torching or explosion was unsuccessful.

Westree, B. 1977. Biological Criteria for the Selection of Cleanup Techniques in Salt Marshes, Conference on Oil Spills, API, p. 231.

Spill cleanup in salt marshes may cause more damage than the oil itself. Techniques for cleanup were compared to the behavior of uncontained oil in the marsh and the potential for damage evaluated. Burning can be used in Sparatina marshes.

Woinsky, S.G. 1972. "Predicting Flammable-Material Classifications," Chemical Engineering, Nov. 27, 1972.

Flammable-material classifications are used in selecting explosion-proof electrical equipment. This paper presents a method for predicting the classifications for single components and mixtures.

Woodyard, D. 1970. "Oil Slick Destroyed by Burning", Oceanology Intl.

A spill of Bunker C oil was successfully burned at sub-freezing temperatures with the aid of wicking agent. The fumed silica wicking agent is non-toxic to marine life, immune to the heat of an oil fire, and can induce a 90% oil burning efficiency.

Yumoto, T. 1971. "Heat Transfer from Flame to Fuel Surface in Large Pool Fires," Combustion and Flame, 17:108-110.

This study experimentally determined the ratio of radiation and convection transfers to total heat transfer from the flame to the fuel surface. This work was done in the heat transfer range where burning rate has a constant value regardless of pan diameter. The burning rate was found to be mainly dependent on radiation.