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Combustion: An Oil Spill Mitigation Tool

August 1979

Published November 1979

U.S. Department of Energy
Assistant Secretary for Environment
Office of Environmental Compliance and Overview
Division of Environmental Control Technology

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16. Abstract

The need for this study was based upon: a) the lack of definitive information available to responsible program managers to decide on the use of combustion as an option and b) the question - what, if any, research should be conducted to optimize the use of this tool for spill mitigation. The scope was designed to evaluate the use of combustion for: in situ in a stricken vessel; oil released upon water; and oil-contaminated debris disposal.

The report consists of Part I, which is a practical guide oriented toward the needs of potential users, while Part II is the research or resource document from which the practical guidance was drawn. The study included theoretical evaluations of combustion of petroleum pool fires under the effects of weathering and an oil classification system related to combustion potential. The theoretical analysis of combustion is balanced by practical experience of oil burning and case history information. Decision elements are provided which can be used as a guide for technical evaluations of a particular oil spill situation. The rationale for assessing technical feasibility is given in the context of other alternatives available for response to an oil spill. A series of research and technology development concepts are included for future research. The ethics of using oil burning are discussed as issues, concerns, and tradeoffs. A detailed annotated bibliography is appended along with a capsule review of a decade of oil burning studies and other support information.

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PREFACE

Under Section 6(b)(3)(Q) of the Federal Nonnuclear Energy Research and Development Act of 1974, the Energy Research and Development Administration, and hence the Department of Energy, is authorized and directed to establish program elements and activities: "...to improve methods for the prevention and cleanup of marine oil spills." This program, which was initiated in FY 1976, has focused upon areas of research outside the priority areas covered by the Environmental Protection Agency, the U.S. Coast Guard, or other public and private efforts. These areas have included: personnel training; chemical treatment of oil spills; and now, the feasibility of burning spilled oil. Future program elements are anticipated to include technology overviews in similarly defined research areas.

Support for development of appropriate curriculum for training oil spill response personnel was provided to Corpus Christi State University, Corpus Christi, Texas. Investigations to determine the merits of using chemical agents in the control and cleanup of marine oil spills are being conducted by the University of Rhode Island, Kingston, Rhode Island.

Pacific Northwest Laboratory was requested to study the feasibility of burning spilled oil. Under joint U.S. Coast Guard/Department of Energy sponsorship, Pacific Northwest Laboratory was requested to prepare a "source book" related to information regarding the burning of spilled oil. That material is presented in this report. In addition, the report discusses options, ethics, and the procedure that would probably be considered before deciding to intentionally burn spilled oil.

ABSTRACT

The U.S. Department of Energy, Division of Environmental Control Technology, and the U.S. Coast Guard, Office of Research and Development, requested Pacific Northwest Laboratory to determine the technical feasibility of using combustion as an oil spill mitigation tool. The need for this study was based upon: a) the lack of definitive information available to responsible program managers to decide on the use of combustion as an option and b) the question - what, if any, research should be conducted to optimize the use of this tool for spill mitigation. The scope was designed to evaluate the use of combustion for: in situ in a stricken vessel; oil released upon water; and oil-contaminated debris disposal.

The report consists of Part I, which is a practical guide oriented toward the needs of potential users, while Part II is the research or resource document from which the practical guidance was drawn. The study included theoretical evaluations of combustion of petroleum pool fires under the effects of weathering and an oil classification system related to combustion potential. The theoretical analysis of combustion is balanced by practical experience of oil burning and case history information. Decision elements are provided which can be used as a guide for technical evaluations of a particular oil spill situation. The rationale for assessing technical feasibility is given in the context of other alternatives available for response to an oil spill. A series of research and technology development concepts are included for future research. The ethics of using oil burning are discussed as issues, concerns, and tradeoffs. A detailed annotated bibliography is appended along with a capsule review of a decade of oil burning studies and other support information.

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EXECUTIVE SUMMARY

The use of combustion as a tool for mitigating pollution from oil spills has been rarely employed, and the success of the application has been reported by few but questioned by many. Pollution control literature is limited in its scientific content explaining the oil combustion mechanisms, and providing explanations of success or failure of oil burning attempts. Fire research literature is primarily directed toward control, not promotion, of fire, and to structural surfaces behavior not the fuel source, e.g., the petroleum pool.

The information given in this report is a result of work by Pacific Northwest Laboratory (PNL) on the feasibility of using combustion to mitigate the effects of oil spills. The study was sponsored jointly by the United States Department of Energy (DOE) and the United States Coast Guard (USCG).

The Department of Energy defined objectives of this study as: gather existing information on actual experiences in the use of combustion as an oil spill mitigation tool; examine the technical feasibility of using the technique based upon reviews of existing tools and experience; investigate the combustion phenomena and explain why the technique is reported with variable success; prepare an annotated bibliography of relevant work; and identify significant issues which must be considered in using the technology. These tasks included the application of combustion to the oil cargo of a stranded or wrecked tanker, oil released into or upon water, and oil-contaminated debris requiring disposal.

The Coast Guard defined objectives as: develop a mathematic model for the burning of oil on water that addresses all environmental and thermodynamic factors as well as the properties of the oil; identify types of oils amenable to spill response by combustion; determine conditions favorable to using combustion; develop limitations or precautions for using existing technology; and provide practical guidance on how to use combustion technology.

Both DOE and USCG set as objectives: determine what related research was being conducted; identify gaps in existing research and development; and explore the ethical basis of using such technology.

Part I of the report contains information and observations drawn from Part II to provide practical guidance on the use of combustion as an oil spill mitigation tool. Part II and its associated appendices is the resource document and includes the data, theoretical examination, and evaluations necessary to meet the objectives of this study.

Part I includes summarized guidance information on oil classification, state of technical feasibility for burning oil both in situ vessel and released. Significant points in establishing an ethic for using combustion plus three decision tree analyses and research and technology development needs complete Part I.

Spill incident and case history data are provided in Part II to establish a magnitude and context for considering the use of combustion. Theoretical explanations are offered which allow a classification of oils by their combustibility potential and which provide a quantitative assessment of the amount of energy necessary to ignite and sustain a given oil pool fire under various conditions of weathering. The technology available to employ combustion is documented and these tools are evaluated in comparison to other non-burning spill response actions. To assist the responsible onscene official in making the evaluation to use combustion as an oil spill mitigation tool three situations were considered. Pertinent information is presented in decision tree format for:

- information elements for in situ tanker oil burning
- information elements for burning oil released upon water
- information elements for burning oil-contaminated debris.

The number of spill incidents which are relevant to oil burning is not directly available. To dispel the thoughts that oil contained in tankers is difficult to start and sustain combustion, cases are available such as illustrated in Figure 1 in which the burning is so intense that elements of the superstructure can turn white hot. Initial 1978 data suggest that 2115 spills lost almost 8 million gal of crude oil, and it is known that in 1977 there were 2,352 crude oil spills involving the release of 12,525,543 gal into both

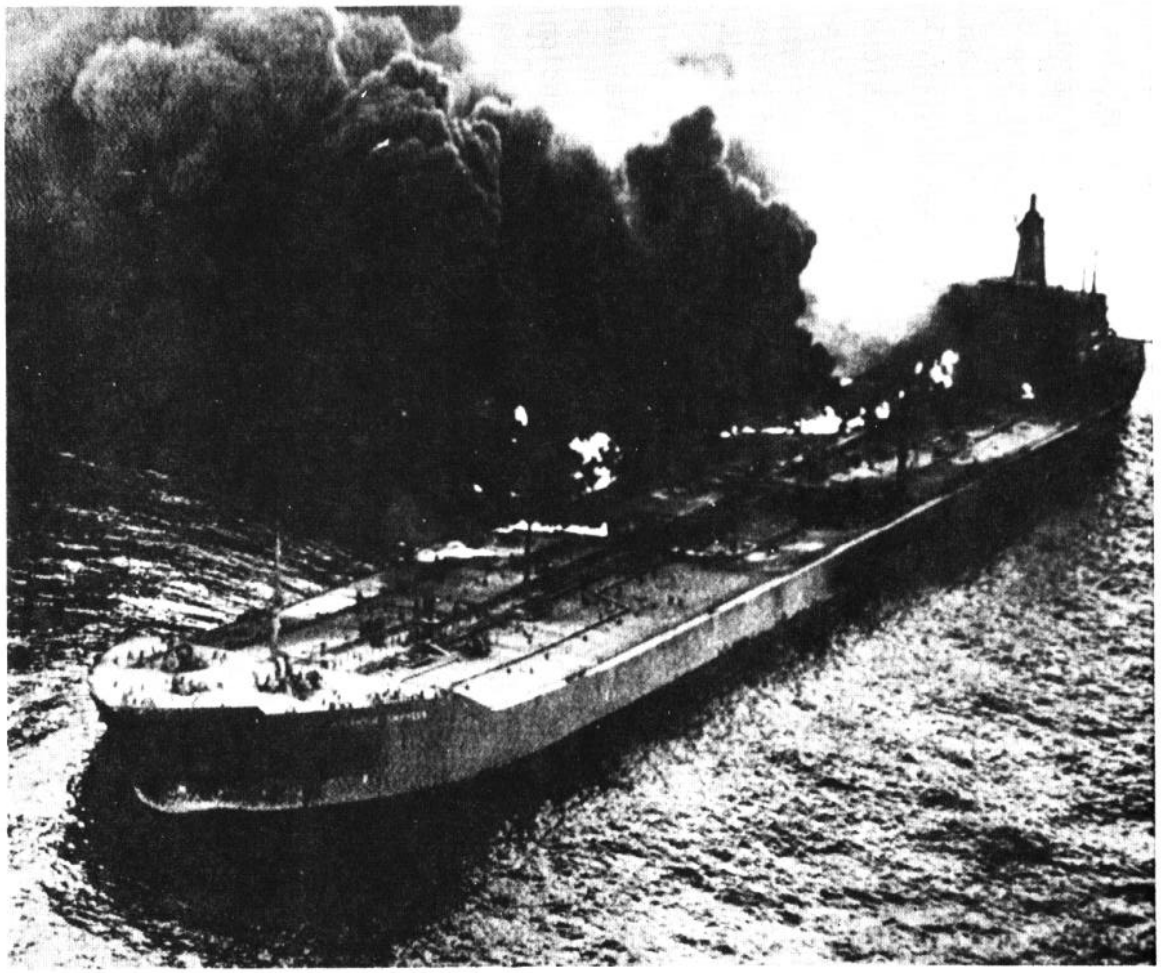

FIGURE 1. Crude Oil Burning In Situ Tanker, ATLANTIC EMPRESS, 288,000 DWT with Cargo of Arabian Light Crude Ignited from Collision with AEGEAN CAPTAIN on July 20, 1979, 28 Miles off Tobago

Source: AP Laser Photo, 1979

inland and open water areas. There were almost an equal number of light diesel oil spills as there were heavy and light crude, but the volume of the crude was 7 1/2 times that of diesel. During the period 1966 to 1977 there were 3,502 casualties involving tankships. An estimated 326 of these casualties occurred in open waters where oil burning could have been considered. It is recognized that the decision to burn a vessel and its cargo to prevent pollution is difficult. However, 11 out of the 44 tankship casualties that resulted in cargo release ended up as a total loss of vessel and cargo. It may therefore be cautiously inferred from these limited data that the decision to burn oil in situ in a vessel is not too extreme when 25% of the casualties result in total loss without using combustion. Another consideration is that salvaged vessels are beginning to experience no-entry-to-port decisions due to potential pollution.

Shipment of oil by more Very Large Crude Carriers (VLCC) and Ultra Large Crude Carriers (ULCC) will continue, but older and smaller tankers will still serve the nearshore areas especially in U.S. waters. The greatest environmental damage potential exists from releases of oil in these coastal areas.

Oil spill slick movement has received much more modeling attention than combustion. A review of oil spill movement models indicated major advances in predicting the movement of slicks but little quantitative work on the mechanisms of weathering. The factors of movement and environmental interactions are important with respect to combustibility of oils because combustibility is inversely proportional to degree of weathering. With the principal factors identified from modeling attempts, the combustion process is expressed in a simplified relationship:

$$H_{comb} \alpha H_{evap} + H_{sens}$$

where

H_{comb} = the heat released upon combustion of a unit of fuel

H_{evap} = the latent heat of vaporization for that unit of fuel

H_{sens} = heat required to raise the temperature of the liquid fuel from ambient to its boiling point.

Based on evaluation of empirical data from pool fires, the above relationship was refined to provide a means for theoretical evaluation of combustibility of individual hydrocarbon mixtures. The equation is:

$$0.02 \times H_{comb} = H_{evap} + C_p (B_p - T_a)$$

where

C_p = the specific heat of the fuel
B_p = the boiling point of the fuel
T_a = the ambient temperature.

This relationship was used to propose an oil classification system to evaluate the potential success of initiating and sustaining an oil burn under a variety of conditions, and to identify various concepts which may enhance the oil combustion process. The following categories of oils were defined.

Cat. No. 1 - those fuels from which ample excess heat is generated to easily meet heat requirements

Cat. No. 2 - those fuels whose radiant heat back to the pool roughly equals to the heat requirements

Cat. No. 3 - those fuels which produce insufficient heat to meet the requirements for burning unaided.

A detailed analysis of crude oil fractions allowed the proposal of a "breakeven point" where the heat required equals the heat generated for the fractions remaining in the crude oil. This analysis indicated that oils with breakeven points at 20% to 30% of fraction remaining are unlikely to sustain combustion, while oils with breakeven points at 80% to 90% should readily burn.

Radiant heat transfer to oil slicks is shown to be more significant than conduction or convection and appears to have received minimal attention by manufacturers and practitioners of oil burning. It is suggested that if an increase of 1% or 2% in the radiant heat transfer could be accomplished, most, if not all, oils could be burned.

Losses due to volatilization are a prime factor in the weathering process. Vaporization theory was employed to determine changes in the combustibility of an oil over time, considering interactive factors such as wind speed. The ignition of Arabian light crude oil was evaluated as an example. Between 0.012 and 0.06 cal/sec-cm^2 of pool surface is required during the ignition phase along with a pulse input of 72 to 714 cal/cm^2 to account for initial heat losses.

Background information regarding technology for combustion was obtained from the literature, personal interviews, and conference participation. The bases for combustion promotion are suggested as modifications which reduce heat losses from the pool, modifications which increase heat feedback to the pool, and modifications which provide external energy to the pool. The types of technology reviewed, many of which are not now commercially available, include:

For burning oil in situ in wrecked vessels:

a. naval and aerial weaponry to destroy vessel and cargo
b. means of creating appropriate deck openings, side vents, and means of using an ignition system to create sustained burn (vessel becomes crude incinerator)
c. offshore platform flaring equipment to offload oil by controlled combustion.

For burning oil released into or upon water:

a. oleophilic wicking agents alone and in combination with other materials
b. sorbents that provide insulating properties
c. hydrophobic insulating materials
d. volatilite additive or primer materials
e. hydroigniting agents alone or in combination with agents noted above
f. laser or other activation energy additives
g. floating furnaces and incinerators
h. fuel resistant booms alone or in conjunction with radiant heat reflectors
i. sinking agents in conjunction with burning.

For burning oil contaminated debris:

a. portable brush burners
b. field-constructed drum burners

c. truck-mounted portable incinerators
d. portable beach incinerators
e. available municipal refuse incinerators
f. specially designed industrial waste incinerators.

An examination of the status of oil combustion research indicated that the most significant recent activity is that being sponsored by the Canadian government. Work in the United Kingdom beginning in the late 1960s was terminated in 1972 and stands as the most definitive work on burning oil in situ in tankers. Other countries have had limited programs and the U.K., as well as Norway, has plans for additional research on ignition and combustion requirements in the immediate future. Specialists in oil pollution control and combustion indicated that it would be highly desirable to form an international research coordination body to facilitate information exchange and minimize duplication of investment by government and industry.

The technical feasibility assessment in this study considered the probability of using burning technology compared to other nonburning alternatives. Case history experience was also used to assess usefulness, and it becomes evident that there will be major incidents where the combustion tool should be carefully considered and employed.

As a result of this study, it appears that oils may be grouped into the following general categories. Oils which:

- are easily amenable to burning (Category 1)

  ..refined cuts having positive net heat available throughout its boiling temperature range

  ..crude oil having a "breakeven point" at greater than 67% by volume.

- are amenable to burning depending upon circumstances and some limited use of combustion promoters (Category 2)

  ..refined cuts having at least a positive net heat available at the upper boiling point of the fraction

  ..crude oil having a breakeven point at greater than 40%, less than 67%.

- require considerable effort and repeated use of combustion promoters to burn (Category 3)

  ..refined cut having a negative heat available throughout the fraction boiling range

  ..crude oil having a breakeven point at 40% or less.

The technical feasibility of burning oil in situ in tankers, on water, and as contaminated debris was prepared by listing conditions and circumstances most favorable to burning and then by comparing the burning technique to other response techniques in a relative ranking matrix. The feasibility of burning oil in situ tanker is a promising concept which is yet to be fully demonstrated and requires investments to be included as a viable oil spill mitigation tool. Burning oil on water is a technically justified concept for categories of oil under certain environmental conditions. Hardware and systems need refinement and demonstration. Burning oil-contaminated debris is proven feasible and its use is limited not by technology but by local environmental policy makers.

It appears that combustion as an oil spill mitigation tool becomes technically feasible* if:

- The subject oil classifies in the first or possibly second category.
- Response action is taken within hours after oil is released.
- Such imminent and substantiated danger exists that intervention is justified.
- The burning site is remotely located from population.
- Weather is expected to change for the worse precluding time required for successful completion of other spill response alternatives.
- The volume of oil is beyond the capacity and capability of other response methods.
- Salvage operations are questionable or abandoned.
- Groundwater is too high to permit land fill burial of debris.
- Quantities and bulky characteristics of debris make land farming too costly.
- Local authorities will permit burning debris.

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* Feasibility should also include social and economic considerations.

- Personnel experienced in oil burning and necessary equipment and material are on scene or available within hours.
- Because of age or damage the vessel is expected to be lost or at best scrapped.
- Vessel stability, weather, and cargo pose an unreasonable risk to responding personnel.

The ethics of using combustion as an oil spill mitigation tool have been described from an examination of concerns of responsible officials, economic considerations and significant issues. The thirteen concerns raised by these officials plus other considerations have been digested into eight issues on the use of combustion. Considerations both for and against burning provide the necessary framework upon which a decision maker can be prepared to make rational determinations with predictable acceptance.

The prevailing attitude is that the technology is yet to be proven and, therefore, reluctance in its use can be anticipated. Experience cannot be gained and this attitude modified until there has been a sufficient investment of resources and reported success. The negative attitudes towards use of burning can be overcome if assurances can be given on the advantages and limitations of the technique for a specific incident. A good example of this is the concern for air quality, as expressed by officials, which would be temporarily relaxed if the technique will really work and result in a benefit to the local populus and the environment.

ACKNOWLEDGMENTS

Several specialists provided guidance, review and comment on this report. Among those to be acknowledged are Hugh Montgomery, Naval Surface Weapons Center; Phil Twardawa, Canadian National Defense; Dave Thornton, Environment Canada; Bernard McCaffey, National Bureau of Standards; and P. L. Smith, U.K. Department of Industry.

Manufacturers and their technical staffs provided considerable helpful information. Representatives of oil companies, the USEPA Oil and Special Materials Division and the USCG Marine Environmental Protection Division contributed data for study.

Dr. John Cece, U.S. Department of Energy, Environmental Control Technology Division, serving as technical project officer, provided a firm guiding influence which allowed the research to be conducted with minimum interruption or deviation. His indepth understanding of USCG operations and needs complemented the efforts of Mr. Kenneth Goldman, the U.S. Coast Guard technical monitor striving to produce practical assessments of the technical feasibility of oil burning.

PNL staff assisting on the project were Amber Wong, Dave Mayer, Dana Christensen, Dick Parkhurst, Sue Gano and Elizabeth Zabek. Alex Rynecki consulted on the marine salvage and insurance aspects. Abbott Putnam, Battelle-Columbus, assisted on combustion concepts.

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PART I

PART II

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FIGURES (contd)

FIGURES (contd)

TABLES

PART I

PART II

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TABLES (contd)

PART I

DIGEST OF PRACTICAL CONSIDERATIONS

PART I

DIGEST OF PRACTICAL CONSIDERATIONS

This part has been prepared to facilitate use of the oil burning information and concepts developed in Part II (Theory, Basis, and Evaluation). Since Part I is presented with minimal detail, derivation, reference, or explanation, the reader seeking the additional documentation is referred to the second part and its associated appendices.

The practical considerations use the study findings and place them in a content of guidance thought appropriate for responsible persons such as research program directors and OnScene Spill Coordinators (OSC) who may be required to evaluate or decide the merits of using burning as an oil spill response tool.

Guidance included in this part covers: conditions which suggest needs for other technology such as burning; oils characterized for burning; and feasibility assessments of burning oil within a stricken vessel, oil released upon water, and oil-contaminated debris. Guidance on the ethical use of burning as a response tool is provided along with the decision steps necessary to implement this type of response. Research and development needs are also included. The practical experiences of government and industry in the United Kingdom and Canada are used to temper optimistic theoretical burning concepts. References cited are included in the Bibliography (Appendix B).

1. CONTEXT OF GUIDANCE

The guidance contained herein uses terminology and summarizes findings detailed in Part II. Combustion or burning is used to discuss applications of fire to: reduce the threat of oil pollution by consuming oil cargo contained within a stricken tanker (in situ vessel); reduce the volume and associated pollution problem of oil released into or upon water; and reduce the volume of oil-contaminated debris, including flotsam and jetsam. Existing oil spill response techniques are severely limited by weather conditions, and costs of cleanup ($6700 + per barrel removed) have escalated to the point that alternative technologies merit examination. The literature upon which much of this study is based contains reasons for optimism in using burning, but sound data are limited. The guidance should therefore be used as it is offered: cautious application of a technology yet to be fully developed which appears capable of significantly altering oil spill response priorities.

Major attention is directed toward marine oil spills, even though much of the application of burning technology is for on-land spills. Oil tankers are considered in more detail than other sources of oil being released into the marine environment, such as offshore platforms. Minimal attention was directed toward technological details of onshore disposal of debris by incineration since that is a subject of another USCG study. Reference is made, but detailed investigation is limited, to Arctic application of oil burning since the Canadian Government's Arctic Marine Oil Spill Program (AMOP) is providing much of this information.

"Oil" is a term that is so inclusive that it often is useful in technical discussions only as a vague introductory description of a class of compounds. Oil is used in this report for convenience, but it should be clearly understood that this complex mixture of hydrocarbons has many unique chemical and physical characteristics which are dependent upon production, geographical origin, and stage of refinement (Figure 1.1) and, therefore, each incident must deal with the specific oil in question.

FIGURE 1.1.

THE MANY FACETS OF CRUDE OIL

Man's ubiquitous and obedient servant

When you stop and think of it, few people have actually *seen* crude oil (including most of us in the petroleum business). "Man's most useful servant," as it's been called, comes up out of the earth in a pipe, and stays in a pipe, or in a tanker, as it flows to the refinery.

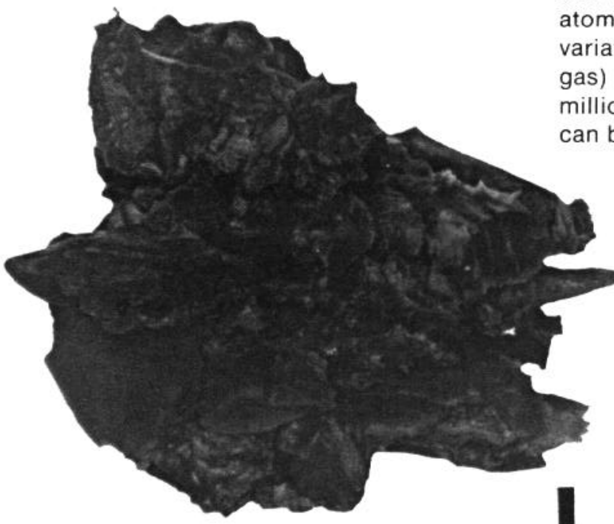
Matter of fact, crude oil doesn't always flow, either—as you might surmise from these photographs. Some crudes, heavy in wax or asphalt, can be as solid as shoe polish. Others are almost as light and volatile as the gasoline you put in your car. There are some crudes that have the consistency of butter. Some are "sweet," meaning that the sulfur compounds present are not corrosive and do not impart a bad smell; other crudes are "sour," i.e., products made from them have to be specially treated to eliminate corrosivity and unpleasant odors produced by hydrogen sulfide and other compounds.

However black or colorful, thick or thin, they all stem from a basic molecule containing one carbon atom linked with four hydrogen atoms. Theoretically, millions of variations on this methane (or marsh gas) molecule are possible, and millions of different hydrocarbons can be formed.

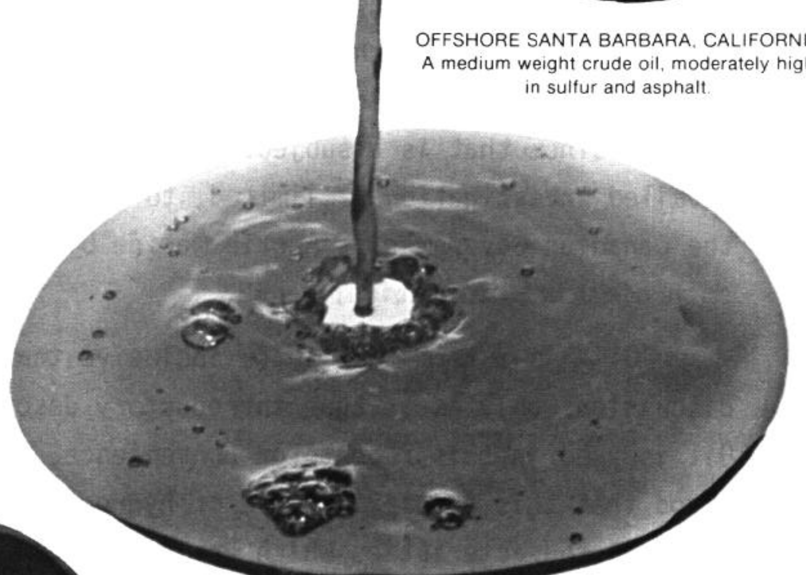
Finally, as these pictures and the map tell, crude oils can come from many lands—and seas, too.

The problem is that they're coming a lot harder nowadays.

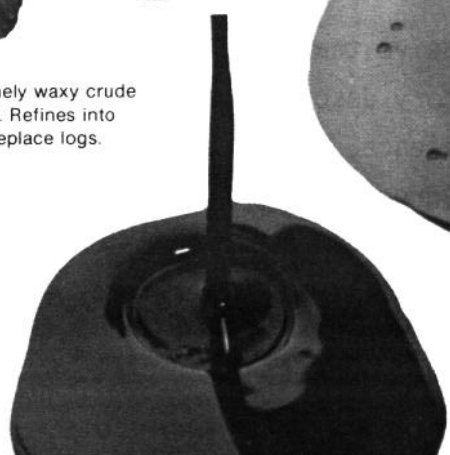
OFFSHORE SANTA BARBARA, CALIFORNIA A medium weight crude oil, moderately high in sulfur and asphalt.



ALTAMOUNT, UTAH An extremely waxy crude oil, solid at room temperature. Refines into gasolines, fuels and even fireplace logs.



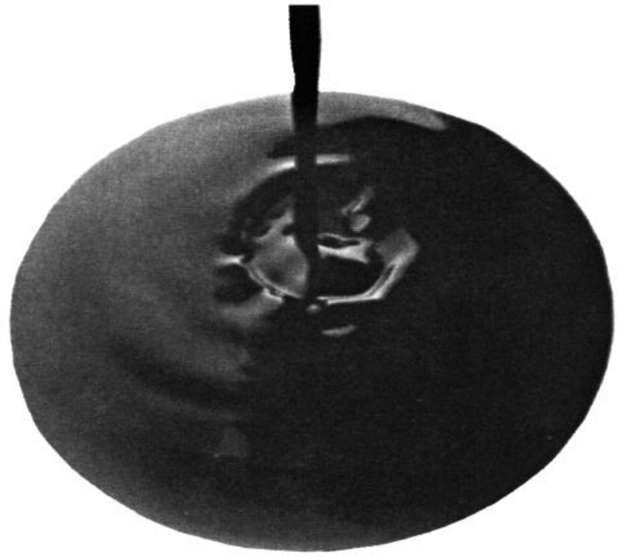
BARROW ISLAND, AUSTRALIA As you can see, a light crude oil. Contains gasolines, kerosene, diesel fuel, but very little asphalt.



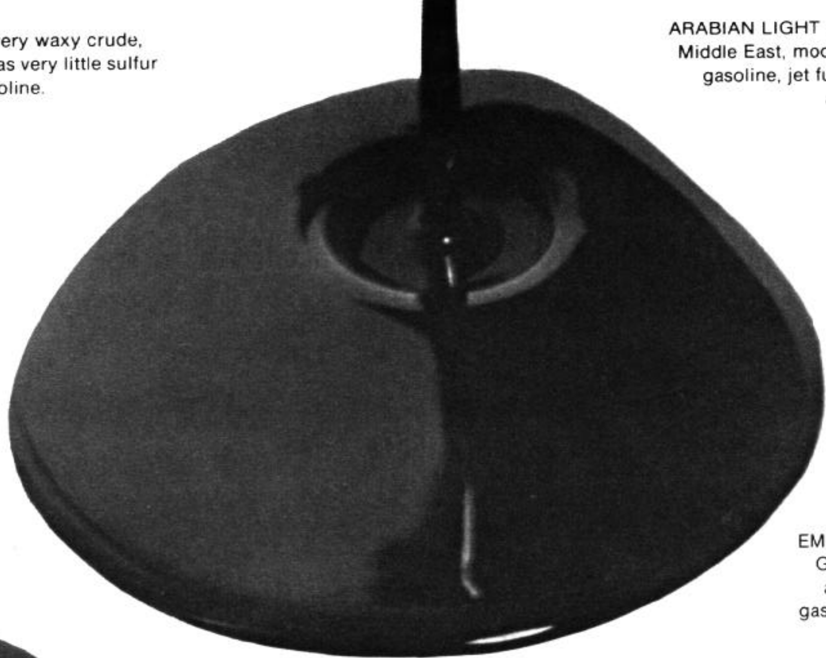
NINIAN, NORTH SEA A low-sulfur crude having good yields of gasoline, jet and diesel fuels and asphalt.

Reprinted with permission from the March 1977 issue of FUEL OIL NEWS

MINAS, SUMATRA Another very waxy crude, solid at room temperature. It has very little sulfur and not much gasoline.

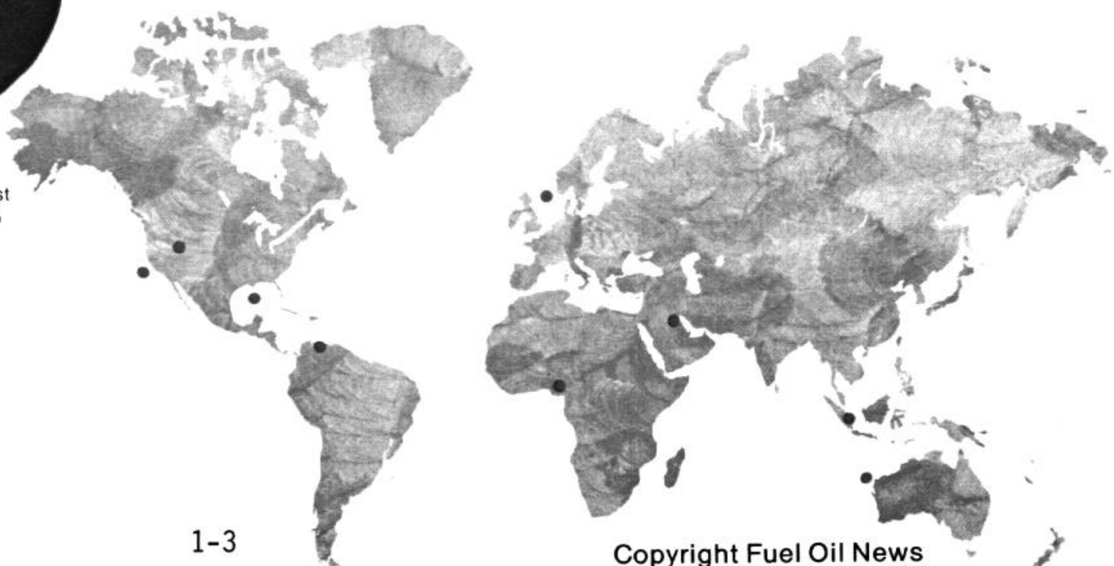


ARABIAN LIGHT This major crude oil from the Middle East, moderately high in sulfur, yields gasoline, jet fuel, diesel, lubricating oils and fuel oil.



EMPIRE MIX A very "conventional" Gulf Coast crude of low-sulfur and wax content, refined for gasolines, diesel fuels and fuel oil.

BOSCAN, VENEZUELA One of the thickest crudes in the world, containing almost no gasoline or wax, but a large amount of high quality asphalt.



2. CONDITIONS ESTABLISHING NEEDS FOR OIL SPILL RESPONSE OTHER THAN PHYSICAL REMOVAL

The continuing movement of oil cargoes and the recognition that an adequate arsenal of oil spill response tools does not exist stimulate the need for investigation of alternate technology. The 1979 quantity of oil being used in the U.S. is estimated at 18.7 million bbl/day of which more than 8 million bbl/day required marine transportation for import. U.S. vessels carry no more than 4% of the imported oil. Predictions have been made that, without artifical import controls or renewed domestic production, U.S. petroleum needs will far exceed 50% import within a few years. This importation will rely to a great extent upon tankers.

The VLCC (Very Large Crude Carrier) is a class of tank vessel which has become the common form of marine oil transport with the first of this size being built between 1956 and 1961. These 100,000+ DWT (dead weight tonnage) tankers represent less than a third of the world's fleet, but describe more than two thirds of the world DWT. The U.S. as both a coastal state and a maritime nation (6% of world tanker fleet) has a unique role due to the oil consuming market represented. Shallow U.S. ports cannot normally accept the VLCC and, therefore, much traffic in nearshore U.S. waters consists of smaller, often older, vessels. U.S. ports range from 13% petroleum import at Mobile, Alabama, to 99.7% petroleum at Portland, Maine, where from 1 to 50 million tons of cargo move annually. Vessels bringing petroleum to the U.S. reflect the recent construction trend of building larger vessels.

An apparent maximum in tanker construction was reached in 1971 to 1975 where 1,344 vessels (32% of world's fleet) were built and represented 50% of the world DWT. A majority of these were in the 240,000 DWT class and above. One of the largest tankers is 544,917 DWT, carries 4.2 million bbl in 37 tanks, and has a draught of 93 ft. U.S. ports cannot accept this size vessel. U.S. waters that are deep enough are often protected by law, e.g., Puget Sound-Port Angeles potential site. Tankers and other vessels move the largest quantities of oil economically, but any oil spills are quite visible to the public and responsible officials. In 1975, vessels spilled some 20 million gallons but shipped almost 200 billion gallons; in 1977, 18 million gallons were spilled and almost 250 billion shipped, which by most safety standards appears reasonable.

There are thousands of oil spills annually ranging from a slight discoloration of the water to releases of thousands of gallons. Crude oil spills and diesel spills are similar in number, but the quantity of crude lost is almost an order of magnitude higher. The locations of the spills are random and no trend can be clearly shown except the obvious: in areas of high production, use, or transport there are more spills. The tanker loss rate (8 in 1976, 14 in the first 6 months of 1977) is of definite concern and can be used as a practical point of evaluation in this study.

Several factors are important in evaluating the most appropriate oil spill response including: oil types and quantities; weather conditions; locations of oil in regard to property and living marine resources; timeliness; manpower required and available; equipment required and available; experience for success of technique; risks to safety of response personnel; effects of response on environment; public perception of decisive action being taken; and costs anticipated to implement response. The present trend in oil spill response can be described as containment and physical removal of released oil (with the exception of growing trena toward use of dispersants), and land disposal of oil-contaminated debris. Stricken vessels are sought by marine salvors until all hopes of recovery of vessel and cargo are lost.

2.1 WEATHER CONDITIONS

High winds, cold temperatures, rough seas, etc., severely limit the use of existing oil spill response techniques. Oil containment booms break or leak oil, skimmers spill or become damaged, and these highly labor intensive cleanup actions subject personnel to undue hardship. Unstable conditions and unknown hazards of stricken tankers pose extraordinary risks to response personnel. Response techniques are required which would extend the range of inclement weather operation and allow mitigation to be implemented with less risk to personnel on scene.

2.2 LOCATION

Oil released such that it causes significant death to wildlife, damage to public and private property, and renders marine produce unmarketable requires a very large commitment by government and industry in standby equipment and personnel. The susceptibility of a localized environment to sustain significant deterioration due to an oil spill does not allow much area, except mid ocean (perhaps), to be ruled a "no-response-required-zone." Vessels are often stranded under conditions which prevent other vessels from reaching the location and rendering adequate assistance. Highly mobile techniques must be available such that a minimum of men and equipment are required to cover a maximum number of locations.

2.3 TIMELINESS

Oil releases or threats of release have established a salvage and cleanup industry proud of its record of quick response to the scene. Often the situation is complex and the techniques employed to mitigate are slow, allowing the quantity of oil released to increase and the damage to spread. With time, the released oil changes physical and chemical character (weathers) and affects the efficiency of the response action. Delays pertaining to stricken vessels can alter the success of salvage as a result of weather changes or deteriorating vessel stability. Techniques are required to effect mitigation of oil spills in hours to days rather than days to months.

2.4 MANPOWER: REQUIRED AND AVAILABLE

Present oil spill response techniques that are labor intensive use local pools of manpower in the vicinity of the incident. Specialists direct the operation and attempt to supervise the often armies of workers. Machinery used is of such a specialized nature that maximum efficiency in operation is achieved only with experienced operators. Occasionally, local attitudes of frustration and anger will prevail to the point that the labor-intensive techniques may be unreliable. Techniques are required to minimize the manpower required and take advantage of existing local and national standby emergency services personnel.

2.5 EQUIPMENT: REQUIRED AND AVAILABLE

Situations are commonly known where ad hoc use of locally available farm and earth moving equipment is pressed into emergency service in time of an oil spill incident. Specialized equipment of any significant capacity must be moved to the site, set up, tested and put into operation. If more than one major incident were to happen, the equipment resources available would be stretched to the limit. Salvage equipment to assist a stricken tanker is not in excess and requires considerable preparation and travel time. Techniques are required which employ the minimum of equipment which could be held on standby and made available locally in a minimum of time.

2.6 SUCCESS OF TECHNIQUE

Success of presently used techniques is reported in terms of quick response, barrels of oil collected, possible environmental harm prevented, and effort and expenses demonstrated by industry or government to local populations. Techniques should be developed such that, when evaluated for total cost per barrel of oil recovered, total energy expended to recover oil, and actual harm caused and prevented vs. environmental restoration, the optimal technique would be used.

2.7 RISK TO RESPONSE PERSONNEL

There are few oil spills which take place in calm waters during the mild weather and yet the safety record of the responding personnel is remarkable considering the conditions under which they must work. Pessimistically then, it is reasonable to express concern that it is not a matter of whether, but when, there is a significant accident involving oil spill response personnel. The commonsense-ad-hoc-approach to response should give way to techniques which are specifically designed to minimize the number of exposed response personnel for the shortest period of time and still accomplish the oil spill mitigation mission.

2.8 EFFECTS OF RESPONSE ON THE ENVIRONMENT

The impacts of vegetation slash and removal (cutting), skimming in intertidal areas, and other physical removal techniques are accepted in practice as are the increased selective applications of detergents to disperse oil into the water column. Chronic exposure and oil spill effects are costly and time consuming to measure and could be at such a level that, within normal aquatic population changes, they represent little significance. Techniques are required so that when evaluated from both a local and global environmental effects viewpoint, or from an acute and chronic exposure and effects standpoint, all the tradeoffs are identified and the minimum impact response is used.

2.9 PUBLIC PERCEPTION OF ACTION

Considerable amounts of time pass from the initial stages of the oil spill incident until the public sees action in the form of men and equipment actually working. The early phases of planning and coordination added to industry and government indecision, logistics problems and delays of jurisdiction plus liability claims do not dispel the public anxiety. Techniques are required which could demonstrate immediate field action by industry and government to mitigate some, if not all, of the potential damage.

2.10 COSTS ANTICIPATED FOR RESPONSE

The revolving fund administered by the Federal government has been used to assure cleanup of oil spills, placing heavy reliance upon physical removal. This $35 million fund, now being replenished for the third time in 8 years, is being subjected to very costly cleanup expenses from employing hundreds of persons, renting considerable amounts of equipment, and purchasing tons of expendable materials. Without compromising the Federal responsiveness, techniques should be available to mitigate oil spills for costs that are nearly a hundredth to a thousandth of present costs.

These factors are part of the conditions which suggest that additional technology is needed to mitigate oil spills. Use of combustion is but one of these alternatives. The minimum investment in this field of combustion technology is more responsible than any of the thermodynamic limitations for its poor state of development and, therefore, lack of acceptance.

3. OILS AMENABLE TO BURNING

The physical characteristics of the variety of oils cover a range and so do their thermal properties. Upon completion of the state-of-the-art review on combustion as it relates to pool fires and movement of oil slicks on water, a classification of oil was initiated (Part II, Section 3). The theoretical examination was confined to released oil combustion as it was considered that combustion of oil confined in a tanker or oil-contaminated debris was either less difficult to explain or had been well studied. The effects of natural forces that disperse and modify oil slicks in water have been studied much more than the combustion properties of slicks. These studies have led to the development of several mathematical models. Each of the model's limitations have been summarized for the processes of advection, spreading, dispersion, weathering, and windfall. Because most of the basic fire research data on pool fires was found to be lacking in information necessary for direct use in oil spill combustion, a simplified combustion relationship is proposed.

The simplified relation for oil slick combustion is designed to allow use of the minimum amount of commonly available data on the wide variety of hydrocarbons and mixtures which may be the subject of a response action. The basis of the relationship comes from the concept that combustion takes place with a liquid only if:

$$H_{comb} \; \alpha \; H_{sens} + H_{evap}$$

where these terms mean heat released upon combustion of a unit of fuel (H_{comb}), latent heat of vaporization for that unit of fuel (H_{evap}), and heat required to raise the temperature of the oil from ambient (4.4°C used in this study) to its boiling point (H_{sens}). These data are available in several publications including some in the USCG CHRIS manuals (A. D. Little, 1974).

It is important to recognize that only a portion of the heat of combustion can be returned to the pool and that the sensible heat for a given fuel is determined as the product of the specific heat of the fuel (Cp) times the difference in boiling point (Bp) and ambient (T_a) temperatures. Relationships of heat transferred back to the pool expressed as resulting burning rate (V in mm/min) was found equal to a constant times the ratio of the heat of combustion to the effective heat of vaporization. Additional considerations of the heat transfer including flame view factors, emissivity, and absorbency suggest that about 2% of the heat of combustion can reach the pool and this occurs by radiation, not convection or conduction. The simplified relationship most useful to this classification analysis is therefore:

$$0.02 \times H_{comb} = H_{evap} + C_p\ (B_p - T_a)$$

Classification of the oils is proposed by using the net heat difference between total heat of combustion released (radiation back to the pool) and total heat required. The simplified relationship allows the use of broad temperature ranges, e.g., as found in distillation products rather than single boiling points. By completing the calculations for a variety of oil products from motor fuel antiknock to resin oil, three fairly distinct groups can be shown. These categories are defined as:

Category 1 including those fuels from which ample excess heat is generated to meet heat requirements; burning can be anticipated under most conditions; the net heat difference is positive throughout the distillation range.

Category 2 including those fuels whose radiant heat back to the pool is roughly equivalent to heat required; burning can be anticipated only under some conditions; the net heat difference is positive at lower distillation temperatures and negative at higher temperatures.

Category 3 including those fuels which produce insufficient heat to meet the heat requirements; burning is not anticipated without significant combustion promotion; the net heat difference is negative throughout the distillation range.

Crude oils would be placed in Category 2 if only generic or average data were used to describe these complex mixtures. It was recognized that there is considerable difference between the potential combustibility of a highly volatile light crude and various waxy heavy crudes. Since the crude oils are made up of differing percentages of many hydrocarbon fractions each having distillation temperature ranges, the approach in categorization was to determine "breakeven points." These determinations employed the same simplified relationship, and calculations were made noting the percent of the crude oil fractions at which the radiated heat of combustion just equaled the heat required. From case history experience it was clear that crude oils with "breakeven points" in the 80% to 90% range easily burn, while oils in the 20% to 30% range are most difficult to burn. The three categories were then modified to include crude oils with similar prospects of burning by:

Category 1 having "breakeven points" at greater than 67% by volume of crude oil

Category 2 having "breakeven points" at greater than 40% less than 67% by volume of crude oil

Category 3 having "breakeven points" at less than 40% (below 30%) by volume of crude oil.

The products and crudes examined are classified in Table 3.1. As more empirical data become available, it will be of interest to reexamine the category divisions. Particular emphasis should be made by reponsible officials to document oil characteristics in marine casualties such as the July 1979 collision involving the ATLANTIC EMPRESS with a cargo of Arabian light crude which burned fiercely.

Using information as developed here the various oil types can be evaluated for their propensity to burn under spill conditions. The actual conditions of the spill site will control, but several oils were selected (Table 3.1) and the probable success of using burning is suggested recalling the categorization indicating use of combustion promoters. Guidance can be further taken by using specific oils in question which have properties analogous to these few selected and evaluated. The modifying environmental factors, technology available, and guidance on use of burning are discussed in the following sections.

TABLE 3.1. Categories of Oil by Likelihood of Combustibility

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	

TABLE 3.1. (contd)

CATEGORY NUMBER 2

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

TABLE 3.1. (contd)

CATEGORY NUMBER 2

Oil Products	Crude Oils	
	Gulf of Suez Blend, Egypt	Cabinda, Cabinda, Angola
	Kuwait Crude, Kuwait	North Slope, USA
	Arabian Medium (Zuhof), Saudi Arabia	Mandji, Gabon
	Fereidoon Bled, Iran	Ratawi, Neutral Zone
	Arabian Medium, Saudi Arabia	Minas (Sumatran Light) Samatra, Indonesia
	Ekhabinskaya, USSR	Burgan (Wafra) Neutral Zone
	Amna (High Pour), Libya	Anguille, Gabon
	Arabian Heavy, Saudi Arabia (Safaniya and Khafi)	Taching, China (PRC)

CATEGORY 3

Oil Products	Crude Oils	
Castor Oil	Gamha, Gabon	Jatibarang, Java, 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	

4. TECHNICAL FEASIBILITY OF BURNING OIL IN SITU TANKERS

The concept is that an oil cargo consumed by combustion in a stricken tanker would lessen the extent of pollution that would result if the tanker were to break up. The following assessment is based upon investigations of case histories and previously conducted research plus careful examination of factors such as techology available, experience of personnel, and motiviation for and reactions to burning by interested parties. The feasibility in 1979 of this approach is conceptually promising with optimism being expressed by several specialists. However, there is required an extensive investment (modest compared to current cleanup costs) in development and demonstration before the concept can be used with a reliable basis. Without these investments, limited progress can be shown by creating detailed reports on:

1. engineering analysis of failure potential from changes in ship section modulus due to deck and hull plate removal and fire effects for different sized tankers
2. engineering analysis of and procedural development for using aerial deployed munitions including metal cutting and reactive incendiaries to remotely burn oil cargo
3. engineering analysis of and procedural development for manual deployment of shaped charges and incendiary materials aboard a stricken tanker
4. procedural development for and use of maritime firefighting techniques to control deliberate oil cargo burns
5. safety analysis of and procedural development for using offshore oil platform waste oil flare burners as routine or emergency deployed off-loading equipment aboard tankers.

Three concepts of burning oil in situ tankers were defined and evaluated. Naval and aerial weapons exist and are most effective for use on similar targets in penetrating metal, and igniting a fuel. It is yet to be demonstrated that these systems, with slight modifications, would provide the cargo volume reduction sought in stricken tankers. However, reactive incendiary weapons and explosive metal cutting specialists are optimistic on the potential success of applying these military tools to this civilian problem. Considerably more confidence, using manually placed shaped charges plus igniters, is expressed by marine salvors and others knowledgeable in vessel design and in providing aid to stricken vessels. The third concept requires less extreme applications of technology because of the use of waste oil flare burners being common on land, on offshore platforms, and on exploratory well drilling ships. Furthermore, a few countries are relying more on flare burners when responding to stricken vessels at sea.

Category 1 and 2 oils are most amenable to in situ burning and Category 3 oils could burn with sufficient metal heat radiation developed in the cargo tanks. The tools may be available in the U.S. to carry out the in situ burn, but lack of explosive stores in Europe and elsewhere limits the concept. There are no commercially available organizations to implement the in situ burn. However, some marine salvors could assist in ship stabilization plus placement and use of explosives. There are no government facilities in the U.S., Canada, or the U.K. with the expertise, equipment, or mission to lead or carry out an in situ oil burning response action. The elements of the technology exist, but have yet to be integrated into a viable response system.

Conditions which can be identified suggesting that in situ tanker burning of oil cargo is a feasible concept worth further development are summarized below compared to the current response option of ship salvage and cleanup:

Minimum Time Available for Response

- salvage and cleanup - several weeks to a few months required
- in situ burn -- 3 to 5 days required, conceptually

Manpower Involved

- salvage and cleanup - up to 500 from several vessels
- in situ burn - less than 50 in aircraft and vessels

Equipment Exposed to Risk

- salvage and cleanup - $100 million in ships and aircraft
- in situ burn - $30 to $40 million in vessel and aircraft

Support Facilities

- salvage and cleanup - extensive, involving several ships and aircraft
- in situ burn - one vessel and one aircraft (ideally)

Value of Resulting Vessel

- salvage and cleanup - $12 million for new to $960,000 for old vessel
- in situ burn - $0 to $200,000 for old vessel and $340,000 for new vessel as scrap

Random Locations of Accidents

- salvage and cleanup - heavy equipment must be moved and set up sometimes far from operations base
- in situ burn - accessible and safe provided 3 miles from population, rapid transport of compact system anticipated

Cost of Response

- salvage and cleanup - up to millions of dollars
- in situ burn - a few hundred thousand dollars

Public Regard for Response

- salvage and cleanup - high costs, much preparation, apparent delay in response, energy spent to recover oil
- in situ burn - cost savings, rapid decision action demonstrated - oil lost versus energy not spent in response

All Weather Response

- salvage and cleanup - inclement weather threatens safety and operations halt
- in situ burn - can be considered in all but most severe weather, assuming air deployment

Civilian Application of Military Technology

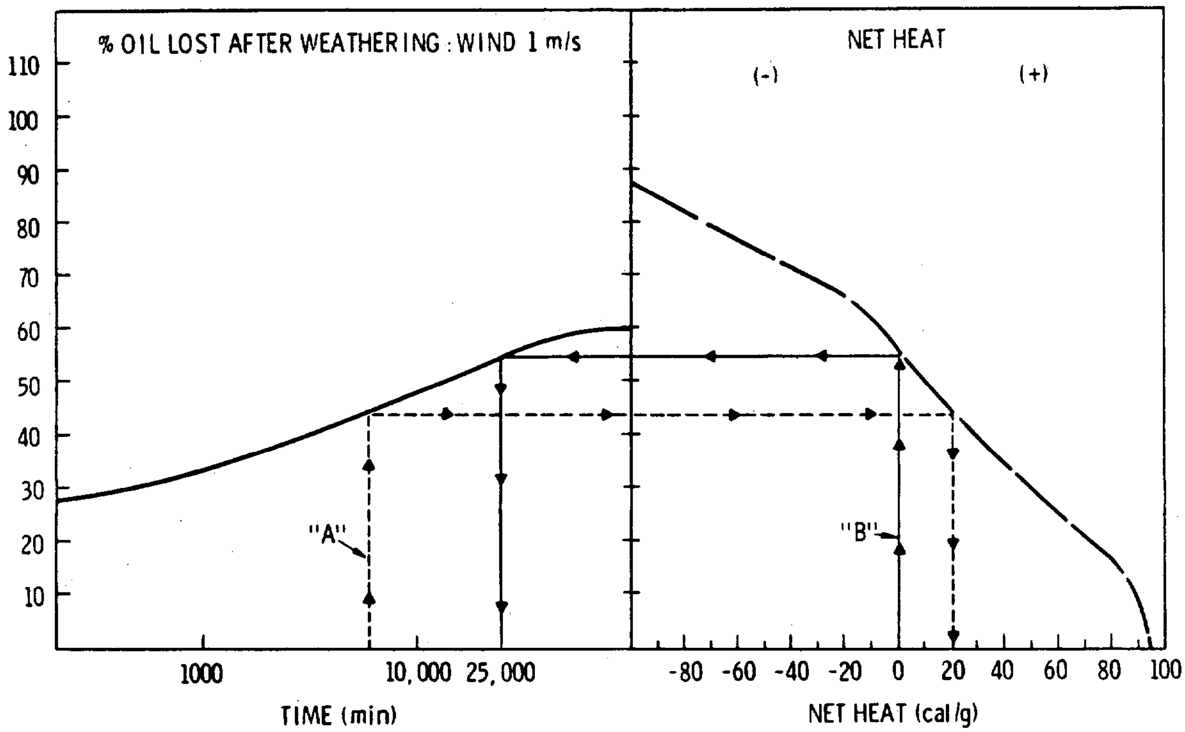
- salvage and cleanup - little involvement except occasional Navy salvage
- in situ burn - defense agencies, equipment techniques, and personnel in full scale; training increases return on military budget expenses

5. TECHNICAL FEASIBILITY OF BURNING RELEASED OIL

The concept is that combustion of oil released upon water and oil-contaminated flotsam and jetsam, which wash ashore, significantly reduces the pollution potential. Case histories, reports of field demonstrations, plus detailed combustion analysis and discussion with specialists formed the basis of this assessment. The concept feasibility in 1979 of burning oil released upon water is technically justified and optmized for categorized oils under certain environmental conditions. Hardware and systems require refinement and demonstration.

Research results from Canadian studies and analyses in this study explain much of the reported poor and sporadic success of this application of burning. Examination of existing combustion promoters establishes no single system as totally satisfactory. It is not evident that combustion promoter manufacturers have deliberately set out to raise the radiant heat capture back to the pool fire of the oil slick. It is suggested that if the radiant heat capture at the pool could be raised by about 1% many more oils could support or sustain combustion.

The effects of ignition of the pool by temperature and wind have been quantified and illustrated using a light Arabian crude oil. The evaporation of volatile fractions and resulting changes in remaining oil fraction's heat of combustion and heat required for vaporization can be used to estimate likelihood of combustion. Demonstration of use of a "weathering chart" (Figure 5.1) facilitates assessing an oil slick of known weathered age which can be evaluated on its percent combustibility. Another use of this chart allows the observation that, without combustion promoters being employed after a determined time, combustion will not be possible under the given wind condition. The ignition analysis is further expanded to derive a relationship between lower flammability limit and number of carbon atoms in a compound from which flash points of oil fractions could be computed. Once flash points are known for each decile fraction of the oil, heat flux required for ignition can be determined. For the examined Arabian light oil, this ignition value was



Examples of the use of this chart are:

1. A pool of Arabian light has weathered for 100 hr (6000 min) in a wind of 1 m/s.
   - Enter at "A" and observe that the oil remaining still has a positive net heat in just more than 15% of the oil volume remaining.
   - Therefore, if sufficient heat can be introduced to ignite the pool, about 10% to 15% can be expected to burn before extinction.

2. A pool of Arabian light is known to exist.
   - Enter at "B" and observe that without primers or combustion promoters oil spill mitigation by combustion is not possible after 416 hr (24,960 min) of weathering in a 1 m/s wind.

FIGURE 5.1. Effects of Weathering on Oil Combustibility (Arabian Light)

determined to be in the range of 0.012 to 0.06 cal/sec-cm^2 of pool surface. This heat flux compares to solar radition at 0.02 cal/sec-cm^2 and glowing embers at 1 cal/sec-cm^2. Further consideration of transient heat requirements provided the estimated ignition heat necessary to sustain combustion. This can be met by either short high energy bursts or longer exposure of the pool to lower energy fluxes.

Trends on the effects of combustion of pools (slicks) of the Category 1, 2, and 3 oils by oil thickness, ambient temperature, exposure time, and wind velocity are shown in Figures 5.2 through 5.5.

The tools currently available within the U.S. to implement a burn of oil on water are at a poor state of development and readiness. Reasonably heavy patent activity has presently not resulted in any commercially available systems with the exception of a few products being offered as wicking agents.

Techniques and systems examined included:

a. oleophilic wicking agents alone and in combination with other materials
b. sorbents that provide insulating properties
c. hydrophobic insulating materials
d. volatilite additive or primer materials
e. hydroigniting agents alone or in combination with agents noted above
f. laser or other activation energy additives
g. floating furnaces and incinerators
h. fuel resistent booms alone or in conjunction with radiant heat reflectors
i. sinking agents in conjunction with burning.

Cleanup contractor, Federal response and state and local personnel, as well as industry, appear to be totally uninterested and ill prepared to use the concept. Federal Regulations (40 CFR 1510) provide no guidance on acceptability of products or efficiency expected other than that case by case determinations will be made by the OSC on the use of burning agents. Manufacturers and Federal agencies have had a poor record of demonstrating the practical use of the concept employing the available technology. Specialists have advised that without the guidance of experienced pyrotechnic personnel,

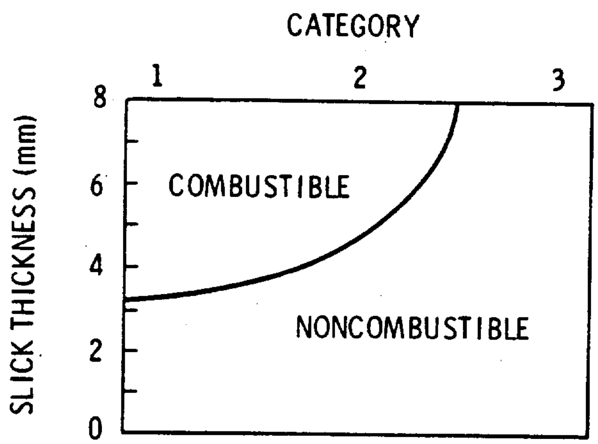


FIGURE 5.2. Trend of Effects of Slick Thickness on Combustibility

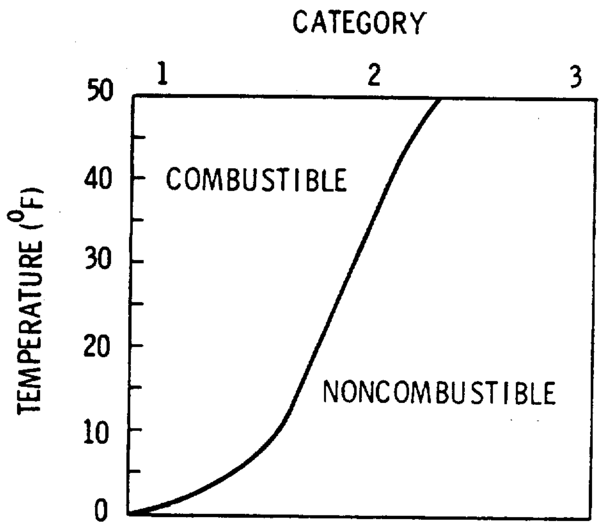


FIGURE 5.3. Trend of Effects of Ambient Temperature on Combustibility

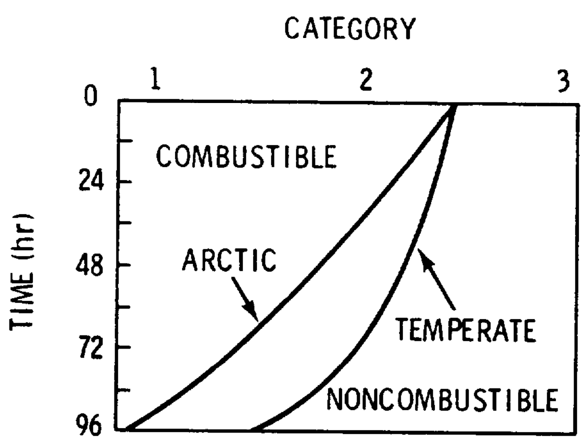


FIGURE 5.4. Trend of Effect of Time Delay on Combustibility

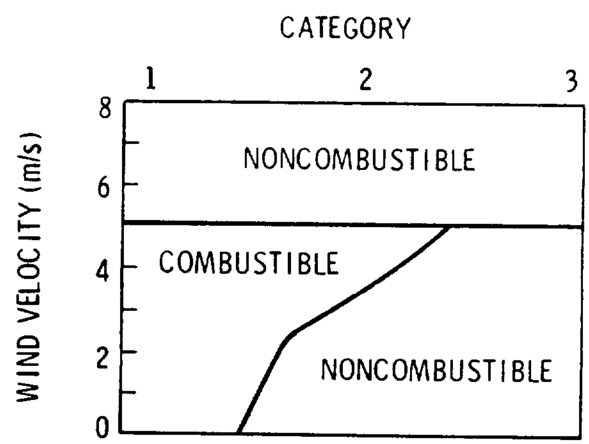


FIGURE 5.5. Trend of Effect of Wind on Combustibility

it is understandable that the demonstrations have been poor. However, optimism by Canadian Government and industry personnel has been shown for use of oil spill combustion on ice, in snow, and in ice-infested waters. Techniques for burning water-in-oil emulsions have also been shown as successful.

Conditions which appear to favor the concept of burning oil released upon water are suggested below in reference to other options:

<u>Limited Time Available</u>

- other options - require extensive equipment and manpower deployment causing some delays ranging from days to weeks
- burning - responses can be very quickly conducted with results immediately known in terms of hours and days

<u>Manpower Required</u>

- other options - physical removal is heavy labor intensive; handling of people, chemicals is not labor intensive
- burning - limited staff required to administer the burn - less than 50

<u>Equipment Involved</u>

- other options - extensive equipment available and used for physical removal and expendable material is used
- burning - can be very limited to moderate; development needed - not much commercially available

<u>Major Spills</u>

- other options - experience demonstrates that new tools are needed
- burning - yet to be shown; commercial availability low - development needed

<u>Light, Fresh or Oils with Positive Net Heat, e.g., Gasoline Grades</u>

- other options - chemical techniques can be effective, but little gained by other techniques due to volatility, density and viscosity
- burning - shown to be combustible and pollution minimized

Ice Conditions

- other options - essentially inadequate
- burning - very effective, especially in confined areas

Moderate to Calm Seas

- other options - physical and other materials feasible
- burning - appears effective, but development needed

Safety of Response Personnel

- other options - more people, movement and handling; potential for accidents rise; moderate to severe weather, hazardous
- burning - fewer persons, less immediate contact with oil, remote burning feasible, but not demonstrated, less chance for injury possible

Costs

- other options - can be high, but recovered oil reduces total cost
- burning - potentially low cost if value of time and environmental danger is weighted more than recovered oil

Remoteness of Property and Population

- other options - can cause logistic problems for equipment and personnel recovering oil
- burning - allows free burning ideally with minimal damage potential

Military and Related Technology Transfer

- other options - other than Navy experience (published) little anticipated
- burning - use of incendiary and delivery systems possible for civilian application

The use of combustion to handle oil-contaminated debris (flotsam and jetsam) washed ashore was evaluated. Other USCG studies have considered this aspect in more detail. The feasibility in 1979 of using this technique is proven and there is considerable equipment and technology available for optimal utilization. A brief examination of frequent oil spill sites compared to existing municipal incinerators indicates that, with the exception of the

West Coast, facilities could be available. Objections to use of the facilities will require regional cooperation. A listing of commercial waste incinerator facilities was compiled along with brief descriptions of equipment. With the technology as advanced, compared to the previous two applications of combustion, it is unfortunate that many state and local bodies are not in favor of combustion of debris but prefer land disposal.

The conditions and circumstances which appear favorable to burning to dispose of oil-contaminated debris are noted below:

Land Availability

- other options - require extensive area for farming or burial and some preparation
- burning - small site required; can be existing facilities

High Groundwater Table

- other options - burial unacceptable in some areas
- burning - debris can be burned on site

Heavy Precipitation

- other options - earth moving slow and difficult
- burning - once burning is initiated only most severe weather would hamper disposal

Permanent Solution Needed

- other options - land farming with time can be permanent, but burial is potentially just storage
- burning - regarded by all authorities as most permanent

Health and Safety

- other options - odors, erosion, flooding or other changes can endanger health
- burning - dead wildlife, other disease vectors are handled and delayed hazards prevented; no proven health hazard from oil spill burning.

Energy Recovery

- other options - only if oil is recovered and separately at much cost
- burning - used as coal pile additive or in recovery incinerator advantages known

Bulky Debris

- other options - not amenable to burial or land farming without extensive preparation (days)
- burning - with limited preparation (hours) can be handled with portable equipment

Limited Transportation Available

- other options - delays to reach suitable burial or farming areas
- burning - can be conducted on site

Beach Sand Needed in Place

- other options - detergents can be used, but aquatic toxicity increased
- burning - manual or automated equipment has been used to process sand on site; some residual ash anticipated

6. ETHICS OF USING OIL BURNING

The ethics question is, if the oil combustion technology concept is practical, should it be used? By carefully examining the concerns of responsible officials and discussing some of the economic conditions issues have been defined. Examination of the reasons for and against using burning as an oil spill response tool establishes a framework for defining an ethic.

It is suggested that the ethics of using combustion as an oil spill mitigation tool must be evolved from reactions as illustrated in Figure 6.1. The actions taken by a decision maker such as an OSC will be defended by his judgment, specific conditions, use of technology and his authority. Many conflicting priorities and demands will influence his decision and those parties making the demands will evaluate and react to his determination. The right or wrong of the decision will be determined long after the oil spill incident is concluded. The guidance offered here is intended to increase the decision maker's awareness of potential concerns of others and to provide substance from which he may establish a rationale for using or not using the combustion tools available.

Part II of this study answers, in detail, the thirteen concerns raised by responsible officials. Questions such as these will be brought to the attention of the OSC including:

1. Does combustion really work to reduce the volume and environmental threat if oil pollution?
2. Assuming that burning does work, is not the air pollution problem posed by burning a more severe threat than the liquid oil itself to health, property (including items such as dwelling paint, clothes hanging to dry), coastal vegetation, and to the public attitude of a community toward governmental decision makers?
3. How safe to the response personnel is it to burn oil under the three conditions and what is the past experience to demonstrate this safety?

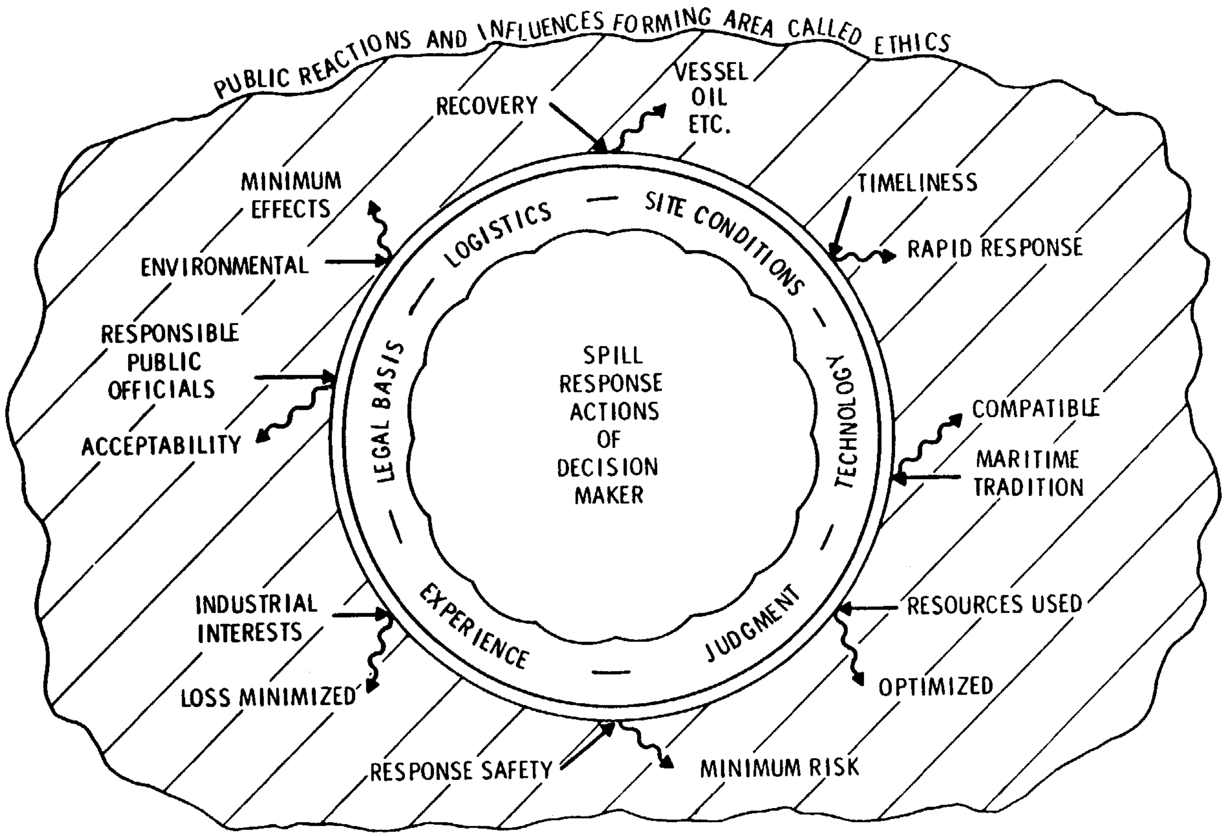


FIGURE 6.1. Ethics of Using Combustion as an Oil Spill Mitigation Tool

4. How fast can an oil pollution threat be mitigated by using the burning option and what residue is left?

5. Because of the perceived drastic nature of using burning, would not the decision maker need broad-based support locally as well as clear authority to initiate this alternative?

6. Is it not wasteful of resources to burn the oil, destroy the vessel, recover no heat or recycle material or salvage value? How can this be justified?

7. What are the effects of burning oil in the surrounding waters, shorelines, such as radiant energy, smoke precipitation, enhanced hydrocarbons released into the atmosphere, spreading of potentially dangerous material onto food crops?

8. Does the burning option place more equipment and response personnel at risk than other possible actions available for implementation, especially during inclement weather conditions?

9. What is the role for the fire department or other fire control officials in a burn response and is the technology developed to where these personnel could employ combustion using conventionally available, or modified firefighting equipment?

10. What would be the effects, when nonburning options cannot be used, of not using the burning options, i.e., doing nothing versus burning?

11. Cost is of no real importance locally or of great importance during a Federally directed response, but is there any savings if the burning option were used?

12. How far away from people or population centers does a burning operation have to take place in order to be safe and to cause a minimal amount of local public concern?

13. Who is presently available and technically competent to conduct the burning action under the three conditions studied in this report?

It is reasonable to assume that those parties who consider themselves damaged by use of the combustion spill response action will be the most interested in the ethical basis of that decision. The situation involving a stricken tanker, which is deliberately burned while reducing the cargo volume by combustion, is the most complex and has the most economic impact. Examination of the vessel interests and the complex economic subtleties, such as insurance leads to the observation that: Burning the oil cargo solely on economic grounds appears justified <u>only</u> in the extremely rare instance where the stricken vessel and cargo are owned by the same party who self insures, and it can be accurately predicted that costs of pollution resulting from breakup will far exceed the value of vessel and cargo.

Factors other than economics appear to be more important in reaching a decision on a response action. The current cost of cleaning up spilled oil is $840 to $6,720 per barrel of oil recovered. These costs cannot be ignored. The underlying ethic of recovering a valuable spilled resource seems questionable when the anticipated sales of the recovered oil is compared with its costs including: oil production and transport; spill clean up; reprocessing; and storage, handling, and retransporting. Another factor which must be considered in establishing the ethics of using combustion is the energy used to recovery energy and protect the environment. Data illustrating the number of persons using energy (derived from oil almost exclusively) to cleanup a spill must be compared with the energy recovered from the oil spill and with energy which could be dedicated to induced natural recovery from actual environmental damage. From an examination of the liability compensation funds and proposed superfunds, it may be suggested that the volumes of money available (hundreds of millions of dollars) are so large and accessible that a conflict in ethics is created between aggressive and broad environmental protection versus economic and energy conservation.

The ethical use of the oil burning spill response action has been summarized into eight issues. These issues are listed in Table 6.1. A discussion for use of burning and against burning is found in Part II, Section 7.3. It may be concluded that there can be a very solid and defensible ethical basis for including combustion in the arsenal of oil spill mitigation tools. The acceptability of this ethic is low due to lack of demonstrated technological success and due to potential inflexibility among environmental policy makers. Both of these will be overcome by technology development investments and by education based on results of generic environmental impact studies.

TABLE 6.1. Issues to Establish an Ethic

Issue 1 - Authority: for success in an oil spill response, there must be leadership which is clearly recognized, accepted, and justified as technically and administratively competent by all parties.

Issue 2 - Action: for success in an oil spill response, the speed of implementing activities should meet or beat the time required for the adverse effects to take place.

Issue 3 - Logistics: for success in an oil spill response, experienced manpower and reliable equipment and supplies with appropriate back-up support must be readily available.

Issue 4 - Safety: for success in an oil spill response, the personnel responding should be provided the maximum safety and health protection under the circumstances.

Issue 5 - Environmental/Health: for success in an oil spill response, wildlife, property, and man's health must be protected.

Issue 6 - Costs and Property Values: for success in an oil spill response, greater attention must be given cleanup expenditures in the context of values of property to be protected (including total environment) and values of property to be lost.

Issue 7 - Energy Recovery: for success in an oil spill response, the oil should be recovered, reprocessed, and used due to petroleum shortages and conservation policies.

Issue 8 - Permanent Solution: for success in an oil spill response, no secondary problems in treating, handling, or disposing should arise.

7. DECISION GUIDANCE FOR USE OF COMBUSTION

The technology has been examined for implementing an oil spill response using combustion to reduce the volume of oil cargo in a stricken tanker, and reduce the pollution potential for oil released upon water and for contaminated debris (flotsam and jetsam). Three decision trees have been prepared which summarize the findings of this study for: burning oil in situ tanker, burning oil released upon water, and burning oil-contaminated debris.

Several guidance statements apply to each of the three conditions examined. Oils can be classified by their likelihood of slick combustion into at least three categories based upon considerations of heat of combustion and heats of vaporization. It appears that combustion as an oil spill mitigation tool becomes technically feasible if:

- The subject oil classifies in the first or possibly second category.
- Response action is taken within hours after oil is released.
- Such imminent and substantiated danger exists that intervention is justified.
- The burning site is remotely located from population.
- Weather is expected to change for the worse, precluding successful completion of other alternatives.
- The volume of oil is beyond the capacity and capability of other response methods.
- Salvage operations are questionable or abandoned.
- Groundwater is too high to permit land fill burial of debris.
- Quantities and bulky characteristcs of debris make land farming too costly.
- Local authorities will permit burning debris.
- Personnel experienced in oil burning and necessary equipment and material are on scene or available within hours.

- Because of age or damage the vessel is expected to be lost or at best scrapped.
- Vessel stability, weather, and cargo pose an unreasonable risk to responding personnel.

7.1 GUIDANCE FOR IN SITU BURNING

As illustrated in Figure 7.1, the decision to burn oil in situ tanker is complex. From previous information in this section plus the information presented in the other sections such as 4.4, Part II, some quantitative guidance can be provided.

The information provided in Figure 7.1 can be explained beginning at the top of the figure. The rapid notification of the incident, within hours of occurrence, has been observed as being significant in assuring a successful response action. Oil burning in situ in a tanker is a significant undertaking and the decision maker bears an ominous responsibility. Therefore, a careful examination of the pollution threat must be made, and if it can be determined that the release is imminent and the damage would be catastrophic, burning may be justified. Under all circumstances where the Federal government decides to invoke the Act of Intervention, it must be adequately justified to not only authorities in the United States but also to international authorities, if that is appropriate.

Tradition of the sea such as No Cure - No Pay has developed the manner in which the marine salvage operators conduct their activity. Recognizing that no salvage operation is conducted as an emergency response but rather as a carefully thought out plan, the appropriateness of in situ burning may hinge upon the salvor's expertise, his availability, and his desire for success. In those cases where the marine salvor has no plan, is unsure of the rate of success, has a modified basic contract form, or in fact has abandoned the salvage operation, burning may be considered as a viable option. This consideration is not viable, however, if the personnel and equipment necessary to assure the in situ burn (Section 4.4, Part II) are either not on scene or will take days to reach the scene and assemble the material.

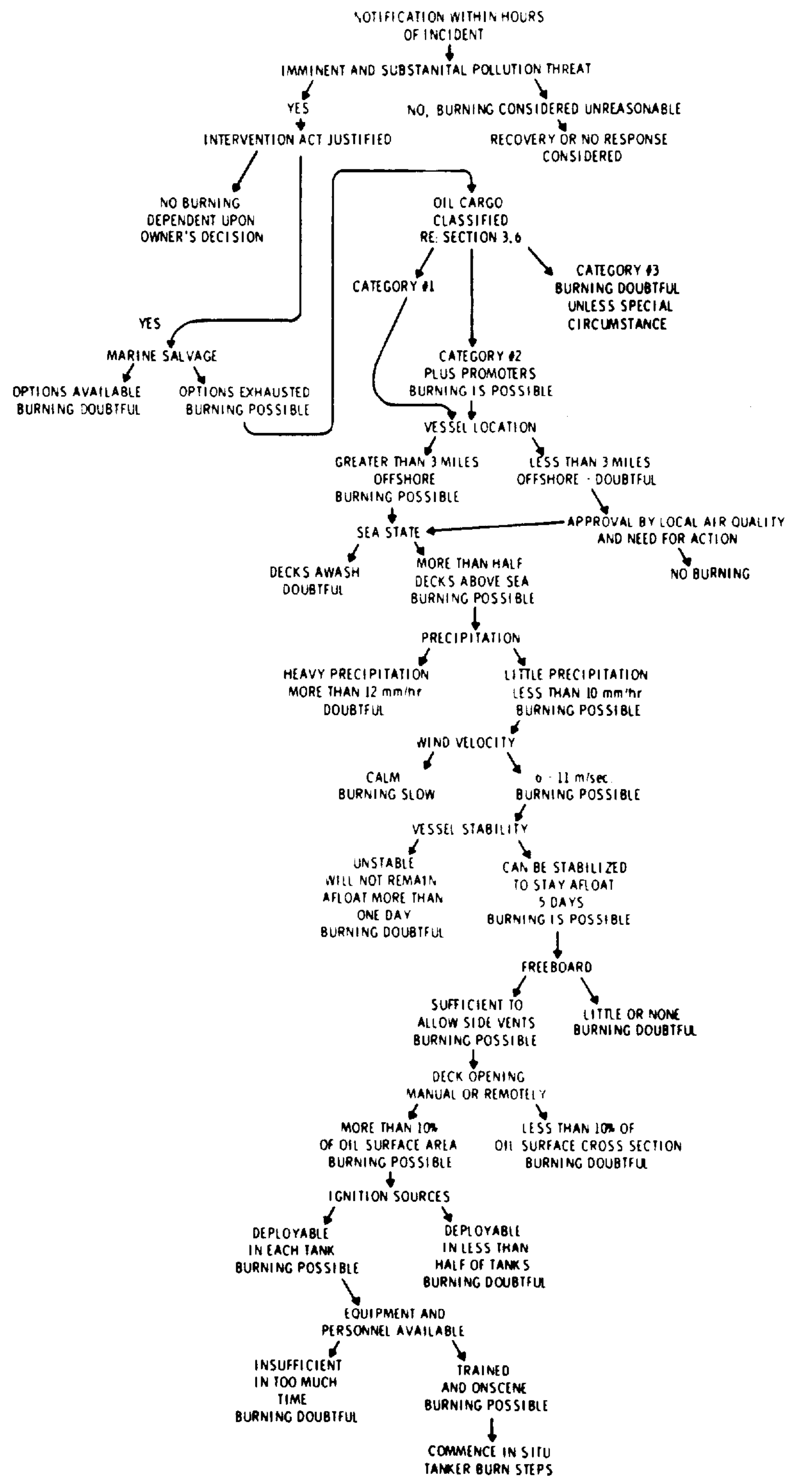


FIGURE 7.1. Options and Actions in situ Tanker Oil Burn

If intervention is justified, an examination of the oil cargo is important. As discussed in Sections 3.6 and 3.7 of Part II, the oils, both refined products and crudes, may be categorized according to their potential combustibility. It would be very conservative to conclude that a Category 3 oil is too difficult to attempt burning, and that a Category 2 oil would require considerable effort in the use of combustion promoters. Category 1 oils should provide a successful burn with limited effort dedicated to ignition, but with considerable attention directed to safety.

Vessel location becomes significant because of the potential for explosion and other safety considerations which may alarm populated areas. Based on the unfortunate incident occurring in Texas City (1949) where ammonium nitrate cargo exploded, to facilitate decision making it is reasonable to consider that burning should not be attempted in the U.S. closer to shore than 3 miles except under request by states. If the vessel is in this location and the sea state is such that at least half of the decks are above water and opening the tanks would not cause additional flooding, then burning may be possible.

Studies conducted in the United Kingdom indicated that burning is possible in precipitation up to 12 mm/hr and in a wind velocity of from 6 to 11 m/sec. Precipitation of more than 12 mm/hr and wind velocities dropping to calm will retard and complicate in situ burning.

Vessel stability and structural integrity should be assured or, if the vessel is in such a precarious situation or due to uneven burning the vessel would sink or capsize, burning is of doubtful value. Casualty work by salvors indicates that not too much attention is required to avoid capsizing. Improper ballasting or unloading in an particular seaway could cause vessel breakup and is therefore of great importance. Since the burning rate is limited, evaluation should be made which would assure that the vessel would stay afloat long enough for the in situ burn to take place. Studies on large-scale model tanks have indicated that it would be reasonable to assume that 5 days would be needed to burn oil cargoes in tanks which are the size being encountered in contemporary tankers. Experience of organizations such as British Petroleum has been that only under the most rare circumstances is a severely grounded vessel offloaded and successfully put back into service. This consideration should be included in the burning evaluation.

Freeboard is an important consideration for in situ burning based on studies indicating that side vents are necessary to maintain a high burning velocity. Information has yet to be produced which would demonstrate for the VLCC or ULCC sized tankers that multiple deck openings would not be sufficient alone to provide the necessary oxygen to ensure combustion. Side vent openings may be a technique which will by necessity be delayed in its application until sufficient oil is burned to allow the vessel to rise in the sea and expose more hull area. The deck opening is an obvious requirement for any in situ tanker burn. At least 10% of the horizontal cross-sectional surface area of the oil must be exposed by deck removal. Techniques have been discussed for doing this manually with personnel aboard the vessel or remotely from vessels and aircraft. Procedures and materials have yet to be demonstrated for safe use aboard a tanker.

The ignition sources, assuming the cargo does not ignite upon deck opening or venting actions, must be deployed in a sufficiently large number of tanks to ensure a uniform and balanced burning. Recognizing that not all ignition sources can be guaranteed to operate, it seems reasonable that if ignition sources may be deployed in less than half of the tanks intended to be burned the in situ burning option is questionable.

Reviewing again the elements in Figure 7.1, it is possible to construct the sequence of events which would assist an OSC in making a decision to commence an in situ tanker burn.

7.2 GUIDANCE FOR BURNING OIL RELEASED ON WATER

The type of oil, quantity, thickness, and age are most important to know. This information can then be used to evaluate the potential combustibility. As shown in Figure 7.2, quantitative decision points are given which are derived from information contained in Part II and engineering judgment. The combustibility of the oil must be considered in reference to spill site location.

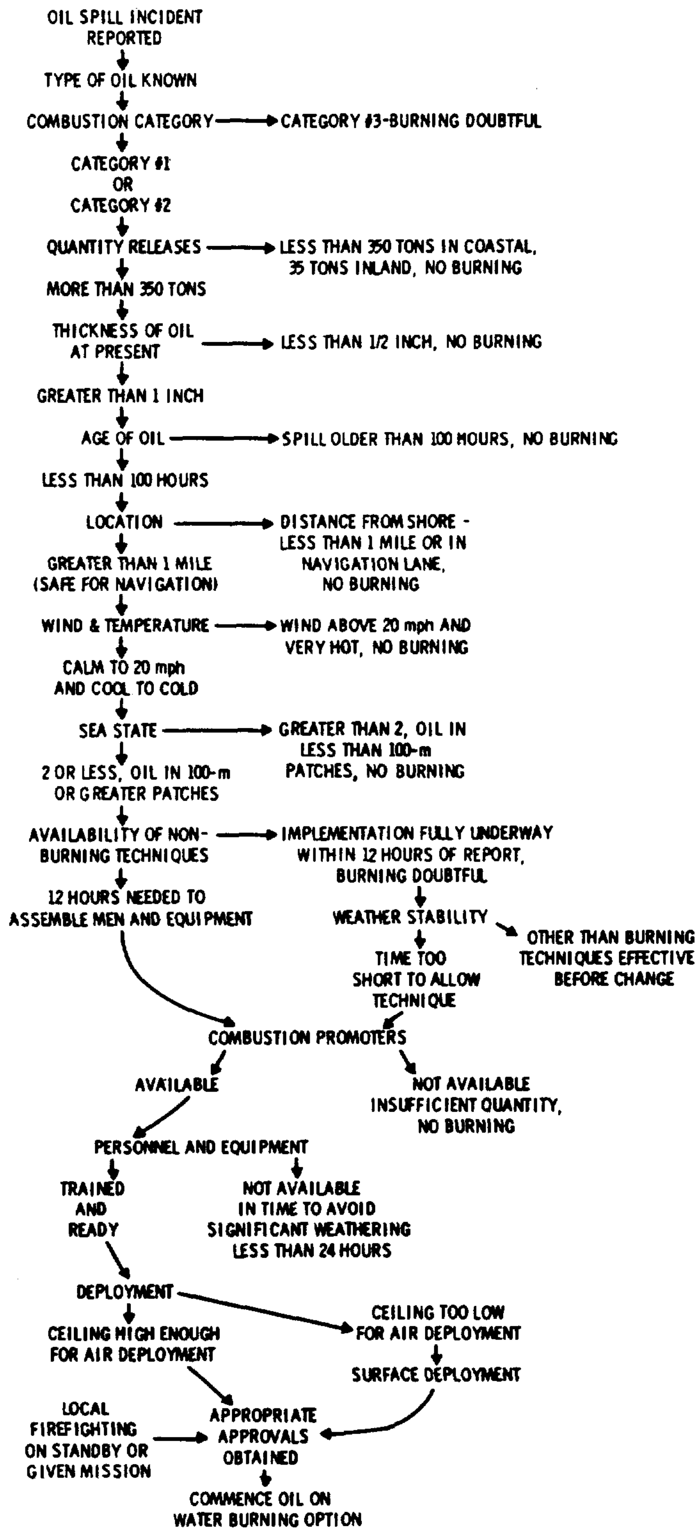


FIGURE 7.2. Oil on Water Burning Evaluation

Among the advantages which burning offers is timeliness, and therefore if the responding personnel are unable to effect the burn quickly much of its usefulness is lost. The weather can work both for and against burning. Unstable weather may not allow sufficient time to implement nonburning techniques. However, without additional technological evolution, the available combustion systems are also limited by severe weather. A key to the successful burn is selection and deployment of combustion promoter systems, not just wicking agents, which are designed to take advantage of the class of oil, the location, and the meterological conditions. At present, these systems are required to be discussed by the OSC and his advisors during the incident.

Since there is some additional degree of risk created by using a response technique which is potentially faster and less costly, special attention must be given to response personnel qualifications and readiness of equipment as well as local firefighting capabilities. Consultation and even mission assignment to local firefighting companies may be feasible during proper contingency planning which would allow these specialists to be involved and on standby, if an unforeseen situation developed. Approvals should pose no problem if the OSC is effectively using a regional or local response team consultation technique as defined in the National Contingency Plan (40 CFR 1015).

7.3 GUIDANCE FOR COMBUSTION OF OIL-CONTAMINATED DEBRIS

Debris requiring disposal as a result of oil contamination can range from beach sand to large bulky objects and wildlife and cleanup materials. As shown in Figure 7.3 after an oil spill has been reported another element of importance is the direction in which the oil moves. If the oil is washing ashore or is anticipated to wash ashore, the debris disposal problem is created. Onscene observation during the ARGO MERCHANT incident demonstrated the concern for handling debris, as there was literally a small army of personnel standing by if the oil were to head for shore. At that point in time the type of oil became significant relative to the burning option. Because of

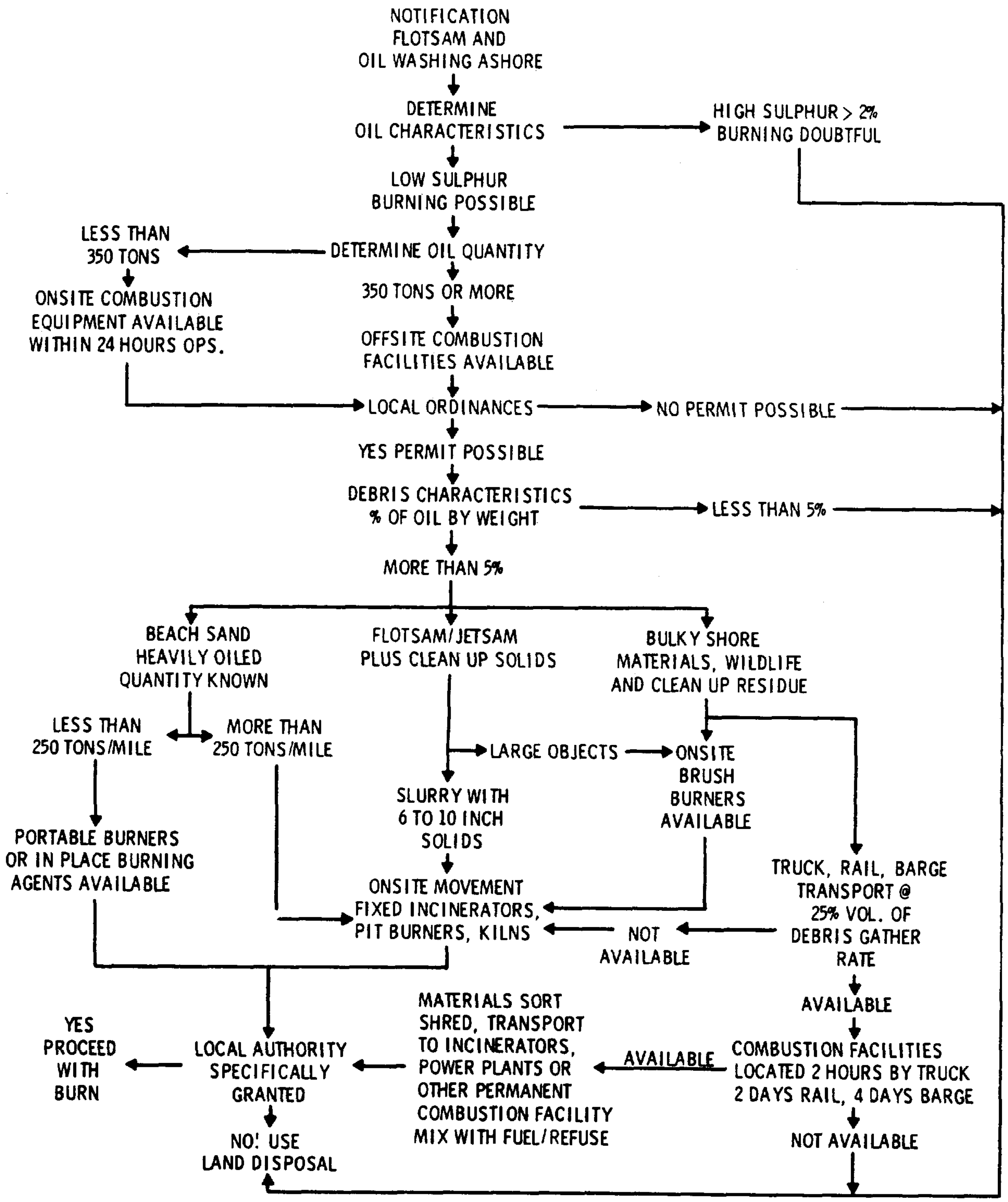


FIGURE 7.3. Oil-Contaminated Debris Burning Evaluation

local ordinances and Federal standards on air emissions and for reasons pertaining to the use of existing incinerator facilities, the sulfur content of the oil is important. The quantity of the oil is significant from the standpoint of the demands of men and material as well as logistics involving transportation and disposal areas which are required. Three hundred and fifty tons is a quantity of oil regarded as a major marine oil spill. It is reasonable, therefore, to consider that less than 350 tons would be an oil spill that would be amenable to onsite handling unless there were extenuating circumstances. Onsite combustion should be immediately initiated and, therefore, equipment should be available and in operation within 24 hr if that response is to be effective. The offsite combustion facilities such as municipal incinerators, power plants, commercial industrial incinerators, etc., are listed in other references and their availability should be determined. However, the burning option is of no value if there are stringent local ordinances which do not permit combustion. In these cases, as shown in Figure 7.3, land burial or farming must be the preferred method of disposing of oil-contaminated debris.

If local ordinances permit combustion, the decision may still be modified by the debris characteristics. If the debris contains less than approximately 3% oil by weight, the debris represents essentially the same type of disposal problem that flotsam recovered from a harbor presents. Land application may in that case be the most economical option to choose. If, however, there is more than 3% oil by weight, this oil-soaked debris poses problems not normally encountered in shoreline debris recovery programs.

Beach sand which has become heavily oiled poses a rather unique problem which can be handled both onsite and at another location. It is reasonable to assume that on a per mile basis if something less than 200 tons of oil have come ashore, portable burners, in-place burning or other systems which use manpower and highly mobile systems may be employed. If, on the other hand, more than this quantity of oil per mile is discharged, then transportable or remotely located systems should be considered. None of these combustion systems can be fully satisfactory because of the resulting ash and oil residue if the beach is used for recreation. Work is under way in the U.K. to make available a steam stripper/oil-water separator which avoids this problem.

Debris that could be characterized as drift materials such as sorbent pads, broken booms, seaweed and other debris which is left behind after the oil spill cleanup activities are candidates for combustion by transportable, stationary onsite combustion systems. If the material has a consistency of a slurry with solids no larger than 6 to 10 in., technology is readily available to handle this material quite efficiently onsite.

Materials such as large objects in shoreline debris and dead wildlife may be handled using onsite brush burner type equipment, or for the large concentrated quantities of materials, transportation and processing in existing combustion facilities may be the option. For the existing facility option to be viable, transportation must be carefully evaluated. To avoid delays in transport and reintroduction of oil from the contaminated debris gathered into the waters, a 25% excess volume in the transportation system should be available. It is desirable that the combustion facilities be located no farther than 2 hr by truck, 2 days by train, and 4 days by barge. These times are significant because of cost and the transportation system's availability to have equipment tied up for period of time. If this transportation system is not available, or the combustion facilities are not within that range, onsite combustion or transportation for local land applications should be strongly considered.

8. NEEDS OF OIL COMBUSTION RESEARCH AND TECHNOLOGY DEVELOPMENT

The research and technology development needs in this field are rather extensive and therefore only a brief reference or listing of the types of work will be included. These observations are based upon the conclusion that there are times and circumstances where combustion, used in place of current techniques, offers advantages of safety, speed, economy, and environmental protection. Several groups of specialists expressed the desire that a central research coordination function be established to enable basic fire research interests and pollution abatement interest to avoid duplication of efforts. This discussion is divided into: 1) research data which should be gathered and published, and 2) technological concepts which should be developed and evaluated.

8.1 RESEARCH DATA GAPS

This study has revealed that additional measurements and/or publication of the following information would be of significance to those persons interested in using combustion as an oil spill mitigation tool.

- Confirm measurements of heat of combustion and heat required for combustion (cal/g) with time of combustion for a sufficient number of crude oils and fuels that predictive relationships may be accepted.
- Measure large-scale hydrocarbon pool fire (20 to 60 m diameter) radiation back to pool under a variety of flame conditions and geometry.
- Measure ignition and fire points as a function of weathering (selected volatile fractions missing) and also under documented variable environmental conditions and include assessments of oxygen limitations for combustion of confined and unconfined pool fires.
- Measure large-scale pool fire ignition using intense high energy releasing (incendiary) type combustion promoters and sustained lower energy releasing combustion promoters.

- Measure large-scale pool fire heat transfer to confirm findings of researchers during the late 1950s and to validate small pool fire observations.
- Develop practical understanding of the rate and extent of emulsion forming mechanisms with the view that this understanding would aid oil spill response including combustion efforts.
- Develop empirical data to correlate combustibility with "breakeven point" data; i.e., where should the boundary be between Category 1, 2, and 3 for most oils.
- Conduct sufficient health-related investigations to establish a factual basis for air pollution concerns or lack thereof when oil burning is to be considered.
- Develop theory and verify effects of altering oil slick radiant energy absorptivity, e.g., using carbon black.
- Develop the relationship and produce data which could be used for approximating the "activation" energy necessary to ignite and sustain the combustion of an oil which is amenable to burning under a variety of environmental conditions.
- Develop sufficient data on hazardous materials and substances other than oil to enable the burning option to be safely considered for response or justifiably rejected.

8.2 TECHNOLOGY DEVELOPMENT

This study has documented the state-of-the-art of several technological areas and assessed the commercial availability of such technology. Concepts which should be individually examined and are candidate for applications in oil spill burning are noted below.

- Test munition systems systematically for both in situ tanker and oil on water combustion. The Canadian-air deployable incendiary study should serve as a basis.

- Demonstrate the feasibility of using precision guided conventional missiles to puncture and ignite oil in tankers as a completely remotely directed and rapidly implemented response.
- Demonstrate safe and effective deployment of explosives aboard ship to open decks, side vents, and ignite the cargo with the view that salvage type personnel may implement such technology.
- Demonstrate the safety and effectiveness of using offloading flares, taking advantage of experience of France, South Africa and the United Kingdom: a) flares which would be emergency installed and used during the incident; b) flares which could be part of the vessel's equipment; and c) existing procedures and equipment used by marine salvors should be modified and demonstrated for successful flare application.
- Demonstrate the effectiveness of barrier or combustion promoter designs which would increase the radiant energy reflected back to the pool.
- Demonstrate effectiveness of systems which could minimize the spreading of oil under burning conditions.
- Demonstrate the use of commonly available fertilizers and hydrocabons to serve as combustion promoters such as ammonium nitrate/diesel fuel for oxidizer explosives to be used in controlled burns.
- Revise USCG "CHRIS" manuals to include oil classification data for burning and steps to achieve oil combustion.
- Demonstrate the effectiveness of physical/chemical means of rapid ignition, e.g., spontaneous combustion materials, lasers, tactical weapons or other means of compact energy addition to allow oil combustion in situ in tankers or on water.
- Demonstrate the effectiveness of removal or modification of the emulsification potential of oil cargoes to reduce "chocolate mousse" formation from oil released on water.

- Demonstrate the effect of a surrounding rim on the combustion of large pool fires.
- Demonstrate the effectiveness of small to medium size air or vessel deployable, self-contained, and remotely operated floating oil spill combustion systems which derive, in part, their power from the oil spill combustion.
- Demonstrate the harm or lack thereof to municipal facilities by infrequent incineration of oil-contaminated debris with a variety of oils and mixture ratios.
- Develop and demonstrate the effectiveness of intertidal or littoral zone burning where 80% water exists in emulsion using high ignition energy composite wicking agent combustion promoters.
- Demonstrate the relative effectiveness of combustion promoters such as wicking agents which are designed and deployed to produce several small independent fires versus the conventional approach of one fire.
- Demonstrate the quantitative effect of optimal wicking agents on the amount of heat of combustion received by the pool, i.e., relationship of α to wicks used.
- Demonstrate the use of an emulsion breaker (heater-treater) fueled, in part, by removed oil and/or debris usable in beach cleaning incidents.
- Given the ranges of "activation" energy necessary to ignite and sustain an oil burn, demonstrate the most cost effective, safe, and efficient delivery systems noted from research of principle above.
- Demonstrate the most effective deck venting procedure for VLCC and ULCC updating 1970 U.K. work on small tanks which required side vents to assure combustion oxygen.
- Demonstrate an oil/water soluble micro-encapsulated ignition agent/ combustion promoter to sustain aged Category No. 2 and Category No. 3 oil burns.

PART II

THEORY, BASIS, AND EVALUATION

PART II

THEORY, BASIS AND EVALUATION

Part II provides a resource document and includes several appendices. References cited are combined with the Bibliography (Appendix B).

The study covered a wide range of technical areas and without the common base of information provided here the several specialists and disciplines would be free to complicate matters by developing and using a variety of terminologies expressing similar ideas. This collection of information should provide a broad enough and documented base to enable attention to be focused on future development rather than review of past or current actions. The details of the study include: history and statistics of the oil spill problem; theory of combustion and movement of oil slicks; examination of technological tools and procedures available for burning oil (in a tanker, released onto water, or contaminating debris). Gaps in technology and research are given and ethical considerations involved in using burning are discussed.

1. INTRODUCTION

Whenever a major ocean oil spill occurs, attention is directed to a variety of related topics such as tanker casualties; damage to amenities of the sea; effects on living marine resources; personnel safety at sea; public welfare; and the effectiveness of available countermeasures. Because of concern for these topics, the all too familiar news items explaining that another vessel has encountered problems and is releasing its cargo into the water continually challenge responsible officials at all levels, both public and private. A recent study for the Department of Energy (DOE), Environmental Control Technology Division, on energy materials transport through the year 2000, concluded that an adequate oil spill control arsenal does not exist (DeSteese et al., 1979). Even prior to that, the Federal government recognized this deficiency. As a consequence, DOE and the United States Coast Guard (USCG) have established programs to assess the problems of oil spills and are actively developing information and understanding as they implement contemporary solutions. This study explores the technical feasibility of one of these solutions, i.e., use of combustion or burning of oil involved in a pollution incident. The many other contributors and reviewers of this work are listed in Appendix A.

The experience gained by the USCG, with emphasis on the December 1976 grounding of the tanker, ARGO MERCHANT, off the East Coast of the United States, underscored the need for a better understanding and documentation of the state-of-the-art in using combustion for oil spill mitigation. As a result, both DOE and USCG are interested in practical information and theoretical explanations which can be used to determine the range of conditions under which the commonly transported distillate fuels, residual fuels, and crude oils are burnable at sea.

1.1 SCOPE OF STUDY

This report has been prepared with full recognition that public and private resource priorities are, in practice, placed upon preventing the release of oil cargoes and in recovery of those cargoes when they are discharged. At the same time, it recognizes the all too clear lesson learned from recent spills such as that from the ARGO MERCHANT: spills will continue to occur, and a significant number will defy recovery. Hence, alternatives such as the use of combustion must also be available. The scope of this investigation is set on three general applications of combustion technology pertaining to oil spills:

1. in situ burning of oil contained in a wrecked tanker which poses an unreasonable risk
2. pool burning of oil released from containment, (not necessarily from a vessel) which is spreading upon water or ice
3. incineration or open burning of oil that has contaminated debris (flotsam and jetsam) and washed ashore.

Investigations into these subjects following the Torrey Canyon incident in 1967 were conducted by a joint United Kingdom/Institute of Petroleum Working Group on Burning Oil. The results of that work are directly related to this project and their pioneering research in 1970 has proved a valuable reference and guide. Significant work has also been performed by the Environmental Emergency Branch of the Canadian Environmental Protection Service in applications and evaluations of oil burning, particularly related to the Arctic Marine Oil Pollution (AMOP) program through April 1979. Some of the results of their investigations have been included in this study. Because of those efforts on burning oil in and under ice, that aspect of burning has been minimized in this study. Other than a few commercial interests there have been few U.S. developments in the field since the U.S. Department of Transportation received recommendations on the need for a more fundamental understanding of the burning process (Arthur D. Little, Inc., 1969).

A broad range of literature, programs, and disciplines was required to provide an adequate theoretical and practical basis of study. These areas included fire researchers, munitions experts, marine engineers and salvors, pollution control experts, engineering response personnel, equipment manufacturers, patent searchers, mathematical modelers, and others. Each of these fields could represent a major study on the topic itself. Thus, as a means for further review of individual fields an annotated bibliography has been included (Appendix B).

1.2 NATURE OF THE PROBLEM

The nature of the oil burning problem develops many significant variables, not the least of which is the complexity of oil. Oil is too simplistic a term to be rigorously applied throughout this study. Visual appreciation of how inadequate one word is to describe the materials under study may be gained by careful examination of the Fuel Oil News reprints of March 1977 (Figure 1.1, Part I). This picture illustrates the variety of crude oils. In addition to the wide range of chemical/physical properties of the various crude oils, many of the refined petroleum products must also be included due to their individual pollution effects and spill potential. Only for the sake of brevity will the term, oil, be used in this study and then it should be understood that reference is being made, very broadly, to petroleum hydrocarbons generally described as distillate fuels, residual fuels, or crude oils. Due to the complexity of oil, portions of this report are dedicated to summarizing properties of significance.

To assist in establishing a common basis of understanding, the nature of the oil burning problem may be delineated by the following observations and assumptions:

Trends in Spills

- The demand for oil continues to increase and more sources are being exploited for the established markets; thus increased demands are placed on transportation and handling, subsequently raising the potential for mishap.
- Very Large Crude Carriers (VLCC) are now in common use as tankers and there is no decrease in this practice, hence the continued potential for large releases of oil now and in the foreseeable future.
- Tankers which are much smaller than VLCCs operate close to shore; a majority of these small tankers are more than 20 years old and often are

alleged to be involved in a perplexingly high loss trend in waters of particular value to living marine resources and amenities.

- Environmental and safety authorities have united through international conventions, and bilateral and regional agreements, to assure that oil spills are prevented and that any oil released is removed or the damage mitigated.
- Costs of spill prevention measures can be viewed as significant to an industry that could be characterized as purchasing and operating equipment which is: 1) often more than 20 years old; or 2) of such excess capacity that about a fifth of the VLCC fleet lies at anchor with little hope of a cargo; and 3) about a tenth of the world's tankage is dormant.
- Because human error causes many of the vessel oil pollution incidents, even with improved equipment oil spills will continue to occur.
- Spill cleanup costs continue to rise as public demands for post-spill action persist along with inflation.

Practical Aspects of Implementing a Burn

- Burning a vessel to mitigate pollution is a concept abhorred by public and private maritime authorities and is regarded as a "last-resort" consideration.
- Cleanup activities can be difficult and hazardous since oil spill response efforts are often required during severe meteorological conditions (often a contributing factor in the incident). This increases the incentive for development of alternatives which can operate under adverse conditions.
- Maritime traditions have established that the more hazardous the conditions and the more valuable the cargo, the greater is the award to the salvor on a "No Cure - No Pay" basis, which implies that considerable time will be provided to allow all reasonable efforts to be made to save life, ship, cargo, and property.
- Experience on the use of burning as an oil spill mitigation tool has been offered by organizations or individuals with a general pollution control

overview responsibility for all countermeasures, or with a specific proprietary interest, and seldom are the scientific data provided to explain a success or failure of the application.

- Types of oil and exact conditions contributing to success or failure are often not presented and may not be known.
- Weathering of discharged oils as a result of response decision delays further complicates successful combustion. This time-dependent phenomenon is difficult to control due to meteorological conditions at the spill site or due to the traditions of response which have evolved.
- Basic fire research is relatively new and has been primarily focused upon understanding combustion principles with a view to controlling fire such as observed during pool fires, spreading, and effects on structure, which suggests that these theories and observations require careful interpretation to be applied to the oil burning problems.
- Modeling combustion, like modeling oil slick movement, is under development and additional work is needed before heavy reliance can be placed upon these tools, but sufficient evidence of progress is available to be optimistic.
- Local authorities and potential damage to existing incinerator facilities can prohibit the use of incineration which often is regarded as the most effective and desirable method of disposal of oil-contaminated debris ranging from a few cubic feet to more than 50,000 yd^3 from a single oil spill. The debris may include dead birds, fish, mammals, seaweed, cleanup materials, contaminated sand and other materials.
- Those required to make decisions involving the use of burning have little information available pertaining to equipment, economics, institutional roles, actual step-by-step procedures, or the status of promising research concepts.

1.3 STUDY APPROACH

The study approach for this project was based on the above observations. Considerable national and international correspondence was used in addition to a comprehensive literature search. No laboratory work was included in this current study. Extensive efforts were made to directly interview other researchers and obtain up-to-date reports. Attendance at selected conferences provided another source of information.

Much of the available information on oil and oil spill statistics comes from case histories and manufacturers' experience (Section 2). Since much of the literature is related to oil spill pollution control, it did not provide the thermodynamic data thought necessary to explain successes or failures of burns. Consequently, a generic burning model was considered to be of value (Section 3).

A review of oil slick movement models resulted in a combined combustion/movement analysis (Section 3). This modeling served as a framework to identify the key combustion variables involved in burning oil under the three study conditions. Once the variables were defined basic fire research literature could be used to obtain quantitative estimates. Comparisons could then be made with the available limited field data to ensure that the model was approximating the oil burning phenomenon or that the significant variables were identified.

A classification of the variety of oils was conducted to determine burning potentials. Circumstances which would affect the burning potential were considered in a range of oils from the heaviest to the lightest (Section 3).

Efforts spent in gathering equipment specifications resulted in summary listings of their availability and limitations (Section 4). Included in these equipment considerations are uses of military weapons as well as civilian equipment and procedures.

The status of research by other countries (Section 5) provided additional background for studying the technical feasibility of oil combustion. The feasibility of using burning technology was approached by gathering information on past successes and failures (Section 6). Detailed examination of documents such as Onscene Coordinator Reports provided an understanding of actual case histories which employed or might have employed oil burning. The feasibility assessment was based upon preparation of event/time sequences of conventional response actions. These considerations determined equipment and logistical support needed to use the combustion tool. Environmental implications of using the technology, laboratory or field testing of promising techniques and detailed fundamental modeling research were not included in this study.

The final effort was to provide an "ethic" of oil burning (Section 7). This section was prepared to illustrate the concerns that must be met by an OSC having acceptable oil burning technology - should it be used?

2. STATISTICS OF OIL AND SPILL INCIDENTS RELEVANT TO OIL BURNING

As is often the case, evaluation of oil spill data and combustion information requires judgment since there are many conflicting reports and generally confusing claims. The literature which is most directly applicable to oil burning as a spill mitigation tool may be characterized, in general, as case histories of field trials and manufacturers experience reports. It is not surprising to find little generalized scientific information other than an individual reporter's own experience or speculation.

The purpose of this section is to provide a basis for evaluating combustion in the context of current situations. Accordingly, facts, statistical evaluations and observations are presented which illustrate:

- types and quantities of oil moving - particularly in and around U.S. waters
- vessels involved in oil transport
- discharges of oil and trend implications.

An annotated bibliography (Appendix B) is included in this report to assist in establishing the technical feasibility of oil burning. The bibliography should provide an appreciation of the diversity of pertinent literature and direct leads for researchers to explore.

Appendix C contains case histories to show possible as well as actual applications of burning. Detailed time/event sequences are given to illustrate the opportunities for burning that could have been used on major documented incidents.

2.1 TYPES OF OIL

To document the extent and variety of materials often referred to under the term, oil, consider that there are well over 100 export streams of crude oil that could enter the U.S. In addition to the crude oils (see Figure 1.1, Part I) there are the various refined fuels and products. As noted in Table 2.1 (Oil and Gas Journal, 1976) the shipping points are all over the world and the properties of the oils vary accordingly. Properties also vary with oils from a single geographical area as evidenced in Table 2.2, which

TABLE 2.1. Crude Oil Export Streams

Most Common Designation of Crude Stream	Producing Country	Gravity °API	Shipping Point
Amna	Libya	36.1	Ras Lanuf, Libya (SBM)
Anguille	Gabon	32.0	
Arabian heavy	Saudi Arabia	28.2	Ras Tanura, Saudia Arabia
Arabian light-Berri	Saudi Arabia	38.8	Ras Tanura, Saudia Arabia
Arabian light	Saudi Arabia	33.4	Ras Tanura, Saudia Arabia Juaymah, Saudi Arabia (SBM) Sidon, Lebanon
Arabian medium	Saudi Arabia	30.8	Ras Tanura, Saudia Arabia
Arabian medium-Zuluf	Saudia Arabia	30.7	Zuluf field (SBM)
Arjuna	Indonesia, Java	37.7	Arjuna field (SBM)
Arzew blend	Algeria	44.3	Arzew, Algeria
Attaka	Indonesia, East Kalimantan	43.2	Santan Term., E. Kali
Bachequero, 16.8° API	Venezuela	16.8	LaSalina, Venezuela Bachequero, Ven. (13°API) Puerto Miranda, Ven.
Bai Hassan Jambur	Iraq	34.1	Tripoli, Lebanon
Bu Attifel	Libya	40.6	Zueitina, Libya
Basrah	Iraq	33.9	Khor al Amaya Iraq (SBM)
Bekapi	Indonesia, East Kalimantan	41.1	Field (SBM)
Beryl	U.K.	39.5	Beryl field (SBM)
Bonny light	Nigeria	37.6	Bonny, Nigeria (SBM)
Bonny medium	Nigeria	26.0	Bonny, Nigeria (SBM)
Boscan	Venezuela	10.3	Bajo Grande, Ven.
Brass River	Nigeria	43.0	Mouth of Brass (SBM)
Brega	Libya	40.4	Marsa el Brega, Libya (SBM)
Bunju	Indonesia, East Kalimantan	32.2	Balikpapan, E. Kali.
Burgan (Wafra)	Neutral Zone	23.3	Mina Saud, Neutral Zone
Cabinda	Angola (Cabinda)	32.9	Molongo field (SBM)
Cinta	Indonesia, Sumatra	32.0	Field (SBM)
Cyrus	Iran	19.0	Field (SBM)
Darius	Iran	33.9	Kharg Island, Iran
Dubai	Dubai	32.5	Field (SBM)
Duri	Indonesia, Sumatra	20.6	Dumai, Sumatra
Ecuador crude (Oriente)	Ecuador	30.4	Puerto Balao/ Esmeraldas, Ecua.

TABLE 2.1. (contd)

Most Common Designation of Crude Stream	Producing Country	Gravity °API	Shipping Point
Ekhabinskaya	U.S.S.R	30.7	Okha, Sakhalin, U.S.S.R.
Ekofisk	Norway	35.8	North Tees, U.K.
El Bunduq	Abu Dhabi	38.5	---
Emeraude	Congo (Brazzaville)	23.6	Djeno, Congo (SBM)
Eocene	Neutral Zone	18.6	Mina Saud, N.Z.
Escravos	Nigeria	36.2	Escravos River, Nigeria (SBM)
Es Sider	Libya	37.0	Sidra, Libya
Fereidoon blend	Iran	31.0	Kharg Island, Iran
Forcados blend	Nigeria	30.5	Forcados, Nigeria (SBM)
Fortiers	U.K.	36.6	Firth of Forth, U.K.
Gamba	Gabon	31.8	Gamba (SBM)
Gulf of Suez blend	Egypt	31.5	Ras Shukheir, Egypt
Handil	Indonesia, E. Kalimantan	30.8	Field (SBM)
Hassi Messaoud	Algeria	44.0	Bougie, Algeria
Hout	Neutral Zone	34.1	Ras Khafji, N.Z.
Iranian heavy	Iran	30.8	Kharg Island, Iran
Iranian light	Iran	33.5	Kharg Island, Iran
Isthmus (see Reforma)			
Jatibarang	Indonesia, Java	28.9	SBM
Kerindingan	Indonesia, E. Kalimantan	21.6	Santan Term., E. Kali.
Khafji	Neutral Zone	28.7	Ras Khafji, N.Z.
Kirkuk	Iraq	35.9	Banias, Syria, Tripoli, Lebanon
Klamono	Indonesia, Irian Java	18.7	---
Kuwait	Kuwait	31.2	Mina al Ahmadi, Kuwait
Labuan light (Samarang)	Malasia, Sabah	36.0	Labuan, Sabah (SBM)
Lagomedio	Venezuela	32.0	Puerta de Palmas, Venezuela
Mandji blend	Gabon	29.0	Cap Lopez, Gabon
Melahin	Indonesia, E. Kalimantan	24.7	Santan Term., E. Kali.
Minas (Sumatran light)	Indonesia, Sumatra	35.2	Dumai, Sumatra
Montrose	U.K.	41.9	----
Mubarras	Abu Dhabi	38.1	Field SBM
Murban	Abu Dhabi	39.4	Jebel Dhanna, Abu Dhabi

TABLE 2.1. (contd)

Most Common Designation of Crude Stream	Producing Country	Gravity °API	Shipping Point
Ninian	U.K.	35.1	---
North Rumalia	Iraq	34.3	Fao/Khor al Amaya, Iraq
North Slope	U.S.A.	26.8	Valdez, Alaska
Oman	Oman	34.7	Mina al Fahal, Oman
Pennington	Nigeria	37.7	Apoi (offshore)
Poleng	Indonesia, Java	43.2	Surabaja
Piper	U.K.	0.08467 (S.G.)	Kirkwall, Orkney Is.
Qatar land (Dukhan)	Quatar	40.9	Umm Said, Qatar (SBM)
Qatar marine	Qatar	37.0	Halul Island, Qatar (SBM)
Qua Iboe	Nigeria	37.4	Qua Iboe, Nigeria (SBM)
Ratawi	Neutral Zone	23.5	Mina Saud, N.Z.
Reforma (Cactus Reforma)	Mexico	33.0	Parajaritos, Mexico
Romashkinskaya	U.S.S.R.	32.6	Ventspils (Baltic) Odessa, U.S.S.R.
Rostam	Iran	35.9	Lavan Island, Iran
Sarir	Libya	36.5	Marsa el Hariga, Libya
Sassan	Iran	33.9	Lavan Island, Iran
Sepinggan	Indonesia, E. Kalimantan	37.9	Lawi-Lawi Term., E. Kali.
Seria light	Brunei	38.8	Field SBM
Statfjord	Norway	38.2	---
Sirip blend 27.1° API	Iran	27.1	Ras Bahrgan, Iran (SBM)
Taching	China (PRC)	33.0	Dairen, China
Tarakan (Pamusian)	Indonesia, E. Kalimantan	19.5	Tarakan Island
Tembungo	Malaysia, Sabah	37.4	Field (SBM)
Thistle	U.K.	37.4	---
Trinidad blend	Trinidad	33.6	Point Galeota, Trinidad (SBM)
Tyumen	U.S.S.R	34.0	---
Umm Shaif	Abu Dhabi	37.6	Das Island, Abu Dhabi (SBM)
Walio Export Mix	Indonesia, W. Irian	35.4	Kasim Term., W. Irian
Zakum	Abu Dhabi	40.1	Das Island, Abu Dhabi
Zarzaitine	Algeria	42.0	La Skhirra, Tunisia
Zueitina	Libya	39.0	Zueitina, Libya (SBM)

Source: Oil and Gas Journal 1976

TABLE 2.2. Venezuelan Crude Oils

Light Oils

Export Stream	Gravity, °API	Shipping Port
Aguasay	38.6	Pto. La Cruz
Anaco	42.4	Pto. La Cruz
Bloque 17	37.8	Pta. Palmas, La Salina, Pto. Miranda
Bloque 10-17	37.7	Pta. Palmas, La Salina, Pto. Miranda
Centro Logo	38.0	Pto. Miranda, La Salina, Pta. Palmas
Ceuta (3)	30.4	Pto. Miranda, Pta. Palmas
Cretaceo (18)	44.0	Pto. Miranda, La Salina, Pta. Palmas
Guanipa (9)	30.6	Pto. La Cruz
Ipire	33.5	---
Lagomar (5)	31.6	La Salina, Pto. Miranda, Cardon
Lagomedio (1)	32.8	Pta. Palmas, Pto. Miranda, La Salina
Lagotreco	31.4	Pto. Miranda, Cardon
Lama	32.6	Pta. Palmas, Pto. Miranda, La Salina
Lamar	37.0	La Salina
Mata	30.1	Pto. La Cruz
Mercedes	29.4	---
Mesa	30.1	Pto. La Cruz
Mezcla Boscan	32.8	Bajo Grande
Oticina	36.2	Pto. La Cruz
Ruiz	31.8	Pto. La Cruz
San Joaquin	42.3	Pto. La Cruz
Tia Juana Light (7)	33.4	La Salina-Amvay
Tucupido	36.0	---

Medium Light Oils

Export Stream	Gravity, °API	Shipping Port
Area LL-980	26.6	---
Barinas	25.5	El Palito
Bombai	19.6	---
Cabimas	20.0	Pto. Miranda
Guanipa (16)	23.4	Pto. La Cruz
Hombre Pintado	26.6	---
La Rosa (12)	24.2	La Salina, Pto. Miranda, Pta. Palmas
Lago mix medium (11)	23.4	La Salina, Pto. Miranda, Pta. Palmas
Leona	24.0	Pto. Miranda

TABLE 2.2. (contd)

Medium Light Oils

Export Stream	Gravity, °API	Shipping Port
Marlago	27.4	Pto. Miranda, Pta. Palmas
Mata	21.8	Pto. La Cruz
Merey	18.3	Pto. La Cruz
Mara	26.4	La Salina
Mara heavy	18.1	La Salina
Bachaquero Ceuta mix	24.0	Pto. Miranda, Pta. Palmas, La Salina
Leona Merey mix	21.6	Pto. La Cruz
Bachaquero-Lagunillas mix	22.5	Pto. Miranda, La Salina
Tia Juana-La Rosa med.-Bachaquero-Lagunillas mix	23.5	Pto. Miranda, La Salina
Boscan mix (4)	23.5	Bajo Grande
La Rosa Lagunillas mix (17)	23.7	La Salina
Oritupano	18.9	Pto. La Cruz
Oscurate	23.2	Pto. La Cruz
Silvestre	26.4	El Palito
Socororo	27.7	El Palito
Temblador	19.4	Pto. Ordaz
Tigre	24.5	Pto. La Cruz
Tia Juana 102, Lo P. (19)	25.2	La Salina, Amvay
Tia Juana med. (14)	24.6	Amvay, Pto. Miranda, La Salina

Heavy Oils

Export Stream	Gravity, °API	Shipping Port
Bachaquero (8)	13.7	Pto. Miranda
Boscan (10)	10.2	Bajo Grande
Laguna (20)	11.6	Pto. Miranda
Lagunillas (13)	15.5	Pto. Miranda
Merey	17.7	Pto. La Cruz
Moricha	12.0	Pto. Ordaz
Monagas heavy	12.0	Caripito
Mara heavy	16.1	La Salina
Bachaquero-Lagunillas mix (15)	16.7	Pto. Miranda, La Salina
Oritupano	17.9	Pto. La Cruz

TABLE 2.2. (contd)

Heavy Oils

Export Stream	Gravity, °API	Shipping Port
Paconsib	12.8	Pto. Miranda
Pilon	14.4	Pto. Ordaz
Quiriquire (21)	16.6	Caripito
Temblador	16.9	Pto. Ordaz
Tia Juana heavy (6)	12.1	Pto. Miranda, La Salina, Amvay

Condensate

Export Stream	Gravity, °API	Shipping Port
Sta. Rosa	49.8	---

Reconstituted

Export Stream	Gravity, °API	Shipping Port
Reconstituted crudes	34.0	---

Source: Oil and Gas Journal, 1976

characterizes oils from Venezuela which are commonly imported by the U.S. The U.S. Bureau of Mines (1975) summarizes the grades and specifications of refined petroleum fuels (Table 2.3) using the rather widely accepted ASTM definitions. This oil combustion study is mostly concerned with the crude oils, residual, and middle distillate fuels. The other fractions have properties such that they do not pose the same spill problems which could motivate the use of combustion. Oils which are of common interest to marine transport are listed as Appendix 1 to Annex 1 of the Intergovernmental Maritime Consultative Organization's (IMCO) 1973 Convention on the Prevention of Pollution of the Sea from Ships. These oils were examined and physical/chemical properties properties reported by the Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP Report and Studies No. 6, 1977 available IMCO, London) as noted in Table 2.4.

The American Petroleum Institute reported on January 17, 1979, that oil in the quantity of 18.7 million bbls/day was consumed by the U.S. in 1978. This quantity included 6.129 million bbls/day crude oil and 1.979 million bbls/day (124.1 billion gal in 1978) of imported oil requiring marine transportation in almost every case. The history of U.S oil imports is given in Table 2.5 and shows that in 20 years the import has risen more than five and a half times with countries such as Nigeria and Saudi Arabia providing more than 30% of this supply growth. A developing source not listed is China which could become significant in the future. Table 2.6 indicates the oil types and import routes to illustrate where in U.S. waters it is probable to encounter various types of oil. U.S. vessels are reported (DeSteese et al., 1979) to carry no more than 4% of the imported oil.

Many forecasts have been made on oil imports, which would define the types of oil shipped and possibly spilled. Figure 2.1 illustrates the decline of domestic crude oil production in the U.S., other than Alaska, and the dramatic predicted rise in imports (EIA 1978). These are termed by the Energy Information Administration (EIA) as midrange projections and may hold true without artificial import controls or domestic upsurge in production. Similar analysis are reported (DeSteese et al., 1979) that by the year 2000 40% to 50% of the petroleum will be imported. These predictions appear conservative.

TABLE 2.3. ASTM Definitions of Fuel Oils Based Upon Burner Types

Number 1 Heating Oil is a light distillate for use in burners of the vaporizing type in which the oil is converted to a vapor by contact with a heated surface or by radiation. High volatility is necessary. Straight run kerosene is a good description of the product used in space heaters.

Number 2 Heating Oil is a heavier distillate than grade 1, intended for use in atomizing type burners which spray the oil into a combustion chamber where the tiny droplets burn higher in suspension. This grade heating oil is used in most residential central heating burners, and in medium-capacity commercial and industrial burners.

Number 4 Fuel Oil (Light) is either a light residual or a heavy distillate, intended for use in burners equipped with devices that atomize oils of higher viscosity than home burners can handle. In all but extremely cold weather, it requires no preheating for handling.

Number 5 Fuel Oil (Heavy) is a residual fuel more viscous than number 5 (light), and is intended for use in similar service; that is, commercial, industrial, and large apartment houses. It requires preheating, particularly in the colder climates.

Number 6 Fuel Oil, sometimes referred to as "Bunker C", is a high viscosity oil used mostly by ships, industry, and for large-scale heating installations. This heavy fuel oil requires preheating in the storage tank to permit pumping and additional preheating to permit atomizing at the burners. The extra equipment and maintenance costs required to handle this fuel usually preclude its use in small installations.

Diesel Fuel is the petroleum fraction used as a fuel in diesel or compression ignition engines. Various qualities are marketed for different engine requirements. Ignition quality is the most important characteristic of diesel fuel because this controls its engine performance; it is classified by a "cetane number." Most diesel fuels fall in the range of 30 to 65 cetane numbers and are classified in three grades:

Grade 1-D comprises the class of volatile fuel oils from kerosene to the middle distillates. Fuels of this grade are used in high-speed engines involving frequent and relatively wide variations in loads and speeds, and where abnormally low temperatures are encountered.

Grade 2-D is applicable for use in high-speed engines involving relatively high loads and uniform speeds. Included in this grade are distillate gas oils of lower volatility.

Grade 4-D covers the more viscous distillates (middle distillates) and blends of these distillates with residual fuel oils. These fuels are used in low- and medium-speed engines involving sustained loads at constant speed, such as large, heavy, stationary type diesel engines.

Kerosene is a group of refined petroleum fractions, distilling after gasoline, and overlapping into the high distillates and middle distillates. Different fractions of kerosene are used for space heating (No. 1 fuel oil) and blended with gas oil to make No. 2 fuel oil, for tractor fuel, jet fuel, and solvent.

Jet Fuels, designated as three types of commercial jet fuels for the ASTM, are Jet A, a relatively high flash point distillate of kerosene; Jet A-1, a kerosene type similar to Jet A, but incorporating special low-temperature characteristics for certain operations; and Jet B, a relatively wide boiling range distillate, a blend of gasoline and kerosene.

Military Jet Fuels are divided into three parts: JP-1 military jet fuel, a kerosene made from selected crudes; JP-4 jet fuel, a blend of 25% to 35% kerosene and 65% to 75% gasoline components (naphtha); and JP-5 jet fuel, a mixture of special kerosene and aviation gasoline specially designed for Navy carrier operations.

Source: U.S. Bureau of Mines

TABLE 2.4. Physical Chemical Properties of IMCO Listed Oils in Appendix I, Annex I

Oil Type	Flash Pt. deg. F	Pour Pt. deg. F	Water and Sediment % vol.	Distillation Temp. 90% Max. deg. F	Saybolt Visc. Universal at 100°F, min.	Gravity deg. API min
Fuel Oil No. 1	100	0	trace	550		35
No. 2	100	5	0.05	675	32.6	26
No. 4	130	20	0.50	420-683	45	36
(light) No. 5	130		1.00		150	24
(heavy) No. 5	130		1.00		350	24
No. 6	150	60+	2.00	492-1262	(900)	23
Diesel No. 1-D	100	-40	0.05	550		
No. 2-D	125	-10	0.05	640		
Aviation Gasoline						
JP-5	140		1.50	550		36-48
JP-6			1.50	470		45-57
Motor Gasoline				356		57
Gas Turbine Fuel Oils						
No. 1-GT	100	0	0.05	550		35
No. 2-GT	100	20	0.10	540-675		30
No. 3-GT	130		1.00		45	
No. 4-GT	150		1.00		45	
Solvent Naphtha						
Refined				145		
Crude, Light				160		(30-53)
Crude, Heavy	110	-50		200		(45-75)
Petroleum Spirits	100					
Asphalt, Grade 60-70	450+			>>500->>1300		-8 - 18
Grade 40-50	450+					
Electrical Insulating Oils						
Mineral Oil Uninhibited	295	-40			65 max.	
Low Pressure Cables	300	-40			98-108	
High Pressure Cables	380	-5			750-800	
Mineral Oil for Capacitors	455	23			2000-2600	
Crude Oil, Louisiana				>850	46	34.4
JP-3			1.5	470		50-60
JP-1	110		1.5	490		35
JP-6			1.5	500		37-50

TABLE 2.4. (Contd)

Oil Type	Flash Pt. deg. F	Pour Pt. deg. F	Water and Sediment % vol.	Distillation Temp. 90% Max. deg. F	se Saybolt Visc. Universal at 100°F, min.	Gravity deg. API min
Distillate Heating Oils						
Grade 1				533-E.P.		42.6
Grade 2				629-E.P.		34.9
Grade 4				754-E.P.		21.2
Residual Heating Oils						
Grade 5			0.16			
Grade 6			0.15			
Kerosene						
Kerosene	115			572-E.P.		42.0
300 Mineral Seal	250					
Long-Time Burning	115			599-E.P.		
Petroleum Spirits	100			410-E.P.		
Heavy Pet. Spirits	125			487-E.P.		
Diesel Oil, Marine	150	0		675	33-45	
Cleaning Cmpd., Solv.	180	10				
Burner Oil, Special	150	15	0.5			11.5
Burner Oil, Heavy	150	50				10.0
Corrosion Preventive Aircraft, Engine	400	10				
Cleaning Oil, Turbine	250	-15				
Internal Combustion Engine, Diesel						
Heavy-Duty 9005	350					44
9020	360	0				50-58
9030	390	10				58-70
9040	400	15				70-85
9050	400	15				85-110
Lubricating Oil, Aircraft Instrument						
Low Volatility	270		70			
Lube Oil, Gear Pet. Base	280	-40				
Rocket Fuel, RP-1	110			525-E.P.		42
Insulating Oil	275	-40				65
Kerosene	115			572-E.P.		42.0
Motor Oil				640-879		24-30
White Oil						29-32
Gas Oil				400-800		30-33
Casinghead (nat.)						76.5
SAE Lube Oils					58-2115	19.0
						31.0
Bunker C (max.)					300 at 122F	8.0

TABLE 2.5. Total U.S. Petroleum Imports by Source
(Thousands of barrels per day)

	1970	1971	1972	1973	1974	1975	1976	1977
Western Hemisphere								
Bahamas	32	150	174	174	164	152	116	167
Canada	767	857	1,108	1,325	1,070	846	599	616
Colombia	45	27	16	9	5	9	21	17
Ecuador	--	--	--	48	42	57	51	55
Mexico	42	27	21	16	8	71	87	179
Neth. Antilles	442	429	424	585	511	332	275	214
Puerto Rico	87	95	102	99	90	90	88	105
Trinidad	217	182	226	255	251	242	273	286
Venezuela	983	1,019	960	1,135	979	702	699	687
Virgin Islands	189	273	303	329	391	406	422	466
Other	52	18	61	28	21	44	44	16
Total	2,856	3,077	3,395	4,003	3,532	2,951	2,675	2,708
Eastern Hemisphere								
Abu Dhabi/United Arab Emirates(1)	63	80	73	71	74	117	254	333
Algeria	8	15	92	135	190	282	432	552
Indonesia	70	111	164	213	300	389	539	533
Italy	83	79	83	125	74	27	37	51
Iran	38	112	142	223	469	280	298	530
Iraq	--	11	4	4	--	3	26	76
Kuwait	36	36	45	47	5	16	5	48
Libya	47	57	123	164	4	232	453	715
Malaysia	N.A.	N.A.	1	12	12	8	18	63
Netherlands	N.A.	N.A.	12	53	43	18	8	31
Nigeria	50	103	251	459	713	762	1,025	1,135
Norway	N.A.	N.A.	2	1	1	17	36	50
Oman	N.A.	N.A.	N.A.	N.A.	1	2	30	79
Qatar	--	--	3	7	17	18	24	67
Saudi Arabia	42	127	190	486	461	715	1,230	1,377
United Kingdom	N.A.	N.A.	10	9	8	11	31	124
Other	134	143	152	244	207	208	174	272
Total	563	848	1,347	2,253	2,579	3,105	4,620	6,036
Total U.S. Imports	3,419	3,925	4,742	6,256	6,111	6,056	7,295	8,744
% Western Hemisphere	83.5	78.4	71.6	64.0	57.8	48.7	36.7	31.0
% Eastern Hemisphere	16.5	21.6	18.4	36.0	42.2	51.3	63.3	69.0

(1) Figures from 1957 to 1971 reflect Abu Dhabi only. Beginning 1972 they reflect Abu Dhabi, Dubai and Sharjah which formed the United Arab Emirates.

N.A. = Not available on individual country basis, included in "Other".

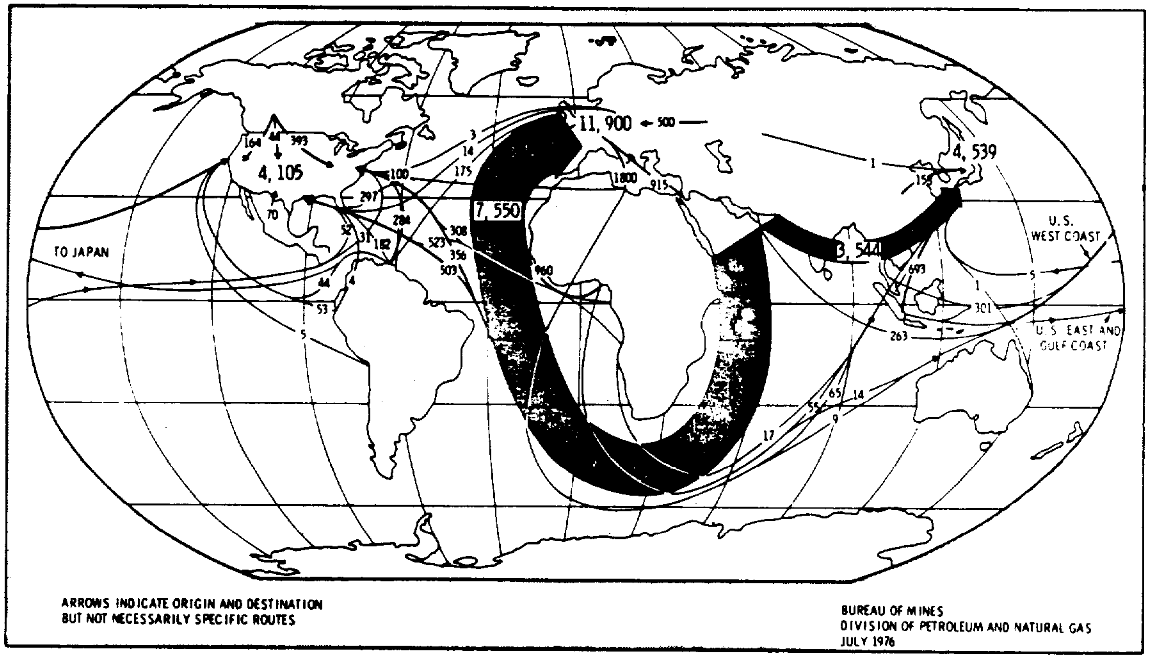
Source: U.S. Energy Information Administration, "Supply, Demand, and Stocks by P. A. D. Districts," Annual Reports. July 1978.

TABLE 2.5. (contd)

	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
Western Hemisphere													
Bahamas	--	--	--	--	--	--	--	--	--	--	--	1	--
Canada	158	87	98	122	204	250	265	303	322	384	450	507	608
Colombia	23	26	36	40	28	25	25	30	51	50	48	52	69
Mexico	38	32	35	17	39	49	48	46	48	45	49	45	41
Neth. West Indies	273	338	324	300	264	297	312	333	361	332	361	392	450
Puerto Rico	5	27	38	36	43	41	44	47	47	60	59	66	72
Trinidad	9	35	33	50	105	82	112	115	132	153	166	189	215
Venezuela	754	711	784	832	800	907	899	931	995	1,021	935	888	876
Virgin Islands	--	--	--	--	--	--	--	--	--	--	36	78	116
Other	5	11	8	2	10	9	21	10	11	21	41	46	34
Total	1,265	1,267	1,356	1,399	1,493	1,660	1,726	1,815	1,967	2,066	2,145	2,264	2,481
Eastern Hemisphere													
Abu Dhabi	--	--	--	--	--	--	--	3	14	13	5	16	14
Indonesia	65	58	55	73	62	67	59	63	61	50	62	73	89
Italy	--	8	4	1	--	--	--	1	2	18	28	49	75
Iran	18	15	25	36	60	49	62	66	79	89	71	68	46
Kuwait	141	197	189	146	130	120	89	69	60	31	23	48	39
Libya	--	--	--	--	--	19	19	39	41	69	42	114	135
Nigeria	--	--	--	--	--	--	--	--	15	11	5	8	49
Saudi Arabia	60	74	68	79	69	73	86	109	144	135	86	60	42
Other	25	81	83	81	103	94	82	93	85	91	70	140	196
Total	309	433	424	416	424	422	397	443	501	507	392	576	685
Total U.S. Imports	1,574	1,700	1,780	1,815	1,917	2,082	2,123	2,258	2,468	2,573	2,537	2,840	3,166
% Western Hemisphere	80.4	74.5	76.2	77.1	77.9	79.7	81.3	80.4	79.7	80.3	84.5	79.7	78.4
% Eastern Hemisphere	19.6	25.5	23.8	22.9	22.1	20.3	18.7	19.6	20.3	19.7	15.5	20.3	21.6

Source: U.S. Bureau of Mines

TABLE 2.6. Significance of Petroleum Import



Port Description	Port Size Million of Tons Annual	Crude Oil and Product as % of Traffic
Seattle	1-20	36
Portland, OR	1-20	35
San Francisco	1-20	25
Los Angeles	20-50	82
San Diego	1-20	63
Houston/Galveston	20-50	59
New Orleans	50-90	29
Mobile	1-20	13
Savannah/Brunswick	1-20	50
Baltimore	20-50	29
Philadelphia	20-50	61
New York	50-90	75.5
Providence	1-20	90
Boston	20-50	91
Portland, ME	20-50	99.7

Source: U.S. Army Corps of Engineers

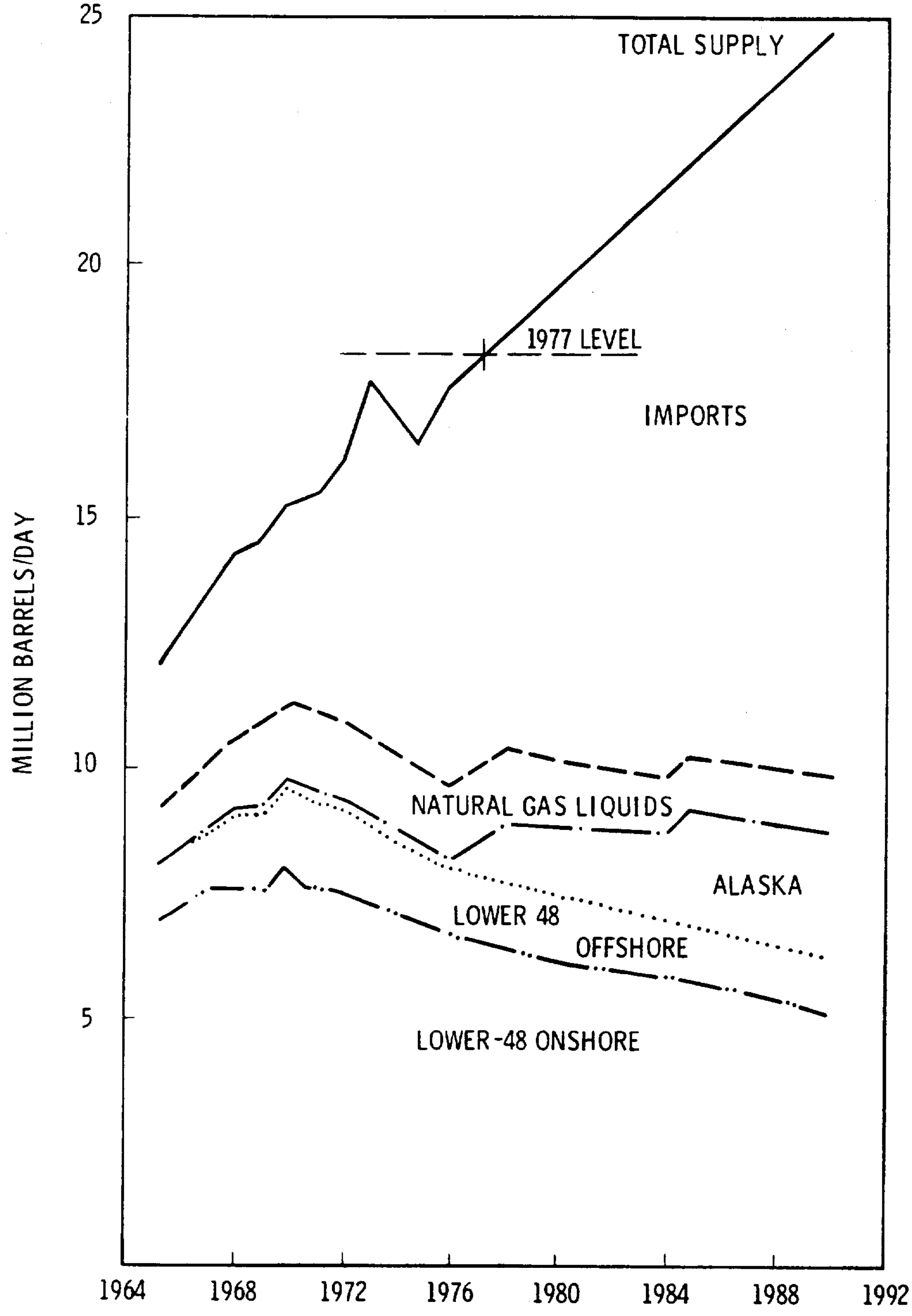


FIGURE 2.1. Projected U.S. Petroleum Liquids Supply (Project Series C)

Source: DOE/EIA-0036/2 (1977) Annual Report to Congress

The data supplied in Table 2.6 may be further examined to note the current petroleum traffic pressure on several ports. As noted Los Angeles on the West Coast and the New England ports on East Coast are locations of highest petroleum traffic.

2.2 TANKER STATISTICS

This section of the report is designed to provide facts pertaining to transportation of "oil" by water. It is fully recognized that statistics pertaining to barges are also important as are those on land-based discharge sources such as pipelines and tankfarm storage areas. To provide a context for evaluating the technical feasibility of using combustion, it seems most appropriate to concentrate upon tankers and open water situations.

It is well publicized that the marine transportation industry has been shifting from small to very large tankers. However, the Maritime Administration indicates that the U.S., with its inability to accept the large draught vessels in its shallow ports, had 1701 tankers call at U.S. ports in 1976 with 629 of these being in the 20,000 to 40,000 DWT class. The first 100,000 DWT (Dead Weight Ton approximately the cargo capacity) were built in the 1956 to 1961 period. There are now (1977 Tanker Registry) 1239 tankers with 100,000 DWT or more. This represents 29% of the world's tanker fleet of 4220 tankers with 6000 DWT or more. However, these 1239 tankers represent more than 68% of the world's tanker fleet DWT. Older data illustrating the flags of register and average age of all tankers of 2000 gross tons and over are tabulated in Table 2.7. These data indicate that 5092 tankers were registered in 1975. The difference in the total figures would be explained as primarily 863 vessels described as 2000 gross tons and over but less than 6000 DWT, and 310 vessels being built in 1976, plus marine vessels scrapped and lost.

The average age for the world's tanker fleet of 6 years and 6 months (determined in Table 2.7) shows the U.S. fleet (6% of the world fleet) to be one of the smaller, older tanker fleets. Both Liberia and Panama (often mentioned in tanker incidents) appear from this table as having younger registered fleets compared to the U.S. fleets. In considering the age of the fleet,

TABLE 2.7. Age Distribution of World Tank Ship Fleet by Major Flag of Registry (as of December 31, 1975)

Year of Construction	Italy No.	Italy Dead-weight Tons	Sweden No.	Sweden Dead-weight Tons	U.S.S.R. No.	U.S.S.R. Dead-weight Tons	West Germany No.	West Germany Dead-weight Tons	Spain No.	Spain Dead-weight Tons	Netherlands No.	Netherlands Dead-weight Tons	All Others No.	All Others Dead-weight Tons	Total No.	Total Dead-weight Tons
Before 1950	12	134,404	1	12,100	8	82,058	0	0	5	49,064	2	44,755	45	457,236	251	4,259,733
1950	2	21,689	0	0	0	0	5	142,860	1	10,800	0	0	15	258,656	41	832,853
1951	4	44,704	0	0	0	0	0	0	1	10,780	0	0	15	242,347	39	723,600
1952	3	54,836	0	0	0	0	0	0	0	0	0	0	24	446,907	60	1,160,430
1953	8	121,440	0	0	5	50,614	0	0	2	29,976	1	17,780	17	339,854	97	2,024,009
1954	10	183,851	1	24,300	10	115,374	1	19,300	4	34,566	2	36,239	30	510,509	148	3,093,415
1955	8	124,791	0	0	12	122,485	1	28,000	0	0	12	221,763	24	514,758	129	2,841,971
1956	4	62,768	0	0	13	135,740	0	0	2	39,645	3	68,709	18	359,132	142	3,650,893
1957	6	142,696	0	0	16	153,951	1	39,733	1	19,000	2	37,264	22	461,018	173	4,934,758
1958	10	296,211	3	100,290	9	61,567	0	0	4	47,489	4	102,449	30	712,598	228	6,713,388
1959	7	198,371	2	66,465	15	157,104	2	101,320	2	28,810	3	54,200	35	1,019,956	237	7,716,276
1960	8	292,130	1	38,240	19	312,567	1	50,900	6	88,558	6	195,601	35	958,577	194	6,086,148
1961	9	352,455	0	0	11	152,293	1	50,640	2	43,242	6	261,772	23	548,850	140	4,950,300
1962	1	38,500	3	88,178	19	302,677	1	53,287	4	84,560	6	274,393	25	737,332	143	5,435,711
1963	4	220,059	1	60,328	21	412,716	2	143,360	2	18,620	3	149,890	18	678,582	136	6,282,182
1964	2	52,898	2	128,440	27	796,379	1	90,600	0	0	0	0	23	1,007,870	180	9,826,024
1965	4	100,139	4	241,220	26	621,557	0	0	2	59,713	0	0	26	895,182	195	10,048,121
1966	8	556,114	5	355,070	28	505,427	4	249,287	2	130,130	6	400,238	25	942,861	179	11,022,093
1967	3	185,852	7	457,490	19	237,219	2	195,720	5	318,585	2	140,920	32	944,861	180	11,018,710
1968	5	336,900	5	476,797	19	246,537	4	516,266	5	299,520	5	837,309	27	924,592	197	14,107,834
1969	7	293,432	7	465,711	31	345,529	1	250,000	7	429,814	2	211,121	26	1,622,361	213	18,437,273
1970	8	817,003	4	254,032	26	268,741	6	584,034	6	259,596	2	499,904	23	1,512,935	218	23,481,434
1971	7	820,227	6	931,750	14	102,294	6	244,809	4	414,120	0	0	20	1,177,062	244	26,688,470
1972	7	970,298	5	875,250	21	134,439	2	34,923	4	816,098	0	0	20	1,217,002	242	29,059,971
1973	14	1,392,708	12	1,170,235	16	123,119	3	320,875	9	679,798	3	561,986	49	3,673,546	324	37,807,922
1974	12	1,623,416	11	1,946,514	6	37,568	13	2,133,298	6	726,486	4	295,159	77	6,222,326	368	46,881,153
1975	18	1,610,378	6	1,597,358	15	650,238	4	572,480	7	1,030,768	2	641,937	79	6,544,169	394	48,059,836
Total	191	11,048,270	86	9,290,768	406	6,128,193	61	5,821,692	93	5,669,738	76	5,053,389	803	34,931,079	5,092	347,144,408
Average Age	6 yrs	5 mos	4 yrs	3 mos	10 yrs	3 mos	5 yrs	3 mos	4 yrs	11 mos	8 yrs	2 mos	6 yrs	11 mos	6 yrs	6 mos

TABLE 2.7. (contd)

Year of Construction	United States No.	United States Dead-weight Tons	Liberia No.	Liberia Dead-weight Tons	United Kingdom No.	United Kingdom Dead-weight Tons	Japan No.	Japan Dead-weight Tons	Norway No.	Norway Dead-weight Tons	Greece No.	Greece Dead-weight Tons	France No.	France Dead-weight Tons	Panama No.	Panama Dead-weight Tons
Before 1950	108	2,162,190	7	199,852	8	135,522	6	107,887	0	0	11	121,689	2	30,400	36	722,576
1950	1	28,740	11	266,176	0	0	0	0	0	0	2	37,170	0	0	4	66,762
1951	2	63,982	8	177,317	0	0	2	43,100	1	16,345	5	108,635	0	0	1	16,390
1952	3	75,158	13	185,278	1	2,990	0	0	0	0	11	173,472	1	13,550	4	108,239
1953	13	367,147	22	515,809	0	0	0	0	1	18,270	18	356,911	1	2,695	9	203,513
1954	14	376,034	35	961,007	6	89,321	1	20,713	4	75,105	20	451,867	3	46,138	7	149,091
1955	6	184,683	29	855,266	6	118,893	0	0	4	68,256	15	328,134	6	147,445	6	127,497
1956	7	218,522	45	1,430,438	10	202,141	2	70,985	5	124,270	23	633,639	6	183,585	4	121,319
1957	10	329,856	63	2,235,912	6	260,365	5	169,237	6	116,534	22	624,273	2	53,578	11	291,341
1958	13	423,561	70	2,576,302	15	383,283	2	79,301	6	131,955	42	1,129,239	3	108,989	17	560,154
1959	15	540,892	69	2,977,741	29	701,350	6	209,495	10	220,797	19	459,455	3	78,463	20	811,857
1960	9	367,059	41	1,605,169	21	507,003	3	102,078	7	153,529	21	782,822	7	299,676	9	332,239
1961	7	309,254	25	1,102,147	20	762,988	5	194,405	10	324,629	10	348,526	7	322,606	4	176,493
1962	4	225,430	18	989,679	22	895,466	7	418,783	10	268,237	5	259,415	6	126,457	12	673,317
1963	5	201,523	32	1,868,470	17	835,431	8	522,843	10	486,304	8	430,981	1	79,327	4	173,748
1964	5	195,968	46	2,884,395	24	1,247,095	12	856,659	15	955,865	11	784,902	4	255,357	8	569,596
1965	3	120,221	53	3,301,599	16	809,003	18	1,303,200	13	709,495	18	1,261,630	7	416,654	5	208,408
1966	1	36,041	34	2,734,462	9	543,730	20	1,801,384	16	1,215,127	12	1,000,014	5	388,134	4	164,074
1967	0	0	33	2,628,004	10	657,418	23	2,093,669	33	2,614,901	3	208,692	5	247,953	3	87,426
1968	3	113,866	22	2,257,990	27	2,378,970	30	2,480,310	22	1,585,750	3	335,200	8	773,533	12	544,294
1969	9	420,703	31	4,084,452	23	3,486,418	26	2,843,801	18	1,740,613	8	1,258,317	6	609,648	11	374,353
1970	10	539,498	46	6,886,114	27	3,999,480	19	2,588,541	24	3,026,642	13	1,550,229	4	694,685	0	0
1971	8	473,297	67	8,364,122	28	3,611,681	29	4,069,120	28	3,180,454	7	710,845	14	2,233,726	6	354,963
1972	7	451,814	48	8,549,869	37	3,424,038	42	5,981,508	22	3,131,549	13	1,356,757	7	918,477	7	1,197,949
1973	8	776,700	60	10,338,477	37	4,407,377	57	6,200,364	26	5,183,047	13	931,117	12	1,937,539	5	111,074
1974	10	853,417	90	14,824,625	32	5,251,174	41	3,377,150	33	4,463,170	8	700,388	14	2,750,109	11	1,676,353
1975	12	745,814	104	16,089,530	33	4,557,729	46	4,690,895	41	5,522,186	8	1,360,904	9	1,420,024	10	1,025,426
Total	293	10,601,370	1,122	100,990,202	464	39,268,826	410	40,225,428	365	35,333,030	349	17,795,223	143	14,138,743	230	10,848,452
Average Age	14 yrs 1 mo		6 yrs 1 mo		5 yrs 8 mos		5 yrs 0 mos		4 yrs 10 mos		10 yrs 0 mos		5 yrs 3 mos		10 yrs 4 mos	

(1) Ocean-going vessels 2,000 gross tons and over.

Source: Sun Company, Analysis of World Tank Ship Fleet, 1947-1973.
Sun Shipbuilding and Dry Dock Company, 1974-1975.

attention should be paid to Table 2.8a and 2.8b. The trend has been to build more and larger tankers each year. The significance of this construction trend is observed in Table 2.8a which illustrates that half of the world's tanker fleet tonnage was built between 1971 and 1975. This represents 32% of the vessels available for service. Seventy-five of the 310 tankers built in 1976 were 240,000 DWT and above. The largest tanker, Batillus (544,917 DWT), was built in 1976; it carries 4,175,000 bbls in 37 tanks, and has a draught of 93 ft.

A simple and clear illustration of the relative sizes of the tankers was prepared by the Exxon Corporation in their Background Series EBS 11/75 "Very Large Crude Carriers" (VLCCs) as depicted in Figure 2.2. A comparison of the information in this figure with the data provided above defines the magnitude of the world tanker fleet.

In 1976 there were eight total losses[a] of tankers worldwide and in the first 6 months of 1977 there were 14 total losses. A total of 1513 tanker accidents occurring worldwide from 1973 to 1977 were reported by National Geographic staff writer Norel Grove (1978). About 77 tankers of the 200,000 DWT or greater size were involved in this record of accident experience, and there were 708 tankers of this size available for service in July 1977.

(a) Total Loss in 1976:

ARGO MERCHANT	(28,234)	Li
ARIES	(19,387)	Pa
BERGE ISTRA	(22,963)	No
BOHLEN	(11,387)	E.G.
CRETAN STAR	(29,892)	CY
EPIC COLOCOTRONIS	(63,675)	Gr
OLYMPIC BRAVERY	(274,000)	Li
SANSNENA	(70,700)	Li

TABLE 2.8. Tanker Construction Trends

Periods of Construction

Tanker Size Class	Period of Most Construction	No. of Ships
6,000 to 19,999	prior to 1955	276
20,000 to 29,999	1956-1960	189
30,000 to 49,999	1956-1961	274
50,000 to 69,999	1961-1965	225
70,000 to 99,999	1966-1970	233
100,000 to 199,999	1971-1975	286
200,000 to 239,991	1971-1975	189
240,000 and above	1971-1975[a]	297

(a) If 1976 construction rate is maintained period will extend beyond 1976

Relative Size and Number of Tankers Built

Period Year	Number Built	Percent World DWT	Percent No. of Tankers
prior 1955	461	3	11
1956-1960	707	6	17
1961-1965	620	9	14
1966-1970	787	21	19
1971-1975	1,344	50	32
1976 -	310	12	7

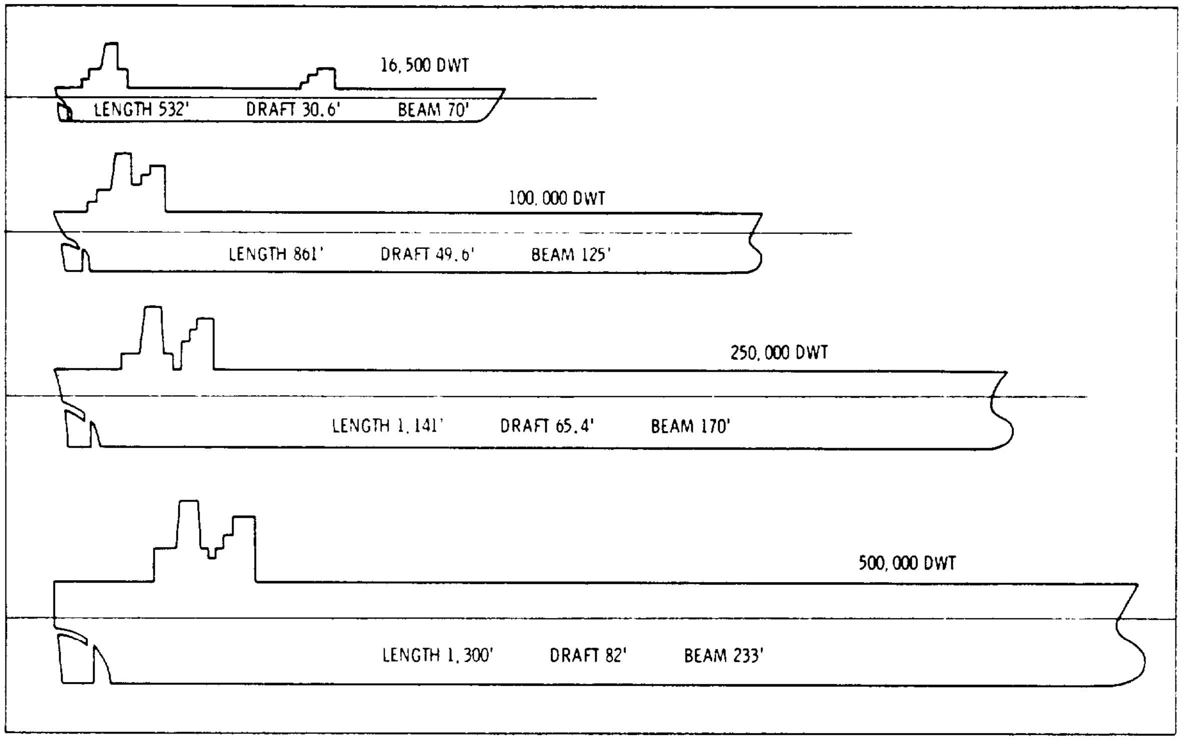


FIGURE 2.2. Relative Sizes of Tankers
Source: Exxon EBS 11/75

2.3 DISCHARGE OF OIL AND SPILL TRENDS

The U.S. Council on Environmental Quality concluded (8th Annual Report on Environmental Quality)[a] that vessels, including barges, were the largest sources of oil spills both in number and volume released. In 1975 approximately 20 million gallons were spilled by vessels shipping 1.83×10^{11} gal of oil. This trend continued showing that in 1977 18 million gallons were spilled of 2.44×10^{11} gal shipped by vessel. However, as Figure 2.3 shows this loss (even though it is substantial) is just over one one-hundredth of a percent of the oil transported by vessels.

(a) Similar statistics were not reported in the Ninth Annual Report.

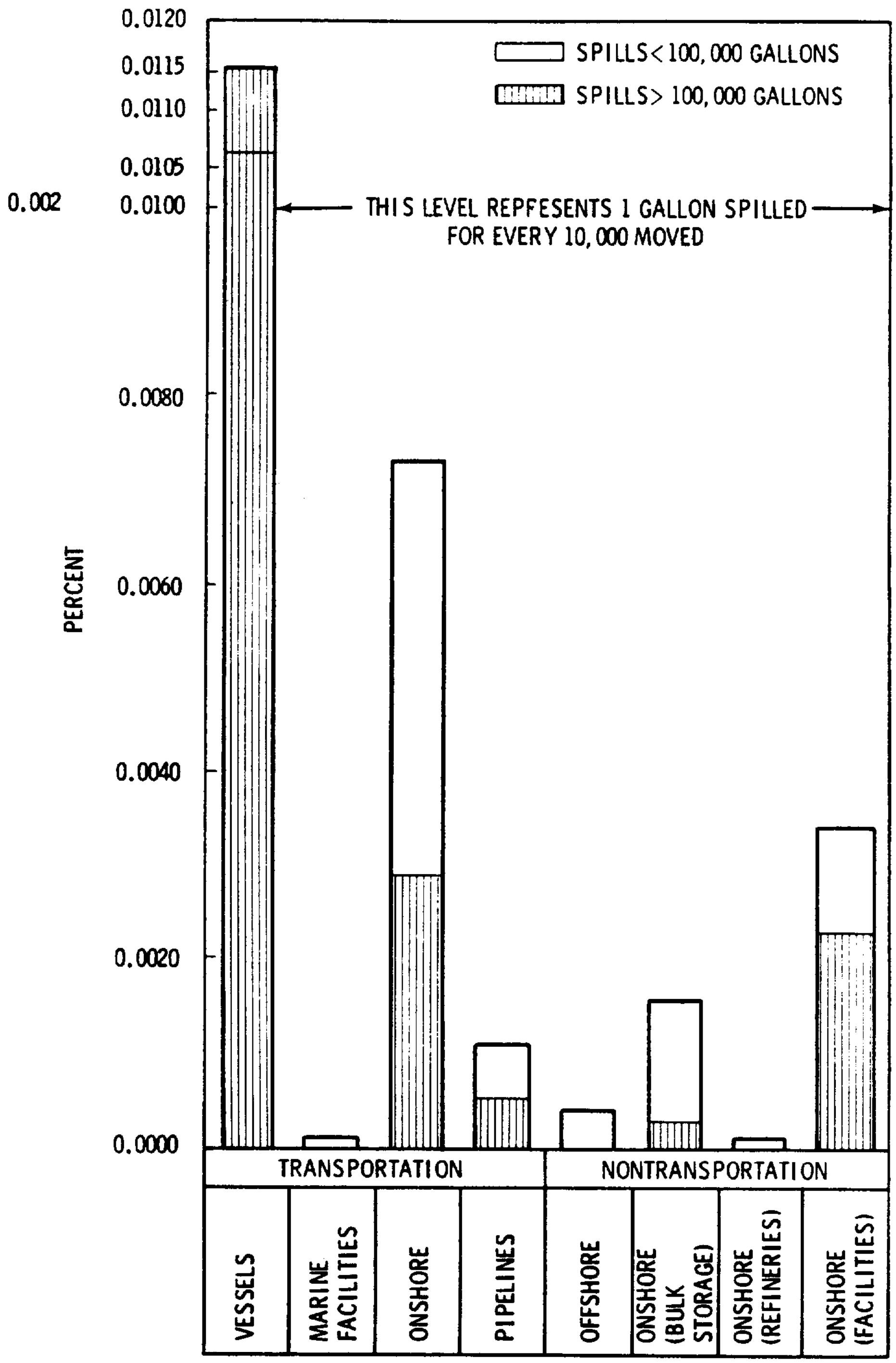


FIGURE 2.3. U.S. Oil Spills

Source: After the Eighth Annual CEQ Report on Environmental Quality, page 231 (modified).

The number of oil spills, location, type of material, and cause of release are just part of the information maintained by the U.S Coast Guard. From an examination of Table 2.9 it can be seen that the 2352 crude oil spills in 1977 involved 12,525,543 gal. Initial 1978 data suggest 2115 spills lost 7,897,922 gal of crude oil. The location of these spills would include land, waters inside the baseline as well as open ocean water incidents. In 1977 there were almost an equal number of light diesel oil spills as there were heavy and light crude combined; however, the volume of crudes was more than 7 1/2 times that of light diesel.

Recognizing that combustion as an oil spill mitigation tool could be objectionable to some authorities, the selection of locations of past spills where combustion could have been employed is important. Appendix C provides a common data base of case histories relevant to this study. The USCG data categorize location of past spills by 12 water body types in five geographical areas. To facilitate an estimate of spills for which burning may have been suitable, the approach is conservative, i.e., to look for spills which happened seaward of the baseline. These incidents will be referred to as "open water spills," but it is recognized that in some river and estuarine situations mitigation by burning has been attempted and may be considered.

During the period from 1974 to 1977, 44 open water oil spills involving releases of 1000 gal or more were reported to the United States Coast Guard. These included 32 minor spills (1000 to 10,000 gal), 6 moderate spills (10,000 to 100,000 gal), and 4 major spills (>100,000 gal). Thirty-one of these incidents occurred in three general offshore regions: 1) southern portion of the California Coast; 2) Gulf Coast adjacent to Texas, Louisiana, and Mississippi; and 3) along the East Coast in the area extending from North Carolina to Maine. Of the 4 major spills, 2 occurred along the East Coast, one in the Gulf of Mexico, and one northwest of the Hawaiian Islands. Five of the six moderate spills transpired along the East Coast and Gulf Coast. All of the major spills occurred greater than 12 miles from shore, while only 2 of the 6 moderate spills were reported at this distance. Slightly greater than half of the minor spills took place within 12 miles of shore, a distance which may be suitable for use of combustion.

TABLE 2.9. Oil Spills by Material -- 1974-1977

	1974	1975	1976	1977
Crude Light				
Number	2,912	822	591	567
Quantity/gal	7,397,525	5,225,649	627,094	10,532,423
Crude Heavy				
Number	772	2,079	2,128	1,785
Quantity/gal	2,227,615	1,571,638	4,567,107	1,993,120
Natural Gasoline				
Number	42	62	73	96
Quantity/gal	1,332	69,181	4,945	23,221
Refined Gasoline				
Number	525	538	639	750
Quantity/gal	1,081,372	2,038,635	749,546	1,030,625
JP-1 to JP-5				
Number	119	100	120	103
Quantity/gal	78,794	32,391	686,175	59,063
Kerosene				
Number	49	52	37	42
Quantity/gal	96,332	885,185	55,427	44,984
Other Distillate Fuel				
Number	170	122	107	115
Quantity/gal	1,661,160	125,149	116,308	61,831
Naptha				
Number	20	16	10	20
Quantity/gal	5,637	1,327	88,236	24,383
Mineral Spirits				
Number	6	9	8	6
Quantity/gal	2,113	469	4,153	692
Other Petroleum Solvents				
Number	22	26	19	27
Quantity/gal	5,466	7,013	2,928	7,436
Diesel Light				
Number	1,667	1,660	1,994	2,301
Quantity/gal	1,024,293	955,947	991,463	1,629,317

TABLE 2.9. (contd)

	1974	1975	1976	1977
Diesel Heavy				
Number	244	220	256	320
Quantity/gal	190,731	88,830	136,409	138,152
No. 4 Fuel Oil				
Number	196	154	114	149
Quantity/gal	305,785	210,084	26,998	76,907
No. 5 Fuel Oil				
Number	65	59	57	74
Quantity/gal	42,962	101,108	112,590	50,183
No. 6 Fuel Oil				
Number	807	715	765	855
Quantity/gal	1,563,435	7,134,807	9,758,049	1,129,604
Creosote				
Number	26	22	47	59
Quantity/gal	153	271	192	1,174
Asphalt-Rondoil				
Number	75	76	67	84
Quantity/gal	73,994	99,013	4,980,236	252,735
Coal Tar/Pitch				
Number	21	28	25	27
Quantity/gal	803	7,341	1,867	5,840
Animal Oil				
Number	22	30	52	28
Quantity/gal	2,898	13,102	25,249	66,982
Vegetable Oil				
Number	35	42	42	42
Quantity/gal	13,983	40,976	70,064	41,143
Waste Oil				
Number	1,141	1,169	1,356	1,574
Quantity/gal	221,253	208,095	135,902	485,430
Lube Oil				
Number	5	17	352	496
Quantity/gal	33	20,372	91,621	69,942

TABLE 2.9. (contd)

	1974	1975	1976	1977
LPG				
Number	15	7	5	2
Quantity/gal	145,315	770	1,094	193
Hydraulic Fluid				
Number	140	131	191	196
Quantity/gal	21,753	2,208	3,930	14,906
Lacquer-Based Paint				
Number	46	78	88	66
Quantity/gal	429	4,917	2,045	26,695
Paraffin Wax				
Number	9	6	4	6
Quantity/gal	4,250	12,382	502	97
Grease				
Number	15	19	4	20
Quantity/gal	862	149	123	10,386
Two or more Oils				
Number	364	363	249	396
Quantity/gal	161,465	2,676,978	198,852	241,156
Pesticide (Oil Based)				
Number	5	3	1	1
Quantity/gal	3,324	430		2
UFO Light Oil				
Number	1,035	1,006	1,096	1,379
Quantity/gal	221,693	91,786	57,619	23,375
UFO Heavy Oil				
Number	445	275	256	222
Quantity/gal	70,896	65,895	57,046	56,892
Other Oil				
Number	861	958	715	713
Quantity/gal	178,453	110,957	442,021	154,107

Source: USCG Marine Environment Protection Division

Nineteen (43%) of the 44 total spills and all of the major spills involved tankships. The major incidents (four of them) were caused by structural failure attributed to collision, grounding, or adverse weather conditions. Seven of the total reported spills were classified as intentional discharges.

The recorded spills involved the release of both refined and unrefined petroleum constituents. Diesel oil and crude oil accounted for 30 (68%) of the spills. All of the major accidents involved either residual fuel oil or crude oil.

No defendable significant trend was proven in the number of spills occurring during each of the 4 years for which data were examined. Furthermore, an analysis of the monthly occurrence of oil spills did not reveal a significant seasonal pattern. (See Section 4.4 for additional tanker loss evaluation.)

In the period 1969 to 1973, releases of oil were most significant in the coastal areas as a result of collisions, but grounding was about equally distributed between coastal and harbor waters, and entrances. The amount of oil released from tankers involved in collisions at sea and at piers was small compared to the total released. The amount of oil released due to collisions in harbors and entrances was about one fifth of that due to groundings. These relationships were established upon comprehensive studies by the U.S. Coast Guard and probable trends were thus established.

Case histories of potential burns of vessels briefed in Appendix C are given along with examples of cases where burning was used. Several reports of use of burning for oil spill mitigation are summarized in Table 2.10. Often key information is lacking or given in vague terms like thickness of residue - "thin or heavy." A brief examination of the table shows that there have been some successes. These few successes, however, have not generally impressed the responsible officials that burning oil is much more than a last effort before giving up on an oil spill response.

TABLE 2.10. Demonstrations of Burning Oil

Oil Type	Condition	Slick Thickness, mm	Approx. Area, m²	Age, hr	Windspeed	Ambient T, °C	Water T, °C	Emulsif ?	Burn ?	Self-Sustaining ?	Residue ?	Promoters	Reference
Ohio Crude (Corning Grade)	Lab-on 1' water	1	0.28	0	0	room	room	no	yes	no	all	None	Castellucci, 1969
Ohio Crude	Lab-on 1' water								yes	yes	no	17 g density open surface cell nodules, 1/4 in. dia. (product report)	
Ohio Crude	Lab-on 1' water								yes	yes	small amount	8 g density open surface cell nodules, 1/8 in. - 1/4 in. dia.	
Ohio Crude	Lab-on 1' water								yes	no	large	1/4 in. foamed polyurethane (non-fire retarding cubes)	
Ohio Crude	Lab-on 1' water								yes	no	moderate	1/4 in. foamed polyurethane (fire retarding cubes)	
Ohio Crude	Lab-on 1' water								no	no	all	foamed polystyrene beads	
Ohio Crude	Lab-on 1' water								yes	partly	some	1/4 in. cubes cellular glass	
Ohio Crude	Lab-on 1' water								yes	partly	some	1/2 in. open surface cell nodules	
Motor Oil	Lab-on 1' water								no	no	all	None	
Motor Oil	Lab-on 1' water								yes	yes	no	open surface cell nodules	
Bunker C	Tidal pools		0.18	24-48		Nova Scotia Feb.	1		yes	yes	no	Sea Beads, IOSOL as lighter fluid	Caskey, J. C., 1970
Bunker C	Tidal basins	6-25	2.8	24-48			1		yes	yes	little	Sea Beads, IOSOL as lighter fluid	Caskey, J. C., 1970
Bunker C	on open water	3-19	5-7	24-48			1		yes	yes	little	Sea Beads, IOSOL ignited with smoke flare	Caskey, J. C., 1970
Bunker C	on open water	3-19	65	24-48			1		yes	yes	1/3	Sea Beads, IOSOL ignited RCNMK 25	Caskey, J. C., 1970
Bunker C	on open water	---	---	0	strong	cold	1		yes	yes	no	None, but booming	Caskey, J. C., 1970
Bunker C	on water, in cove	25-305	230	24-72	25-30 knots	cold	!	water on top	no	no	yes	Sea Beads, napalm, flares	Caskey, J. C., 1970
Bunker C	on beach		0.18		20 knots	cold	1		yes	no	yes	Sea Beads primed w/diesel oil, ignite w/oil soaked rag	Caskey, J. C., 1970
Bunker C	on beach	51-102	0.28		light	-19°C	1	yes	yes	no	foaming	Sea Beads primed w/diesel oil, ignite w/oil soaked rag	Caskey, J. C., 1970
Bunker C	on open water		4.8x10⁵	144	high	-2.2	ambient		yes	yes	2%	Cab-o-sil ST-2-0 fumed silica-0.1-0.5% w/w	Woodyard, 1970
African Crude	outside lab trough	5.4	0.28	0				no	yes	yes	no	Composted domestic refuse	Vaux et al., 1971
Bunker C	on open water	152-508	994	96	moderate	0.5°C	14.2°C	yes	no	no	yes	Tullanox 500, JP-4 fuel flares - Dispersion problem	USCG, 1977
#6 Fuel oil	burn pans	1.6-6.3		0	0	30°C	oil 4-8°C	yes	yes	yes		None - longer torching	USCG, 1977
#6 Fuel oil	burn pans	1.6-6.3		0	0	30°C	oil 4-8°C	yes	yes	no	yes	Tullanox 500	USCG, 1977
#2 Fuel oil			2.6		15-20 knots	10°C			yes	yes	easily removed	3,556,698 patent	Tully, P., 1971
#4 Fuel oil													Tully, P., 1971
#6 North Slope crude	on snow/ice	6.3		< 24	0-14 knots	not aff.	not aff.					None - fuel soaked rags	McMinn, 1973
Heavy arabian crude	open water boomed	25	12	12	1.1 knots	21	15	---	yes	yes	yes	Kontax (45 kg) boom	Menagie, 1970
Light arabian	open water	5	2000	0	1.1 knots	21	20	no	yes	yes	1-2%	Kontax (200 kg)	Menagie, 1970
Crude oil residue	beach	30	5	24	moderate				yes	yes		Kontax	Menagie, 1970
#6 fuel oil	on water, lab	13-17	2.2	0					no	no		Pyraxon	Freiberger, 1971
#6 fuel oil	on water, lab	13-17							yes	no	yes	Cab-o-sil	Freiberger, 1971
#6 fuel oil	on water, lab	2.5-6.3							yes	yes	no	Sea Beads 1 lb/12-15 ft²	Freiberger, 1971
#6 fuel oil	on water, lab	19	0.6	0		5	5		yes	yes	20%	Straw 80 g	EPA, 1971
#6 fuel oil	on water, lab	19	0.1	0		8	7		yes	no	2/3	Ekoperl 1/4 lb	EPA, 1971
South Louisiana Crude						summer			yes	yes	10%	None, boom	EPA, 1971
Bunker C					15-20 knots						10%	Sea Beads, blow torch	EPA, 1971
Ceuta Crude	on ice	7.6	23		5 mph	4			yes	yes	easily (44 l removed	Peat (16 lb), 8 l diesel oil	Coupal, B., 1976
Ceuta Crude	5" water on ice	12.7	23		5 mph	4			yes	yes	easily (95 l removed	Peat (28 lb), 14 l diesel oil	Coupal, B., 1976
Ceuta Crude	5" water on ice	17.8	23		5 mph	4			yes	yes	125 lb	Peat (36 lb), 18 l diesel oil	Coupal, B., 1976
Bunker C	ice	7.6	23		8 mph	0			yes	yes	93.5 lb	Peat (16 lb), 8 l diesel oil	Coupal, B., 1976
Bunker C	ice	12.7	23		8 mph	0			yes	yes	126 lb	Peat (28 lb), 14 l diesel oil	Coupal, B., 1976
Bunker C	6" water on ice	17.8	23		8 mph	0			yes	yes	124 lb	Peat (36 lb), 18 l diesel oil	Coupal, B., 1976
Crude	on water	3.50	36.2				near freezing		yes	yes	6-25%	Pyraxon	Energetex, 1978
Prudhoe Bay Crude	on water										2-10%	Glaeser, fumed silica, glass beads, straw	Glaeser and Vance, 1971
Kuwait Crude	on water	3.2	0.034						yes	yes	50%	None	Energetex, 1978
Kuwait Crude	on water	3.2	0.034						yes	yes	2%	Expanded vermiculite	Energetex, 1978
Kuwait Crude	on water	3.2	0.034						yes	yes	2%	Expanded vermiculite and Sea Beads plus dicyclopentadienyliron	Energetex, 1978
Kuwait Crude	on water	3.2	0.034						yes	yes	2%	Asphalt coated vermiculate	

3. THEORY OF OIL COMBUSTION AND MOVEMENT

Attention is dedicated in this section to the combustion mitigation theory of oil spilled into or upon water, specifically, the pool fire phenomenon and oil slick movement. Information is gathered to enable investigators to consider composite modeling of phenomena thought to occur during a burning operation such as oil slick thinning, breakup, and dispersion due to melting.

The basic processes of oil spill movement and combustion are reviewed, along with the state-of-the-art in oil spill modeling. Because many factors affecting an oil slick are not understood, a model is proposed in this section as a more simplified and practical approach to explaining the oil slick combustion process. This model uses the pool fire phenomenon as a basis.

Also addressed are the classification systems for defining the wide range of oils. These classifications can be used in examining the ignition potential of a specific type of oil.

While this section is involved with oil in water, oil in vessels and oil-contaminated debris are also important when considering the feasibility of combustion. Burning oil in vessels is recognized as an important area of theoretical development, but the analysis of the pool fire in this section is thought to be sufficient to approximate significant burning characteristics useful for that application. Extensive studies in the United Kingdom in the early 1970s provided theory along with laboratory and large-scale testing. These studies (Diederichsen et al., 1972 and 1973) appear to stand alone in the literature with minimal work having been reported subsequently. In situ burning is discussed further in Section 4. Burning of oil-contaminated debris is thought to derive its theoretical basis from incinerator and field burner design. Section 4 on equipment and technology addresses these systems and provides sufficient reference to understanding the operation and application of burning to mitigate the oil spill problem.

3.1 SOURCES OF INFORMATION

A very limited amount of work has been performed to describe and provide understanding of the pool fire phenomena. Hence, much of the current knowledge on the subject is drawn from related work in such areas as:

- boiler and incinerator design
- radiation damage from conflagration
- forest fire propagation
- radiant heat transfer.

As a consequence, quantitative descriptions of relevant interactions are fragmented and have not been integrated into a cohesive statement. Perhaps the most succinct statement of the state-of-the-art is that contained in the concluding remarks of a British review (Hall, 1972):

> Free-burning fires differ from more conventional all-gas diffusion flames in that the fuel is made available by feedback of heat to the condensed phase. The rate of fuel consumption depends therefore on a complex interplay of vapour flow, reaction rate, gas mixing in the flame zone and heat transfer. A burning pool exhibits these features at their simplest. Nevertheless, even this system is too complicated for comprehensive analytical treatment from first principles. Consequently, information on the burning of liquids at a free surface is still largely restricted to phenomenological descriptions. However, there is some understanding of the general effect on burning rate and other combustion characteristics of fuel properties, pool diameter and environmental conditions and some empirical correlations have been produced.

Based on that conclusion, the assessment of combustion for mitigation of oil spills must rely on qualitative treatment of data and relations derived from parametric analysis of limited observations. A description of the pool fire phenomena which follows will serve as a basis for attempting to classify the combustibility of oil under several conditions.

The review of the oil slick movement models was accomplished by literature review of models noted in Table 3.1 and by discussion with contemporary investigators. Appendix B lists the papers and other references used in this review.

TABLE 3.1. Oil Slick Movement Models Reviewed

Model	Advection: Wind	Advection: Current	Advection: Waves	Spreading: Fay	Spreading: Blokker	Dispersion	Weathering: Evaporation	Weathering: Sub-Surface	Weathering: Emulsification	Weathering: Other	Wind Field: Measured	Wind Field: Simulated
1. Ahlstrom (1975)	Wind factor	Tidal regional		As a diffusional process		Markov Random Walk				Can add source/sink terms	X	
2. Berridge, et al. (1968)					X							
3. Blokker (1964)					X		X				X	
4. Cole, et al. (1973)	Wind factor	Permanent and tidal		As a diffusional process		Random Walk					X	
5. Deepwater ports project office (1976)	Wind factor	Neglects tidal		Viscous and surface tension regimes			X	Dissolution			X	
6. Fallah and Stark (1976)						Vertical dispersion random walk		Vertical dispersion			X	
7. Fallah and Stark (1976)	Wind factor	X									Probabilistic random wind data	
8. Fay				X								
9. Hoult (1972)				X								
10. Isakson et al. (1977)	Wind factor	Wind coupled plus tidal and geostrophic		X								Constant magnitude and direction
11. Jeffery (1971)					Experimental verification							
12. Kim (1974)	Wind factor											
13. Lissauer (1977)	Wind factor	Tidal and freshwater		X							X	
14. Lissauer (1977)	Wind factor	At spill site only										Wind roses
15. Lissauer (1975)	Same as No. 14 except advection can be modeled solely due to wind via a wind factor or as the sum of wind drift and currents.											

TABLE 3.1. (contd)

Model	Advection			Spreading		Dispersion	Weathering				Wind Field	
	Wind	Current	Waves	Fay	Blokker		Evaporation	Sub-Surface	Emulsification	Other	Measured	Simulated
16. MacKay (1977)					X	Artificial and natural	X	Dissolution, vertical diffusion	Oil-in-Water	Horizontal diffusion		
17. Miller et al. (1975)		Hydrodynamic model								Weather reports	Wind generation model	
18. Munday et al. (1970)	Wind factor	Tidal and others									X	
19. Murray et al. (1970)		Assumed constant over several hours		Neither Fay or Blokker, modeled as a diffusional process							At 4-hr intervals	
20. Murty and Khandekar, 1973		Wind generated tidal, and freshwater										
21. Orthlieb (1971)	Wind factor	X		Plus wave height correction							X	
22. Premack and Brown (1973)	Wind factor (a function of latitude and wind speed)	Hydrodynamic model		X							At 4-hr intervals	
23. Stewart et al. (1974)	Wind factor	Tidal, river flow, geostrophic									From literature and measured	
24. Vagners and Mar (1972)	Wind factor	Tidal		Battelle(2) equation								Hypothetical
25. Waldman et al. (1973)	Not a model but discusses important influences X	X	X	X		Based on Okubo's work						
26. Wang and Hwang (1974)	Wind factor	Tidal (measured or from hydrodynamic model)		X		A consequence of the numerical scheme					X	
27. Warner et al. (1972)		Vertical eddy viscosity treatment									X	
28. Webb et al. (1970)	Wind factor as a function of latitude or from James	tidal, geostrophic	Permanent,								X	
29. Williams et al. (1975)	Wind factor	As a random variable based on current-time history						Dissolution, precipitation, dispersion of sub-surface oil	X		X	As a random variable

3.2 CONTEXT OF DETERMINING FACTORS

In the field of oil spill modeling there are multiple parameters to consider. This is further complexed when combustion modeling is added. The major processes involved in movement of an oil spill are advection, spreading, weathering, dispersion and wind. Figure 3.1 indicates the complexity of the problem and represents the factors influencing an oil spill. In any composite modeling attempt, decisions are necessary regarding the detail required of the model, process selection, the type of model required (e.g., a trajectory prediction versus a stochastic analysis), whether it will be used in open or sheltered water, and the justifiable expense for performing a calculation. These decisions are related to one another since the more precise and inclusive models will require longer run times and a more accurate and detailed data base.

The various processes affecting movement of an oil slick are not entirely understood. To fill these gaps some modelers have used an order of magnitude approach to get an approximate description of the process. Despite the difficulties involved some fairly comprehensive models have been developed in recent years that work reasonably well.

The combustibility of oil from water surfaces is a function of fuel composition, fuel layer thickness, water and air temperatures, fuel-water emulsification, and wind. There are three major determinants of these factors illustrated in Figure 3.2: weather, water temperature, and time since the oil was spilled. The nature and extent of subsequent effects on combustibility are discussed later.

The influence of time on oil slick movement characteristics is particularly important. As fuel oil is exposed to the air and water environment, volatile components are lost by evaporation; fuel layer thickness diminishes; and fuel-water mixing results in increased emulsification. Thus, the determination of burn feasibility must account for the drastic effects of fuel exposure.

The fuel composition is a function of the initial fuel characteristics, the degree of weathering, and the extent of combustion. Generally, as time passes, the oil becomes more difficult to burn.

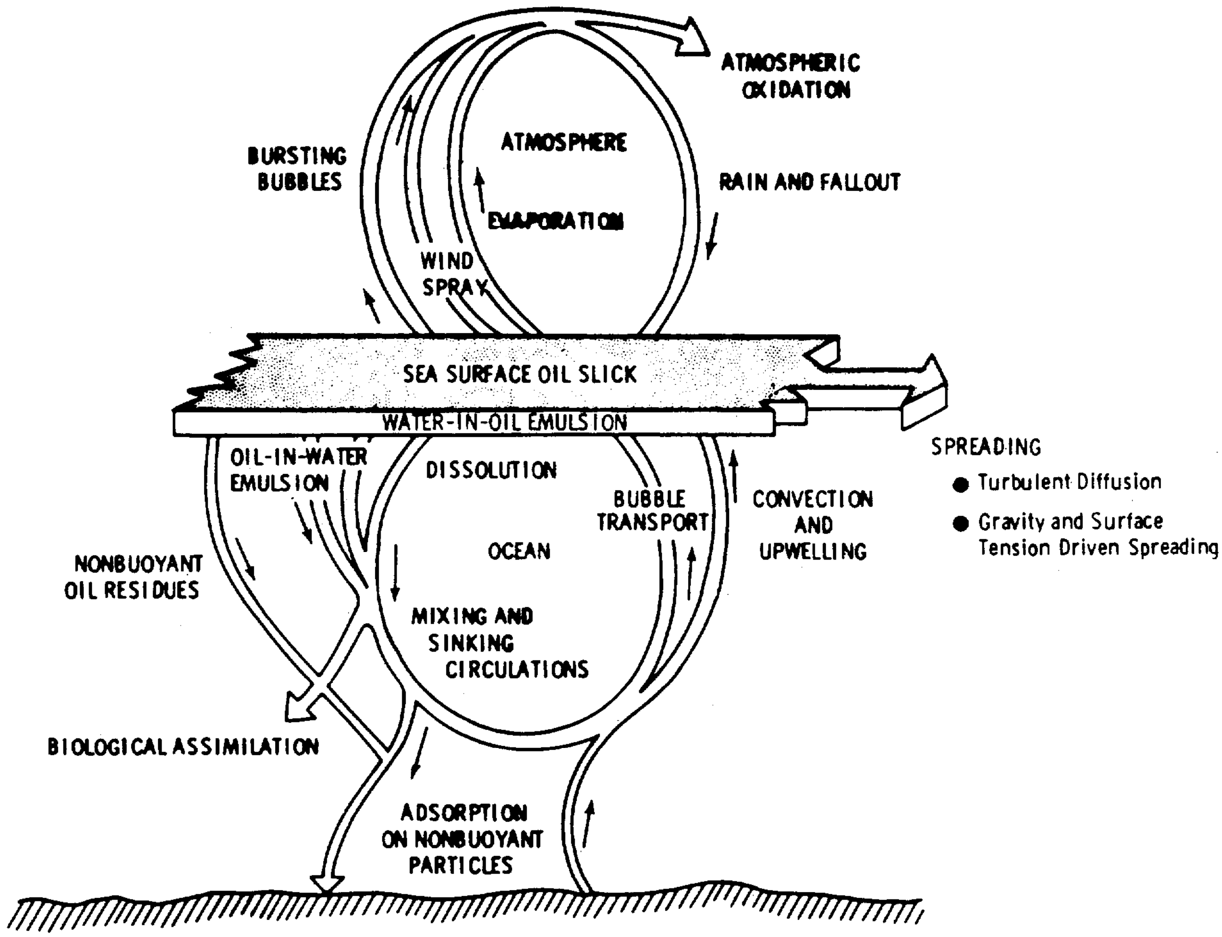


FIGURE 3.1. Natural Forces that Disperse and Modify Oil Slicks in Water

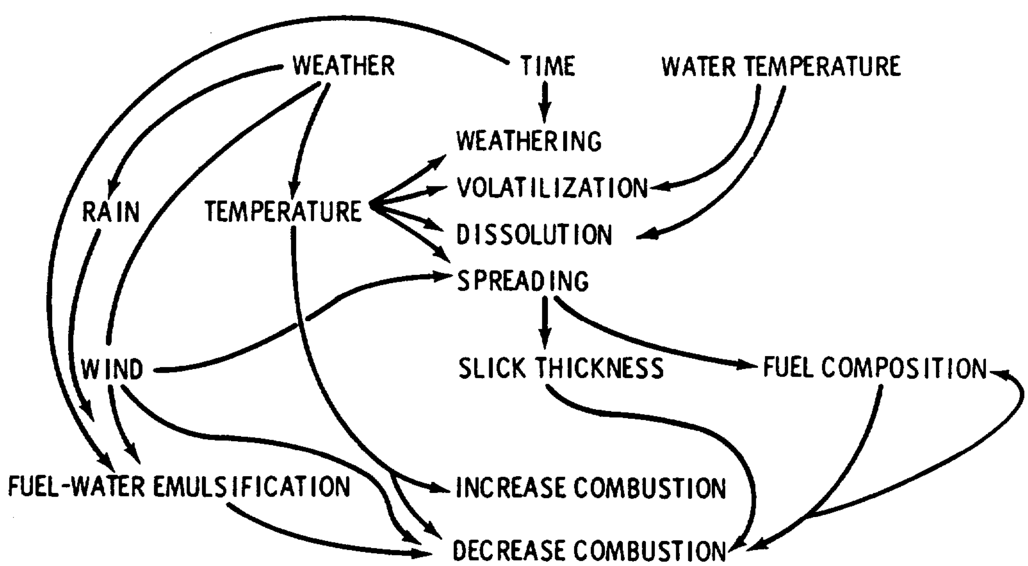


FIGURE 3.2. Factors Affecting Slick Combustibility

3.3 BASIC PROCESSES OF OIL SLICK MOVEMENT AND COMBUSTION

The processes and factors involved in movement of oil slicks and combustion are as follows.

3.3.1 Advection

Advection as applied to oil spill movement is the process by which an oil slick is transported horizontally along the water surface. Drift due to wind, waves, and currents are the basic causes of advection.

Drift due to wind is generally accounted for through a wind factor approach. An oil drift vector is calculated as a percentage (wind factor) of the wind vector. In addition the drift vector is rotated up to 45° (deflection angle) to account for the Coriolis effect. Much disagreement is found in the literature regarding the acceptable values to use for the wind factor. The suggested values range from 2% to 5% with 3% being the most common assumption. The deflection angle has been considered to be in the range of 0° to 45° with 0° most commonly used in sheltered waters such as harbors and bays and 20° being used most often in open waters. The wind factor has also been modified to account for wind speed and latitude (Premack and Brown, 1973).

The wind factor approach has been used extensively and owes its popularity to its simple approach. It has a serious disadvantage, however. The wind factor cannot be adequately applied in shallow waters where the effects of bottom roughness and the nearness of shorelines are felt (Stolzenbach et al., 1974).

Other approaches to modeling wind drift have been attempted. Wind-driven hydrodynamic models have been used to produce water currents which were used to determine oil spill trajectories. The disadvantage to this approach is that an operational hydrodynamic model must be in existence for any spill site that requires modeling. Another approach, used by Warner et al. (1972), involves an extension of Ekman's (1905) work describing wind-induced currents. This approach can account for the unsteady effects of the wind driving force. It suffers from the same disadvantages as Ekman's original work, however, because it is based on the assumption of a spatially uniform wind field and a constant vertical eddy viscosity. Understanding of the vertical eddy viscosity is poor and generally valid equations for predicting its value do not exist.

Wave transport of oil on water is not well understood since it is intimately tied to the wind effects. Good models for describing wave transport do not exist and, consequently, none of the models reviewed try to account for wave transport except for the model proposed by Wang et al. (1974). This model simply modifies the wind factor to account for wave drift. The factor used is in the range 0.92 to 1 and, in light of the uncertainty in choosing a wind factor, is basically insignificant.

Advection due to currents is generally accounted for by assuming the oil spill drift is the sum of all the current vectors. Depending on the location being modeled certain currents may be neglected (e.g., in deep water far from shore tidal currents may not be considered). Information on the current field is required so that reliable predictions of the current vectors can be made. Generally, the current field data are either measured, taken from the available literature, or predicted by an existing hydrodynamic code. The last choice has the disadvantage of requiring an operational hydrodynamic code for the region of interest.

3.3.2 Spreading

The spreading of oil slicks on water is generally modeled for movement using results traceable to J. A. Fay and verified by Hoult (1972). The so-called Fay-Hoult model is based on three spreading regimes. The first regime is experienced during the early stage of the spill, and it is characterized by a gravity-driven spreading force and an inertial retarding force. The next regime involves a gravity spreading force counteracted by a viscous retarding force, and the final regime is modeled by a surface tension spreading force and a viscous retarding force. This model is extensively used in oil spill composite models and gives an excellent explanation of oil spread on a calm sea. The model, however, does not predict asymmetric spreading, and the effects of external factors, such as wind and currents, are not considered.

Blokker (1964) has also proposed a spreading model, but it has not met with much widespread acceptance. The model considers the effects of evaporation on oil spreading, but it does so at the cost of neglecting surface tension and viscous effects. It is generally felt that the Blokker model is inferior to the Fay-Hoult formulation. Blokker's model has not compared well with data from actual spills.

Considering combustion of oil slicks, the fuel layer thickness is directly related to the oil viscosity and the degree of exposure. The Fay-Hoult and Blokker equations appear to be the most applicable tools for predicting oil slick thickness. Because of oil's insulative properties (about four times that of water) the thicker the slick the more vigorous the burning. Thickness of 3 mm is necessary to sustain most crude oil combustion without the aid of promoters. Similarly, under still conditions, decane will sustain combustion until thickness drops to 1.5 to 2 mm or less (Hall, 1972). Atallah (Hall, 1972) has defined the critical thickness for fuels as that thickness at which heat conducted through the film into the water is equal to that radiated from the flame to the fuel. For a typical oil, that thickness is estimated to be 1.3 mm (Hall, 1972). It would follow that combustion would begin to decline when the fuel layer becomes small enough to allow heat loss to the water. Similarly, oils at this thickness or less could be expected to be more difficult to ignite. This thickness can be predicted based on Khudyakov's (1953) relation for temperature at depth in a pool fire:

$$t - t_o = (t_s - t_o) \exp(-Kx) \qquad (1)$$

where

t = the liquid temperature at depth x mm,
t_o = the initial temperature of the liquid,
t_s = the temperature at the surface,
K = a coefficient.

For the selection of the critical depth, assume that t, the fuel temperature at x, is within 10% of the initial temperature t_o, and the surface temperature t_s is B_p, the fuel's boiling point. Khudyakov's equation then simplifies to:

$$0.1\ to = Bp - to \exp(-Kx) \tag{2}$$

or

$$X = \frac{-1}{K} \ln \left(\frac{Bp - 0.1\ to}{to} \right) \tag{3}$$

At least one experimental measure is required to determine the value K. Hall (1972) notes that empirical data do not always correlate well with Khudyakov's relation. Others (Energetex, 1978, for example) have provided similar analyses using heat flux, as discussed later. These data suggest that oil spreading will soon render a slick too thin to sustain combustion. Hillstrom (1970) demonstrated how the flame will accelerate this thinning process by enhancing advection.

3.3.3 Dispersion

Dispersion is a factor in the spreading of oil that has not been extensively considered in oil movement models. The random effects of wind and waves on the oil tend to make the slick spread more than is predicted by the Fay-Hoult model. A limited number of models have tried to account for this through the application of a simple Fickian diffusion model. There is very little information available pertaining to oil dispersion on water, which probably accounts for its exclusion in most models.

3.3.4 Emulsification

Emulsification is very significant to oil slick combustion. Whereas dispersion as noted above may include emulsification, it is not limited to that process. Little information was gathered on modeling this aspect. Its importance justifies future explanation because observations of spilled crude oil have revealed a propensity to form water-in-oil emulsions. The latter has been dubbed "chocolate mousse" and is quite stable once formed. Oil converted to this state is difficult to ignite and burn, especially as it weathers. The water content (up to 80%) acts as a heat sink utilizing the limited amount of heat directed back to the pool for heating and vaporization, but produces no heat of combustion itself. Since water has a specific heat roughly twice that of oils, and a latent heat of vaporization roughly 10 times that of oils, vaporizing 1 g of water will require heat that could otherwise provide 5 g of fuel. Since water has a lower boiling point than many oils, it will be preferentially vaporized. For instance, should gasoline be susceptible to water-in-oil emulsification (which it is not), water in excess of 7.5% would remove the chances of a successful burn. Hence, an oil's tendency to form these emulsions or the environmental conditions, e.g., mixing, can greatly affect its combustibility. Recent studies in Canada have demonstrated the combustibility of fresh crude oil spills forming water-in-oil emulsions. It was reported (Energetex Engineering) that once ignition was achieved, the combustion of the water-in-oil emulsion was intense (due to micro explosions), and the residue left was similar to that remaining after burning the same oil in a non-emulsified state.

The presence of water in fuel also causes frothing and boilover which reduce absorption of heat radiated back to the pool. This in turn reduces the burning rate, which decreases frothing. The burning rate subsequently goes up again. This cycle of burning repeats itself over and over again with a net rate well below that for dry fuel. At higher water levels, the frothing action actually extinguishes the flame. Khudyakov (1953) has reported frothing of heavy petroleum with as little as 0.1% water. Extinction occurred with a fuel oil and a heavier oil containing 6% to 7% water. Pavolova and Khovanova (1958) found combustion of crude petroleum with 4% to 8% water unstable. Combustion was impossible when water was >8%. Inhibition of mazut combustion occurred at 0.6% to 0.7% water.

In a comprehensive study of water-in-oil emulsions, Berridge et al. (1968) determined that distillates do not generally form "chocolate mousse." Only crude oils and Bunker C were noted to form any kind of a stable water-in-oil emulsion. Further study revealed that the tendency to emulsify is directly proportional to asphaltene content, the residue-creating fraction of oils.

For those oils which are susceptible, emulsifiction can occur within an hour under rough sea state. Hence, mitigation by combustion will not be effective for crude or Bunker C slicks allowed to remain in rough seas for any length of time. Time for crude oil emulsification to occur will be shortened under rainy conditions, but distillates will not be affected (Berridge et al., 1968).

3.3.5 Weathering

Weathering (used as a very broad modeling term) has an important influence on slick growth and therefore on slick movement modeling. The major weathering processes, evaporation, dissolution, precipitation and emulsification, affect the slick volume and its chemical and physical composition. Little concrete information is available for many of these processes, which possibly accounts for the few models that include weathering to any degree.

Evaporation is most important during the first few days of a spill and is the most reliably modeled weathering process. The factors involved in evaporation are quite extensive and depend on the composition and chemical make-up of the oil and the environmental conditions. It is relatively easy to predict which components will evaporate, but predicting the evaporation of individual components as a function of time is more difficult due to the dependence on the ever-changing environmental factors; as always there is a trade-off. The complexity of the evaporation model can range between a general model that accounts for all oil components to a simple model that treats the oil as a single substance and relies on empirical evaporation curves. Also, the model can be more or less complex depending on the degree to which environmental factors are accounted for.

Dissolution and precipitation of oil have been modeled, but generally very little is known about these processes during an oil spill. Consequently, the best that has been achieved so far is to model these processes on an order of magnitude basis using simple first order expressions.

Emulsification is another important weathering process affecting slick movement and, as noted above, combustion. Besides the chocolate mousse effect, an oil-in-water emulsion can be formed which is simply small droplets of oil that disperse into the water. None of the models reviewed have characterized the chocolate mousse formation and only two described the oil-in-water emulsion (MacKay, 1977; Williams et al., 1975). Emulsification of oil is so poorly understood that the best approach so far has been a first order equation that gives order of magnitude information only.

There are a variety of other weathering processes including biodegradation, photochemical and chemical oxidation, and sedimentation. They can be relatively slow acting and are therefore not of prime interest to this study unless the model simulation is run for an extended period of time (more than a few days to a week).

3.3.6 Wind Field

Modeling the wind field plays an important part in accurate descriptions of the slick advection. The wind effects also influence the weathering and spreading of the slick although these effects are generally neglected due to the lack of information describing these processes adequately. An accurate description of the wind field will significantly enhance the accuracy of a trajectory prediction.

The basic wind field descriptions rely on measured data. This information is either used directly, averaged to form some kind of a probability function, or used as a basis for a numerical wind field model. There are differences between wind data measured onshore and offshore. This has prompted some modelers to base the wind field descriptions on onshore and/or offshore data (Williams et al., 1975). A further difficulty that arises in modeling wind fields is the sparsity of wind measurement stations. A consequence of this is that spatial variations in the wind field are generally not as reliably modeled as time variations. Many models do not consider spatial variations at all.

The direct approach to wind field modeling uses the wind data at the time of the spill to represent the wind field. In some cases this information is projected in order to acquire a prediction of the oil slick path. In its simplest form, and also the most unrealistic, the wind speed and direction are assumed constant throughout the simulation period. This may not be too bad an approximation where the time span considered is quite short (i.e., the spill is very close to shore). Generally this is an inadequate assumption. The more realistic models update the wind field for each time step.

Stochastic models tend to take the wind data and perform statistical averaging. This usually results in a probability distribution for a given period of time, usually a month. The probability distribution gives the probability of a given wind speed occurring from a given direction during the time period considered. The final slick movement modeling approach that has been tried is to use a numerical wind field model. This approach suffers from the requirement of having a reliable numerical wind model for every spill site considered.

Effects of wind on oil slick combustion must be carefully considered and the modeling is complex. The presence of wind in the combustion zone may increase or decrease combustion rates depending on its velocity and environmental conditions at the time. Studies with small diameter flames have revealed that up to a limiting velocity, wind increases burning rate. This effect is due to several mechanisms. Convective heat transfer may be enhanced with the wind currents. Radiative heat transfer can also be increased through several factors. For example, wind increases mixing between air and fuel, thus promoting more complete combustion and a cleaner flame with potentially higher flame temperatures. Wind also tilts the flame and may increase the view factor; i.e., more of the total radiant heat is directed to the pool based on a cylindrical flame shape. These effects are more pronounced with small diameter fires (Hall, 1972), or small fires on a large pool of fuel.

When wind velocity gets sufficiently large, it reaches the extinction point and puts out the fire. This effect may be attributed to a disruption of heat flow from the flame to the pool. Hirst and Sutton (1961) found the extinction point to be 5 m/s for aviation kerosene in a 12.7 cm square tray. Larger scale studies by Hägglund and Persson (1976) did not experience as severe an extinction. However, oil pool is subject to wind-generated waves, which in turn slow the burning rate (Eggleston et al., 1975) and therefore leave a greater amount of residue.

3.3.7 Temperature

Water and air temperatures during a burn will influence combustion. Higher temperatures increase the net heat differential between heat of combustion produced and heat required for vaporization by decreasing sensible heat requirements. This can increase burning rate and reduce the thickness at which flame extinction will occur as well as increase the potential for sustaining a burn depending upon the properties of the oil.

Elevated temperatures prior to a burn will reduce the combustibility of any given oil by increasing the vaporization and dissolution components of weathering. Under warmer conditions, a greater fraction of the volatile constituents in oil will evaporate in a given time. This raises the initial boiling rate of oil and hence increases sensible heat requirements. Even without elevated temperature, this process will occur over time. Empirically derived relations have been developed to describe the change in oil composition as a result of evaporation. If compositions are well known, theoretical constructs can also be employed. Weathering must be considered as a process that is continually changing the composition of the oil.

The level of effects will vary directly with the nature of the oil itself. Berridge et al. (1968) reported a spectrum of effects for different crudes. They note that Libyan Zelten (Brega) and Nigerian Light yield relatively low residuum fractions (>700°F) and therefore will be removed quite rapidly by evaporation. This effect will be particularly pronounced with Zelton since 31% (weight basis) of the crude boils below 400°F. Crudes with small low boiling fractions such as Tia Juana Medium will evaporate slowly, while special bitumen crudes such as Tia Juana Pesado will evaporate even more slowly since 78% is residue boiling at temperatures >700°F. Evaporation is also enhanced by wind, wave action (stimulates airborne dispersion of aerosols and sprays), and increased surface area from spreading.

As previously noted, the volatile components of oils which are lost through evaporation are similarly the more readily burned fractions which increase combustibility of the composite fuel. Hence, the more combustible oils can withstand greater lengths of weathering time before they lose their ability to sustain ignition. While extensive quantitative data are not available, limited empirical observations provide some guidance for rules of thumb. Laboratory tests with crude oil by Krieder (Sivadier and Mikolaj, 1971) revealed that essentially all light fractions with boiling points below 216°C were gone after 24 hr of weathering, while loss of fractions boiling up to 270°C took 20 days. In similar field tests in Cook Inlet, Alaska, Kinney et al. (Sivadier and Mikolaj, 1971) reported loss of the fractions boiling below 126°C from crude oil in the first 8 hr of exposures. In similar experiments, Smith and MacIntyre (1971) found that fuel oils 2, 4 and 6 lost the fraction boiling at 200°C and at 210°C in 25 and 50 hr, respectively.

In addition to affecting vaporization and spreading, elevated temperatures can also increase dissolution of oil constituents. For the most part, however, dissolution does not affect combustibility as defined here. Empirical studies (Smith and MacIntyre, 1971; and Burwood and Speers, 1974) have shown that dissolution involves the middle boiling range aromatics in oils. Evaporation outstrips dissolution for the lower boiling aromatics, while aliphatic and high boiling aromatics are solubility-limited. Since the middle boiling range aromatics (220 to 280°C) are not the critical ones with respect to ignition and sustained combustion, their loss will not likely affect combustibility. It could enhance it if these aromatics constituted the majority of the less volatile matter in an oil, but this is unlikely. With fuel oils, Smith and MacIntyre (1971) determined solubility losses over 40 hr were in the range 0.5 to 5.3%. On this basis, dissolution is not considered a significant factor in determining combustibility of oils.

3.4 REVIEW OF MODELS

Little diversity in modeling techniques is available for describing oil slick movement. The usual approach is to select the processes that are deemed most important and for which enough data are available, and incorporate these into a composite model. A decision is made to use a model for each process that is felt to be the most accurate. In many instances good approximations are not available and, as a consequence, order of magnitude approaches are taken.

The approach most often used is to account for advection by superimposing the wind drift on the current vectors. Wind drift is described usually by some form of the wind factor approach. Spreading is generally modeled by the Fay-Hoult spreading regimes. It is generally agreed that Fay-Hoult model does not adequately describe the real-world behavior of oil slicks but it is the best model available. The other processes may or may not be modeled depending on the detail and complexity of the model. Generally, if a comprehensive, accurate data base is available describing the wind and current fields, the wind factor approach will give a reasonable estimate of the slick trajectory.

Ideally, a mathematical model which would allow the prediction of potential for successful combustion with all #2 category oils under a given set of circumstances. This would become the decision maker's principal tool in determining whether or not to attempt a burn. While modeling of combustion is a complex undertaking which currently cannot be accomplished from first principles, some progress has been made with portions of the phenomena. Most pertinent to this study is the work on modeling pool fires such as that reported by Kanury (1974). This is augmented by models of entrainment and momentum flux (Becker and Yamazaki, 1978), pool fire radiation (Modak, 1977), and radiation from smoke layers (Orloff et al., 1978). For accuracy these formulations are extremely complex and require extensive input data. Simplifications can be made without extensive loss of accuracy (Spalding, 1962). At that, however, the models have largely been directed to prediction of radiation hazards to nearby objects and not to the determination of when and how combustion will proceed with a pool of fuel on water. None of the models presently accommodate such complicating factors as surface wave motion, emulsification, and slick spreading. Moreover, required input properties such as emissivity, mean free path, and soot production, have not been reported for most oils or crudes. Hence, though models are approaching a stage where they may be of use in predicting combustibility, they are not sufficiently developed to address the problem at hand.

Barring the availability of such a combustion model, a simplified approach is offered in Section 3.5 to assist in assessing the effect various parameters will have on combustibility. Since the state-of-the-art is more advanced for modeling oil slick movement, the following three models are discussed in greater detail: 1) the Battelle Oil Spill model; 2) the University of Toronto model; and 3) the Seadock model.

3.4.1 Battelle Oil Spill Model (Ahlstrom, 1975)

Battelle's oil spill model can operate in two modes, either in a deterministic mode or in a stochastic mode. It accounts for oil spreading and advection and is applicable to instantaneous, intermittent, or continuous spills.

The model includes the effects of tidal currents, regional currents, and wind drift. Spreading is modeled via a simulation of Fay-Hoult's spreading model as a diffusional process. Other processes can be readily added such as evaporation and other weathering phenomena as valid equations become available. This is a unique feature that allows the model much flexibility. Beaching of oil can also be modeled. In the deterministic mode the slick can be viewed as up to 24 distinct chemical fractions. Up to 10 simultaneous spills can be specified and the advection patterns can be steady or transient. In addition, the diffusion coefficients can be varied spatially and with time. The stochastic mode can also handle up to 10 simultaneous spills, and there can be up to 100 arbitrarily shaped spill sites and/or a probability matrix of up to 200 x 200 nodes. Both modes allow real-time solution monitoring, display and control.

The model makes many assumptions, some of which are too detailed to allow adequate coverage here. Only the simpler assumptions will be discussed. The wind factor is assumed equal to 3% and the deflection angle is taken as 0. The latter assumption is made due to the lack of data on the value for the region being modeled. The Fay-Hoult spreading is considered to be modeled by a diffusional process that is characterized by an equivalent diffusion coefficient. The diffusion due to turbulence is characterized by a turbulent eddy diffusion coefficient, and it is assumed that the two diffusion coefficients can be added. It should be pointed out that the equivalent diffusion coefficient is set equal to zero once the slick reaches the radius predicted by the Fay-Hoult model. The oil slick is modeled by breaking it up into sub-patches. The movement of each sub-patch is assumed independent of all the other sub-patches. The advection of the slick is determined by assuming that all the drift vectors from the various mechanisms (i.e., wind drift, tidal drift, and drift due to other currents) can be vectorially summed.

An extensive amount of data is required to operate this model. Monthly wind probability distributions are required in the stochastic mode. These are composed of a joint probability function consisting of wind direction (every 45°) and speed (every 5 knots) on a monthly basis. The model uses the monthly probability function to generate random wind vectors with the probability of a vector occurring weighted by the probability distribution. In the deterministic mode, current and wind conditions are projected from onsite, real-time measurements and a historically derived correlation. The oil spill volume, location, composition, and the time of the spill are also required. In addition, tidal stage data, salinity, temperature distribution, and a beach "sticking" function are required. The beach "sticking" function is dependent on the beach characteristics, the phase of the tide (ebb or flood), and the ratio of the tide to the average maximum annual tide.

The model was field tested for two cases and worked reasonably well. It was used to predict the path of a 200-ft log boom that escaped from its mooring. The prediction of its recovery point was quite good. An oil spill was also simulated, but due to the qualitative nature of the observations the results were not quite as conclusive although the prediction seemed to agree with the observations.

This model is flexible and has many features to recommend its use. Of particular interest is the ability to easily modify the program to include complex source/sink terms when appropriate equations are available. This could allow modeling of additional weathering effects. The model does not consider advection due to waves, but this is expected considering current inability to describe wave advection. The assumption that all the individual sub-patches are independent of each other neglects the resistance to motion caused by the other slicks.

In general, this model is well developed and allows for easy addition of other effects. It has been verified and works reasonably well.

3.4.2 University of Toronto Model (MacKay, 1977)

This model is an oil spreading model with primary emphasis on dispersion and dissolution. It considers a large number of the major weathering parameters, although it is made clear that many of the approaches are order of magnitude estimates only. The model does not consider any kind of oil transport along the water surface other than the basic spreading phenomena.

Information on slick size, thickness, properties, composition, amounts of oil evaporated, dissolved, and dispersed, and the concentration history of the hydrocarbons dissolved in the water column is generated by this model. The simulation of oil composition allows the oil volatilities and aqueous solubilities to be reproduced.

Spreading is assumed to be characterized by patches (1 to 10 mm thick) and as surface tension slicks (approximately 10 mm thick) by the Blokker (1964) formulations. The evaporation model assumes that Raoult's law applies to the hydrocarbon mixture and that the atmosphere acts as an infinite reservoir with zero concentration. The oil layer is also assumed to be at the water temperature. The vertical diffusion model requires that the upper water layer (to about 10 m depth) be assumed to have a zero concentration gradient. This assumption is justified in the paper on the grounds that the observed vertical eddy diffusivities in the upper 10 m layer are large enough that concentration gradients decay swiftly. In order to model dissolution the resistance to dissolution is considered to lie in a stagnant layer immediately below the oil slick. Dispersion is included in the model and can account for both natural and artificial dispersion. Natural dispersion is a function of the turbulence conditions, presence of natural surfactants, and the oil properties. Since little information is available describing natural dispersion it is approximated by a simple first order equation. When artificial chemical dispersants are applied they are assumed to act instantaneously.

The model also assumes that evaporation of hydrocarbons that have been dissolved in the water body is negligible. It is further assumed that biodegradation, sedimentation, and chemical and photochemical oxidation are negligible since these processes operate quite slowly relative to the others.

Horizontal diffusion is included in the model and requires the assumption that dissolved and dispersed hydrocarbons come from the thick portion of the slick (the slick is modeled as a thick region containing about 90% of the oil and a thin slick containing the remainder). Perfect mixing of the slick is also assumed. The Blokker spreading model is used and has the inherent assumption that the slick spreads symmetrically.

The information required to operate this model is quite extensive. Some of the information has been obtained from lab-scale experiments which raise questions about the validity of these values in actual practice. An evaporative mass transfer coefficient (MTC) is required. These values have been obtained from correlations based on pan evaporation experiments. An MTC for dissolution is also required and has been based on pond experiments. This value has been assumed constant, although there are questions regarding its functional dependence on the wind speed and surface roughness. A solubility enhancement factor is used which is obtained from the literature. Pure component solubility data are required along with information on the dispersion constant as a function of the sea state. The dispersion constant has been determined from experimental evidence. A Blokker spreading constant was assumed based on data by Jeffery (1971). Wind speed data, temperature, and times of artificial dispersion are also required.

This model has not been field validated which probably raises the greatest question about its usefulness. Many of the mass transfer coefficients are based on lab-scale data which may not readily scale up to a full-scale oil spill. The model does not treat advection in any form, although it appears possible to include these effects. It is set up to model the major weathering processes, although admittedly it does this in many cases on an order of magnitude basis. At this time this may be the best approach that the available knowledge allows. Due to the almost complete lack of information on water-in-oil emulsification (chocolate mousse) this phenomenon has been neglected as have some of the slower weathering processes, e.g., biodegradation, sedimentation, and oxidation (chemical and photochemical). These processes probably are not too significant unless the oil spill simulation is run for more than a few days to a week.

This model could have important application in any detailed oil spill simulation. It also indicates the additional work that is required to allow adequate representation of many of the processes that affect oil spills.

3.4.3 Seadock Model (Williams et al., 1975)

This construct was developed to model a possible spill from a proposed deepwater crude oil unloading facility, called SEADOCK, off the coast of Texas. It is a stochastic oil spread and trajectory model for use on instantaneous spills.

Many of the important aspects of oil spill drift and weathering are accounted for in this model. Spreading is described by Fay-Hoult's spreading model. The weathering models account for evaporation, dissolution, and oil precipitation. In addition, the model keeps track of the subsurface oil due to dissolution.

A wind factor of 3% is used along with a deflection angle of either 0° or 15°. The effect of changing the deflection angle appears to be minor as the predicted probable impact areas were nearly the same for both cases. To account for the differences in onshore and offshore wind data the region of influence of the wind is broken into three regions. When the slick is more than 5 miles from the coast only the offshore data are used. In the area 2 to 5 miles from shore a weighted percentage of the onshore and offshore wind is used and within 2 miles of shore only the onshore wind data are used. The wind drift and current vectors are assumed to be additive. Precipitation of the oil is accounted for by assuming that the slick volume is reduced by 1% for each time step when the appropriate conditions for precipitation are met (shallow water and a wind in excess of 20 mph). It is also assumed that for this site, biodegradation and other long-term chemical changes are negligible considering the relevant time frame. Subsurface dispersion has been modeled by using a three-dimensional statistical dispersion model that has been developed by Okubo (1962).

The Seadock model requires extensive wind and current data. The current is taken from measurements at 10 ft and 30 ft depths and from available current charts. The wind data are measured offshore and taken from National Weather Bureau data from a nearby city. Gaps in the wind data are filled in with a first order Markov model. The Markov model uses the direction data and discretizes it into 16 directions averaged over a month. This results in a direction matrix. The magnitude data are combined with the direction data to form a monthly probability distribution for each direction over a given speed range.

This is a fairly comprehensive model, but again due to lack of information some of the processes are modeled quite crudely. The model has not been field validated, and as a consequence it is difficult to determine if the model is accurate.

3.4.4 Concluding Observations

The creation of a composite combustion model based upon first principles has been recognized as possibly more complex than the collection of data would warrant. Based upon the review it was determined that a more simplified and practical approach should be evaluated to explain the oil slick combustion process. This model is proposed in Section 3.5 and uses the pool fire phenomenon as a basis.

The three oil slick movement models summarized adequately represent the state-of-the-art in oil spill models. It is apparent that many of the factors affecting an oil slick are not well understood. It is this lack of knowledge that has limited much advancement in modeling techniques. Almost without exception advection is treated by a wind factor approach superimposed on the local currents. Advection due to waves is rarely modeled because of its complex coupling with the wind. Generally, many of the weathering factors are not modeled not because they are not important but because there is insufficient knowledge to understand the processes and the interaction with all the environmental factors. Normally when the weathering processes are considered, an order of magnitude approach is used, with the possible exception of evaporation which is better understood and modeled.

Table 3.2 briefly identifies the capabilities available for modeling oil spills. The major limitations of the individual process models and areas that need development are noted. Examination of the table indicates that there is room for improvement in all phases of oil spill modeling. The major thrust of oil spill models has been the prediction of spill trajectories or impact

TABLE 3.2. Advantages and Limitations in Models

Process	Capabilities	Limitations	Development Needed
Advection			
• Wind drift	• can be reasonably approximated by a wind factor approach	• not adequate in shallow waters or near shoreline	• values for the wind factor and deflection angle need to be better quantified • a wind drift model for near shore and shallow water
• Wave drift	• wave drift models are not currently available		• wave drift model
• Currents	• can usually be accounted for by measurements • or, by a hydro-dynamic model	• requires extensive data acquisition • site specific • not available for all areas	• would require hydro-dynamic model development for all areas to be considered
Spreading	• can model calm sea spreading by the Fay-Hoult formulation	• can not account for assymetric spreading due to wind, waves and other environmental influences	• models that predict assymmetric spreading
Dispersion	• can account for additional spreading not predicted by the Fay-Hoult model	• not enough data available to allow an evaluation of these models	• need more data and field validation to allow adequate evaluation of the process and models
Weathering			
• Evaporation	• can predict which components will evaporate, but predicting evaporation rates is more difficult	• not enough data available to allow an evaluation of these models	• field validation and testing are required to allow an evaluation of these models and to permit modelling of the environmental influences
• Dissolution and precipitation	• order of magnitude approximations only	• not enought data to allow evaluation of these models	• field validation and testing required to allow evaluation of these models
• Emulsification	• order of magnitude analysis of oil-in-water emulsification	• no models currently available to model water-in-oil emulsification • not enough data to allow evaluation of these models	• more data and field validation necessary to allow evaluation and further development of these models
• Bio-degradation, photo-chemical and chemical oxidation, and sedimentation	• none		• unless model is to be run for more than a few days to a week, can probably neglect these effects; otherwise a comprehensive data acquisition and model development program will need to be undertaken
Wind field	• usually modelled based on measured data	• due to the sparsity of measurement stations spatial variations are usually neglected • differences in onshore and offshore data usually not accounted for • requires an extensive data base for accurate results	• this approach seems generally adequate, although improved models that involve spatial variations and the effects of land masses would be desirable
	• has been modelled with a wind field model	• site specific • generally not not available for all areas	• this approach would require wind field model development for most regions

points. This has been achieved with reasonable accuracy when sufficient information has been provided on the currents and wind field. Weathering, on the other hand, has not been modeled nearly as extensively or reliably. Weathering has only a minor effect on the slick trajectory and involves complex interactions of many environmental factors, hence its omission from many models. Some modelers have considered weathering processes, but due to the general lack of field validations these treatments must be viewed as qualitative assessments. This deficiency is particularly critical when contemplating combustion mitigation of oil spills, since weathering is a significant factor in reducing the combustibility of oils.

With respect to deterministic models, it is apparent that given detailed data on the wind and current field coupled with a wind factor approach reasonable slick trajectories can be predicted. It is possible to do a good job of modeling the slick trajectory (although there is room for improvement), but predictions of what happens within the slick cannot be made with the same level of precision.

3.5 OIL SLICK COMBUSTION - SIMPLIFIED RELATIONSHIPS

As discussed in Section 3.4, the modeling of the combustion of an oil slick using the factors and techniques of oil slick movement models can become very complex. With the purpose in mind that any relationship or explanation of the process should be of practical use, a model is proposed here which may be useful in the classification of oils and in making assessments on the probable success of using combustion as an oil spill mitigation tool. The model derivation begins with establishing the parameters of pool fires.

The burning of liquid fuels differs from that of gas or solid fuels in that combustion does not occur on the liquid itself. Rather, the site of combustion is the combustible vapor above the pool formed through volatilization of the liquid. Ignition, therefore, requires evolution of sufficient vapor to form a fuel:air mixture within the flammability range. Once ignition is accomplished, combustion can be sustained only if a continuous supply of vapor is available. That supply is provided through the vaporization of liquid fuel as a result of heat transferred back from the flame. When combustion is complete, the rate of combustion just equals the rate of vaporization and the heat output from the flame to the pool is just that required to maintain the rate of fuel flow back to the flame.

Hydrocarbon pool flames following the above considerations were examined in recent Canadian studies (Energetex, 1978). It was further suggested that in pool fires the rate of combustion is proportional to the rate of regression of the liquid surface (burning rate). It was assumed that heat losses from a hydrogen pool were small and, therefore, the heat directed back to the pool ($\dot{q}''$) is equal to the product of the burning rate (r in mm/min), the fuel density (ρ in g/cm^3) and the enthalpy (Δh in cal/g) which is required to evaporate or volatilize a unit mass of fuel. The latent heat of vaporization was used as the enthalpy, which would appear as not including energy required to raise the oil from ambient to the boiling point. In the reported analysis the heat transfer is estimated using an amount of heat thought required rather than the amount of heat produced and determining the fraction thereof which is directed back to the pool. When the hydrocarbon pool is floated on water the analysis suggests that the heat flux back to the pool ($\dot{q}''$) is fully absorbed while its equal ($r\rho\Delta h$) is carried away with the vapor. This does not account for surface reflection or soot absorption and emissivity. A straightforward relationship is suggested employing the fuel's thermal conductivity (λ), the oil surface (T_o) and water (T_w) temperatures, and the thickness of the oil (ΔZ). It was not clear that this relationship agrees with measurements (Khudyakov, 1953) which indicate that T_w approached T_o for equivalent depth of water as for oil. If the relationship were valid, a concise explanation of the minimum oil thickness is offered using as the burning oil slick heat balance the following:

$$\dot{q}'' = r\rho\Delta h + \lambda \left(\frac{T_o - T_w}{\Delta Z}\right) \tag{4}$$

and when no burning, i.e., r = 0, then

$$\dot{q}'' = \lambda \left(\frac{T_o - T_w}{\Delta Z}\right) \tag{5}$$

from which it is suggested that the minimum thickness that will support combustion can be determined.

Under some conditions other considerations become important; e.g., vapor may escape unburned and hence the vaporization rate would exceed the burning rate. However, a description of the heat balance required to sustain combustion offers a means of predicting if a given liquid fuel will sustain burning under a given set of circumstances. It is clear that combustion is feasible only if:

$$H\ comb > H\ evap + H\ sens \tag{6}$$

where

$H\ comb$ = the heat released upon combustion of a unit of fuel,

$H\ evap$ = latent heat of vaporization for that unit of fuel,

$H\ sens$ = heat required to raise the temperature of the liquid fuel from ambient to its boiling point.

Since only a portion of the heat of combustion will reach the pool where it can promote fuel vaporization, the relation is more usefully written:

$$\alpha\ H\ comb > (H\ evap + H\ sens) \tag{7}$$

where

$$\alpha = \frac{H\ \text{returned to the pool}}{H\ comb}$$

Therefore, the development of an evaluation procedure for determining which fuels and which sets of circumstances will be amenable to pool combustion on water depends on the extent to which these terms can be quantified.

3.5.1 Heat of Vaporization

The heat requirement for vaporization of fuels is readily determined since it (heat/unit time) is the product of the latent heat of vaporization (heat/unit mass) and the mass flow rate (unit mass/unit time). The latent heat of vaporization is a physical property often reported for liquid substances. Among the best sources of this information for oils and other hazardous substances are the CHRIS Manual (Arthur D. Little, Inc., 1974) developed for the U.S. Coast Guard and the Oil and Gas Journal (1976). For those hydrocarbons for which specific values are not available, close approximations can be made. Published values of latent heat of vaporization for oils and refined fuels generally fall in the range 60 to 80 cal/g. The specific value for crude oils can be estimated based on the temperature and API gravity (Cragoe, 1929). This work was based on studies at the Bureau of Standards of available data on the thermodynamic properties of hydrocarbons and mixtures. The relation derived defines latent heat of vaporization as a function of temperature and specific gravity (or API gravity). Studies by nine teams were employed in the parametric analysis covering 46 hydrocarbon solutions.

To determine the effective heat required for establishing liquid fuels in the vapor phase, the sensible heat must be added to the latent heat.

3.5.2 Sensible Heat

The sensible heat requirement is defined here as the heat required to raise the temperature of the fuel from its ambient level to the level necessary for vaporization. In general, that would be to the temperature designated as the fire point for a fuel (the temperature at which combustion will be sustained), which is usually just above the flash point (the temperature where the fuel will ignite). Since the approach selected in this study deals with the amount of heat back to the pool, it is assumed that the sensible heat requirement of interest is limited to the heat needed to raise the temperature of the fuel to the point where stable combustion is sustained. Empirical studies have identified this temperature as the fuel's boiling point. This implies that once the vapor leaves the pool, heat from conduction and convection are sufficient to raise the vapor temperature to the fire point.

With pure liquids, the surface will attain a temperature at or just below the boiling point. For complex mixtures such as hydrocarbon fuels, the surface temperature will begin at the lighter end's boiling point but will slowly rise as the more volatile constituents are depleted (Rasbash et al., 1956). During laboratory studies, Rasbash et al. (1956) determined that a temperature gradient is set up through the pool with ambient levels maintained at a depth of slightly greater than 40 mm. For thin slicks ($<$10 mm) on water, the gradient is virtually the same as that of a pool of pure fuel (Hall, 1972), thus indicating that conductive losses downward from the pool are not significant. This observation is misunderstood or ignored by many practitioners as statements are made referring to the heat sink of the water body as being the burn inhibiting factor. This phenomenon is of importance only for thin slicks (<2 mm) close to the end of a burn. Similarly, for slicks of any size such as diameter > 1 m, conductance out horizontally is insignificant. Therefore, sensible heat requirements can be approximated by the heat required to raise the fuel from the ambient temperature to the boiling point of the fuel, or:

$$H\ sens = Cp\ (Bp - T_a) \tag{8}$$

where

Cp = specific heat of the fuel,
T_a = ambient temperature,
Bp = boiling point for the fuel.

Cp values for oils and other hazardous materials can be found in the CHRIS Manual (Arthur D. Little, Inc., 1974). Values for hydrocarbons do not vary greatly. Those for oils and distillates are reported in the range 0.44 to 0.53 Btu/°F over the temperature span 10 to 120°F. Specific values for crude oils can be determined as a function of API gravity and temperature (Cragoe, 1929).

The ambient temperature T is selected to match the circumstances being evaluated. For this analysis, a value of 4.4°C (40°F) is reasonable since many general analyses employ this number as an average ocean temperature. Other temperatures could be selected.

The boiling point of the refined products can also be found in the CHRIS Manual (Arthur D. Little, Inc., 1974). For many crude oil products this boiling point will be given by a range (plots are given in Oil and Gas Journal, 1976). Use of the lower value will yield an analysis of ignitability. Use of the mid or upper value would address the amenability of the fuel to complete combustion. When boiling point data are not available, information on distillation fractions can be employed for both crude and refined products.

3.5.3 Heat Transferred to the Pool

Determining the amount of heat transferred to the pool requires quantification of two terms: the total heat potentially released during combustion, and the fraction of that heat directed back to the pool. The total heat value is readily obtained as the heat of combustion value reported for fuels. This value can be obtained from the CHRIS Manual and from Cragoe (1929) as well as Ethyl Corporation (1951). Heat of combustion values for petroleum stocks and distillates generally fall in the range 9000 to 10,500 cal/g. This range should be noted as more than a hundred times the heat of vaporization which was discussed above. These values assume complete combustion. For very precise determinations, the values must be adjusted to account for actual heat release.

The remaining value to be determined is α, the fraction of total heat directed to the pool. This is a difficult parameter to measure and currently requires interpretation of a limited amount of data. Heat transfer from the flame can result from any of three mechanisms: conduction, convection, and radiation. In a review of these mechanisms, Hottel (1959) determined that for large diameters, radiation would predominate. When laboratory data were compared to a model of radiant heat transfer (Masliyah and Steward, 1969) they were found to fall well within the predicted range for burning rates. Similar results are reported for pool fires with plastics (Markstein, 1978). Other investigators have emphasized the role of convection in heat transfer (Spalding, 1953; Emmons, 1953). When burning rate data for large diameter pools were plotted, they were found to describe the relationship (Burgess et al., 1961):

$$V = K \frac{H\ comb}{H\ vap} \tag{9}$$

where

K = 0.076

V = large diameter burning rate for the fuel, mm/min

H comb = heat of combustion for the fuel, cal/g

H vap = effective heat of vaporization for the fuel, cal/g

Since the above equation implies direct proportionality with T (temperature) rather than T^4[a], as would be the case with radiative transfer, it was assumed to support the case for predominantly convective transfer. It has been shown for larger pool fires that the H comb/H vap ratio can also be derived from an analysis involving radiative transfer (Burgess and Hertzberg, 1974). This relation is particularly true if radiation back to the pool is a constant function of total heat of combustion, an observation which holds for most hydrocarbons (Burgess et al., 1961).

Empirical studies involving direct measurement of heat transfer mechanisms have revealed that both radiation and convection proceed concurrently with the predominant mechanism being a function of the fuel itself. Corlett (1968, 1970) found that convection was of major importance with hydrocarbon materials such as methane, ethylene, ethane, acetylene, butane and carbon monoxide in 10-cm (4-in.) pools. Similarly, Rasbash et al. (1956) reported that combustion of methanol requires transfer of significant amounts of heat by convection. However, with benzene and more complex fuels such as gasoline and kerosene, radiant heat transfer is the major mechanism of heat transfer to the pool. Yumoto (1971) found radiant transfer was 70% and 61% of total heat transfer for hexane and gasoline, respectively. The fraction of total heat release which can be attributed to radiation is positively correlated with pool diameter size and the number of unsaturated bonds in the fuel.

The latter correlation may reflect enhanced soot production (prime source of radiation emission) with higher levels of unsaturation. The correlation with pool size is related to mass transfer and combustion in the fully turbulent zone at fire diameter greater than 1 m. With turbulent flames, soot radiation is not as uniformly directed away from the pool. Hägglund and Persson (1976) report on a flame pulsation taking place as vapor-soot-flames bulge, combust and rise. The rapid flow of fuel vapors from the pool and

(a) Classic heat transfer analyses (Hottel, 1959) instruct that the heat directed back to the pool (q) is found by:

$$q = \sigma \ (T_s^4 - T_s^4)$$

where T_f is flame temperature and T_s is pool surface temperature and σ is the Stephan Boltzman constant.

flame buoyancy effects tend to minimize convective currents back to the pool. Hall (1972) concluded from the literature that in pool fires with a radius greater than 1 m, radiation becomes the predominant heat transfer mechanism.

Radiant heat transfer (q) is also a function of the emissivity (e_t) of the flame. This correction factor has been used to account for non-black body conditions so that the Stephan-Boltzman relationship may be used:

$$q = e_t \sigma T^4,$$

where T is the absolute surface temperature. Emissivity is known to be a function of both radiation wavelength and temperature. Partially burned hydrocarbons form a soot which has been identified as a major source of radiated heat (Hammond and Beer, 1974). This correlates with the previously described reports that radiant transfer is of major importance with petroleum product fires since oils and distillates produce soot when burned.

More detailed analyses have been presented by deRis (1978a,b,c) on the relationships of soot and effects on flame radiation. Extensive studies have been related to pool fires for several plastics where considerable theoretical discussion has been put in the context of measurements taken. Absorption-emission coefficient derivation is shown to be related inversely to the radiation wavelength and directly to the soot volume fraction. Attempts at equating these relationships establish the need for a dimensionless constant which is suggested to account for soot chemical composition. The luminous radiation can then be modeled using spectral absorption-emission coefficients for the mixtures of gases and soot. The radiant heat flux (q) to the pool surface is shown by deRis (1978a,b,c) to be:

$$q = \sigma T_f^4 (1 - e^{-Klm}) \tag{10}$$

where σ is the Stephan-Boltzman constant, T_f is the flame temperature, K is the absorption-emission coefficient and lm is the mean beam length determined as being proportional to the flame volume to flame area ratio.

Work reported by Hägglund and Persson (1976) investigated the effects on flame radiation by soot and illustrated the magnitude of radiation produced by soot in flames created by burning JP-4 fuel. These studies included measurements taken on pool fires up to 10 m in diameter. Figures illustrated clearly the radiation that soot particles would produce without the presence of the absorbing gases which are evolved during combustion. It was also shown that the radiative output decreases with an increasing width of fire, discounting the soot effects. Measurements taken indicated that this fuel could produce radiant energy $\geq 9\ W{\cdot}cm^{-2}$ over the majority of the flame surface. The smoke column emitted $\leq 2\ W{\cdot}cm^{-2}$ and therefore can usually be neglected. Maximum radiation of $13\ W{\cdot}cm^{-2}$ was observed at a flame depth of 150 cm which was an optically thick flame. Pool fires of 5 and 10 m diameter radiated lower at 8 and $6{\cdot}W\ cm^{-2}$, respectively. Flame temperature for the maximum radiation was about 1250°K.

The above considerations indicate that the combustibility and ultimate burning rate of oil pools is a function of radiant heat transfer. As a fuel's vapor is oxidized, it releases heat which increases the rate of vaporization and hence the amount of available fuel. With more fuel available, increased heat releases and higher temperatures would be expected. Unchecked, this would describe an accelerating phenomenon of explosive proportions. Other related phenomena, however, restrain the process. As fuel flow increases, combustion is less complete and unburned vapors and soot form. This process increases the thickness of the flame and its tendency to reabsorb radiation within itself and also creates a vapor layer between the flame envelope and the pool which is an active infrared radiation self-absorption zone. The effect on flame temperature is unclear. It could be held below the theoretical maximum as a result of reduced realization of total heat of combustion for the fuel, and heat could escape in the form of sensible heat of unreacted fuel components. The tradeoff between luminous, heavy soot flames and clear, hotter flames in terms of radiant energy output has not been well characterized. An increased fuel flow creates a deeper and denser vapor layer between the flame and the pool which effectively screens radiation from the liquid. This suggests diminishing heat return to the pool which will retard burning rates until a balance is reached.

The current state of knowledge (1979) is still insufficient to allow accurate prediction of heat transfer back to the pool on purely theoretical or first principle grounds. The center for Fire Research of the U.S. National Bureau of Standards is actively working on consistent sets of flame measurements to control fire. Workers such as deRis (1978a,b,c) and others have made process in predicting radiation from sooty homogeneous combustion gases of known composition. Theory exists to extend this work to inhomogeneous combustion situations, but limitations still exist, e.g., accounting for the radiant blockage by pyrolysis vapors near the surface of the pool.

While some data have been collected on fuels by direct measurement, this obviously applies only to those fuels which will sustain combustion. It does not allow for prediction of combustibility of untested materials. For these materials, a means of approximation is required. The simplest such means would be the identification of a constant fraction of total heat released which is returned to the pool. Such identification must be made through analysis of empirical data on related fuels. Rasbash et al. (1956) reported the estimated radiant heat transfer to the pool for four fuels provided in Table 3.3. For the fuels with greater emissivity - benzene, gasoline, and kerosene - the radiant heat is sufficient to meet the latent and sensible heat requirements for combustion. Based on use of the fuels' reported heats of combustion, the radiant heat to the pool represents 1.2% to 2.5% of total potential heat released. These estimates must be considered as maximums since they were derived assuming ideal black body absorption by the pool and no absorption by the vapor layer. These estimates, however, neglect convective contributions which may represent an additional 20% to 100% of the radiant contribution (Yumoto, 1971).

TABLE 3.3. Radiant Heat Transfer from Flame to Pool

Fuel	Heat Input to Vaporize Fuel (cal/min)	Heat Input to Raise Liquid Temperature (cal/min)	Total Heat Requirement (cal/min)	Estimated Heat Transfer to Pool (cal/min)	Heat of Combustion (cal/min)	Fraction of Heat Directed to Pool
Methanol	13,500	4,000	17,500	3,000	260,000	.0115
Benzene	27,500	4,500	32,000	36,000	2,400,000	.015
Gasoline	10,500	3,000	13,500	21,500	1,000,000	.0215
Kerosene	9,000	6,000	15,000	15,500	620,000	.025

Directly measured laboratory data for other hydrocarbons are presented in Table 3.4. While many of the latter materials were found to have predominantly convective mechanisms for heat transfer to the pool, they create a relatively consistent data set wherein an average of 2% of the heat of combustion is estimated as transferred to the pool through radiation. This average is a conservative number since on the low side the radiant fraction arithmetic average is 2.4% and on the high side it is 3.1%. Keeping the radiant transfer at 2% compensates for losses such as radiation absorption in the vapor and reflection at the pool surface. This 2% then can be employed for the purpose of estimating α, the fraction of total heat directed toward the pool. It should be noted that calculations of α in this manner eliminates some of the need for using actual versus theoretical values for heat of combustion since the empirical data will have already accounted for major differences. The remaining disparities will be those between the completeness of combustion in the experimental setup and those in a large-scale pool fire.

TABLE 3.4. Estimated Radiant Heat Input to Pool from Hydrocarbons (after Corlett, 1970; after Alger et al., 1976)

Fuel	Radiant Fraction of Total Heat Release
Methane	0.004-0.22
Propane	0.009-0.05
Ethane	0.026
Butane	0.025
Ethylene	0.023
Acetylene	0.028-0.07
Ethyl Acetylene	0.04
Carbon Monoxide	0.048
Hydrogen Sulfide	0.014
JP-5 (after-Alger)	0.023

Support for selection of a constant value 2% for α, the fraction of total heat directed back to the pool as radiant energy, can be found in empirical studies and theory. Parker (1974) has reported that for hydrocarbon pool fires, approximately 25% of heat production is released as radiant energy. This is supported by Burgess et al. (1961) and Kanury (1974) and employed in subsequent pool fire models. For large pool fires, the value may be somewhat lower. The fraction of that 25% which will be directed to the pool is dependent on the view factor. For estimation of radiant heat output, flames are conceptualized as a cylinder with a constant height (H) to diameter (D) ratio characteristic of the fuel. For liquid natural gas (LNG), that ratio is roughly H/D = 3. If the pool is visualized as sitting immediately below the flame, the view factor would be the ratio of cylinder cross-sectional area to total cylinder surface, or:

$$F = \frac{\pi R^2}{2 \pi R^2 + \pi 2RH} = \frac{R}{2 \cdot R + 2 \cdot H}\text{; and} \tag{11a}$$

$$H = D \cdot 3 = R \cdot 6 \qquad \text{leaving}$$

$$F = \frac{1}{14} = 0.0714 \approx 0.07$$

where

F = view factor,

R = flame radius,

H = flame height = 3 diameters = 6R.

This yields an estimate of $\alpha = 0.25F = 0.25 \times 0.07 = 0.018$. For large hydrocarbon fires, Blinov and Khudyakov (1957) found a ratio of h = 4R which would yield a view factor of 0.10 and the value of $\alpha = 0.025$. These compare favorably with the $\alpha = 0.02$ estimate recommended. As the pool diameter becomes very large, the H/D ratio is likely to decline, thus raising the view factor F. At the same time, the fraction of total heat release presented by radiation also appears to decline with very large pools. These effects counter each other and tend to stabilize the value of α.

The assumption of cylindrical geometry for flame/radiant heat transfer is also conservative for determining view factors. Some researchers would suggest that the sphere is a more appropriate model for heat transfer by radiation. The view factor of a sphere, being proportional to segment surface areas, would vary depending upon the distance of the centroid of the sphere from the pool surface. In the case where the centroid and the pool surface coincide, the view factor is:

$$F = \frac{\pi R^2}{1/2\ 4\pi R^2} \qquad (11b_1)$$

$$F_1 = 0.5$$

where the surface of the flame/radiant transfer sphere is tangent with the surface of the pool, the view factor is found as area of spherical sequent divided by by total surface area:

$$F_2 = \frac{A_{x2}}{A_T} = \frac{(1.414R)^2 \times 0.92010}{4\pi R^2} \qquad (11b_2)$$

$$= \frac{1.414^2 \times 0.92010}{4\pi} = 0.15$$

and the view factor when the surface of the sphere is above the pool:

$$1.0 \times R,\ F_3 = \frac{A_{x3}}{A_T} \qquad (11b_3)$$

$$F = \frac{(0.8944\ R)^2 \times 0.82896}{4\pi R^2} = 0.053$$

Therefore, the three position considerations using a sphere would yield estimates of back radiated heat fraction $\alpha = 0.25F$:

H/D = 0	Case 1:	0.25 x 0.5	=	0.125;	12.5%
H/D = 1	Case 2:	0.25 x 0.15	=	0.038;	3.8%
H/D = 3/2	Case 3:	0.25 x 0.053	=	0.013;	1.3%

Case 1 is too large to be considered based upon measurements taken by others (Parker, 1974; Burgess et al., 1961a,b; Kanury, 1974; and Blinov and Khudyakov, 1957). Case 2 is also greater than that which has been measured. Case 3 is below measurement and also requires that there be a considerable gap between the flame and the pool surface which appears unlikely based upon field observations.

Several investigators (deRis, 1978, and others) often use an assumed pyramid (for square) or cone (for circular) pool fires as the flame shape. In the present case if the cone were used and the h/R is assumed as 6 as for LNG fires or 4 as reported by Blinov and Khudyakov (1957):

$$F = \frac{11\ R^2}{\pi\ R\sqrt{R^2+h^2}} \quad ;\ \text{for } h/R = 4,\ F = 0.242 \tag{11c}$$

$$;\ \text{for } h/R = 6,\ F = 0.164$$

therefore, $\alpha = 0.25F$ or 0.0606 for h/R = 4 and 0.0412 for h/R = 6. Both of these values are higher than the limited field measure data available and are higher than that obtained assuming cylindrical geometry. Therefore, the most conservative approach appears to be to use the cylinder as an assumed flame shape. Work by Raj et al. and Welker et al. (1965) support the use of the cylindrical assumption.

As will be noted later in this report, the use of 2% as the fraction of heat radiated to the oil slick pool is significant enough to merit careful examination. Some investigators would suggest an α value greater than 2%, since most available data are for combustion under ideal stoichiometric conditions. Effects of excess air and other actual conditions in the field can alter the efficiency of combustion. As discussed, 2% can be supported as demonstrated geometrically and as being in agreement with many reported measurements. Another examination was reported by Alger et al. (1976) where investigations on the burning of JP-5 indicated that an average radiation flux of 1.41 cal/cm^2-sec was observed during burning rates of 0.007 g/cm^2-sec. As noted elsewhere, the heat of combustion for JP-5 is 10,300 cal/g. Energy release would be 0.007 x 10,300 = 72.1 cal/sec for each cm^2 of pool surface. Considering the measured radiant energy on the pool surface: 1.41 ÷ 72.1 = 1.956% is the portion of the total heat of combustion. This again supports the 2% suggested above for hydrocarbon pool fires.

3.5.4 Estimates of Combustibility

Based on the previous discussions, it is suggested that petroleum based fuels and similar materials can be evaluated for their ability to sustain combustion in a pool fire through use of the relation:

$$0.02 \times H\ comb = H\ evap + Cp\ (Bp - Ta) \qquad (12)$$

where

H comb = the total reported heat of combustion for the fuel,
H evap = the latent heat of vaporization for the fuel,
Cp = the specific heat of the fuel,
Bp = the fuels boiling point,
Ta = the ambient temperature.

While the evaluation is not qualitatively precise, it can be employed to assess the use of combustion for mitigating oil spills. Three applications are considered here:

- classification of oils, Section 3.6, with respect to their amenability to sustaining a pool fire
- evaluation of potential success, Section 3.7, in initiating a pool fire under various environmental conditions;
- identification and assessment of approaches to enhancing pool burning (see Section 4 on equipment and technology).

3.6 CLASSIFICATION OF OILS

As described in Section 2, the bredth of coverage of the term, oil, must be more quantitatively defined to enable any sort of predictive or reproducible evaluation. Since this or any other report can have little effect upon requiring more specific terminology used in the literature describing oil spill problems, a normalization of significant characteristics of the oils used is desirable to facilitate the rational assessment of burning technology.

Ultimately, such a system is envisioned as a direct aid in determining the feasibility of firing spilled materials on a real-time basis. At present several classifications of petroleum and its products are available. These classification systems do not address combustibility per se, but a review of each is instructive.

In the 1973 Oil Spill Conference Proceedings, Beynon of the U.K. presented the information in Table 3.5 to summarize the specification of non-U.S. crude oils by wax content. Westree (1977) submitted the data in Table 3.6, which illustrates classification of oil properties pertaining to effects and emergency response needs. Work undertaken by a GESAMP (Group of Experts on the Scientific Aspects of Marine Pollution) working group on the Impact of Oil on the Marine Environment also considered a classification system, but dropped it as too controversial.

The above systems do not offer a means of differentiating those oils which will sustain combustion from those that will not. Whereas ranking by pour point and viscosity suggest the extent of volatiles in the compositions, they do not address the ability of the oil to ignite and sustain combustion. A ranking by flash point could be made. However, this ranking would relate to ignitibility and not to the ability of the oil to sustain combustion. Recognition of the above sets the stage for identification of alternative physical parameters or combinations of physical parameters which would provide a quantitative measure indicative of which oils can be burned in the open environment.

One approach stems from the work of Burgess et al. (1961) wherein it was described that burning rate V in a container of infinite diameter could be described by the equation:

$$V = K \frac{H\ comb}{H\ vap} \tag{13}$$

Oils could be classified by burning rates determined from this equation. Empirical data with specific oils would then be employed to define a threshold burning rate below which oils would not sustain open combustion.

TABLE 3.5. Specification of Crude Oils

Category	Country	Type	Loading Terminal	Density d15/4	Viscosity cSt 100°F	Pourpoint °F	Pourpoint °F Residue 200°C	Distillation ASTM °C 20%	30%	40%
1. High wax content	Gabon	Gamba	Sette Cama	0.872	28.5	86		269	---	---
	Libya	Es Sider	Es Sider	0.841	5.7	48		152	200	253
	Libya	Libyan high pour	Ras Lanuf	0.846	12.7	70	not	187	244	---
	Libya	Sarir	Marra el Alariga	0.847	11.9	75		178	242	292
	Nigeria	Nigerian light	Bonny	0.844	3.59	70	relevant	157	203	246
	Egypt	El Morgan	Ras Shukhair	0.874	13.0	55		185	240	298
2. Moderate wax content	Quatar	Quatar	Umm Said	0.814	2.55	0	40/50	133	170	211
	Quatar	Quatar marine	Halul island	0.839	4.1	10	40	146	187	233
	USSR	Muhanovo		0.835	4.18	32	55	149	192	236
	USSR	Romashkinskaja	Novonossisk	0.859	6.9	25	40/45	159	210	265
	Algeria	Zarzaitine	La Skirra	0.816	4.56	5	40	143	183	234
	Libya	Brega	Marsa el Brega	0.824	3.6	0	45	142	186	237
	Libya	Zueitina	Zueitina	0.808	2.9	10	50	129	159	194
	Iran	Iranian light	Kharg island	0.854	6.6	25	50	157	206	257
	Iran	Iranian heavy	Kharg island	0.869	10.2	19	45	158	213	270
	Iraq	Northern Iraq	Tripolis/Banias	0.845	4.61	5	50	142	184	240
	Abu Dhabi	Abu Dhabi	Djebel Dhanna	0.830	3.42	0	40/45	143	181	223
	Abu Dhabi	Abu Dhabi-Zakum	Das island	0.825	2.9	5	45	124	166	212
	Abu Dhabi	Abu Dhabi-Umm Shaif	Das island	0.840	3.8	5	40/50	134	178	218
	Norway	Ekofisk		0.847	4.5	25	50	140	200	240
3. Low wax content	Algeria	Hassi Messaoud	Bougie	0.802	1.95	<-22	<40	113	148	181
	Algeria	Arzew	Arzew	0.809	2.4	<-22	<40	128	163	197
	Nigeria	Nigerian medium	Bonny	0.907	14.1	<-22	<40	251	275	300
	Nigeria	Nigerian export	Forcados	0.872	5.8	<-22	<40	189	228	268
	Kuwait	Kuwait	Mina al Aghmari	0.869	10.6	1	<40	164	218	282
	Saudi Arabia	Arabian light	Ras Tanura/Sidon	0.851	5.45	<-22	<40	159	205	258
	Saudi Arabia	Arabian medium	Ras Tanura/Sidon	0.874	9.7	5	<40	169	225	283
	Saudi Arabia	Arabian heavy	Ras Tanura/Sidon	0.897	19.1	<-22	<40	200	257	---
	Neutral Zone	Kafji	Ras el Kafji	0.888	18.1	<-22	<40	185	254	---
	Iraq	Southern Iraq	Fao/Hohg al Amaya	0.847	5.78	9	<40	165	210	263
	Oman	Oman	Mina al Fahal	0.861	8.7	-17	<40	175	233	283
	Venezuela	Tia Juana medium	Puerto Miranda	0.900	16.8	<-22	<40	224	285	---
4. Very low wax highly viscous	Venezuela	Bacchaquero	Puerto Miranda	0.978	1280	5/19	---	---	---	---
	Venezuela	Tia Juana pes	Puerto Miranda	0.980	2983	27	---	---	---	---

Source: L. R. Beynon, 1973 Oil Spill Conference

TABLE 3.6. Four Classifications of Oils

Types of Oil	General Oil Industry Classification	Emergency Response Classification	Substrate Penetration	Toxicity
Motor gasoline Jet fuel Kerosene Naptha	Light distillates	Light fuel oils	Very high degree in all marsh types	Very high direct and indirect toxicity
Diesel fuel oil No. 2 fuel oil No. 4 fuel oil	Heavy distillates			
No. 6 fuel oil Bunker fuel oils		Heavy fuel oils	Very low degree in all marsh types	Little chemical effect; serious physical interference
Crude oil sources: Libya, Nigeria, Iran, Iraq, Kuwait, Saudi Arabia, Venezuela, Canada United States Algeria, etc.	Crude oil	Crude oil	Highly variable, depending upon viscosity	Highly variable, depending upon low boiling fractions present and degree of weathering

Source: B. Westree. 1977 Oil Spill Conference, Santa Barbara, CA.

There is a problem with this approach in that for most oils and petroleum products, H comb and H vap fall within a very narrow range of values. The tables of Cragoe (1929) illustrate this clearly. As a consequence, a rating based on these parameters will not provide sufficient differentiation between oils to create a practical continuum.

From the discussion of pool fire dynamics, it is apparent that boiling points, and therefore sensible heat requirements, for oils vary considerably. As a consequence, some oils are difficult to burn continuously because the flame does not direct sufficient heat back to the fuel to maintain a constant vaporization rate and subsequent burning rate. Hence, a workable oil classification scheme should consider this parameter as well as H comb and H vap. The most logical section of these factors at this time is that provided by evaluation of Equation (12) (Section 3.5) on heat balance:

$$0.02 \text{ H comb} = \text{H vap} + \text{Cp (Bp-Ta)} \qquad (14)$$

Oils can be classified based on the net difference between the total heat of combustion released (H_{comb}) and the total heat requirement. This is similar to the "B factor" developed by Kanury (1974) as indicative of burning rate. A relative ranking based on net differences is provided in Table 3.7 for a number of oils and distillates. Since these materials often have a broad boiling range rather than a discrete boiling point, a degree of judgment is required in selecting relative placement for some entries. For instance, most distillates contain both light and heavy fractions. The light fractions are much more amenable to ignition and sustained combustion. The degree to which these fuels will ignite and sustain combustion is dependent upon environmental conditions at the time of the combustion attempt. The broad classification categories are then created to identify three categories of materials are:

1. those fuels from which ample excess heat is generated to meet heat requirements; burning can occur under most environmental conditions
2. those fuels which direct radiant heat back to the pool roughly equivalent to heat requirements; burning will occur only under some environmental conditions
3. those fuels which produce insufficient heat to meet requirements for burning; burning will not occur unless artificial promoters are used.

Oils in the No. 1 category are prime candidates for combustion related responses to spills. It is unlikely that oils in the No. 3 category would ever be candidates for open combustion without combustion promoters. Oils in the No. 2 category may be burned under favorable conditions or if appropriate combustion promoters can be employed. Some of these materials may also ignite but not burn completely. The evaluation matrix discussed later in this report for combustion feasibility will be particularly pertinent for these oils.

Generic data on crude oils as a group results in their placement in category No. 2. Specific crudes, however, vary widely depending upon their makeup. Hence, it is important to look at crude oils in greater detail. A heat balance evaluation of all major import oils as of 1976 was performed. Each oil was divided into fractions (deciles when possible) and evaluated in

TABLE 3.7. Relative Combustibility of Oil Products

Material	ΔH Comb. (cal/g)	ΔH Required (cal/g) Initial-Final	2% ΔH Comb. (cal/g)	Net Heat Available 2% ΔH Comb Initial	Net Heat Available ΔH Required Final
CATEGORY NUMBER 1					
Motor Fuel Antiknock	10,100	99	202	103	103
Compounds with Lead Alkyls					
Gasoline and Flash Feed Stocks	10,400	81 - 144	208	127	64
Jet Fuel No. 3	10,300	90 - 198	206	116	8
Coal Tar	9,690	107 - 136	194	86.6	58
Kerosene and JR No. 1	10,300	151 - 180	206	55	26
Jet Fuel No. 5	10,300	177	206	29	29
Fuel Oil No. 1 and 1D	10,300	151 - 200	206	55	6
CATEGORY NUMBER 2					
Asphalt	9,320	94 - >226	186	92	<-40
Jet Fuel No. 4	10,300	158 - 210	206	48	-4
Gas Oil	10,300	157 - 255	206	49	-49
Fuel Oil No. 4	9,700	115 - 343	194	79	-149
Fuel Oil No. 2 and 2D	10,800	201 - 226	216	15	-10
Fuel Oil No. 5	10,000	170 - 335	200	30	-135
Bunker C	10,000	167 - 343	200	33	-143
CATEGORY NUMBER 3					
Diesel Oil	10,000	203 - 226	200	-3	-26
Castor Oil	8,860	192	177	-15	-15
Spray Oil	10,300	213 - 242	206	-7	-36
Rosin Oil	10,000	208 - 255	200	-8	-55

the manner of the distillates in Table 3.7, i.e., 0.02 (H comb) = H evap + Cp(Bp - 40°F) using temperature and gravity data from the Oil and Gas Journal (1976) and thermodynamic property data published by Cragoe (1929).

The data resulting from the calculations provided in Table 3.8 reveal that crude oils vary greatly in the extent to which these components will sustain combustion. Those with breakeven points (point at which heat requirements just equal radiation inputs) in the 80% to 90% range should readily burn under pool fire conditions, while those in the 20% to 30% range are not likely to sustain ignition. This analysis, when augmented by empirical data, will be of value in estimating residues and calculating energy added requirements to provide a sustained burn. Since most of the thermodynamic properties of interest (e.g., heat of combustion and latent heat of vaporization) vary with API gravity, it may appear that API gravity could be used to categorize crude oils with respect to combustibility. However, when API gravity and break-even points are analyzed for the crude oils in Table 3.8, the correlation is very poor, as evidenced in Figure 3.3. Hence, gravity alone is not sufficient to determine the combustibility of oils.

It should be noted that the absolute values (but not the relative ranking) for oils and hence the location of the boundaries between categories will vary with the value selected for α. As noted previously, 2% was selected on the basis of review of a limited number of hydrocarbons. The effect of having alternate values for α can be seen in Figure 3.4. The diagonal lines represent the point where the net heat value (α H comb - H required) is zero. Hence, for any operator line (α = 1, 2 or 3%) the most combustible oils will be those to the left of the diagonal. Those straddling the diagonal would fall in the middle category of combustible oils and those to the right would be in the third or least combustible category.

The practical significance of Figure 3.4 is the graphic illustration directing attention to techniques which must be developed and phenomena to be measured in the field. If only 4% of the total heat of combustion could be reflected or directed to the surface of the pool (from Figure 3.4), all oils would be amenable to mitigation by combustion. Recognizing the direction of past technology development and the minimal attention to this apparent relationship, future development work should focus upon this principle.

TABLE 3.8. Comparison of Heat Balance for Imported Crude Oils

Crude Oil	Net Heat by Decile (cal/g) - 0.02 H Comb - ΔH Vapor Cp(Bp-40°F) 10	20	30	40	50	60	70	80	90	100	Breakeven Point Approximate Vol.%
Attaka, E. Kalimantan, Indonesia		+95	+86	+79	+68	+62	+48	+34	+23	-16	91
Tembungo, Malaysia	+101	+86	+72	+56	+38	+33	+24	+16	+3		87
Seppinggan, E. Kalimantan, Indonesia		+105			+49		+15			-27	86
Poleng, Java, Indonesia		+111	-35	+76		+49→		+6		<-18	84
Labuan Light, (Samarang) Sabah, Malaysia	+174	+77		+53			+22		-28	-45	82
Es Sidar, Libya	+86	+79		+23			+1			-97	82
Brass River, Nigeria	+112	+92	+83	+73	+59	+39	+25				81
Serei light, Brunei	+112	+92		+56			+18		-40	<-82	80
Pennington, Nigeria	+103	+80	+65	+49	+33	+25	+16	0	-25		75
Melahin, E. Kalimantan, Indonesia	+106			+88			+11		<-26		71
Qua Iboe, Nigeria	+112	+92	+76	+59	+43	+23	+11	-12	-40		70
Hassi Messaoud blend, Algeria	+100	+86		+66	+48		+16		-18		68
Beryl, U. K.	+109	+97	+80	+66	+45	+24	+5	-24	-56		67
Bonny light, Nigeria		+90	+76	+59	+42	+22	+6	-17	-51		67
Arabian light (Berri), Saudi Arabia	+113	+89	+73	+52	+36	+21	+7	-33	-68		67
Mubarek, Sharjah, UAE	+89	+84	+70	+48		+12		-4?		-93	67

TABLE 3.8. (contd)

Crude Oil	Net Heat by Decile (cal/g) - 0.02 H Comb - ΔH Vapor Cp(Bp-40°F) 10	20	30	40	50	60	70	80	90	100	Breakeven Point Approximate Vol.%
Escravos, Nigeria	+103	+86	+72	+55	+31	+21	+2	-21			66
Trinidad blend, Trinidad Tobago	+95	+67	+51	+39	+24	+16	+1	-11	-32		66
Bekapi, E. Kalimantan, Indonesia	Estimated from Crude Oil API Gravity of 41.1°										66
Arjuna, Java, Indonesia	+111	+97	+76	+64	+36	+18	0	-31	-59		65
Zakum, Abu Dhabi		+92	+77	+62	+43	+22	0				65
Hout, Neutral Zone	+90	+86		+66	+48		+16		+13		65
Thistle, U.K.	+102	+79		+36			-33			-92	65
Basrah, Iraq	+100	+76	+40		+23			-40		-93	65
Badak, E. Kalimantan, Indonesia	Estimated from Crude Oil API Gravity of 39.4°										65
Mubarras, Abu Dhabi	Estimated from Crude Oil API Gravity of 38°										65
Brega, Libya	+113	+92	+75	+60	+43	+20	-3	-31	-68		64
Murban, Abu Dhabi	+107	+87	+75	+57	+43	+21	-2	-27	-61		64
Arzew blend, Algeria	+105	+78		+54	+31		+7	negative			64
Umm Shaif, Abu Dhabi	+103	+90	+70	+55	+33	+19					64
Walio export mix, West Irian, Indonesia	+102	+79	+67	+50	+33	+20	-2	-30	-66		64
Qatar (Duckhan), Qatar	+102	+76		+42		+23		-46	<-94		64
Kerindingan, E. Kalimantan, Indonesia	+106		+88			+15		<-25			63

TABLE 3.8. (contd)

Crude Oil	Net Heat by Decile (cal/g) - 0.02 H Comb - ΔH Vapor Cp(Bp-40°F) 10	20	30	40	50	60	70	80	90	100	Breakeven Point Approximate Vol.%
Statfjord, Norway	+110	+92	+76	+55	+33	+16	-7	-34	-69		62
Qatar Marine, Qatar	+104	+93	+71	+55	+36	+16	-7	-34	-75		62
El Bundug, Abu Dhabi	+71	+64		+42		+15		negative			62
Sassan, Iran	+106	+78	+51		+16		-12	-49		<-94	61
Piper, U. K.	+109	+79	+50		+13			-13			61
Montrose, U. K.	+91		+83	+50		+17		-21			61
Forcados blend, Nigeria	+100	+75	+55	+38	+24	+11	-8	-28	-49		61
Zarzaitine, Algeria	+116	+88	+63	+40		+17		<-23			60
Ekofisk, Norway	+108	+84	+68	+50	+34	+13	-11				60
Forties, U. K.		+90	+73	+50	+31	+11	-16	-45	-95		59
Rostam, Iran	Estimated from Crude Oil API Gravity of 35.9°										59
Bai Hassan, Janbur, Iraq	Estimated from Crude Oil API Gravity of 34.1°										59
Kirkuk, Iraq	+110 +102	+92	+72	+53	+33	+16	+1	<-21			58
Bu-Attifel, Libya	+103 +93	+67		+29			-35		-77		58
Handil, E. Kalimantan, Indonesia	+106	+56	+34		+15						57
Darius, Iran	+101	+91	+71	+51	+29	+4	-23	-54			56
Oman, Oman	+109 +31		+46	+21			-39				56

TABLE 3.8. (contd)

Crude Oil	Net Heat by Decile (cal/g) - 0.02 H Comb - ΔH Vapor Cp(Bp-40°F) 10	20	30	40	50	60	70	80	90	100	Breakeven Point Approximate Vol.%
Zueitina, Libya	+90	+67	+45		+18	-9		-47		<-91	56
North Rumaila, Iran	Estimated from Crude Oil API Gravity of 34.3°										56
Tyumen, USSR	Estimated from Crude Oil API Gravity of 34°										56
Cinta, Indonesia	Estimated from Crude Oil API Gravity of 33.9°										56
Ninian, U. K.	+103	+85	+69	+47	+24	-1	-23	-54			55
Reforma (Cactus Reforma, Isthmus) Mexico	+101	+84	+63	+42	+22	0					55
Iranian Light, Iran	+102	+85	+65	+42	+20	-1	-25	-59			55
Arabian Light, Saudi Arabia	+91	+84	+61	+39	+18	0	-16	-55	-92		55
Strip Blend 27.1 API, Iran	+118	+95	+54	+24		-19			-98		55
Iranian Heavy, Iran	+103	+85	+65	+43	+21	-3	-35	-97			54
Romashkinskaya, USSR	+103	+85	+63	+43	+20	-3	-34				54
Bunju, E. Kalimantan, Indonesia	Estimated from Crude Oil API Gravity 32.2°										54
Lagomedio, Venezuela	+100	+81	+61	+40	+19	-4	-27	-45			53
Dubai, Dubai	+104	+84	+42	+22	+9	-14			<-49		53
Bonny Medium, Nigeria	+97	+57	+42	+24	+10	-2	-22	-44	-64		53
Tarakan (Pamusian) E. Kalimantan, Indonesia	+56	+37	+30	+21	+9	-3					53
Ecuador (Oriente), Ecuador	+102	+78	+55	+33	+11	-4	-34				52

TABLE 3.8. (contd)

Crude Oil	Net Heat by Decile (cal/g) - 0.02 H Comb - ΔH Vapor Cp(Bp-40°F) 10	20	30	40	50	60	70	80	90	100	Breakeven Point Approximate Vol.%
Sarir, Libya	+116	+87	+63	+39	+15	34			<-81		50
Gulf of Suez Blend, Egypt	+111	+76	+55	+33	+12	-12	-34	-69			50
Kuwait Crude, Kuwait	+106	+85	+61	+40	+13	-12	-42				50
Arabian Medium (Zuhof), Saudi Arabia	+106	+82	+61	+38	+11	-12	-41	-77			50
Fereidoon Blend, Iran	+100	+81	+61	+38	+11	-12	-40	-73			50
Arabian Medium, Saudi Arabia	+96	+79	+57	+36	+13	-14	-40	-78			50
Ekhabinskaya, USSR	Estimated from Crude Oil API Gravity of 30.7°										50
Amna (High Pour), Libya	+102	+76	+52	+27	+7	-17	-44				48
Arabian Heavy, Saudia Arabia (Safaniya and Khafi)	+112	+84	+57	+34	+4	-24	-66				47
Cabinda, Cabinda, Angola	+100	+79	+47	+23	0	-24					45
North Slope, USA	+95	+72	+47	+25	+1	-21	-45	-75			45
Mandji, Gabon	+102	+74	+49	+22	-2						44
Ratawi, Neutral Zone	+111	+71	+42	+20		-39			<-95		43
Minas (Sumatran Light) Sumatra, Indonesia	+91	+65	+40	+21	-5	-37	-55				43
Burgan (Wafra) Neutral Zone	+92	+73	+40	+21		-43			<-102		42
Anguille, Gabon	+104	+97	+54	+40	+9	<-23					41
Taching, China (PRC)	+112	+95	+71	+52	+23	-36			<-92		40

TABLE 3.8. (contd)

Crude Oil	Net Heat by Decile (cal/g) - 0.02 H Comb - ΔH Vapor Cp(Bp-40°F) (deciles 10, 20, 30, 40, 50, 60, 70, 80, 90, 100)	Breakeven Point Approximate Vol.%
Gamba, Gabon	+105, +96, +64, +35, +16, <-19	38
Eocene, Neutral Zone	+91, +63, +45, +20, -37, <-98	36
Emeraude, Congo (Brazzaville)	+100, +86, +64, +40, +15, <-23	33
Cyras, Iran	+95, +55, +20, -11, -41, -72	31
Bachequero, 16.8° API (Bachequero Heavy), Venezuela	+85, +41, +10, -13, -36, -58, 84	29
Jatibarang, Java, Indonesia	+115, +84, +46, +7, -28, <-70	26
Klamono, Irian, Java, Indonesia	Estimated from Crude Oil API Gravity of 18.7°	26
Duri, Indonesia	+116, +82, +55, +19, <-5	21
Boscan, Venezuela	Estimated from Crude Oil API Gravity of 10.3°	15

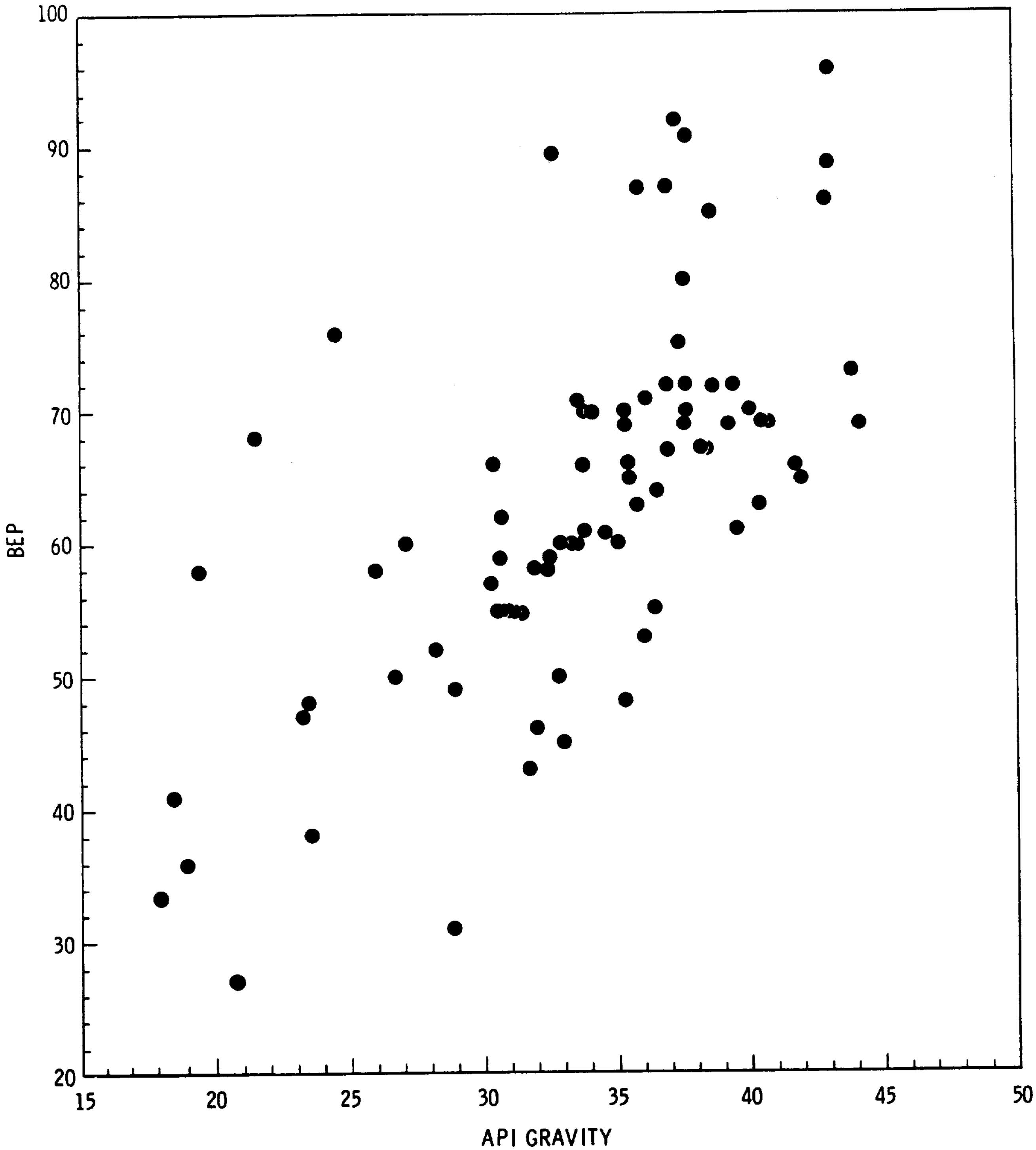


FIGURE 3.3. Correlation of Crude Oil Breakeven Points and API

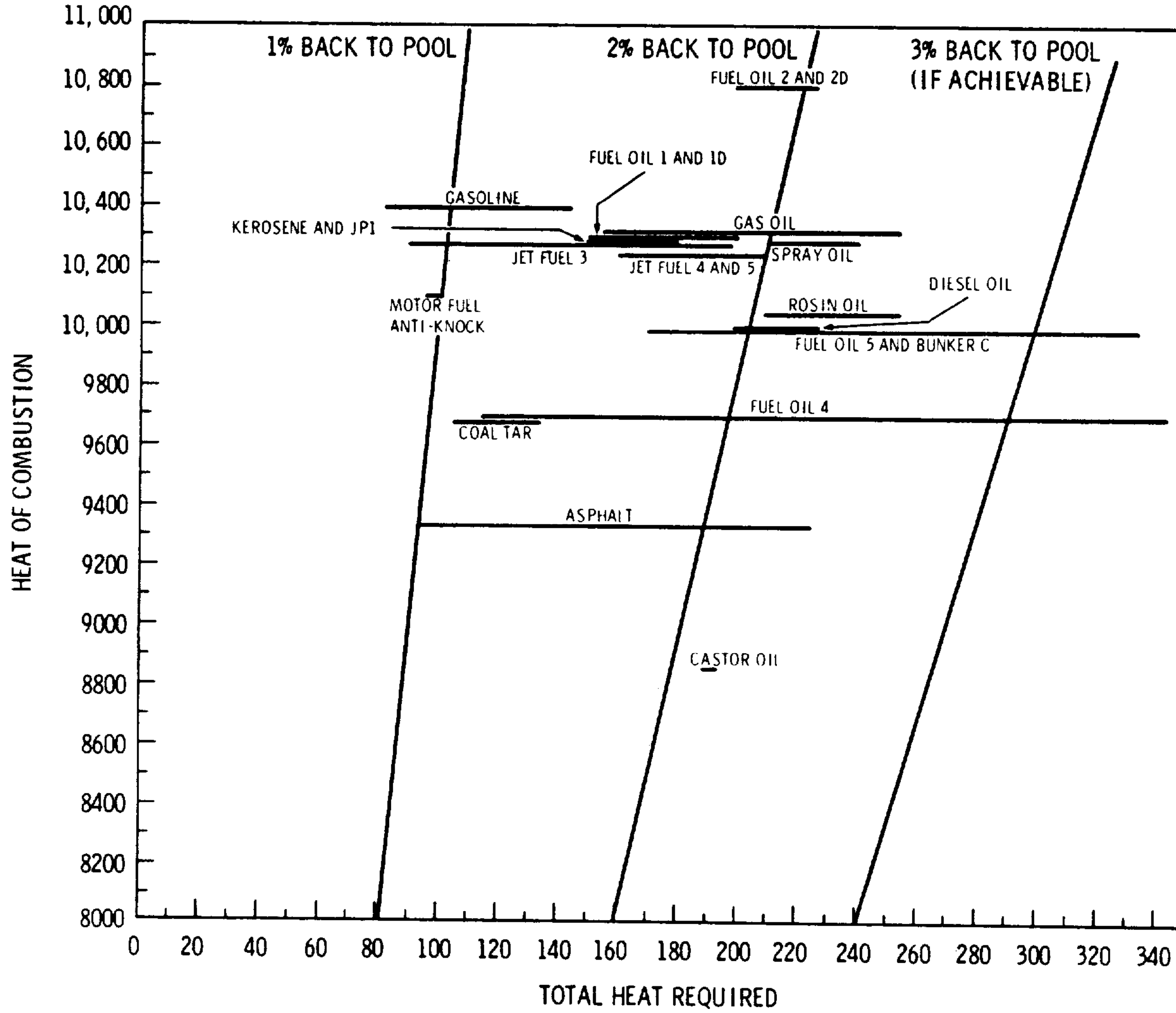


FIGURE 3.4. Radiant Heat Reflected Back to Pool

3.7 EVALUATION OF IGNITION POTENTIAL

By careful review of the model derived in Sections 3.5 and 3.6 to classify oils, additional observations may be made which can be useful in assessing the potential success of igniting an oil. Using the classifications developed in Section 3.6, categories of oil were defined as:

1. those fuels from which ample excess heat is generated to easily meet heat requirements
2. those fuels which direct radiant heat back to the pool roughly equivalent to the heat requirements
3. those fuels which produce insufficient heat to meet requirements for burning.

Examples of those oils were given in Table 3.7, which shows the relative combustibility of oil products.

The water and air temperatures were noted in Section 3.3 as influencing combustion. This influence is shown in the net heat calculations where higher temperatures during a burn decrease the sensible heat requirements, thereby increasing the net heat differential (H comb - H required). Thus, for each 10 degrees Farenheit temperature above the assumed 40°F in the model developed in Sections 3.5 and 3.6, the heat differential increases by roughly 5 Btu/lb. For Category 1 oils, this will merely increase the burning rate and reduce the thickness at which extinction will occur. For Category 2 oils, increases in air and water temperatures will increase the potential for sustaining a burn. The likelihood that a specific oil will become burnable will depend on the magnitude of the temperature change and the original value of the heat differential. As a rule of thumb, temperature differences of less than 20°C (above the 4.4°C employed for characterization) are not likely to have a significant effect for most Category 2 oils.

Considering the discussion of temperature in Section 3.3, the relationship developed in the model, and the observations of the previous paragraph, it would appear that time of weathering and elevated temperatures will not affect Category 1 oils significantly. If a sufficiently thick slick remains, these oils will ignite. For Category 2 oils, however, weathering beyond 24 hr in temperate weather and 48 to 72 hr in arctic weather is likely to render the slick noncombustible without promoters of some kind. Under windy conditions, evaporation is accelerated and these threshold times are likely to be reduced.

It was noted in Section 3.3 that evaporation is a significant variable affecting the combustibility of crude oil. Blokker (1964) has noted that evaporation of hydrocarbons can be described by the relation:

$$\frac{dv}{dt} = \frac{-\pi}{4} \text{Kev } V^a \, D^{(2-B)} \, pM = d \left(\frac{\pi}{4} D^2 \bullet h\right) \tag{15}$$

where

v = volume of oil in m^3

t = time in min

Kev = const. 1.2×10^{-8}

V = Wind speed in m/sec

D = diameter of pool in m

p = vapor pressure in mm H_g

M = molecular weight

$a = \frac{2-n}{2+n}$

$B = \frac{n}{2+h}$

n = Sutton's turbulence parameter (0.25 for neutral air)

This expression is rearranged to:

$$t = \frac{\Delta h \; D^B}{\text{Kev } V^a pM}$$

for a slick of thickness Δh M, where Δh is the slick thickness which decreases in time t. In this case t is the time required for evaporation of the entire pool. For oils, Blokker finds good agreement using:

$$t = \frac{\Delta h \; D^B}{\text{Kev } V} \sum \frac{1}{pM} \tag{16}$$

with a representative of pM for each fraction. Based on this approach, a relative extinction curve can be defined for each oil fraction once a representative value for pM is selected. The latter is accomplished through use of estimation procedures.

From the Clausius-Clapeyron relation:

$$\ln P = \frac{-Qvap}{RT} + \ln Py \tag{17}$$

where

$Qvap$ = molar heat of vaporization = $qvap\ M$

R = gas constant

P_y = pressure at boiling

Hence,

$$p = P_y\, e^{\left(\frac{-Qvap}{RT}\right)} \text{ and } P_y = e^{\left(\frac{Qvap}{RT_B}\right)} \text{ since } P = 1 \text{ at boiling } (T_B)$$

then

$$p = e^{\left(\frac{qM}{RT_B} - \frac{qM}{RT}\right)} \tag{18}$$

From Trouton's rule for nonpolar hydrocarbons

$$M = \frac{21}{q}\, T_B \tag{19a}$$

Hence,

$$p = e^{\left(\frac{q(\frac{21}{q})T_B}{R\ T_B} - \frac{q(\frac{21}{q})T_B}{RT}\right)} \quad \text{from Equation (18)}$$

$$= e^{\left(\frac{21T_B}{R}\ (\frac{1}{T_B} - \frac{1}{T})\right)} \tag{19b}$$

and

$$pM = \left[\frac{21T_B}{q}\right] e^{\left(\frac{21T_B}{R}\ (\frac{1}{T_B} - \frac{1}{T})\right)} \tag{19c}$$

for p in mm Hg, this translates to

$$pM = \left[\frac{15{,}960T_B}{q}\right] e^{\left(\frac{21T_B}{R}\ (\frac{1}{T_B} - \frac{1}{T})\right)} \tag{20}$$

Based on this relation (20), calculations have been made for Arabian light crude (API grav 33.4, per Table 3.9) assuming a slick area of 40,000 m^2 Δh = 10 mm (volume 400 m^3), V = 5 m/s, T = 278°K (5°C). (Note: calculation for each decile is based on Δh = 1 mm or 10% of the slick).

TABLE 3.9. Arabian Crude Fractional Losses

Decile Fraction	qvap (BTU/lb)	qvap (cal/g)	TB (°F)	pM	t (min)
10	152	85	100	16,686	3
20	123	69	230	1,646	47
30	103	58	320	332	234
40	98	55	400	73	1,064
50	80	45	490	17	4,566
60	71	40	560	4	19,405
70	56	31	680	0	∞
80	45	25	790	0	∞
90	42	24	920	0	∞

These values are plotted over time for each fraction in Figure 3.5. The effect of varying wind speed can be seen in Figure 3.6. The relationship of air temperature increase may be visualized in Figure 3.6 from 5°C to 17°C reducing the percent oil remaining by 1/2 at a given point in time and at 27°C it is reduced by 1/3.52. The 40% remaining as noted in Figure 3.5 for the composite and in Figure 3.6 for various wind speeds consists of the fractions with boiling point greater than 327 to 337°F. These fractions will be composed of aromatics within carbon chains of greater than 16°, of paraffins, C_{19} and above; and naphtheno aromatics, C_{19} and above. It is these fractions which should persist after 25 days of weathering.

Considering the above observations on fractional loss of crude oils in light of the breakeven point (BEP) analysis of Section 3.6, oil may be

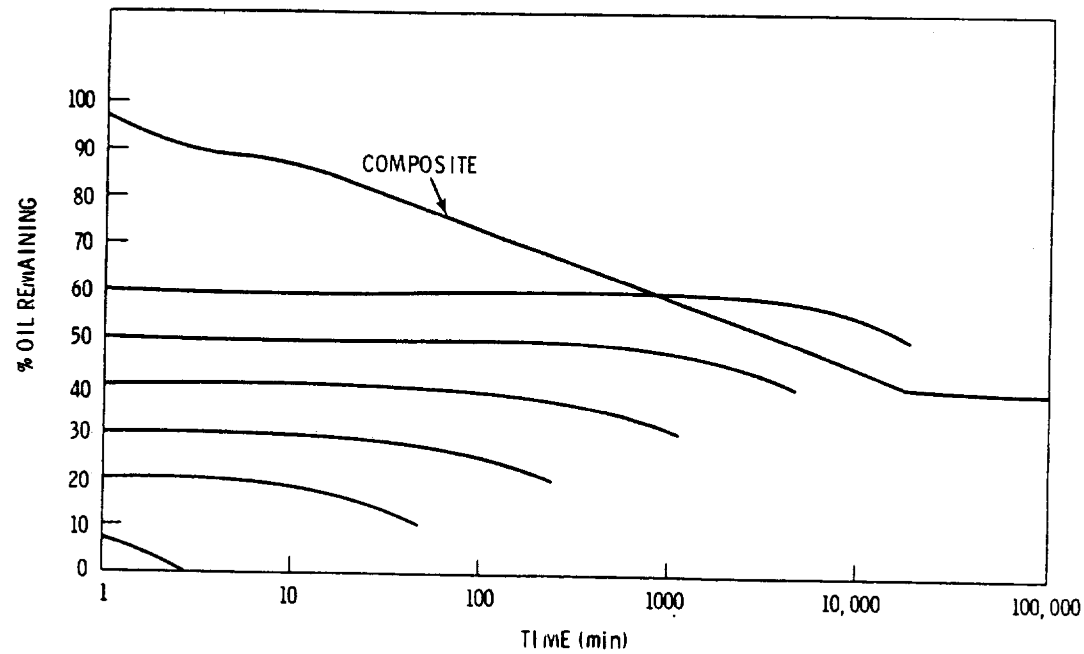


FIGURE 3.5. Time to Vaporization for Deciles and Composite Arabian Light (V = 5 m/s)

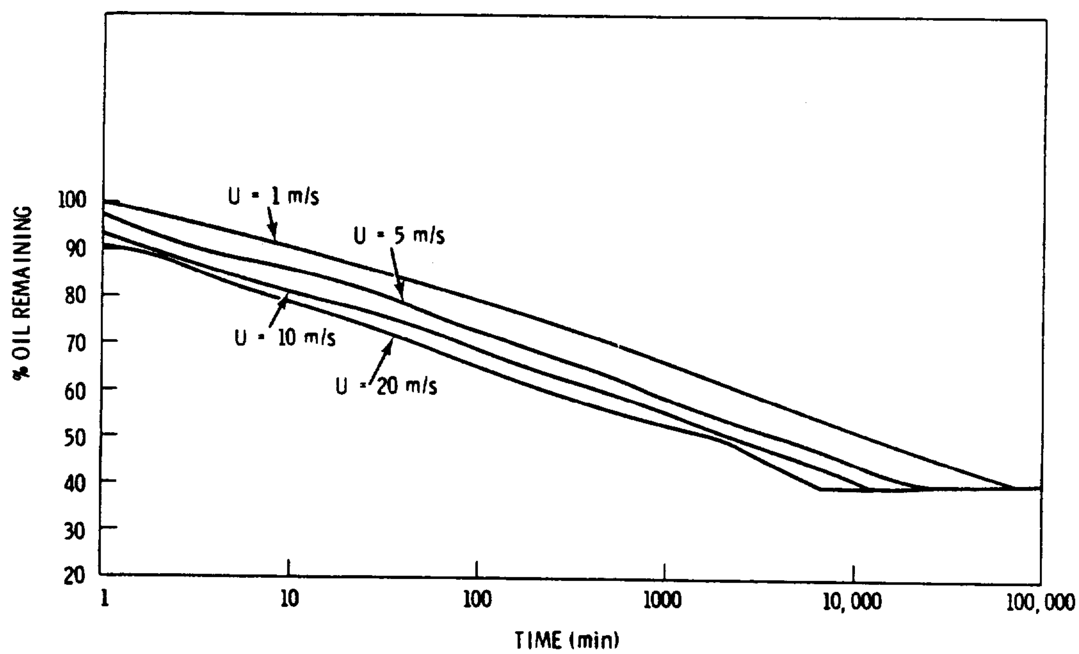


FIGURE 3.6. Effect of Wind Speed (U) on Vaporization Rate of Arabian Light at 5°C

graphically characterized by plotting net heat output per oil fraction as shown in Figure 3.7. The Arabian light (BEP = 60 or 55%) used in this example was also used as the previous discussion model oil. The area under the curve above the abscissa is a measure of the excess heat from combustion. The area below the abscissa and above the curve represents the excess energy required to sustain combustion or that required to burn the heavier fractions.

If crude oil were not such a complex mixture, the excess heat radiated back from combustion of lighter fractions would ideally meet the energy needs for combustion of heavier fractions. Under the ideal circumstances combustion would proceed until the area above the abscissa equaled the area below the abscissa for about 97% of the Arabian crude being consumed by combustion. The light fractions would act as the "primer" for combustion promotion.

Under actual conditions it must be recognized that petroleum vapors rising from the pool are composed of compounds and possess characteristics which are different from those in the oil pool. It is noted (Gaydon and Wolfhard, 1970) that these vapors follow Raoult's law defined below; where partial pressure of the vapor determines a vapor composition. Clearly the vapor above a crude oil pool is more concentrated in the volatile constituents or consists of products from pyrolysis of nonvolatile high-molecular weight hydrocarbons, while the pool becomes more concentrated in the heavier fractions.

This vapor composition effect on combustion may be seen at various increments of the combustion/distillation process by referring to Table 3.10. It can be noted from this examination that while the volatile fractions with the excess heat are burning, the heavy fractions which require the added energy are not being volatilized and burned to any significant degree. Therefore, the excess heat is being used to increase vaporization/combustion rates rather than effectively burn the more resistant compounds. As noted in Section 3.5, the increased rates of burning do not necessarily help in increasing heat feedback to the pool (radiant energy absorption, thicker vapor zone, incomplete combustion, etc.). It follows then that less of the theoretically available heat reaches the pool and combustion may be predicted to terminate in the vicinity of the breakeven point (BEP) (see Figure 3.7).

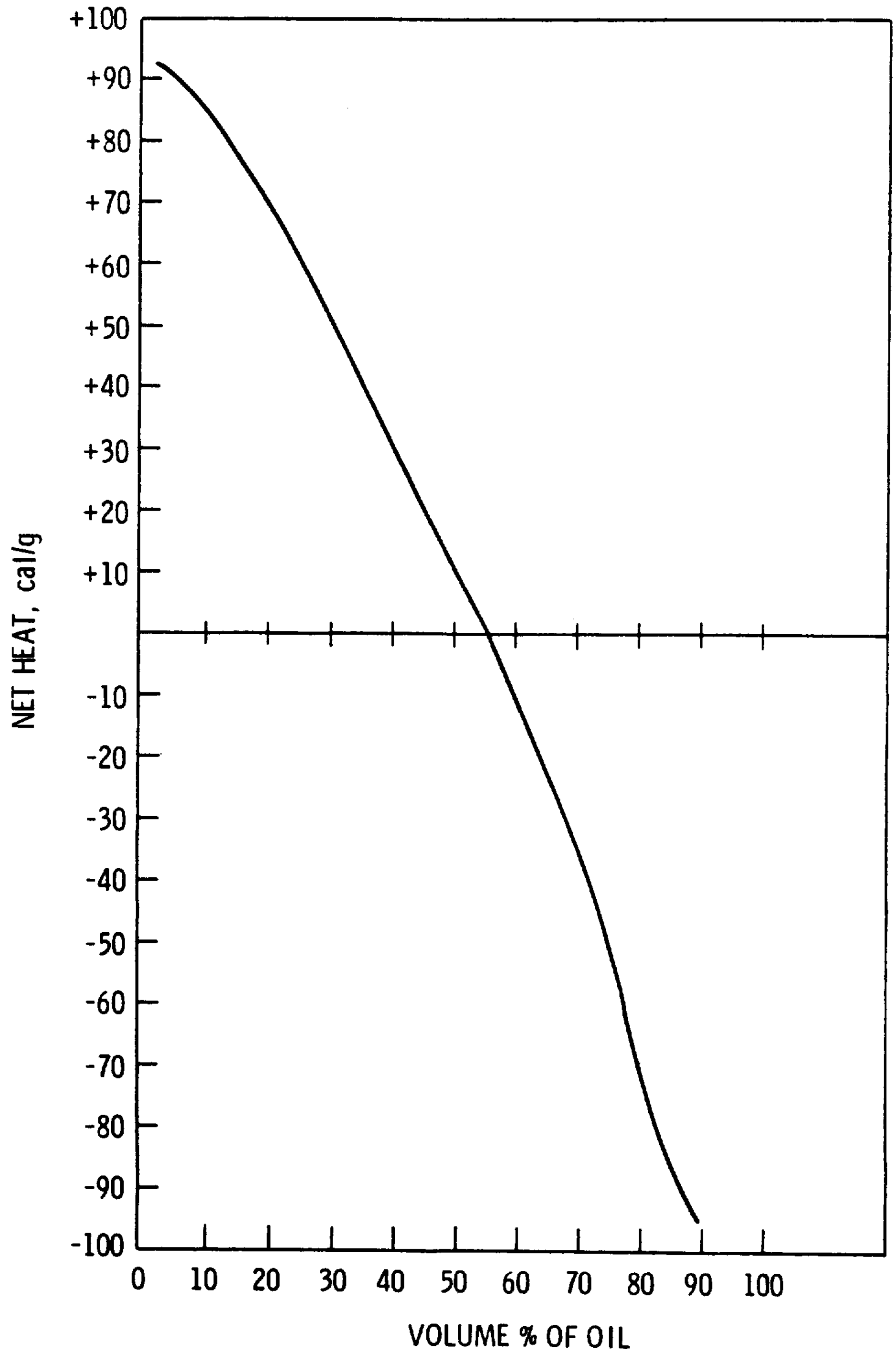


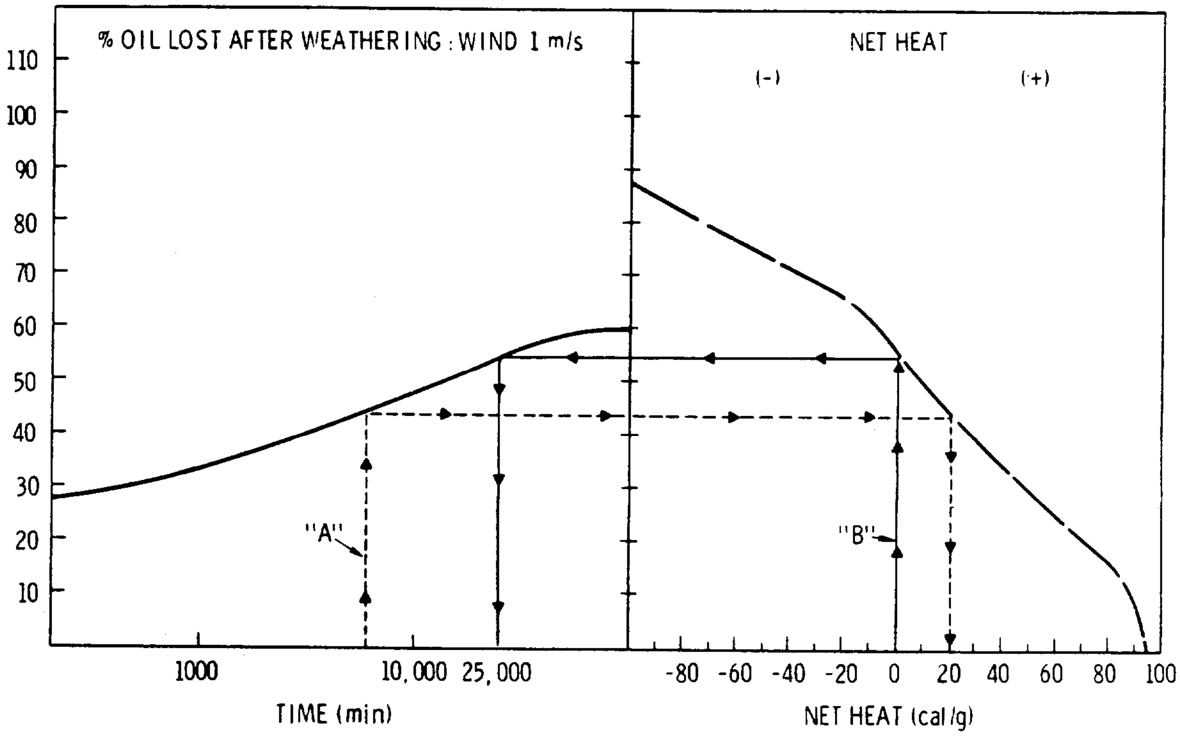
FIGURE 3.7. Combustion Energy Produced and Required

TABLE 3.10. Progressive Change in Vapor Constituency (Arabian Light)

Oil Fraction	TB °C	TB °K	p mm Hg	Vapor Fraction	% Vapor Fraction After Distillation of Given Oil Fraction				
					10	20	30	40	50
10	38	311	217	91.6	--	--	--	--	--
20	110	383	14	5.9	14.6	--	--	--	--
30	160	433	2	0.8	12.7	78.5	--	--	--
40	204	477	0.4	0.2	2.3	12.8	79.3	--	--
50	246	523	0.07	--	0.4	3.2	18	80	
60	289	566	0.01	--	--	0.4	2.7	18	80
70	356	633	--	--	--	--	--	2	18
80	417	694	--	--	--	--	--	--	2
90	489	766	-	--	--	--	--	--	--

This analysis is supported by many field observations and trials of a variety of combustion tools indicating that all oils will burn initially, until the light fractions with the excess heat are depleted. As also has been observed in the field, the ignition of an oil and the extent to which it will combust is most dependent upon weathering. Normally, weathering is explained as a loss of the light fractions. However, information of a quantitative nature is sparse, but using the fractional crude oil characterization analysis above, reasonable estimates can be made.

If the change in a crude oil's composition with time of weathering is considered as that illustrated in Figure 3.6, the loss of each fraction over time can be predicted. Using the plot as shown in Figure 3.7, the net heat available from combustion of each fraction of the crude oil may be seen. By superimposing these observations as shown in Figure 3.8 (only using percent of oil lost instead of percent of oil remaining in Figure 3.6) the weathering of a crude oil may be quantified.



Examples of the use of this chart are:

1. A pool of Arabian light has weathered for 100 hr (6000 min) in a wind of 1 m/s.
   - Enter at "A" and observe that the oil remaining still has a positive net heat in just more than 15% of the oil volume remaining.
   - Therefore, if sufficient heat can be introduced to ignite the pool, about 10% to 15% can be expected to burn before extinction.
2. A pool of Arabian light is known to exist.
   - Enter at "B" and observe that without primers or combustion promoters that oil spill mitigation by combustion is not possible after 416 hr (24,960 min) of weathering in a 1 m/s wind.

FIGURE 3.8. Effects of Weathering on Oil Combustibility (Arabian Light)

Generally, the higher the wind speed the more upward the percent lost curve moves. With the addition of the combustion promoters the net heat curve is shifted to the right.

The net heat curve is related to ignition by considering flammability limits, fractional changes, and number of carbon atoms present resulting from both original oil properties and weathering observations which have been reported. After weathering, significant fractions of crude oil have been noted supporting sustained combustion. The feasibility of burning these oils is, therefore, not solely restricted to the energy content, but must consider if ignition is possible.

Ignition is not well understood for turbulent combustion of pools of fuel. Some work has been done with laminar flames and premixed gases (Overly et al., 1978, and Spalding, 1957), but for the most part, the determination of flammable limits and flash points is an empirical exercise. A few oils have been characterized (Thiele, 1927) by lower flammability limits being estimated by mole fraction breakdown. Butler et al. (1956) found a relatively good correlation between boiling point and flash point for middle distillates. This observation was based upon noting that the product of the molecular weight and the vapor pressure equals 15.19 as the flash point is approached. A good correlation for distillate fuels (10%) distilled) was shown by Mullins (1959) between distillate level and flash point.

As reported by Hall (1972), sustained combustion of a fuel is achieved when the fuel is raised to the fire point. This temperature has been found to be several degrees above the flash point implying that at the flash point, insufficient heat is generated to sustain combustion. However, calculation of a flash point can produce an estimate of the fire point. In practical terms, the flash point is the temperature at which sufficient vapor is released to create a fuel air mixture at the lower flammability limit (the lean limit). Therefore, flash point can be approximated from partial pressure relations. As noted in Equations 17 through 19, the Clausius-Clapeyron relation yields:

$$P_u = e^{\left(\frac{21T_B}{R}\left(\frac{1}{T_B} - \frac{1}{T}\right)\right)} \tag{19b}$$

where terms are recalled as:

P_u = partial pressure (atm)

T_B = boiling point (°K)

R = natural gas constant

T = temperature (°K)

From Raoult's Law:

$$P\ y_i = P_{ui}\ X_i \qquad (21)$$

where

P = pressure (atm)

y_i = concentration of i in the vapor phase (% vol.)

P_{ui} = vapor pressure of i

X_i = concentration of i in the liquid fuel (% vol.)

At atmospheric pressure:

$$Y_i = P_{ui}\ X_i$$

Combining relations:

$$Y_i = X_i\ e^{\left(\frac{21T_B}{R}\ (\frac{1}{T_B} - \frac{1}{T})\right)}$$

or

$$T = \frac{21T_B}{R\ (\frac{21}{R} - \ln \frac{Y_i}{X_i})} \qquad (22)$$

Now, if y_i is set equal to the lower flammability limit, the resultant T should be the flash point T_{fp}. Hence, flash points for crude oil fractions can be estimated if data are available on flammability limits. Once again, empirical data are not available and a means of approximation is necessary.

Egerton (1953) reported that for pure chemicals, flammability limits are a function of heat of combustion such that the known flammability limit (L) for compound A can be used to calculate the flammability limit for compound B by using the ratio of their respective heats of combustion H_C:

$$X = (H_{CA}/H_{CB})^L$$

Similarly, Burgess and Hertzberg (1974) found that the product:

$$K = \frac{LL}{100} H_C$$

where

LL = lower flammability limit

H_C = heat of combustion

increases with carbon number for normal saturated hydrocarbons until it reaches an asymptotic value of 11.6 Kcal/mole for hexane and higher paraffins.

To test the applicability of this relation to petroleum fuels, a plot was made of heat of combustion versus lower flammability limit. As is evident from observing Figure 3.9, the available data on petroleum fractions do not reveal the anticipated relation. The correlation breaks down for complex fuel mixtures because the lower flammability limit is a function of the light ends (Affens, 1967), while the heat of combustion is a composite value for the

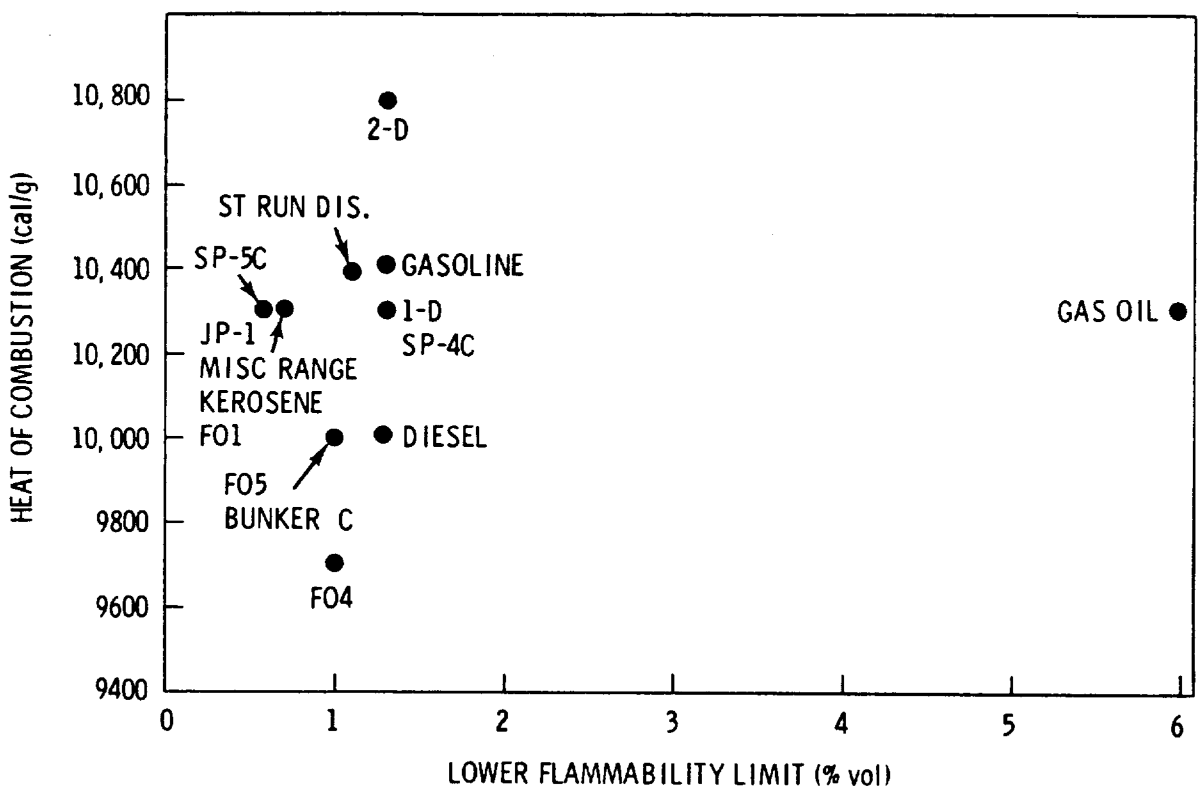


FIGURE 3.9. Relation of Lower Flammability Limit to Heat of Combustion for Petroleum Fractions

total fuel. Hence, fractions with the same initial boiling point would have the same lower flammability limits but different upper boiling points would change their average heat of combustion. A much more significant relation was found when lower flammability limit (described as volume percent of gas mixture) was plotted as a function of the number of carbon atoms (Figure 3.10). The plot consists of data from the unsubstituted hydrocarbons listed in Table 3.11. These include paraffins, aromatics, cycloalkanes, and naphthenics, and are therefore representative of petroleum constituents. A few sulfur-bearing compounds are also included to represent high sulfur oils.

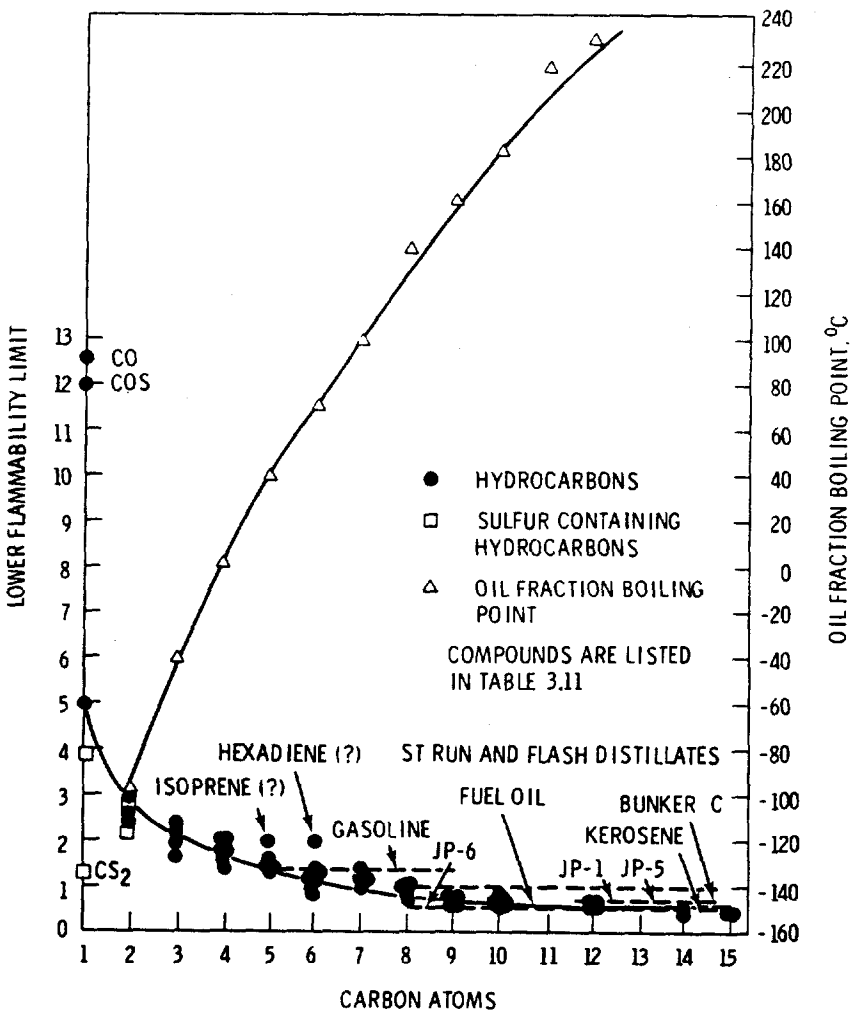


FIGURE 3.10. Values Based on Data from NFPA, 1973

TABLE 3.11. Unsubstituted Hydrocarbon Data used for Plot in Figure 3.10

Hydrocarbons	Lower Flammability Limit	No. of Carbon Atoms
Butane	1.9	4
Butene	1.6	4
Benzene	1.3	6
Carbon Monoxide	12.5	1
Cresol	1.4	7
Cyclohexane	1.3	6
Decane	0.8	8
Dodecane	0.6	12
Ethane	3.0	2
Ethylbenzene	1.0	8
Ethylcyclobutane	1.2	6
Ethylcyclohexane	0.9	8
Ethylcyclopentane	1.1	7
Ethylene	2.7	2
Heptane	1.05	7
Hexane	1.1	6
Isobutane	1.8	4
Methane	5.0	1
Methylbutene	1.5	5
Methylcyclohexane	1.2	7
Methylpentane	1.2	6
Methylpropene	1.8	4
Methylstyrene	0.7	9
Naphthalene	0.9	10
Nonane	0.8	9
Octane	1.0	8
Pentane	1.5	5
Pentene	1.5	5
Propane	2.2	3
Propylbenzene	0.8	9
Propylene	2.0	3
Styrene	1.1	8
Tetramethylpentane	0.8	9
Toluene	1.2	7
Trimethylpentane	1.1	8
Vinyl Acetylene	2.0	4
Xylene	1.1	8
Dimethylbutane	1.1	6
Acetylene	2.5	2
Anthracene	0.6	14
Bicyclohexyl	0.7	12

Hydrocarbons	Lower Flammability Limit	No. of Carbon Atoms
Biphenyl	0.6	12
Butadiene	2.0	4
Butylbenzene	0.7-0.8	10
Cyclopropene	2.4	3
Decahydronaphthalene	0.7	10
Diethylcyclohexane	0.8	10
Diethylpentane	0.7	9
Dimethyldecalin	0.7	12
Dimethylpentane	1.1	7
Dimethylpropane	1.4	5
Dipentene	0.7	10
Hexadiene	2.0	6
Isobutylbenzene	0.8	10
Isoheptane	1.0	7
Isohexane	1.0	8
Isopentane	1.4	5
Isoprene	2.0	5
Isopropyldicyclohexyl	0.5	15
Isopropylbiphenyl	0.5	15
Methylcyclopentadiene	1.3	6
Methylethylhexane	0.7	9
Pinane	0.7	10
Propyne	1.7	3
Tetradecane	0.5	14
Tetrahydronaphthalene	0.8	10
Sulfur Cpds		
Ethyl mercapton	2.8	2
Carbon disulfide	1.3	1
Dimethyl sulfide	2.2	2
Methyl mercapton	3.9	1

There is no measurable effect on the lower flammability limit. As is evident from Figure 3.10, the values quickly converge to allow accurate prediction of flammability limits for fractions with an average chain length of four carbons or more. Branching, isomerization, and unsaturation have only minor effects.

Figure 3.10 also presents a curve revealing the boiling range for oil fractions as a function of chain length. This allows ready approximation. Limited data on petroleum fraction lower flammability have also been superimposed on Figure 3.10. The lower end of each fraction fits the function very well. Since the lower, more volatile constituents will come off first and thus create the lower flammability limit, the correlation validates the function for its intended use.

Given the data in Figure 3.10, it is now possible to calculate the flash point, T_{fp}, for petroleum fractions. Equation (22) is employed using boiling point data from Figure 3.10 for T_{BP} and lower flammability limit data from Figure 3.10 for Y_i.

Calculations for flash point of pure alkanes have been made with Equation (22) and are compared to published values in Figure 3.11. The predicted values are lower reflecting deviations in the temperature-vapor pressure relation from the Clausius-Clapeyron equation. Agreement is still close enough for the purposes here. Predicted values for fractions of a petroleum mixture (taken as 10% by volume for this sample calculation, i.e., X_i = 0.10) yield flash points 30 to 40° above that for the pure alkane. This fits well with expectations since the petroleum mixture reduces partial pressures as a result of the partial pressures of other constituents. This in turn raises the flash point. The correlation with published data for petroleum product flash points is excellent.

Given the above relations, it is now possible to predict the flash point for fractions of a well-characterized crude oil. For instance, the properties for each decile can be derived as is done for Arabian light in Table 3.12.

In turn, the flash point data can be used to determine the heat flux required to yield ignition. It should be noted that this requirement is less than the heat requirement calculated for stable burning in the breakeven point

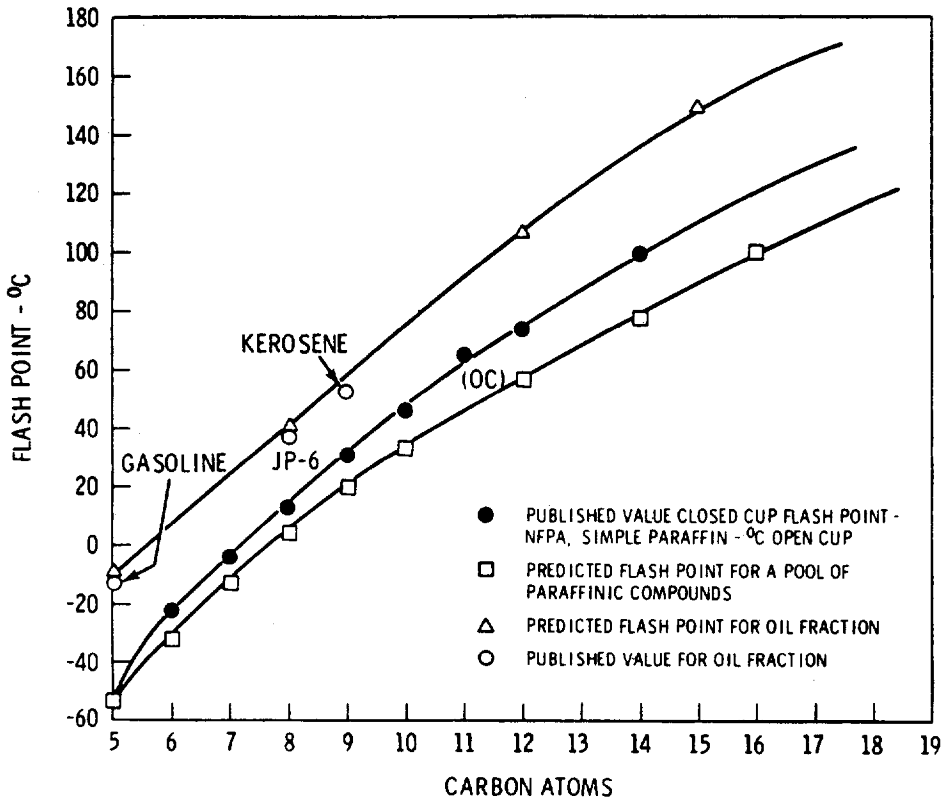


FIGURE 3.11. Published Values of Flash Point of Pure Alkanes

TABLE 3.12. Predicted Flash Point for Fractions of Arabian Light

Oil Fraction	T_B °C	From Figure 3.10 Average Chain Lengths-Carbons	From Figure 3.10 Lower Flammability Limit - Y_i	From Equation 14 Flash Point (°C)
10	38	5	0.015	-9
20	110	7	0.011	44
30	160	9	0.008	76
40	204	10	0.007	108
50	246	15	0.005	131
60	289	17	0.005	165
70	356	22	0.004	209
80	417	26	0.004	256
90	489	28	0.004	311

analysis since the flash point is below the boiling point where the pool will reside during stable combustion (Hall, 1972). The surface temperature of the pool progresses from the flash point to the boiling point over a period of 10 to 20 min (Rasbash et al., 1956). Heat flux calculations for ignition of each fraction of Arabian light are given in Table 3.13 for 1 cm^2 at a relative burning velocity equivalent to that at the lean limit. (This assumes that fuel flow upward just meets the downward burning velocity and therefore establishes the volume of air that must be taken to the lower flammability limit in a unit of time.) A velocity of 3 cm/sec is employed here since that is the lowest velocity observed (Spalding, 1957). Hence, ignition heat flux must be capable of filling 3 cm^3 to the lower flammability limit each second. The calculation for Q_{ig} then becomes:

$$Q_{ig} = LL(3)(\rho v)\ Hv + Cp\ (T_{fp} - T_a) \tag{23}$$

where

Q_{ig} = heat flux for ignition (cal/cm^2-sec)
LL = lower flammability limit (vol. fraction)
ρv = vapor density (g/cm^3)
Hv = heat of vaporization (cal/g)
Cp = heat capacity (cal/g°C)
T_{fp} = flash point (°C)
T_a = ambient temperature (°C)

Since ρv can be calculated from (mol wt./29) ρa, Equation 15 becomes:

$$Q_{ig} = LL(3)(\text{mol wt.}/29)\rho a\ \ Hv + Cp\ (T_{fp} - T_a) \tag{24}$$

where

ρa = density of air under same conditions
mol wt. = molecular weight of constituent.

Calculations for Arabian light are given in Table 3.13.

The heat flux data in Table 3.13 clearly display a marked increase in ignition energy input requirements for heavier petroleum fractions. For Arabian light, heat requirements increase by a factor of 5 between the first and the ninth decile. This is a range of 0.012 to 0.06 cal/sec-cm^2 of pool surface. For reference, solar radiation is on the order of 0.02 cal/sec-cm^2 and radiation from a bed of embers is about 1 cal/sec-cm^2 (Steward, 1978).

TABLE 3.13. Ignition Heat Flux Calculations for Arabian Light Fractions (ρ_a = 1.3 mg/cm^3, T_a = 4°C, C_p = 0.5 cal/g°C)

Oil Fraction	Lower Flammability Limit	Molecular Wt (21/Hv) T_B	Heat of Vaporization Hv (cal/g)	Flash Point T_{fp} (°C)	Sensible Heat $C_p(T_{fp}-T_a)$ cal/g	Q_{ig} (cal/cm^2-sec)
10	0.015	77	85	-9	-7	0.012
20	0.011	117	69	44	20	0.016
30	0.008	157	58	76	36	0.016
40	0.007	182	55	108	52	0.018
50	0.005	244	45	131	64	0.018
60	0.005	297	40	165	81	0.014
70	0.004	429	31	209	103	0.032
80	0.004	583	25	256	126	0.047
90	0.004	670	24	311	154	0.063

Hence the lightest decile of Arabian light (roughly gasoline) could be ignited under solar radiation. The heavier ends would require three times solar radiation.

The above heat requirements are the net energy input needed for ignition. It is recognized that heat losses will eliminate the ability of an ignition energy source to achieve that net unless it: 1) exceeds the net value requirement, and 2) is sustained for a sufficient time to overcome transient conditions. Empirical data demonstrate this fact in that they reveal a discrete ignition delay time. Work reported by J. W. Smith in the Proceedings of the 1969 U.S. National Oil Spill Conference Seminar (Appendix E) determined a 1 to 2 sec delay at 15°C. Similarly, as noted in Appendix G, attempts by the U.S. Coast Guard to ignite #6 fuel oil required exposure of 40% of the slick to a propane torch for 45 sec. If it is assumed that these delays represent the time required to meet transient needs to establish heat gradients in the fuel, they can be calculated in terms of excess energy input needed to allow the fuel to reach the net ignition energy requirement. A conservative estimate for this excess can be calculated from the heat content of the oil at depth at ignition. As noted previously, Khudyakov (1953) described the equilibrium temperature profile in a burning pool as:

$$t - t_o = (t_s - t_o) \exp(-K_x) \tag{25}$$

Work by Rasbash et al. (1956) yields a value of $K = 0.45\ cm^{-1}$ for kerosene and gasoline. Heat required can then be determined from the relation:

$$dg = d\,(m\,C_p\,[T_x - T_o]) \tag{26}$$

where

dg = the increment in heat required for 1 cm^2
m = mass of fuel in a cm^2 column
C_p = specific heat for fuel
T_x = temperature at °C
T_o = ambient temperature = 4°C in this analysis.

This translates to

$$dg = d\left(x\,\rho\,C_p\,(T_f - T_o)\,e^{-kx}\right)$$

where

x = incremental depth in the fuel

ρ = density of fuel in g/cm^3

T_f = flash point temperature in °C

Integrating,

$$g = \rho\ C_p\ (T_f - T_o) \int_o^{\infty} x\ e^{-kx}\ dx$$
$$= \rho\ C_p\ (T_f - T_o)\ (1/k^2)$$

For petroleum hydrocarbons, this reduces to

$$g = \frac{0.5}{0.2}\ (\rho)\ (T_f - T_o)$$
$$= 2.5\ \rho\ (T_f - 4)$$

The transient ignition energy requirement for Arabian light oil is calculated in Table 3.14. These values are conservative since Khudyakov's relation is given for the pool at equilibrium and may not hold for the point in time at which the flash point is needed. On the other hand, the relation does not account for convective losses to the air. The transient requirement can be met through brief administration of a high energy flux, or a longer exposure to lower fluxes.

From the model developed in Sections 3.5 and 3.6 and the discussion in Section 3.3 on spreading and slick thickness, it is suggested that once slick thickness falls to a point where heat conduction to the water exceeds the net difference between H comb and H required, the combustion enters a stage of rapid decline which cannot be reversed without the addition of combustion promoters.

While sufficient data do not exist to provide specific quantitative relations for ignition as a function of slick depth, guidelines can be estimated from empirical data. For Category 1 oils, ignition may be difficult once thickness drops below 2 to 3 mm. For Category 2 oils, slick thickness should exceed 5 mm if ignition is to be attempted.

TABLE 3.14. Heat Flux and Transient Energy Requirement for Arabian Light

Fraction	Heat Flux (cal/cm^2-sec)	Tf (°C)	(g/cm^3)	Transient Heat Required (cal/cm^2)
10	0.012	-9	0.67	--
20	0.016	44	0.72	72
30	0.016	76	0.78	140
40	0.018	108	0.78	203
50	0.018	131	0.83	264
60	0.024	165	0.83	334
70	0.032	209	0.88	460
80	0.047	256	0.90	576
90	0.063	311	0.93	714

Considering the discussions of processes in Section 3.3 and the observations of the relationship developed from the model in Sections 3.5 and 3.6, combustibility of the oils (see Table 3.7) is affected by time, temperature, wind and oil thickness. Each oil is susceptible to these factors to varying degree and without extensive empirical work only semi-quantitative thresholds can be suggested as shown in Figures 3.12 through 3.15 for combustion parameter trends.

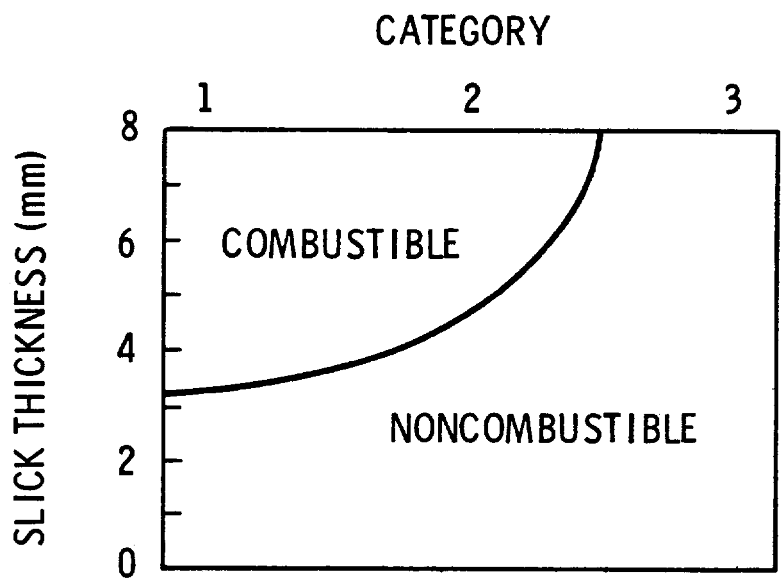


FIGURE 3.12. Trend of Effect of Slick Thickness on Combustibility

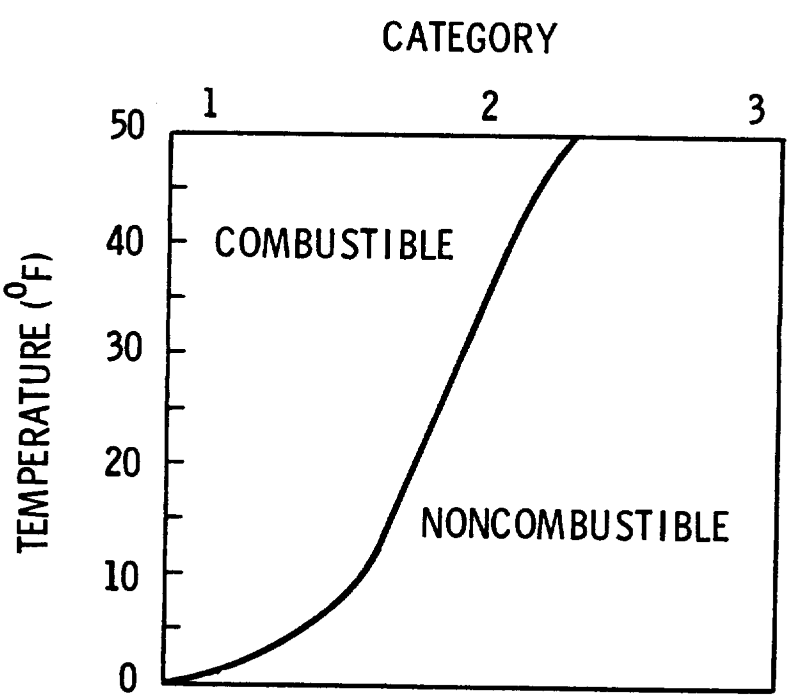


FIGURE 3.13. Trend of Effect of Ambient Temperature on Combustibility

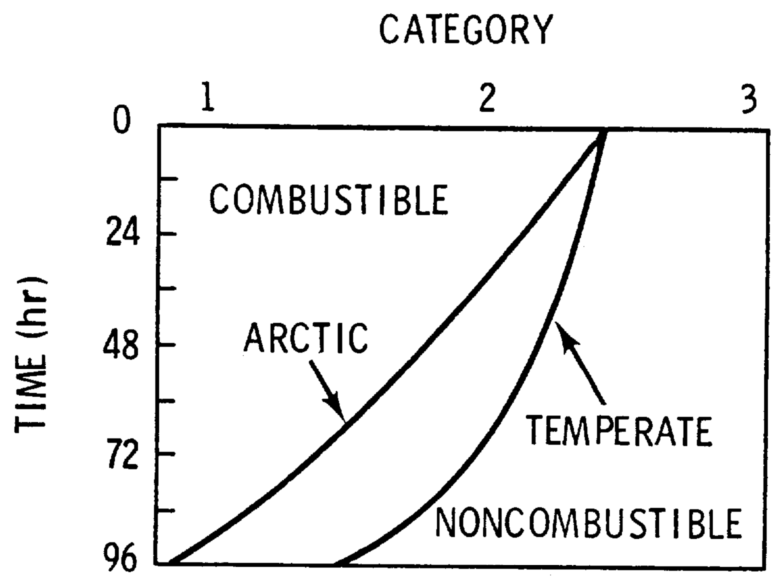


FIGURE 3.14. Trend of Effect of Time Delay on Combustibility

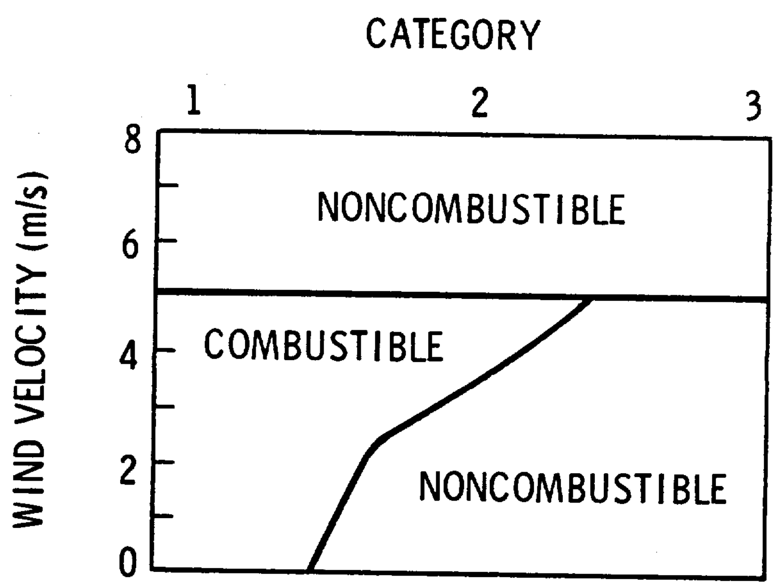


FIGURE 3.15. Trend of Effect of Wind on Combustibility

4. RELEVANT TECHNOLOGY FOR COMBUSTION

This section provides an overview of available technology and commercial activity, and lists several systems. Also given are idealized schematics of how the technology would be or has been used to mitigate oil spills:

1. in situ vessels
2. oil released on water
3. oil-contaminated debris

Combustion itself depends on heat balance. Combustibility is often enhanced through the use of wicking agents or combustion promotors.

4.1 BASIS FOR PROMOTING COMBUSTION

This discussion is most applicable to oil release situations; however, it is considered appropriate for both in situ and debris disposal combustion. Many of the principles are common, but the constraints vary depending on the location of the oil that is to be burned. Use of the model and the pool fire discussions developed in Section 3 should provide the continuity necessary to evaluate the available technology highlighted in this section.

The ability to sustain combustion of pooled oils can be increased through modification of the combustion environment. With respect to oil spills, this has most commonly been attempted with wicking agents. These additions, enhance combustibility by isolating the flame from convective currents in the fuels and reducing conductive heat losses from the pool. Wicking agents are described in Section 4.5. The intent of this narrative is to identify the means of promoting pool fires primarily of Category No. 2 hydrocarbons as defined in Section 3.6.

From the model developed in Sections 3.5 and 3.6, it is evident that the key to successful ignition and sustained combustion of oil slicks on water rests with the heat balance. Combustion will be achieved only if adequate heat is available to the pool to meet the needs for temperature elevation and vaporization of the fuel. Approaches to this can be divided into three categories: 1) modifications which reduce heat losses from the pool, 2) modifications which increase heat feedback to the pool, and 3) modifications which provide external energy to the pool. Specific examples are discussed below.

4.1.1 Heat Loss Reduction

It has been shown that fuel in a pool fire is supplied through vaporization of the liquid. Energy for the vaporization process is provided via radiation and to some extent convection from the flame. The stable burning rate is reached when the heat directed back from the flame just meets the heat requirements to maintain a vaporization rate equal to the burning rate. While it has been suggested that a relatively constant amount of heat is available, it is also true that not all of this heat is utilized. Some is lost. Any reduction in losses would increase burning rates of Category No. 1 oils and possibly render some Category No. 2 oils combustible.

A review of heat transfer mechanisms suggests three routes by which heat may be lost from the pool: 1) conduction to the water column, 2) convection currents in the water column, and 3) transmission or reflection of radiant heat by the pool. As noted earlier, Hall (1972) reports that the first mechanism, conduction, is not likely to be significant in static water since the water merely replaces a layer of fuel. However, Blinov (1955) found that the temperature at the oil-water interface was only slightly lower than the temperature at that depth in a pool of pure oil. Since the specific heat for water is roughly twice that of oils, this implies a greater heat requirement to maintain the gradient. With thin slicks, the water is brought to its boiling point and heat of vaporization requirements increases losses. The rising water vapor also quenches the flame. With convection and currents in the water column, losses go up even more.

One effect of wicking agents is to interpose a layer of insulation in the oil pool, thus reducing heat losses. Similarly, conductive and convective heat losses could be minimized through intentional use of low heat conductive additions. Materials such as polyethylene have a density intermediate between oils and water, and thermal conductivity roughly half that of water. Alternately, additives could be placed in the oil to reduce its thermal conductivity and hold more heat near the surface. Another effect of a wicking agent is to vaporize the fuel fraction in proportion to its pool concentration, thereby retarding the light fraction rapid burnoff discussed in Section 3.7. As noted before, if the net area above the abscissa in Figure 3.7 exceeds that below the "breakeven" curve, virtually all of the oil can be burned. It follows, then, that wicking agents allow much more complete combustion. If wick design is improved to maximize heat of combustion directed back to the pool, this would leave only fuels with a negative heat balance, e.g., rosin oil, as non-combustible in a pool fire situation using combustion promoters.

However, since oils do not act as total black body absorbers, some radiative heat may also be lost through reflection or transmission of incident energy from the flame. This was shown by Khudyakov (1946): that while absorption is wavelength dependent, relative absorptivity could be described as benzene less than ethanol less than water. For a given body, it can be shown that for a specified wave length,

$$a + \tau + \phi = 1$$

where

a = absorptivity
τ = transmission
ϕ = reflection

While data are scarce on spectral properties of many oils, some do exist for examination. German work (Schmidt, E.) with lube oil found adsorbtivity equivalent to 0.82 for an infinitely deep pool. This represented a ceiling value from those of 0.27, 0.46, and 0.72 for oil depths of 0.001, 0.002, and 0.005 in., respectively. Algers et al. (1976) reports a value of 0.90 to 0.95 for jet fuel No. 5. The difference, 0.10 to 0.05, was found to be reflected rather than transmitted. Hillstrom (1970) found that 25% activated carbon added to a pool could render nearly all fuels combustible with little residue. In the lube oil case, there may be merit in the use of a lampblack additive (α = 0.945) to increase the capture of incident radiant energy. In the JP-5 case, such an approach is not likely to have a significant effect. Further study of the spectral properties of oils may be warranted, however. For one thing, powdered carbon placed in oil will float on the surface and act as a wick, in addition to increasing radiant energy capture and providing some structure to the oil.

It should also be noted that the tendency of a to increase with depth of oil, in the case of the German work, suggests that a contributory factor in the extinction of burning with thin slicks may be related to reduced capture of incident energy as well as increased losses through conduction to the water.

4.1.2 Increased Feedback from the Flame

Combustibility may also be enhanced by increasing the feedback of energy from the flame. As noted in Section 3.5, radiant heat incident on the pool may be as little as 2% of the total theoretical heat of combustion. Doubling that value would render virtually all oils combustible (see Figure 3.5). An example of this is found in the effect of wind on burning rates. As the flame is tilted with the wind, the view factor increases and thus a greater fraction of total radiation is incident on the pool. It has also been found that the propagation of many small flames in checkerboard fashion yields greater total combustion than a single large flame (Huffman et al., 1969). This is accredited to a larger aggregate view factor with multiple flames and suggests a preferred approach to use of wicks or ignition promoters. Advantage may be found in discrete "lily pad" like wicks rather than mass application of granular wick modules.

Alternately, attempts may be made to reflect heat back to the pool which would otherwise be radiated outwards. In the extreme, this might take the form of a reflective boom or vessel. There are, of course, technical limitations such as sooting as well as logistics problems to be considered. Since the luminosity of flames is largely a function of soot, reflective surfaces may quickly be blackened and hence converted to absorbers. Placement to the side of the pool could minimize soot interference and address a larger fraction of the total radiant heat flux.

Heat feedback may also be enhanced through manipulation of the amount of heat of combustion released, as radiation versus that released through convection/conduction. As noted earlier, most oil pool fires have been found to radiate a relatively constant 25% of the heat of combustion, and the bulk of energy incident on the pool is radiative. Some observers report that the major source of this radiation is soot. It follows then that heat feedback may be increased if soot production is increased. Increased soot production has been accomplished through addition of SO_3 to diffusion flames and nitrogen to premixed flames with kerosene (Gaydon and Wolfhard, 1970). Such a modification will likely be accompanied by increased smoke emissions and their concomitant adverse impact. Heats may also be increased through addition of oxygen. If inexpensive sources of concentrated oxygen (50%) can be obtained, the addition could enhance combustibility. The United Kingdom is currently funding research in this area (re: Shipping Requirements Board, Ministry of Trade).

4.1.3 Energy Addition

If combustion cannot be sustained through heat available back from the flame, it may be promoted through introduction of energy from an outside source. Such is the case with enhanced combustibility of oils at elevated ambient temperatures as discussed previously.

In considering the addition of outside energy, it is important to determine if such inputs need to be continuous or impulse at the time of ignition only. The latter would be the case if the energy requirement was more of an activation energy which, after causing ignition, would be replaced by increased heat releases from the flame. This suggests greater heat feedback to the pool at higher burning rates until some threshold rate is obtained which is capable of sustaining itself. The existence of such a value is doubtful. Rather, there appears to be diminishing returns with higher burning rates. This can be explained from basic principles. For instance, flame temperatures may not increase proportionately with burning rate. Hence, the driving force for radiative heat transfer may not increase sufficiently with burning rate to increase the rate further. At the same time, as the burning rate increases, the layer of fuel vapor between the pool and the flame increases in size and density. It thereby becomes a more effective screen to radiation back to the pool and thus reduces heat transfer.

Recognizing these constraints on the combustion process, it is suggested that fuels requiring input of outside energy will require that input throughout the burn rather than as a pulse at initiation. The most widely used approach to energy augmentation is the addition of a primer. Primers are highly combustible fuels such as gasoline, which produce an excess of heat back to the pool when burned. When used with fuels that are difficult to burn, this excess energy serves to meet heat requirements for vaporization of the primary fuel and hence makes combustion of the combined materials possible at a burning rate somewhat lower than that for the primer alone. As suggested earlier, these effects are most pronounced when the primer has a boiling range similar to that of the primary fuel. If the temperature differences are great, the combination will act like other crude oils and burn the primer off with little effect on heavy fractions.

Since higher boiling liquid primers often suffer the same drawbacks as higher boiling oil fractions, i.e., the additional heat of combustion is less than the additional heat requirements, there are few which could assist in oil combustion. The alternatives include: the use of low boiling primers in conjunction with wicking systems; and use of solid primers. The demonstration of these systems should illustrate the properties of the wick which transports and combusts fuel in the same ratio as it occurs in the liquid state rather than selecting the light ends as the free surface of the pool allows. The solid primer takes advantage of the solid combustion phenomena, thereby avoiding the requirement that the pool surface be held at a low temperature in the range of the primer's boiling point. Wood chips or sawdust may be an attractive solid primer since a bed of embers will radiate (Steward, 1978) at 1 cal cm^{-2} sec^{-1}.

4.2 COMBUSTION PROCESSES, CONCEPTS OR OPERATIONS

In general, the concepts (many not commercially available) for using combustion as an oil spill mitigation tool may be summarized as follows: (It may be of interest to review Appendix E for a capsule summary of oil combustion development events over the last decade.)

For burning oil in situ wrecked vessels:

(a) using naval and aerial weaponry to destroy vessel and cargo

(b) creating appropriate deck openings, side vents, and using ignition system to create sustained burn (vessel becomes crude incinerator)

(c) using offshore platform flaring equipment to offload oil by controlled combustion.

For burning oil released into or upon water:

(a) using oleophilic wicking agents alone and in combination with other materials

(b) using sorbents that provide insulating properties

(c) using hydrophobic insulating materials

(d) using volatile additive or primer materials

(e) using hydroigniting agents alone or in combination with agents noted above

(f) using laser or other activation energy additives

(g) using floating furnaces and incinerators

(h) using fuel resistant booms alone or in conjunction with radiant heat reflectors

(i) using sinking agents in conjunction with burning.

For burning oil-contaminated debris:

(a) using portable brush burners

(b) using field constructed drum burners

(c) using truck-mounted portable incinerators

(d) using portable beach incinerators

(e) using available municipal refuse incinerators

(f) using specially designed industrial waste incinerators

(g) also, reports are known of using oil in a clean and emulsified state in steam boilers with or without a cutting distillated.

4.3 COMMERCIAL ACTIVITY

The following statements were prepared based upon knowledge gained in the period up to Summer 1979. Intensive international correspondence, telephone interviews, and review of U.S. patents and technical literature plus personal experience were used as the source of this information.

4.3.1 Burning Oil in Vessels

There are no commercial ventures available to undertake burning oil in vessels. The only attempts were conducted by government organizations and were reported as less than satisfactory. Very high interest in the technique and technology development has been expressed by industry, both shippers and carriers, but no recent or current experience or data are available from any testing or trial attempts. Military research and development as well as operational personnel have expressed confidence that controlled systems could be prepared using available components and minimal testing to confirm design and operational parameters. To date, the most definitive work upon which commercial interests could develop systems is that conducted in the United Kingdom between 1970 and 1973 (Diederichsen et al., 1972). A likely commercial segment to attempt this would be marine salvors, but their motivation and income is derived from saving life, vessel, and cargo with the more hazardous providing greatest awards. Flaring equipment used on offshore platform is currently available, but it has never been used to offload a tanker.

4.3.2 Burning Oil Spill on Water

Considerable commercial activity and interest existed regarding burning an oil spill on water during the period 1969 to 1973. Most of this interest was reported as demonstration, testing, patent activity, and a few actual applications. Interest has been maintained by only a handful of commercial enterprises. Indications are that new approaches, systems, and applications of technology are being considered by manufacturers. A survey of more than 50 active oil spill cleanup contractors and 39 cooperatives indicated little burning experience and reservations that local authorities would permit the response.

A few had tried this technique several years ago, and a few would be interested if it were legal and technically feasible, but most preferred the oil recovery technology.

4.3.3 Burning Oil-Contaminated Debris

Commercial activity was noted here primarily from portable incinerator and brush burner manufacturers. More than 35 incinerator manufacturers were contacted. Several of the cleanup contractors had some limited experience in using burning and were aware that local authorities had allowed burning of oil-contaminated debris. Use of municipal incinerators has been evaluated. In addition to local approvals, complications exist pertaining to potential damage to facilities and equipment not designed to withstand higher heats of combustion and sulfur content. Some governmental efforts in Europe have resulted in simplified beach and pit burner designs which can be constructed in the field from locally available material.

4.4 OIL BURNING TECHNOLOGY - IN-VESSEL COMBUSTION

The use of combustion to mitigate oil spill pollution has been tried, often as a last resort, and (as noted in Section 2.4 and Appendix C on case histories) the involvement of the vessel in the burning varies. One of the earliest cases which involved oil burning and a vessel occurred in 1923 in Japan's Yokahama Harbor. A massive (unknown) quantity of fuel oil was reported as being eliminated from the harbor surface. This was accomplished by burning a wooden ship, and it is suggested that the timbers acted as wicks and successfully burned an otherwise unignitable oil spill.

The frequency of situations a relayed above which have been repeated throughout the world is hard to determine. The number of explosion and fire incidents which occur aboard ship and the concern of governments to protect the living marine resources and coastal amenities plus the escalating public and private costs of cleanup have continually raised the question on the feasibility of burning oil in a vessel to prevent its release. In-vessel combustion requires very specialized knowledge and experienced maritime personnel. Experience in this field has been evolving for many years on a case by case basis, rather than by a designed program. The sinking of tankers along the U.S. Atlantic coast and Gulf of Mexico during the opening stages of World War II released considerable volumes of oil which when ignited created many shipboard infernos. A Sea-Grant Study conducted at MIT in Cambridge, MA estimated the oil lost at 157 million gallons within 56 miles of the East Coast in the first 6 months of 1942. These tankers were small and often carried refined products, but the physical forces allowing or prohibiting burns in these vessels are the same forces which must be considered here.

In 1967, the TORREY CANYON was involved in the first major VLCC tanker disaster, releasing some 34 million gallons of Iranian crude oil off the coast of France and Britain. After failure of attempts to free the vessel from the rock reefs upon which it was impaled and after pumping and dispersant techniques were proven incapable of handling the massive quantities of oil spilled, it was decided to burn the oil in situ. At that time some 20 million gallons of petroleum remained on board the vessel. In order to burn the oil, it was postulated that the tanker had to be opened, either by precision cutting of tank apertures or by massive bombing. It took a decision by Prime Minister Harold Wilson to take action. The bombing technique was utilized primarily based upon safety and time considerations. Forty 1000-lb conventional high explosive bombs, treated with aluminum to enhance burning, were dropped upon the half-filled tanker. Time delay fuses were set for 0.035 sec so that the explosion would occur after the bomb had broken through the 1.25-in. steel deck. The bombs were followed by dropping underwing aviation fuel tanks to enhance burning by the addition of volatile components. In all, 6800 gal of aviation fuel were used. Fires burned visibly for 2 hr following the last drop. The bombing, which cost $560,000 in 1967 dollars, is regarded as having been largely successful for in situ burning but unsuccessful for nearby weathered oil slicks. However, specialists in marine salvage have been critical of the bombing approach in favor of placement of the explosives on board the vessel with great precision.

The above incident stimulated several activities within the Government of the United Kingdom and private interest groups. An intensive research program was undertaken and results were produced in the period of 1970 to 1973. These results represent the near state-of-the-art in burning oil in situ. Some of the participants were part of the advisory team which worked on the

TORREY CANYON and therefore were experienced in what practical questions needed answers. A working group was set up by the Institute of Petroleum (Maybourn 1971) and commissioned research was reported (Hall, 1972, Diederichsen, 1972, 1973).

A degree of confidence was expressed on October 16, 1970, suggesting that this IP Working Group should be able to specify how to burn oil in situ in a tanker by the end of 1970. Studies on pool fires and research on burning rates in vented tanks were reported along with the details of the complex variables. It was concluded (Diederichsen, 1973) that under some conditions it was possible to ignite and burn up to 97% of the crude oil contained in a tanker.

Briefly, the working group found that during a moderate breeze, oil in the wing tanks on the windward side would burn at 150 mm/hr (6 in./hr). Approximately 70% of all fuel oils were reported as being ignitable and burn at 75 to 113 mm/hr (3 to 4 in./hr). The burning rate was plotted against tank size for a variety of wind conditions as noted in Figure 4.1. Conditions necessary for combustion were summarized from these model tank studies as:

1. Vents must be created in top and side of the tank equal to 10% of oil cross-sectional area.
2. Side vents can be cut only after oil level has burned down (without them, extinction may occur).
3. The "how to vent and ignite" was recognized as a separate field of study and expertise.

These recommendations require serious design and operation analysis to be safely employed on a real tanker.

The Marine Pollution Subcommittee of the Intergovernmental Maritime Consultative Organization approved a Manual on Oil Pollution in 1972 which was later published (IMCO, 1973), and even though this work was largely that of United Kingdom investigators, no mention was made of how to burn oil in situ in tankers even though other aspects of burning were briefly addressed. (This manual is under current revision to reflect USCG information made available since 1972.)

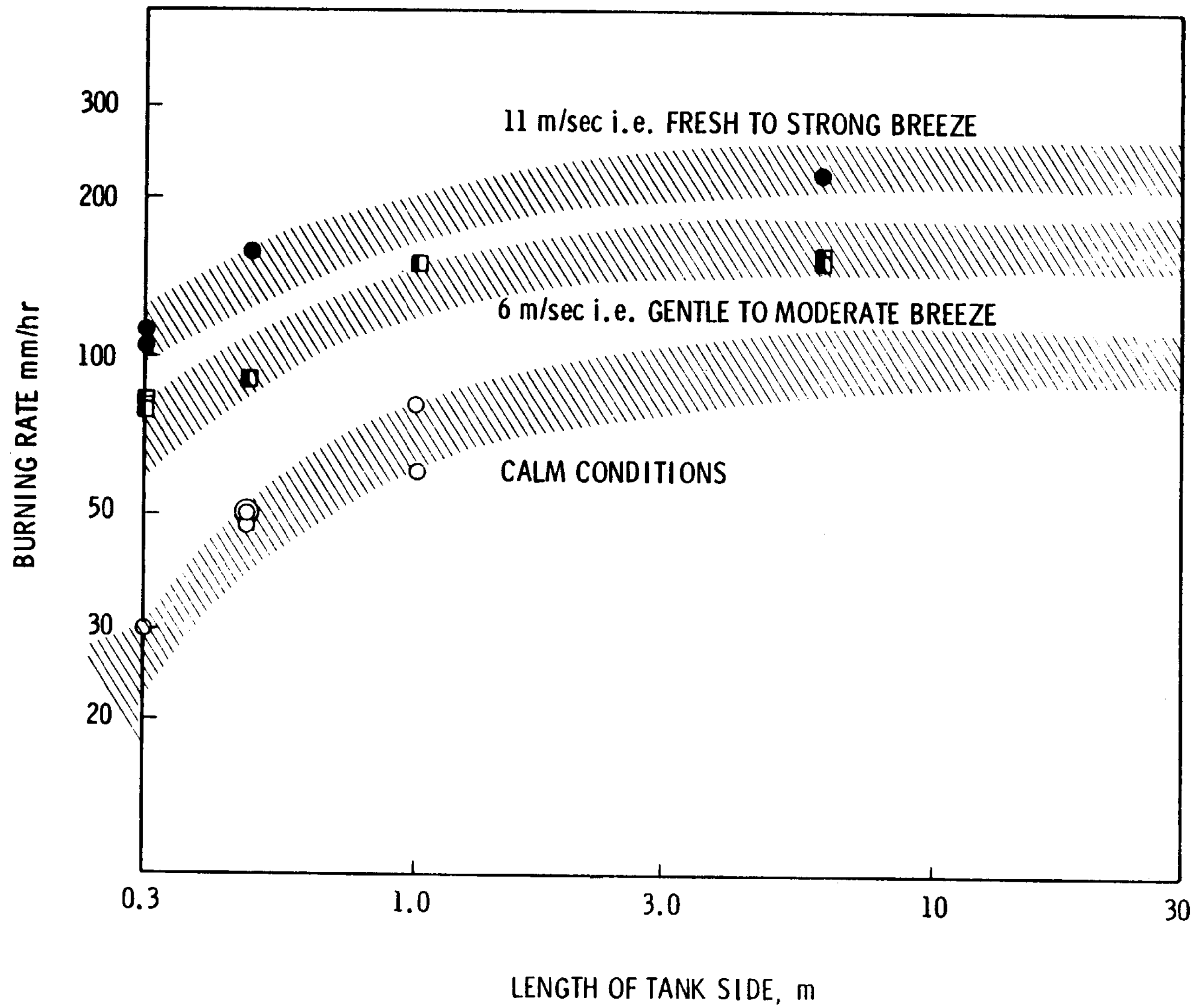


FIGURE 4.1. Variation of Burning Rate with Tank Size (10% and 11% venting)

Source: Diederichsen et al., Technical Report 72/9, Rocket Propulsion Establishment

It would appear that the definitive steps for "how to" burn oil in situ in a tanker were not produced by the IP Working Group or anyone else. The British Department of Trade personnel responsible for coordinating measures to combat oil spills have tended to rule out the use of in situ burning as impractical. However, in light of the tanker casualties in 1977 and 1978 they are reconsidering their position and proposing to launch further work to determine if burning can be devised into an acceptable and effective method of oil spill mitigation.

Several stricken vessels have been involved in oil discharge situations where an attempt was made to burn either the oil on board or the oil spilled. These attempts were generally not successful for reasons that are often difficult to document. Therefore, a picture of the possible marine conditions and probable frequency of occurrence would be useful to establish the value of burning technology development.

The USCG has documented 3,502 casualties involving tankships and tank barges (see Table 4.1) of which 326 occurred in ocean waters where oil burning may have been a consideration for pollution mitigation. However, the decision for deliberate destruction of a vessel is a difficult one and additional considerations are warranted. USCG data indicate that 11 out of 44 tankship casualties that resulted in the release of cargo ended up as total losses of the vessel and cargo. This 25% loss history which is documented from 1970 to 1977 implies that oil burning as a pollution mitigation tool could rationally be used in one of every four cases and still not affect the vessel's rate of loss at sea. It should also be recognized that the burning action need not result in a total loss of the vessel at sea. Salvage value of scrap metal, etc., can be considerable. Furthermore, as discussed later, the trend is now more common for even a salvaged vessel to be refused safe port, if there is a chance of oil pollution during navigation or while in port. The result is the vessels are towed to sea and sunk anyway. However, it must be understood that there are tremendous frustrations that are experienced in the initial aspects of a casualty wherein the determination of a constructive total loss is very hard to make. Only from an onsite survey will the cost of salvage, cost of

TABLE 4.1. Annual Total of Marine Casualties (Federal fiscal year)

	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
						TANKSHIPS						
	219	199	227	234	211	193	206	247	210	211	257	214
						TANKBARGES						
	251	200	351	464	463	497	497	536	590	665	796	889
Total	470	399	578	698	674	690	703	783	800	876	1053	1103

Source: Data from USCG Incident Reporting System

vessel repair and comparison to insured and uninsured values be feasible, and this is not known at the time of the casualty. Examples are available noting many vessels which were pulled off strand, brought into shipyards for a precise evaluation of the damage on dry dock and only then, after a significant expense has been incurred, is the determination made that the vessel is a constructive total loss. The vessel may then be sold to shipbreakers.

Incidents such as this allow the shipowner to recover his loss of the vessel determined as constructive total loss and also those expenses he may have incurred following a "sue-and-labor" provision of his insurance policy. Insurance companies, e.g., Lloyd's, have avoided this situation by creating an open form. This form establishes the "No-pay - No-cure" guiding rule and that residual values must be achieved in order that the marine salvor can be renumerated. Knowledge of these maritime traditions makes it most difficult for the USCG to exercise its fully legal authority to act for the U.S. Government and sieze and burn a vessel.

With the experience of in situ burning being sparsely documented, research results somewhat positive, and government attitudes very cautious, the following sections define the concept. This discussion is followed by listings of equipment and material that are considered by selected experts in their fields as potentially applicable to in situ oil burning.

4.4.1 Procedures for in situ Burning Oil Cargo within a Stricken Tanker

It is vital to an efficient burn action that an early decision be made to instigate the procedure. (Steps for implementing an in situ burn are illustrated in Figure 6.4). Rapid assessment of the situation is needed to first decide if the casualty endangers the U.S. coastline and/or offshore resources within the territorial sea, the boundary of the U.S. owned continental shelf, or the 200 mile fishing limit. The actions of the shipowner, the ship's crew (or the shipowner's agent in the case of foreign flag vessels) should be fully assessed to determine: 1) where aid can be rendered, or 2) if the corrective actions are adequate enough to mitigate, or otherwise correct, the circumstances. This decision is most difficult to get. Experienced salvors know that the ship's master or crew will not decide; the assigned operator will not decide; and the ship's owner will be reluctant to decide, since his underwriters have split interests between hull and machinery and pollution. Should the findings be negative the Intervention of the High Seas Act (PL 93-248) should be promptly evoked (Appendix F). Once invoked, the response action under Section 5(3) permits the following action "... remove, and if necessary, destroy the ship and cargo which is the source of danger..."

Tests within the U.K. following the TORREY CANYON casualty (1967) indicated that to ignite and sustain a burn of crude oil within the confines of a cargo compartment demands the removal of 10% to 20% of the deck plate covering the tank. Twenty percent of deck area lost is questionable practice. US/DOC/MARAD personnel report that the heaviest decks of tankers plying U.S. waters are constructed of 1 1/4 in. steel plate. USN ordnance personnel report that shaped charges (defined in Section 4.4.3) are available to cut through plate of this thickness. Care must be taken however to ensure that the section of plate removed is clear of the deck beams and supports which would require additional placement and loading to cut with shaped charge explosives. Representatives of Ensign Bickford Co., Aerospace Division, Simsbury, CT, suggest that all shaped charges be laid and detonated at one time, as the detonation could cause oil ignition and prevent reboarding of the vessel. The success of the cutting is a function of precise explosive positioning and standoff distance assuming high order explosive detonation.

Prior to undertaking any action, however, the vessel must be securely moored into position with ground tackle since the proposed burn action is actually a system of offloading. The continued burn will lighten the vessel and, unless heavily water flooded, reinstitute buoyancy to permit the vessel to float free from the stranded position. A secure system of anchoring the vessel in place will ensure that a burning, drifting hulk will not float free into open water to become a hazard to navigation. An alternative to the use of boring wires, chains and anchors commonly associated with ground tackle would be to ballast down the vessel prior to burning. Once the vessel is secured in position, the placement of the shaped charges could be a manual procedure. This would involve trained demolition teams strategically positioning magnetic or mastic held charges onto the deck space over as many as 36 cargo compartments. The teams would further have the responsibility of positioning pyrotechnic/pyrophoric materials within the various cargo compartments to fully initiate the burn action.

The numerous salvage jobs where shape charges have been used to a great extent, including the salvage of the tanker IGARA and several other projects, all required very extensive time for placement of the charges and much additional time for the design and positioning of the firing circuits. This was not accomplished quickly and, therefore, sufficient time must be allowed for this work. The complexity of positioning pyrotechnics and pyrophoric material within the vessel further complicates the actions. Opening up manhole accesses may allow fumes to come on the main deck creating hazards for personnel in operation, particularly if the cargo is volatile and the location is in the tropical climates. In stranding configurations, it is not uncommon to have seas breaking over the vessel. Great difficulty and much patience is required on the part of the explosive team in the positioning and placement of the explosives on a deck that might from time to time be within the splash zone and be awash.

Once the demolition teams have completed their assigned tasks, and abandoned the stricken vessel, the charges would be remotely activated from a safely located assist ship or aircraft. It is assumed that the detonation of the shaped charge could result in a sympathetic ignition of the pyrophorics or that a delayed ignition system would instigate the burn action. It should be realized that some cargo compartments may be under water and not accessible to prepare for a burn action; under such conditions as much cargo as possible aboard the vessel would still be burned to prevent its release to the surrounding waters.

An alternative to the manual action would involve the fabrication of shaped charges that could be lowered to deck level by one or more helicopters. USN ordnance specialists (Indian Head, MD Naval Center) appear to support this technique, which may require specially designed transportable charges to implement the action. The procedure would greatly reduce the possibility of injury to the demolition teams and is worthy of further investigation to overcome the obvious problems of misalignment of charges over longitudinal and transverse scantlings. Once the positioned charges have been detonated, helicopter, or fixed wing aircraft, would be used to drop or otherwise direct pyrophoric materials into the open cargo compartments to sustain a burn. It should be clearly understood that this concept is beyond the current capabilities of the salvage community.

Once the contents of the stricken tanker have been ignited, a number of operational problems develop that require indepth investigation. Testing by the United Kingdom revealed that as a burn of crude oil continues, a "coking" action develops and the unburned residue cakes on the surface of the burning oil restricting the oxygen supply, smothering the fire. Some form of bubbling or stirring action is needed to break up the surface caking. This could possibly be conducted by firing chemically charged missiles into the compartments for agitation purposes or allowing boiling action of water introduced into the tanks to break up the cake. The U.K. tests also revealed that as the oil level drops, additional sources of air must be provided to sustain combustion.

Openings in the side hull of the vessel, above the cargo level line, could meet the oxygen demand. If initially attached, specially prepared limpet mines with magnetic attachment on the ship's side could form the necessary air openings. Problems develop from the capability to approach the burning tanker close enough to position and attach the mines (remote detonation of the mines presents no problems since it is presently state-of-the-art). An alternative response would entail shelling the ship side to gain air openings. It would, however, be difficult to determine the cargo level line since observations by aircraft would be restricted by smoke and flame. Forward looking infrared radar (FLIR) systems aboard U.S. Navy ships may serve as a rapid remote level sensor. The accuracy of the shelling then becomes a predominant factor.

Another concept involves a series of air to ground bombs or missiles that could be fired at the stricken tanker using the aim accuracies available from laser ranging. The missile would be equipped with an explosive head to penetrate the deck plate and a split second later the weapon would shower pyrophoric materials into the cargo compartment. In this manner the need for surface-assist ships and intense manpower would be reduced and personnel would not be subjected to the possibility of severe injuries boarding the stricken tanker. The type of missile and the modified special purpose design would warrant further investigations. It is felt (incendiary specialist Naval Surface Weapons Center, Dahlgren, VA), however, that an existing weapon could be modified at a nominal cost. The action would entail a series of overflights by one or more aircraft. Missile firings would continue until all cargo compartments had been opened and the oil cargo ignited. Technical problems such as breaking up the coke layer on the surface of the burning oil requires attention.

If the burn could be sustained at a rate greater than 200 mm/hr, then for VLCC tankers with 90-ft (27.4-m) deep tanks it would take from 5 to 6 days to burn the cargo. This burning rate could be higher initially, but would probably decrease significantly as the oil level dropped. The burned out hull could then be towed for scrapping or to a deep water sink area. Firefighters assigned to the USN indicate that there is experience available for controlling hydrocarbon fires onboard ship. If this were practiced, the burning concept would be to burn that quantity of oil necessary to free the vessel or empty the damaged tanks and then put the fire out.

It is important to note that the structural configuration of the tanker must remain favorable for taking the traditional bending moments and shear loads associated with a ship in a seaway. If the burning of the ship causes extensive damage to the main deck and the side shell and all associated scantlings, the ship may be significantly weakened. In this weakened condition, it might be reasonable to shift the neutral axis rather low in the vessel, which will allow a much reduced range of bending moments that the ship can be subjected to before breaking. Also, it is not uncommon in situations of severe stranding, particularly in cases where severe seas are running and the point of ground reaction is not all-supportive of the vessel's bottom, to experience conditions where the vessel's back will break. In these instances, it would be very difficult to move the vessel after burning out cargo.

4.4.2 Oil Flaring in situ Burning

The manual venting/igniting or remote application of weaponry to burn oil in situ in a tanker are two alternatives; a third is to employ a system for flaring oil as it is pumped overboard. Two conditions are visualized: 1) a situation where a vessel is aground and which, if offloaded, could get under way again, and 2) a stricken vessel which is a total loss candidate. Equipment from the offshore oil industry presently exists which may be adaptable to this need.

Prime concerns of The Intergovernmental Maritime Consultative Organization's Maritime Safety Committee, the Safety of Life at Sea Convention, U.S. Coast Guard regulation, and tanker owner operational guides are the designs to prohibit the use of open flame in and around an oil-laden tanker. For the flaring approach to be considered feasible beyond the initial technical aspects considered in this section, these concerns will require accommodation. Assuming that these concerns can be overcome, the first case would be most attractive if a tanker could be standardly equipped with a flaring system. In this manner, experts such as IMCO's Design and Equipment Subcommittee could make careful safety examinations and recommendations pertaining to installation, operation and securing of the system. If safety tests and analysis would allow it, the tank cleaning waste discharges may also be minimized using flaring. Special requirements for stowage and securing the systems while in port would be of interest to the U.S. Coast Guard and their existing expertise could be complemented by the offshore industry and other controlling Federal agencies such as the U.S. Geological Survey, the Bureau of Mines, Bureau of Land Management, the U.S. Environmental Protection Agency, and the U.S. Occupational Health and Safety Administration. Existing employment of these flaring systems on exploration offshore drilling vessels and by the South Africans for lightening stricken vessels would appear to minimize the development needed.

In the second case or in a modified first case, where a vessel was not equipped with a flaring system, the addition of a pumping/flaring system to the stricken tanker may be quite feasible. Marine salvors could support this approach as could shipowners; however, in view of the relatively small number of tankers in the world fleet that have experienced severe casualty, it may not seem reasonable to require the permanent or even temporary installation of flaring systems on these ships. These flaring systems, in conjunction with the pumping systems, could be operated on an ad hoc basis and used only as required. They can be attached to the vessel in a preconfigured manner by salvage contractors or such groups as the strike teams organized by the U.S. Coast Guard. Experienced marine salvors express the view that "the rare use and requirement of such a system on an average sea-going tanker certainly does not warrant its installation on a permanent basis." Coastal states, property owners, fishermen and environmentalists may not be willing to accept this view in light of current incident rates (see Section 2 on Spill Statistics).

This operation could be undertaken with the view that cargo salvage was of lesser importance to vessel and environment. The USCG now employs air deployable selfpowered pumping systems and has had considerable success in offloading cargo under appropriate conditions which permit that approach. Manufacturers of the offshore flaring system indicate high reliability and safety in using these systems on isolated offshore platforms. In practice, units are able to handle 12,000 to 20,000 bbl of oil waste per day, create no water pollution and claim a smokeless burn. The systems would require submersible or deckmounted pumps and suction hose to reach the bottom of the tank (50 to 95 ft). A preferable exception would be if the vessel's oil movement system were operational. The safety aspects of using ship's gear are much more favorable over methods wherein opening main deck access is required such as ADAPTS or the traditional salvage step of "over-the-top-pumping." The oil fuel pressure ranges from 75 to 500 psi and these units are available from locations in at least Texas, Louisiana, Pennsylvania, and Canada. Air lifting the approximate 9200 lb of critical equipment is well within USCG helicopter H-3 ratings if the load is broken into: 1) burner and boom, and 2) oil pump and air compressor with flow lines. Other military helicopters or the civilian counterparts are capable of lifting 20,000 to 30,000 lb and could handle the whole system (more than one system).

Calculations indicate that with two 20,000 bbl/day burners operating, a total of 62 in. of freeboard could be gained in 24 hr on a grounded or stricken 28,000 DWT tanker. This additional 5 ft of free board could well set free a grounded tanker. At present there are no data to suggest that this application will not work when the effort is being conducted to save the ship. Optimistically it may be suggested that tankers in the 20,000 to 25,000 DWT range carry from 150,000 to 200,000 bbl of oil and, therefore, it would take as much as 4 to 5 days for two flaring systems to burn the entire cargo. The limit on the number of flares which may be employed has not been established nor has the evaluation of how much oil would need to be burned to significantly mitigate the potential oil pollution problem under the variety of conditions of groundings and collisions which can occur.

4.4.3. Oil Burning Equipment and Materials - in situ Tankers

The information provided here lists materials and equipment which may be used for producing a successful oil cargo burn in situ in tankers. The discussions in Sections 4.4.1 and 4.4.2 were written at a generic level and the intent here is to provide identification of specific products and materials which may be employed. Product endorsement is not implied nor withheld by listing in this report.

Status of Technology on Deck and Side Plate Cutting

Deck plates and other steel covering which must be removed prior to effective in situ burning can be accomplished by several means (refer to Section 4.4.1 for procedure outline). Explosives have been used for steel cutting in military applications to the extent that handbook type formulae and data are available such as in Explosives and Demolition, U.S. Army Field

Manual FM 5-25, February 1971. Plastic explosives (C4) and sheet explosives (M118) have high detonation velocities which give great cutting power. The application to cutting I-beams, built-up girders, steel plates, columns and other structural steel sections has been reduced to relationship of weight of explosive to cross-sectional area to be cut. Readily available TNT is included in the list of applicable explosives. The use of the ribbon charge method employing C4 plastic explosive is reported as effective in cutting steel plate 3 in. thick and the logistic support required appears to be manageable for application to stricken vessels.

There are numerous systems available on the U.S. commercial market, and a variety can be used separately or in conjunction with each other to accomplish the task of opening the main deck and the side shell. The critical aspects of shape charges are positioning, the associated firing circuits, the necessity for the explosive to go high order, and the standoff distance. Particularly where linear grains per foot are low, the positioning and the spacing is extremely critical for them to cut the steel plate.

Successful use of explosive shape charges in a number of salvage cases has been shown by A. Rynecki and others including:

T.V. IGARA, Oil/Ore Carrier, 960 ft in length, 136,400 DWT, South China Sea, 1974

Hopper Dredge A. MACKENZIE, 268 ft in length, 3400 tons, Galveston Ship Channel, Texas, 1974

M.V. ELIAS, Tanker, 605 ft in length, 30,000 DWT, Philadelphia, Pennsylvania, 1975

S.T. CORINTHOS, Tanker, 754 ft in length, 56,882 DWT, Marcus Hook Refinery, Pennsylvania, 1975

Shaped Charges. Many patents have been issued by the U.S. Patent Office in the field of shaped charges. As shown in Figures 4.2 and 4.3, the evolution of the cross section on linear shape charges, and Figure 4.4, cross section of and operation of a conical charge, the shapes vary depending upon the designed use. The principal of operation is summarized by a manufacturer as:

Linear Shaped Charge is a continuous explosive core enclosed in a seamless metal sheath. Shaped in the form of an inverted "V", the continuous liner and explosive produce a linear cutting action. This application of the Munroe effect is enhanced by careful control of charge dimensions and configuration as well as liner and backer thickness and uniformity. (ENSIGN-BICKFORD-Technical Data Sheets).

Lead Flexible Linear Shaped Charge (FLSC) in its present form and aluminum linear shaped charge (ALSC) are widely used for stage separation, vehicle destruct, emergency escape systems and many other applications where remote, fast and reliable cutting of materials is required. Properly designed FLSC assemblies are unaffected by severe vibration and shock and have an inherent reliability limited normally only by the initiation mechanisms.

A variety of shapes have been evaluated in the development of effective FLSC and the most efficient - Configuration IV is presently available sheathed either with lead (FLSC) or aluminum (ALSC) in core loads of 5 to 400 grains/ft.

The operating steps of the shaped charge are illustrated in Figure 4.5 in six sequential figure drawings which explain:

- a is sectional view of the shaped charge device according to this invention before detonation.
- b is a sectional view of the shaped charge device of this invention after detonation.
- c is a sectional view of the shaped charge device later in time than b.
- d is a sectional view of the shaped charge device later in time than c.
- e is a partial section view of the shaped charge device of the invention later in time than d.
- f is a plan view illustrating the shaped charge impinging on a target wall.

The state-of-the-art of steel cutting using shaped charges is well advanced. However, application to stricken tankers laden with a variety of petroleum based materials is not well documented. In fact, the reports of the TORREY CANYON options indicated that for personnel safety this option was not used. Another concern with applications in Europe is the lack of available stores to quickly implement this technique.

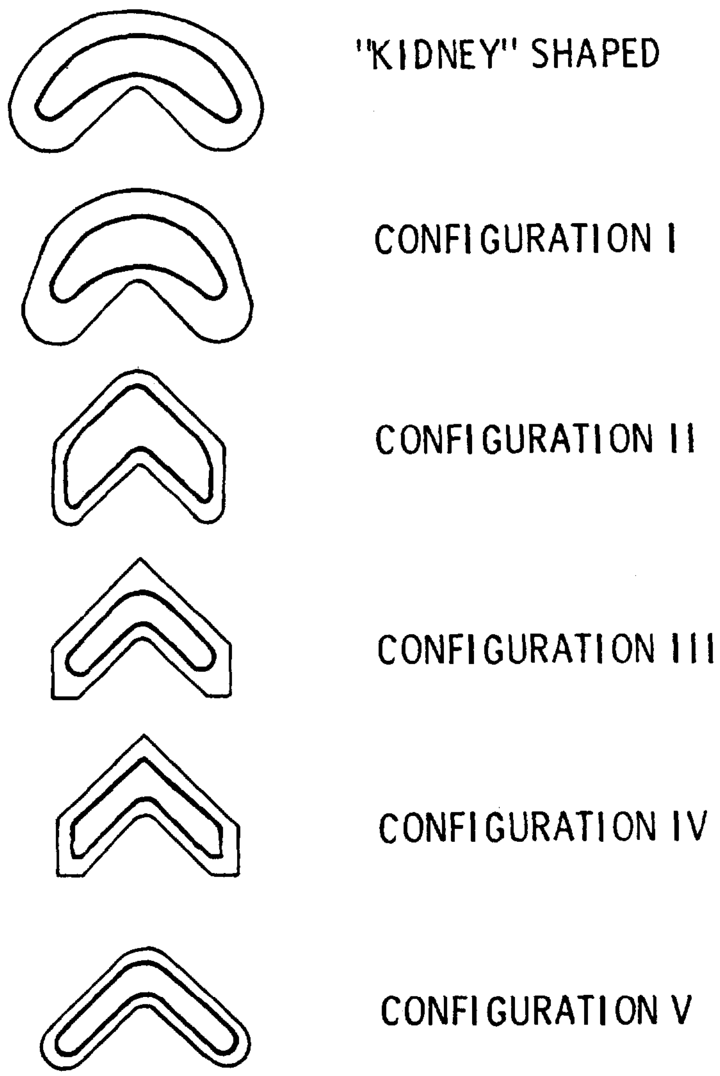


FIGURE 4.2. Evolution of Shaped Charge Configurations

Source: Ensign-Bickford

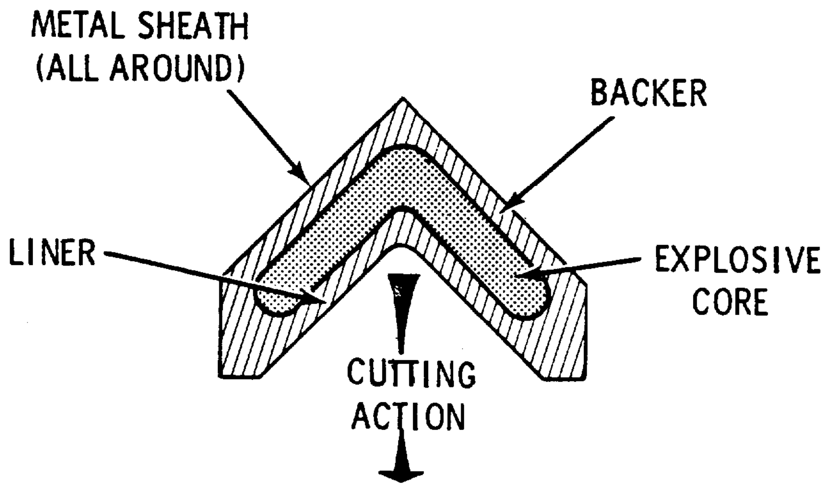


FIGURE 4.3. Linear Shaped Charge (Either Lead or Aluminum Encased)
Source: Ensign-Bickford: Space Ordnance Division

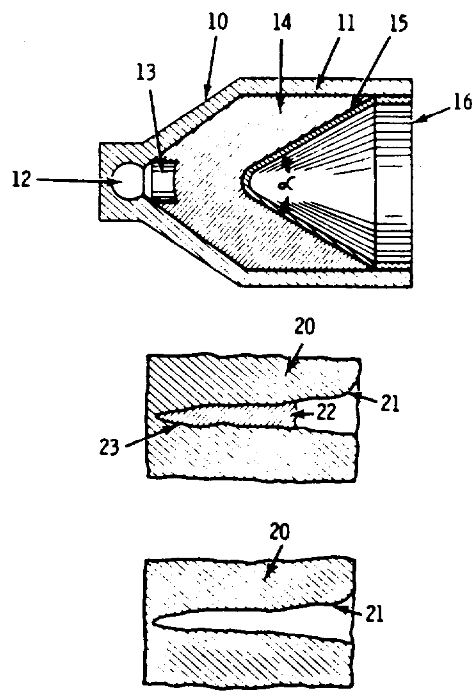


FIGURE 4.4. Shaped Charge Perforating Apparatus. The conical shape is used for small deep hole cutting which progresses as noted here.
Source: U.S. Patent 3,128,701; J. S. Rinehart et al., April 14, 1968.

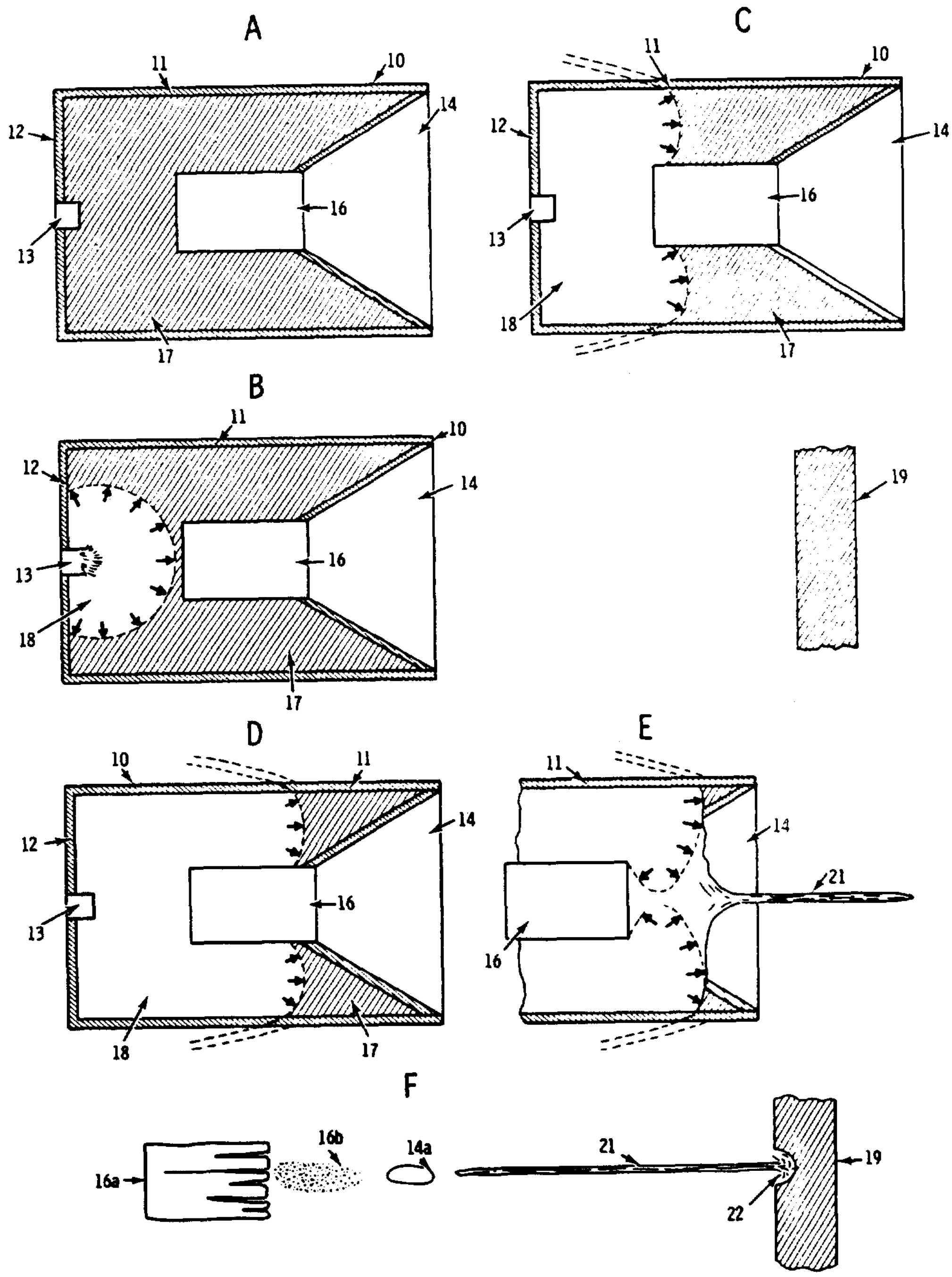
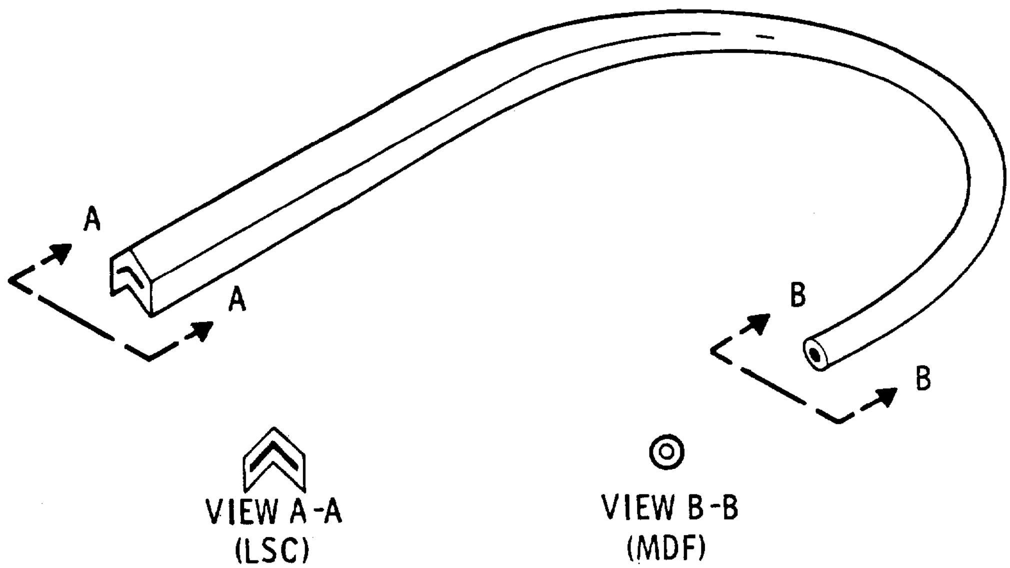


FIGURE 4.5. Shaped Charge with Secondary Target Defeating Mechanism (see text for sequence)

Source: U.S. Patent 3,948,181; J. J. Bergstrom, April 6, 1976.

The evolution of the shaped charge is growing through continuous reexamination. Early in the development of mild detonating fuses, it became evident that shape (cross section) was important in controlling directional effects. The flexible linear shaped charge is offered as having advantages of cutting where it is desired with considerable efficiency. As shown in Figure 4.5, the configuration of the cross section has changed with some manufacturers reconsidering shapes similar to configuration IV or V for normal applications. In addition to configuration evolution, other modifications were made so that the shaped charge could be formed for transition to a mild detonating fuse. Figure 4.6 is a typical product data sheet illustrating this application.

Use on oil tankers would follow a procedure of either preshaped or field shaping the charge to cut open more than 10% of the cargo tank deck. The charge would be held by magnets, epoxy, or other steel bracketing mechanisms. A blasting cap (e.g., No. 6) or prima cord connected to the shaped charge serves as the initiator. These caps can, of course, be electronically activated remotely. Practice has shown it is far safer to use prima cord firing legs and it is better not to use direct electrical systems in each shape charge firing, but use them in trunk lines with blasting caps at the commencement of the run leg. The strength of the core load will be dependent upon the deck or plate thickness to be cut. As noted in Table 4.2, steel of various thicknesses is used up to about 1.25 in. Explosive experts have advised that under ideal conditions about 300 to 400 grains/ft will cut 0.5 in. mild steel, but that something less than 1500 to 2000 grains/ft would be required for steel 1.5 in. thick. In instances where marine salvage work is done and steel plate to cut is not necessarily perfect and does have some deformation to it, it is necessary to use larger charges because of the inability to exactly position them. In these instances it is not uncommon, noting salvors' operational experiences, to use as much as 1 lb for each running foot to cut 1-in. plate. The blast-through effort needed to sever and part the cut line is important and significant. In addition, questions of joints and corners needed to be considered in the positioning of the shape charges and a certain



LINEAR SHAPED CHARGE SIZE (GR/FT)	MILD DETONATING FUSE SIZE (GR/FT)	LSC LENGTH (FT)	MDF LENGTH (FT)	TRANSITION LENGTH MAX. (IN.)
5	1 TO 2	UP TO 25	UP TO 25	0.50
7	2 TO 3	UP TO 25	UP TO 25	0.50
10	2 TO 4	UP TO 25	UP TO 25	0.75
15	2 TO 6	UP TO 25	UP TO 25	0.75
20	5 TO 10	UP TO 25	UP TO 25	1.0
25	5 TO 12	UP TO 25	UP TO 25	1.0
50	5 TO 20	UP TO 25	UP TO 25	1.25
100	10 TO 30	UP TO 25	UP TO 25	1.50
200	10 TO 40	UP TO 25	UP TO 25	2.00

FIGURE 4.6. Formed Transitions Linear Shaped Charges to Mild Detonating Fuse

Source: Ensign-Bickford

TABLE 4.2. Steel Types and Thickness on Tankers Requiring Cutting to Provide Adequate Venting

	Deck	Side Shell	Shell Strake	Type Steel
92a	1.125 EH	0.93 Mild	1.125	H.S.
93a	0.8125 DH	0.81 DH	0.81 DH	H.S.
98a	0.9375 in. (MS-B)	0.9375 in. (MS-A)	1.125 in. (MS-CS)	Mild
100b	0.875 in. (DH 36)	0.72 in. (AH 36)	0.875 in. (DH 36)	Higher Str.
101b	1.25 DH	1.0 Mild	1.25 DH	Mild and H.S.
116a	1.00 in. (DH 36)	1.00 in. (MS-B)	1.00 (DH 36)	Mild and H.S.

Source: Maritime Administration, Division of Naval Architecture

amount of blast-through is desirable at these positions. Larger core loads make the logistic problems very significant. Once the openings are cut the ignition of the oil is possible.

Shaped charge systems have several configurations and purposes, such as shown in Figure 4.5, which are designed to provide a secondary mechanism which can be pyrophoric or ignitable. This may have application by placing in one unit the deck cutting and oil igniting agents. The system as offered claims that:

> When the charge is ignited the resulting detonation wave collapses the liner into a high velocity jet or slug that perforates the target after which the follow-through agent is driven through the perforation. The follow-through agent may be pyrophoric or ignitable and such agents will increase the temperature and pressure particularly if the target is a closed target.

This would appear to fit the generalized conditions of a closed cargo tank containing crude oil or refined products.

Weapons Used for Cutting. Additional information on weaponry (Twardawa, Canadian National Defense) indicates that opening holes in 1.5 in. steel plate is within the state-of-the-art; e.g., British No. 1 Mark 3 Beehive is capable of penetrating 9 in. of mild steel or 6 in. of armor plate. This weapon contains 6.7 lb of TNT/PETN (75/25) or RDX/TNT (50/50). Other available systems include British Mark No. 1 at 1 lb TNT. The U.S. shaped charge, M3A1 will effectively penetrate 1.5 in. of steel using 30 lb of a material referred to as composition B. The concept could employ either linear or conical shaped charges and applications testing would demonstrate the most effective.

Other Cutting Tools. Conventional cutting torches using acetylene or MAPP gas or equivalent can be used on steel at thicknesses such as the decking, but the possibility of explosion would normally rule them out due to the need to have personnel in the immediate vicinity operating the torch. Another application which would probably be rejected on similar grounds is the "burning bar" (Figure 4.7). This device would be used under some wet circumstances where the torch could not. The burning bar is a device used to crack through metal used in safes and other reinforced areas. It involves an intense heat application which cuts the metal with a burning action. The device, generally field fabricated, can be made from a 4-in. diameter pipe section a few feet long into which aluminum and iron bars are inserted. One end of the bar has a cap and nipple inlet for an oxygen supply (portable oxygen cylinder). Heat from an oxy-acetelene torch is then applied to the bar inserts in the other end of the pipe and intense heat is generated for entire length of the aluminum and iron bars.

Conventional armor piercing ammunition has been suggeted as appropriate for cutting open vessel decking. However, the quantities required plus less than uniform agreement among experts suggests that further study is required to evaluate this approach.

Status of Technology of Using Incendiary Type Weapons

Since the early 1960s, considerable DOD effort has been expended in the feasibility demonstration and development of reactive incendiary munitions of

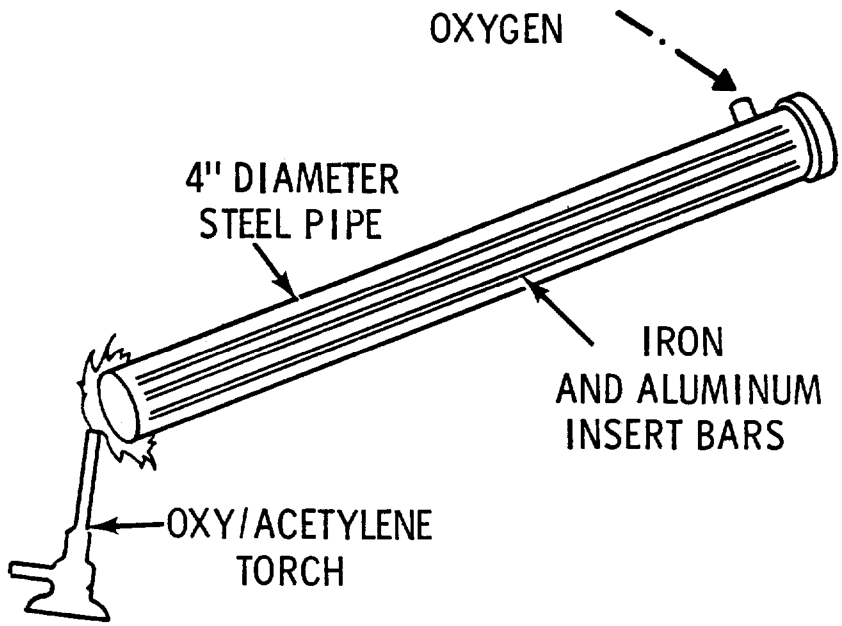


FIGURE 4.7. Burning Bar

varying types and incendiary configurations. The mechanism for ignition of fuel targets is summarized in Appendix G. The munitions listed in Table 4.3 are those which have either been produced or which could be produced in the near term.

The objective of reactive incendiary munitions is the ignition and combustion of various hydrocarbon products under a wide spectrum of circumstances. Some typical examples are as follows:

a. Fuel

  (1) Containment

   - Truck fuel tanks
   - Aircraft fuel cells
   - 55-gal drums (single and multiple)
   - Massive storage
   - Aboveground distribution
   - Armored fuel tanks

TABLE 4.3. Reactive Incendiary Munitions

Munition Types	Munition	Description	Incendiary Configuration	Developer	Status
Bomblets/ Submunitions	APAM	Mechanically fused bomblet with dual mode capability	Zirconium ring	Navy	Inventory
	BLU-61A/B	Spherical fragmentation cluster bomblet	Compacted zirconium sponge disks	Air Force	Out of production, but should be available
	BLU-63/B	Spherical cluster bomblet Smaller than BLU-61	Two Titanium-Teflon Pellets	Air Force	Inventory
Missile/Rocket Warheads	MK 90	12-in. diameter warhead for Navy STANDARD missile	Zirconium liner	Navy	In production
	AIM 9-L	5-in. diameter warhead for advanced Sparrow missile	Zirconium disc	Navy	In production
	MK 63 Mod 2	5-in. diameter warhead for Zuni rocket	Discrete zirconium fragments or zirconium liner	Navy	Inventory
Projectiles	40mm (MK I, MK II) Improved Projectile	40mm projectile developed in 1970 for gunship use in Southeast Asia	Mischmetal liner	Navy/AF	Produced in 1970-71. Probably not in current inventory
	40mm MK 162	Advanced 40mm projectile developed to supersede above round	Zirconium liner	Navy/AF	Developed, but not produced
	20mm M56A4PIP	Incendiary product improvement of M56 ammunition	Zirconium or titanium-teflon base pellet	Army/AF/ JTCG	Production pending
	30mm HEI GAU-8/A	HEI projectile for use against ground targets	Compacted Zirconium or titanium-teflon base pellet	Air Force	Engineering development
	20mm Improved	Replacement for M56 HEI for air-to-air applications with M61 gun systems	Zirconium cup	Air Force	Engineering development

Source: Naval Surface Weapons Center, G35:HEM:SZ, 8030.

(2) Stationary versus moving

(3) Types

- DF-2 diesel
- Jet A-1
- Gasoline

(4) States

- Liquid (contained)
- Spray (confined)
- Spray (open)
- Puddles
- Liquid Streams

b. Other flammable liquids

(1) Hydraulic fluids

(2) Liquid chemicals

c. Light structure susceptible to vaporific-type effects

d. Explosives and propellants

(1) Stored

(2) Truck cargo

(3) Warheads

(4) Missile fuels

(5) Gun propellants

Primary Candidate Systems. The following incendiary systems appear to be applicable in combustion technology.

Fuel Air Explosive (FAE): This weapon relies on a combination of detonation and incendiary action to clear large areas of land to develop helicopter landing sites. A common fuel is ethylene oxide. Incendiary experts have indicated that the developed action is too short to generate a successful oil burn and the bomb relies too largely on detonation action to be of use. There is, however, a red phosphorus/butyl rubber smoke screen device which is a take-off on the FAE that, although in the experimental stage, may be useful as an igniter. This device generates up to 6000°C of heat.

Triethylaluminum Gel/Aluminum Alkyl: In gel form this material is used in the M235 warhead for the M202 portable multishot flame weapon. As Aluminum Alkyl, the material is a large-volume specialty pyrophoric item in commercial use. The material is, however, very reactive with air and warrants carefully planned and executed handling and storage procedures.

Triethylboron: Triethylboron is also a pyrophoric substance but has two advantages over Triethylaluminum to the extent that: 1) it is lighter than water and will float, and 2) it is not quite so reactive in air. The material is somewhat experimental, and presently is in a semicommercial status. Once produced, however, it has limitless shelf life and can be readily stockpiled.

MK 25 and MK 58 Red Phosphorous Marker Flares: These units may have application as air-dropped igniters. The flares have a 2-in. freeboard in the water and may have application on thick oil slicks. They are equipped with a battery that is activated and develops ignition upon contact with seawater.

MK 6 Red Phosphorous Marker: This type of unit could have application as an in situ igniter as it is equipped with an Ensign-Bickford pull wire activator.

Thermite ($Al + Fe_2O_3$): This very "hot" material, 2000 to 3000°C, was first used in incendiary bombs and demolition charges in World War I, and has since been used for welding metals together. The charges could be set or floated on the oil following which they could be fuse ignited to provide an activation delay of up to 2 hr. This would give time for all personnel to abandon the vessel and response craft to clear the casualty site. Thermite is a self-contained material known to be an excellent incendiary. Although it is normally a powder, a pelletizing process was developed in the 1960s by the Naval Surface Weapons Center (NSWC). This would facilitate its use within a warhead casing and enhance spreading upon detonation.

Blu-63/B Cluster Bomblet (Air Force): Of the incendiary munitions which are currently in production, the Blu-63 is perhaps the most promising candidate for oil spill ignition. It is a tennis ball sized spherical bomblet which contains explosive, two titanium-teflon pellets, and a spin-armed fuse which is expected to function upon water impact. The submunitions are air-dropped from a single canister, 600 at a time, and cover an area the size of several football fields with burning particles. Simple modifications to the Blu-63 to make it more effective in oil spill ignition include, if necessary, increasing the amount of incendiary per bomblet, changing the incendiary to a self-contained composition, and/or using the bomblet as a carrier for dispersal of a wicking or combustion enhancing agent over a larger area.

MK273 Mod 0 Firebomb Igniter (Navy): This device is used to ignite the napalm of a firebomb and consists of a canister containing small magnesium-teflon pellets, which are dispersed over a 300-ft radius. The pellets will burn under water and will float on the surface. Modifications would be required to make the device suitable for dropping into an oil spill. Although this item is out of production, it should still be available and could be produced again, if necessary.

MK82 Laser-Guided 500-lb Bomb (Air Force): For in situ burning, a possible candidate weapon is the laser-guided bomb (LGB), which can be accurately placed at specified points on the vessel. The MK82 bomb has been investigated with incendiary materials, and can be modified easily to accommodate a self-contained incendiary charge. A single explosion of this weapon would create a large fireball that would vaporize a large volume of oil, aiding combustion. It may also be possible for the weapon to be filled with materials such as a wicking agent or highly volatile agent which could be burst-spread over the surface of the oil, then ignited by an incendiary device. A self-propelled surface-launched variant of the LGB, the Modular Guided Glide Bomb (MGGB), has been demonstrated by NSWC.

Attention should be drawn to studies completed for the Canadian Environmental Protection Service which addressed the "Testing of Air-Deployable Incendiary Devices for Igniting Oil on Water." Safety fuses proved to be the most reliable mechanism for activating solid fuel and solid propellant igniters. Air deployment was reported as workable.

Flaring Equipment Applicable to in situ Oil Burning

Section 4.4.2 outlines the use of flaring equipment which is common around crude oil exploration vessels, platforms for production and refinery operations, but built-in institutional safeguards prohibit the application aboard tankers. This technology may be very appropriate in light of the apparent safety record of use on offshore platforms; the many difficulties in physical removal and cleanup of released oil; the problems of in situ combustion; and the sensibility of use of systems compatible with normal salvage operations including the almost completely abandoned concept of pumping cargo overboard.

The size of the tanker vessels appear to allow the installation of flares with adequate spacing used as in other installations. Practice is to locate the flares on land in a 100 ft plus square area away from any structures, etc. As the specifications for some of the available equipment are listed it should be recalled from Figure 2.2 that tankers generally are:

16,500 DWT x 532 ft long x 70 ft beam
100,000 DWT x 861 ft long x 125 ft beam
250,000 DWT x 1,141 ft long x 170 ft beam
500,000 DWT x 1,300 ft long x 233 ft beam

Assuming the wind direction can be engineered to avoid blow back of the flare over the deck, it would appear that even the smaller tankers could be equipped with a flaring system. The large tankers may accommodate multiple systems. Figure 4.8 is illustrative of the arrangement of burner and boom to create the flare at a safe and controlled distance. The figure demonstrates the application of the flare operating on an offshore platform. Figure 4.9 is another manufacturer's concept of the burner design. Figure 4.10 shows the flare in operation and it may be assumed that since a man is standing at the rear of the flare that: 1) the heat must not be intense radiating back to the platform (ship); and 2) experience is such that safety considerations would allow a person to be that close. Another arrangement is shown in Figure 4.11 where the burner is safely placed upon a pedestal and rotations of almost 360° are possible to meet wind conditions. This could possibly be useful for bow or stern application.

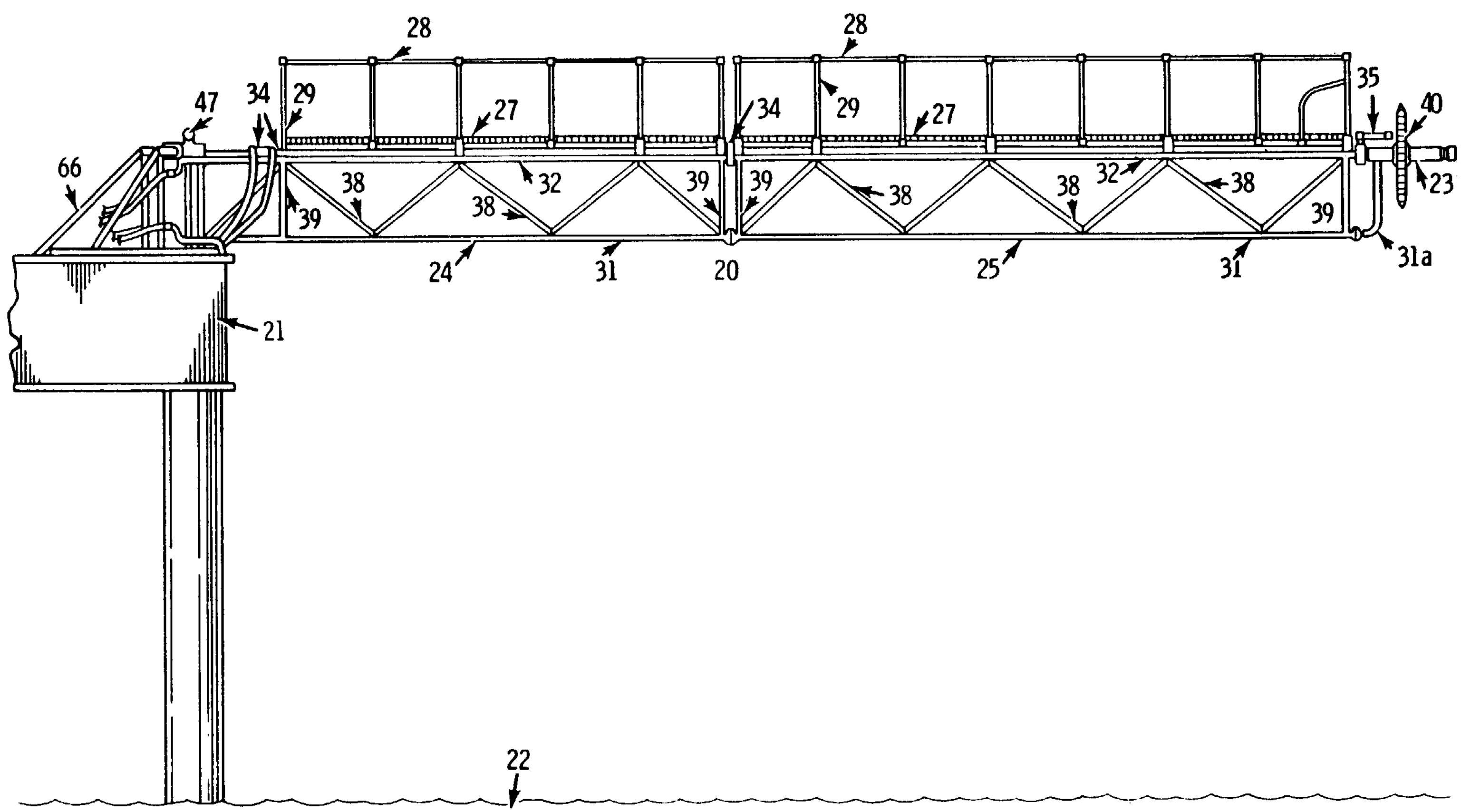


FIGURE 4.8. Burner with Boom Arrangement for Offshore Waste Oil Flaring

Source: U.S. Patent 3,807,932, J. DeWald, April 30, 1974.

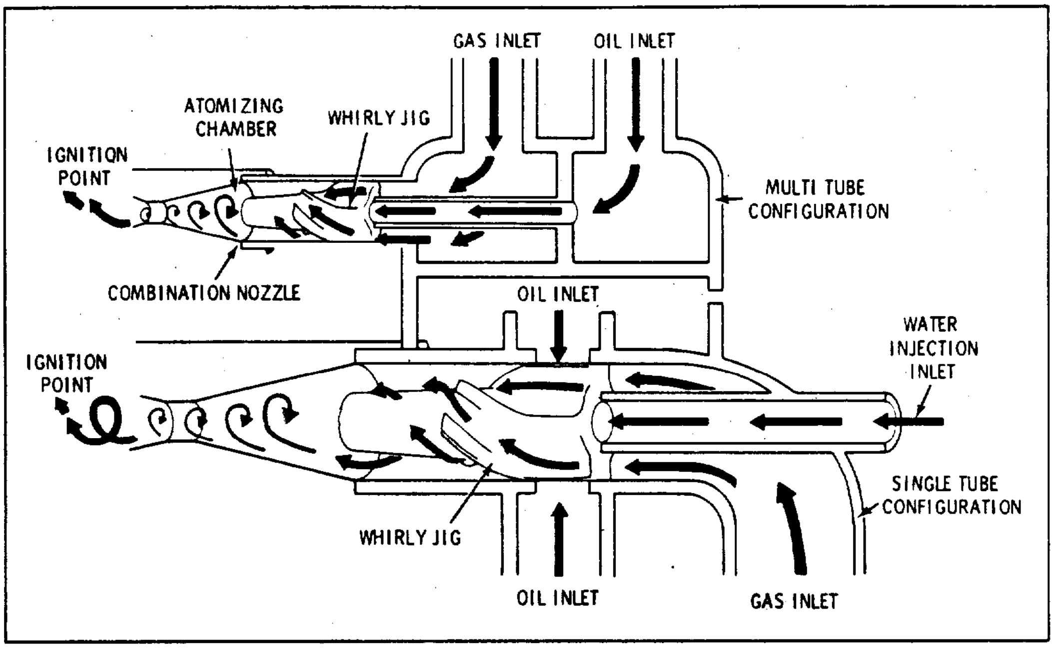


FIGURE 4.9. Liquid Hydrocarbon Burner

Source: Porta-Test Systems, Ltd. Edmonton, Alberta, Canada

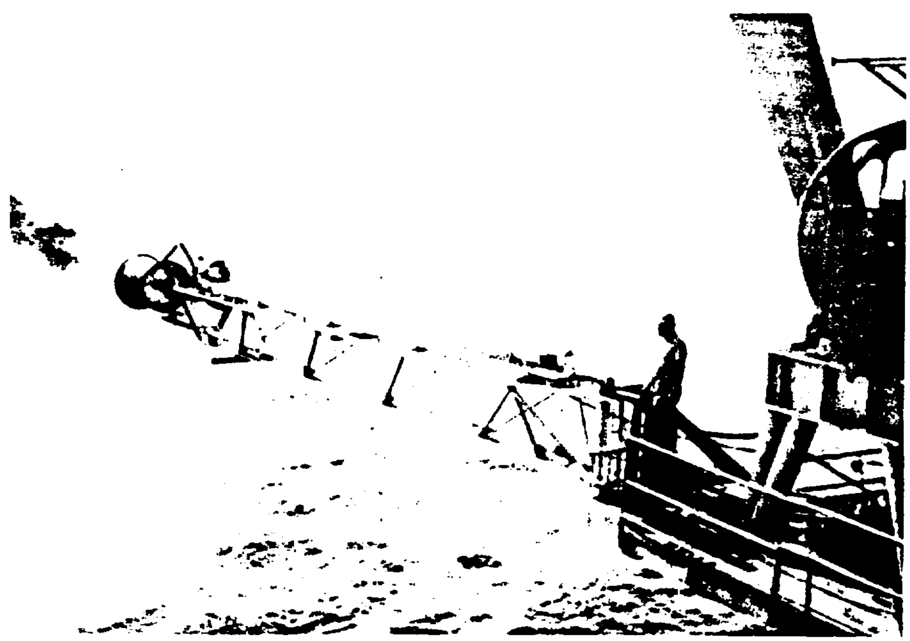


FIGURE 4.10. Noralco Oil Burning Unit

Source: NORALCO, U.S. Patent No. 3807932

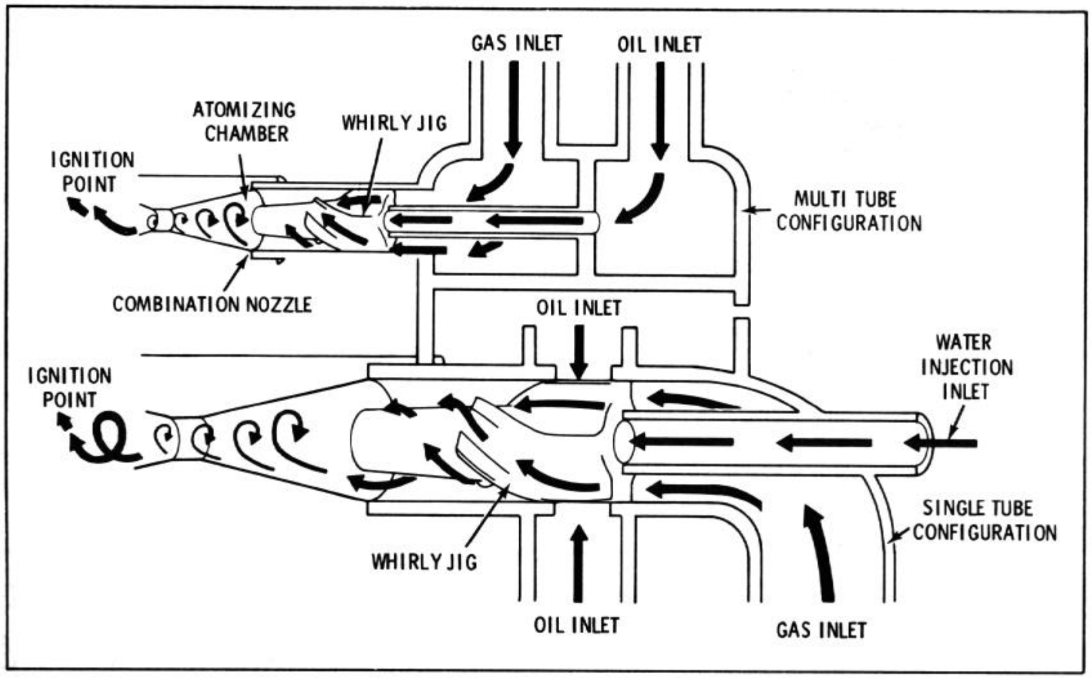


FIGURE 4.9. Liquid Hydrocarbon Burner

Source: Porta-Test Systems, Ltd. Edmonton, Alberta, Canada

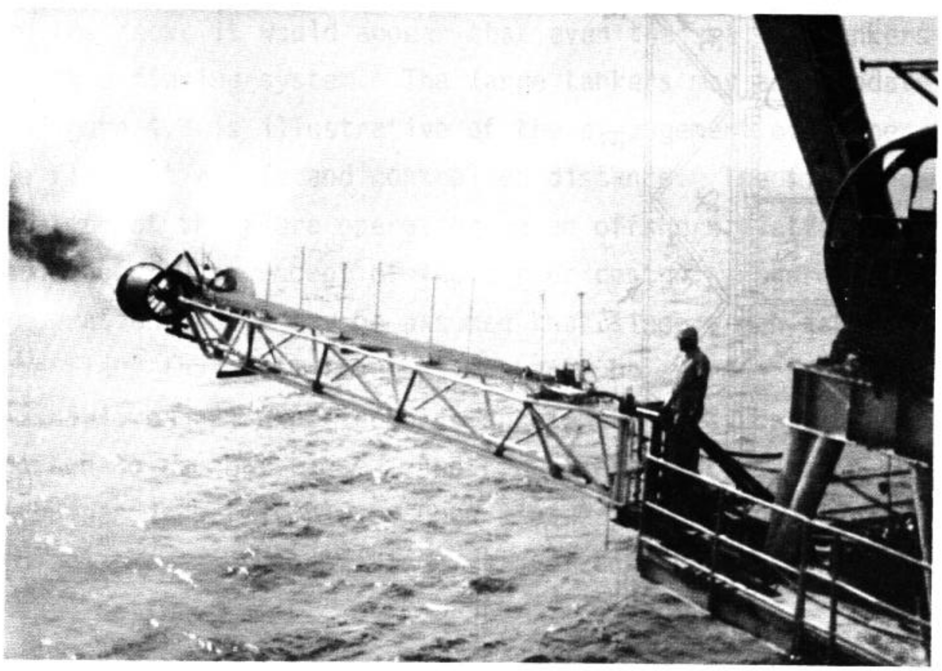


FIGURE 4.10. Noralco Oil Burning Unit

Source: NORALCO, U.S. Patent No. 3807932

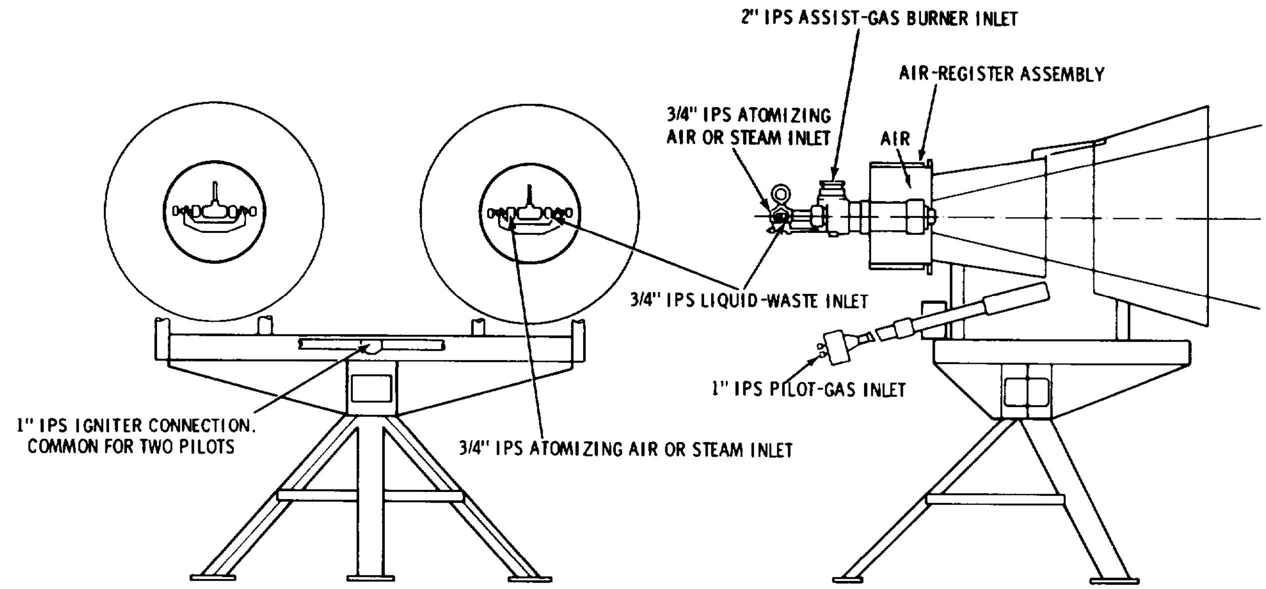


FIGURE 4.11. Pedestal-Mounted Dual Burner Flare for Waste Oils
Source: National Air Oil Burner Co., Inc.

Manufacturers Claims. The following systems are claimed to operate by controlling the mixture of air, water, and waste oil in an atomized state to assure rapid and complete combustion.

Porta-Test Systems, Ltd., Edmonton, Alberta, Canada: The Porta-Test Liquid Hydrocarbon Burner incorporates the inherent flow energy of liquids and gases to produce mechanical atomization for efficient clean combustion. This end is achieved by the effective use of a patented device known as a Whirly Jig and two flow nozzles. These components assembled together in conjunction with a Vortex Tube comprise a Single Burner Tube.

The Whirly Jig (see Figure 4.9) can be described as a fixed vane assembly that contains a hollow cylindrical core. The liquid that is to be burned is introduced through the hollow core of the Whirly Jig and passed through an oil nozzle. Simultaneously, atomizing gas is introduced over the vanes of the Whirly Jig and is given a high velocity spin. As a result, the flow characteristics of the spinning stream generates a suction force in the core of the Whirly Jig and is transmitted through two inlet ports, or the core inlet of the Whirly Jig. The pressure differential thus created provides a flow assist for the entering liquid. The liquid and atomizing gas leaving the Whirly Jig enters the mixing chamber where the high velocity gas shears the liquid stream into fine particles. After passage through the combination nozzle the mixture emerges as a fine spray.

Burner capacity and performance is governed by the number of burner tubes employed and by the proper selection of nozzle combinations and sizes. These are related to desired disposal rates and the physical properties of the liquid and gas to be used.

Porta-Test Liquid Hydrocarbon Burners can be single or multitubed in design and can utilize water injection rates on the order of 30%. External concentric water rings can be provided to aid in heat dissipation. The absence of moving parts and stainless steel construction in heat-affected zones provides maintenance free operation under normal burning conditions.

NORALCO, Metieve, Louisiana: The burner is a lightweight, easily portable system with capacity developed to handle the high volume requirements of the North Sea area. The burner has a 20,000 BOPD (barrels of oil per day) maximum capacity with a minimum of 75 BOPD. Atomization of fuel is created by a "Venturi Atomization System" and is claimed as a revolutionary principle. The burner does not require compressed air, since air is drawn through the rear orifice of the equipment and is directed in a swirling manner by the venturi vanes into the combustion zone at a high velocity which depends on the fuel burn rate and combustion heat generated in the front of the burner.

A two-ring system of water nozzles continuously sprays water from 360° around the burner in a vertical plane to minimize heat radiation to the rear of the burner. To minimize the amount of smoke created by the combustion of the fluid fuel, a controlled amount of water is sprayed in a ring around the flame and in the same direction as the flame. The amount of water required for optimal smoke suppression varies with the volume of fluid fuel being burned and is hydraulically controlled.

Fluids (oils) to be burned are directed from a well (cargo tank) through a valve cylinder inlet and distributed 360° around a control sleeve. This system provides correct atomization of the fluids under variable pressures and/or flow rates by the movement of the control sleeve. The sleeve hydraulic system is operated from the control panel. Air is intensified as it proceeds through the venturi profile.

BMW Corporation, Houston, Texas: Similar to NORALCO's equipment, a portable packaged unit contains boom and control cab. The system appears mobile and quickly adaptable to the tanker needs. The "BIG JOHN" burner and the "SHIFTY BOOM" are offered as a system for use on offshore platforms.

Otis Engineering Corporation, Dallas, Texas: The OTIS/NAO CB-12 and CB-4 Burners utilize a natural induction air draft concept as shown in Figure 4.11 which eliminates the need for a forced air blower. This feature is made possible, in part, by the two-piece "can" type design and construction of the burner head. Air enters between the two "cans" of the burner head to help optimize air-oil mixture for clean burning.

The two-piece "can" construction also provides an entry point for a second water ring - another important feature - for the two water rings. Numerous, strategically located, spray nozzles contribute significantly to water control. And water control is critical to clean burning at low volumes.

Three burner nozzles, or "guns" are located at the rear of the smaller "can" of the burner head. These "guns" may be fired singularly, in pairs, or as a complete unit to more efficiently burn fluid over the wide range of volumes. These "guns" are easily detached from the head and simple to disassemble for cleaning.

The OTIS/NAO Burner (similar to that shown in Figure 4.11) utilizes a remote ignition principle which does not require electrical energy to be delivered to the pilot on the head. As a result, radiation in the area of the pilot does not pose a problem to the ignition system.

Atomization of oil and compressed air is accomplished externally to the gun of a CB-12 or CB-4 burner. This feature all but eliminates the possibility of over pressurization of the oil stream; a situation that can cause a back-up of air in the air line. CB can handle up to 1,200 BOPD.

The OTIS/NAO CB-12 Burner is so constructed as to afford manual directional control, up to 30° off center either left or right, from the control end of the boom. The CB-4 provides ±40° from center, and this directional adjustment can be made during testing operations. There is no need to shut down operations in the event wind shift makes adjusting the direction of the head desirable for better leeward burning.

Booms are available which permit either horizontal or vertical storage, and provisions can be made for a completely independent boom manipulation system which does not require the use of a rig boom.

Johnston/Schlumberger, Houston, Texas: Waste oil burners consisting of three and four headed units can handle API 32° oil at flow rates from 100 to 12,000 and 16,000 BOPD at pressures up to 465 psi. Air, water, and propane gas pilot light are required. Rotation at a 60° maximum angle is possible. Comments are typical. Weight of the burner is 1660 lb to 1875 lb and which is 65 in. x 49 in. x 71 in. in size.

John Zink Company/Baker Tool Company, Houston, Texas: This burner, operating on the same principle as the NAO burner, can handle up to 10,000 BOPD. High pressure air (or gas) atomizes the oil, and high pressure water is used to eliminate smoke. Operating specifications are similar to NAO. Additional data are available in a report (Peterson et al., 1975), which discusses alternatives for storage and disposal of Alaskan oil spills.

Flare System Operations. It is difficult to generalize on equipment specifications, but those taken in part from one manufacture and shown in Table 4.4 should be representative of the state-of-the-art. These systems have been applied to land-based operations and to offshore oil production platforms. None of the systems suggested above are known to have been used aboard any vessel with the exception of NORALCO which offers the dual oil burner as part of an oil well drilling ships' equipment. The configuration is amidship with the boom directed upward.

4.5 OIL BURNING TECHNOLOGY - RELEASES ON WATER

Existing law and regulation in the U.S. make the decision to use burning technology a case by case evaluation. The National Oil and Hazardous

TABLE 4.4. Representative Specifications of Flare Systems

- Burners

  Oil Flow Rate 75 to 20,000 bbl/day

  Pressure 80 to 450 psi; maximum rated 2000 psi

  Water Supply flow adjustable up to 650 bbl/hr (455 gpm)

  pressure maxim 500 psi

  Size 28 in. x 34 in. x 40 in.

  Weight 286 lb

  Connections Required

  Pilot Gas 10 gal butane tank

  Water Supply 2 in. WECO figure 100 union

  Oil Supply 3 in. WECO figure 200 union

  Gas Flare (probably not needed here) 2 in. WECO figure 200 union

  Operator Controls

  Lines and control panel allow remote operation

- Boom

  Rigid, preferably collapsible

  Motion Safety, rolling $\pm$ 7.5° in 12 sec

  pitch $\pm$ 5° in 12 sec

  heave 50% above value of g

  Wind Design 50 mph transverse

  Size - Retracted at deck level 6 ft x 27 ft skid

  Extended boom length 55 ft

  Weight 8,000 lb (with burner)

- Initiation Time

  Quick attachment connections self-contained permanent piping boom reaches 55 ft in 5 min or less, other alternatives can be designed.

- Support System

  220/440 V, 60 cycle, 3 phase, 7.5 hp motor as hydraulic system prime mover. Diesel power prime movers also used.

Source: NORALCO; BMV.

Substances Pollution Contingency Plan (40 CFR 1510) at 1510.2006 establishes authorization for use of burning agents as follows:

> 2006.1-1 All discharges. The OSC (Onscene Spill Coordinators) may authorize the use of burning agents only when their use:
>
> 2006.1-1.2 will result in the least environmental harm when compared to other removal or disposal methods.
>
> 2006.1-1.3 Prior to authorizing use under 2006.1-2, the OSC must obtain the approval of the EPA RRT (Regional Response Team) representative and all applicable State and local public health and pollution control officials.
>
> 2006.2 Special restrictions on burning agent use.
>
> 2006.2-1 The OSC will evaluate the suitability of burning agents on a case-by-case basis. Burning agents should be inert materials that will not, in themselves, be a water pollutant. The addition of oils (such as gasoline or solvents) as an igniter shall be avoided unless it is necessary under 2006.1-1.
>
> 2006.2-2 A technical data program for burning agents will not be established at this time.

As noted in Section 2006.2-2, data similar to dispersant evaluation information have not been gathered to date.

Attempts to burn oil which has been released into or upon water involve both devices and materials. The materials will be discussed as combustion promoters and the delivery systems for these materials as well as other devices for burning oil on water will be discussed as equipment. A recent review (Energetex, 1978) of combustion promoters is a most helpful reference. Section 4.1 indicates the perceived principles to enhance combustion have motivated manufacturers to offer certain products. However, it was not apparent that a firm grasp of the significance of radiant heat in this combustion application has been employed.

Figure 4.12 illustrates that the use of burning for oil on water is only one consideration in the total of spill mitigation responses. However, of the six alternatives noted in Figure 4.12, burning may well be the fastest, least expensive, and in selected cases, e.g., Arctic, it may be the most environmentally safe response action. Technology available to implement this alternative is primitive and not well accepted by public authorities. Often the onscene personnel, such as salvors or cleanup contractors, have had such poor experiences with burning that they would not consider it further.

4.5.1 Combustion Promoters

The 34 million gallon tanker, TORREY CANYON, which lost most of its cargo to the sea in 1967, provides one of the most widely published accounts of attempts to use oil burning on the surface of the water. An incendiary block ("tile") was used in an attempt to ignite oil on the water surfaces, but this was unsuccessful, due to the mixing of the layer to form an emulsified "choclate mousse." This incendiary tile of plastic coated sodium clorate was dangled by cable from a helicopter into the oil. When an electric current was passed down the cable the block burst into flame. This system failed to ignite the oil. Napalm bombs were dropped upon the slicks (timed to explode just above the water surface) to ignite the floating oil with no success, probably because the 9-day old oil had weathered considerably.

Since that incident, industrial activity has been dedicated to developing a variety of materials which are claimed to enhance the ignition and combustion of oil released on water. Table 4.5 illustrates some of the U.S. patent activity in this field of combustion promoters. By a careful examination of the disclosures, one may understand the range of activities which are being pursued to use combustion to address spills of oil on water. The Patent Numbers have been provided to allow follow-up investigation. With all these patents it would appear that responsible officials would have more experience and/or faith in use of the technology and that the National Plan (40 CFR 1510 and following) would provide detailed acceptability guidance.

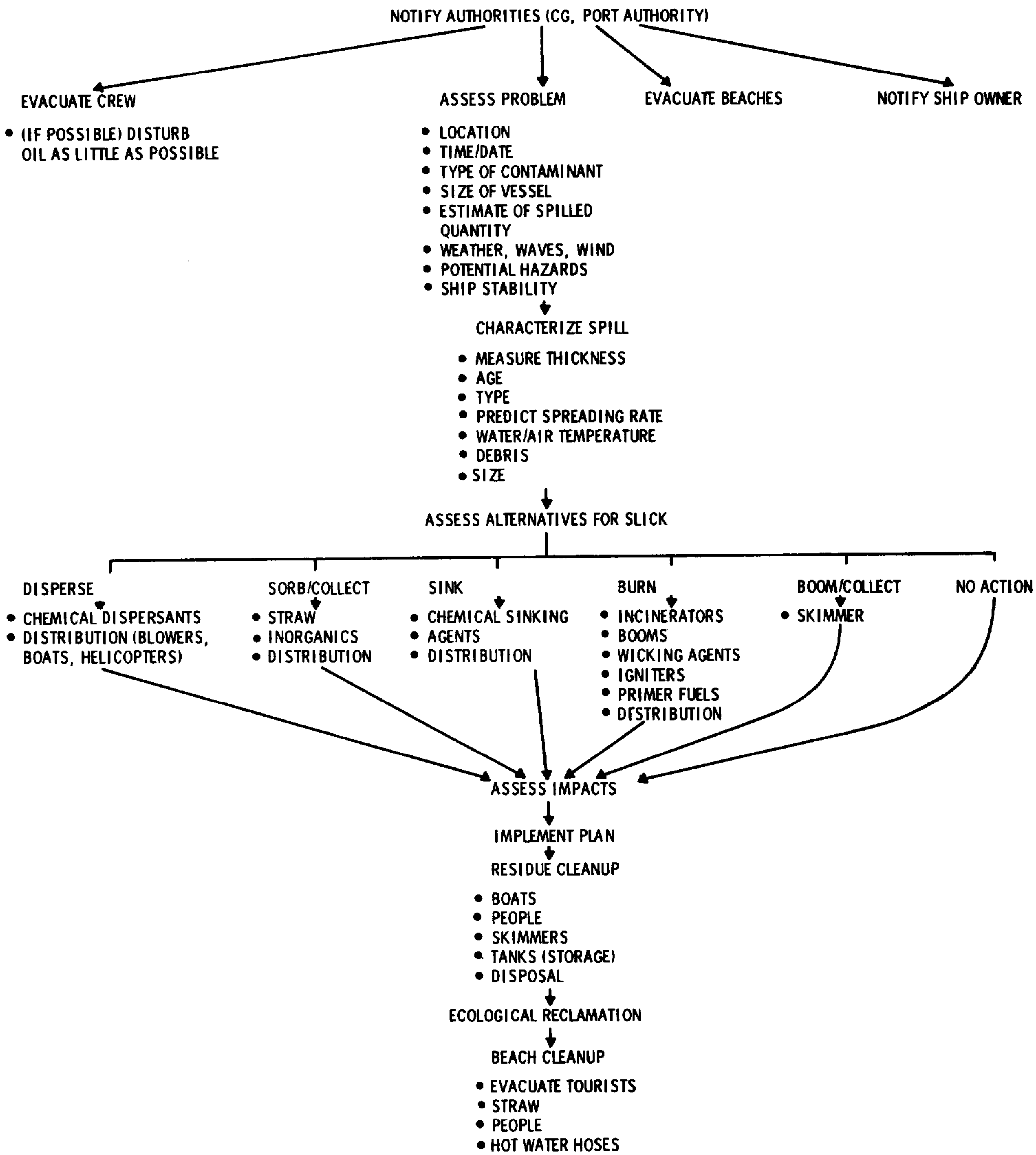


FIGURE 4.12. Options and Actions for Oil Spill on Water

TABLE 4.5. Selected Patents Illustrating Industrial Activity

Patent No.	Date	Description
3,677,982	July 18, 1972	Petroleum oil floating on the surface of water is removed therefrom by adsorbing the oil on a treated cellulose sponge and then burning the adsorbed oil from the sponge while it remains in contact with the water. During the combustion, the treated cellulose sponge continues to adsorb oil and deliver it to the combustion zone.
3,661,497	May 9, 1972	A process for the substantially complete combustion of a layer of combustible liquid floating on a body of water comprising spreading a layer of substantially spherical ceramic nodules on the upper free surface of the layer of combustible liquid. The nodules are wetted with the combustible liquid and the combustible liquid is ignited on the upper surface of the nodules until combustion is self-sustaining. The combustible liquid on the upper surface of the nodules consumed by combustion is continually replaced with combustible liquid from the layer until substantially all of the combustible liquid in the layer is consumed. The cellular ceramic nodules have a multiplicity of separate closed cells and the outer surface of the nodules has a plurality of cup shaped recess portions.
3,661,496	May 9, 1972	A process for the substantially complete combustion of a combustible liquid including the combustion of a layer of the combustible liquid floating on a body of water. Cellular ceramic nodules are prepared by coating uncellulated pellets with a particulate carbonaceous parting agent and cellulating the coated pellets in a rotary furnace or kiln. The cellular ceramic nodules obtained by the above process have a relatively thin coating of the carbonaceous parting agent thereon and a relatively smooth continuous outer skin. A layer of the coated cellular ceramic nodules is formed on the upper surface of the combustible liquid with a substantial number of the nodules in contiguous relation with adjacent nodules in the layer. The upper exposed surfaces of the coated nodules are wetted with the combustible liquid to form a film or layer thereon and the wetted films on the exposed surfaces of the nodules are ignited until combustion is self-sustaining. The combustible liquid films on the exposed upper surfaces of the coated nodules consumed by combustion are continually replaced with combustible liquid from the bulk of the liquid until substantially all of the combustible liquid is consumed.
3,749,667	July 31, 1973	Method for disposing of oil spilled at sea by first burning the oil and thereafter applying an inorganic sinking agent. The sinking agent particles, less than 50 mm in size, are dispersed over the burning oil and become coated with the oil residue which is absorbed onto the particles as they sink. The sinking agent particles may be sand, gravel, chalk, gypsum, slag of heavy materials like iron, ore, and the like.
3,696,051	October 3, 1972	Oils floating on the surface of open bodies of water can be removed by burning them in situ in the presence of an oleophilic particulate material such as vermiculite which has been treated with a metallo cyclopentadienyl compound such as dicyclopentadienyliron.

TABLE 4.5. (contd)

Patent No.	Date	Description
3,705,782	December 12, 1972	An oil slick is destroyed by applying thereto finely divided particles of a compound capable of generating a combustible gas, upon contact with water, allowing the particles to contact the underlying body of water so that bubbles of combustible gas rise through the oil film and admix therewith, so as to enhance the combustibility of the oil, and then igniting the oil-gas mixture to burn and destroy the film, e.g., calcium carbide to form acetylene gas.
3,607,791	September 21, 1971	A method for removing hydrocarbons from the surface of a body of water by placing a polypropylene sheet over and in contact with the hydrocarbons and combusting those hydrocarbons passing onto the upper surface of the sheet.
3,589,844	June 29, 1971	A process for absorbing and burning away oil or other combustible liquids on water or other noncombustible liquids wherein absorbent and/or surface active noncombustible inorganic foamed particles are spread out over the combustible liquid, the combustible liquids are absorbed by the particles and the liquid absorbed by the particles is ignited.
3,556,698	January 19, 1971	The present invention provides an improved method for the elimination of water and land borne spills by burning. Broadly, certain particulate solids are applied to the spill and the resulting system is thereafter fired. Such treated spills are more easily ignited and the combustion thereof is more complete than experienced with untreated spills. When certain conditions pertaining to the type and amount of treating agent applied to the spill are met even further benefits accrue to the process of the invention. Said benefits reside in improved physical character of the burned residue which is more amenable to physical removal thereof from the water or land mass than the burned residuum of untreated spills.
3,902,998	September 2, 1975	Rice hulls are floated on water contaminated with oil to absorb the oil which is then removed by skimming the combined oil-rice hull material from the water.
3,886,067	May 27, 1975	Oil slicks on surface waters are controlled by applying oleophilic foam material to the slick from a boat or airplane. In one case the material foams and binds the oil to form sponge-like clods which can be skimmed from the surface by another ship. In another embodiment chips of the film material which are formed on board the craft are applied to the oil slick.
3,728,208	April 17, 1973	A porous alkali metal silicate foam having oleophilic-hydrophobic properties is provided for use in oil spill control and removal. The silicate foam is preferably formed from a blend comprising solid and liquid alkali metal silicates and an oil absorption-water repellent agent. The blend is pelletized, heated in an oven to expand the material into foam particles, and then shredded, graded and retreated with an oleophilic-hydrophobic agent to coat the internal and external surfaces and thereby further enhance the oil-absorption characteristics.
4,102,703	July 25, 1978	There are provided water-repellent compositions comprising hydrophobic, finely-divided particulate metal or metalloid oxides. The compositions of the invention are useful in imparting water-repellent properties to porous substrates coated therewith.

Combustion promoters, as one of the subsets of patented technology, are a group of materials, natural and manmade, that can be applied to the surface of an oil slick to aid in maintaining combustion of the oil. Examples are listed in Appendix J. Additional information has been reported in Canadian Studies (Energetex, 1978). The least expensive and most readily available of these materials, Group A, are natural organic fibers which have low insulating properties but are oleophilic (oil attracting) and would wick oil to the flame during combustion.

The second group, Group B, is processed minerals and chemicals which absorb the oil within themselves. These materials would have a definite insulating value but do not necessarily selectively sorb oil. Once the material is distributed within the oil layer the thermal insulating value of the oil layer is increased.

The third group, Group C, is processed materials treated to be hydrophobic (water repelling). These materials, when added to the oil layer, will decrease the thermal conductivity of the oil layer.

The fourth group, Group D, is materials which alter the volatility of the oil while acting as combustion promoters.

Group E is chemicals which will ignite on contact with water and may be used to start a spill burning. These may be used by themselves or in conjunction with a combustion promoter. Selected incendiary weapons which could be used as combustion promoters are noted below.

Apart from the previous considerations pertaining to burning oil within a stricken tanker, the opportunity to use reactive incendiary weapons to burn oil released upon water has been considered. This novel approach could be safer, faster, more economical, and more reliable than conventional physical removal technology. Success of such a concept, as viewed by the Naval Surface Weapons Center, depends upon two factors: 1) the application of an effective ignition source to initiate combustion, and 2) the ability of the fuel to sustain burning after ignition, either with or without an agent to augment combustion.

On-the-shelf incendiary munitions exist which, in current or possibly modified form, have a significant probability of ignition of oil on water. The state-of-the-art is such that testing would be required for a definitive answer. Investigations of such munitions and incendiary materials would be coordinated with laboratory studies to determine the ability of specific oil types to sustain combustion as a function of water and air temperature, wind conditions, combustion promoters, and other relevant parameters.

Several incendiary materials are available which could potentially be effective in ignition of oil fires. Section 4.4.3 discussed munitions for in situ vessel burning and Table 4.3 listed weapons and their development status. Effective metallic incendiaries include zirconium and titanium sponge and mischmetal (the mixture of rare earth metals from which lighter flints are made). Thermite ($Al + Fe_2O_3$) is representative of a large family of metal-metal oxide reactions and is highly energetic, low in cost, and self-contained (i.e., does not require atmospheric oxygen to react). Proprietary materials which are currently being marketed as reactive incendiaries include: 1) titanium-teflon (Ordnance Research, Inc.), which is low in cost and readily available; 2) PBI (Plastic Bonded Incendiary, developed by American Service Products, Inc.), which is self-contained and may be varied in density; and 3) QAZ/QAT (Quasi-Alloy of Zirconium/Titanium, developed by Quantic Industries, Inc.), which may be cast into unusual shapes for varying applications.

Of the incendiary munitions which are currently available, the BLU-63B cluster bomblet (see Section 4.4.3) is perhaps the most promising candidate for oil spill ignition.

The recent Canadian studies (Energetex) on air deployable incendiary devices were directed at burning oil in melt pools in Arctic climates. The draft report provides documentation of feasibility and limitations of use:

> In the air deployment test, it was proven that oil slicks could be successfully ignited by air-deployed incendiary devices. Although safety fuses proved to be the most reliable mechanisms for activating solid fuel and solid propellant igniters, it was felt that the electrical starters could be improved to match the reliability of safety fuses. The ignition probabilities of all

igniter and starter combinations tested ranged between 60% and 80%. KONTAX igniters performed poorly in air-deployment aplications, due mainly to their excessive production of calcium hydroxide foam. KONTAX igniters had the largest flame area, as well as the most intensive flame radiation of the igniters tested. Solid propellant and solid fuel igniters had similar flame areas, with the latter emitting the more intensive radiation of the two. Solid propellant igniters burned with the highest flame temperature, whereas KONTAX and solid fuel igniters burned with considerably lower flame temperatures.

4.5.2 Combustion and Support Equipment

The principle of increasing radiant energy capture during oil spill combustion is one approach which a few equipment manufacturers, as opposed to material manufacturers, have considered but abandoned. No commercial systems are presently available for oil-on-water combustion. Both Pittsburgh Corning Corporation and British Petroleum carried out sufficient developmental testing to file for patents and carefully study the market. Two of the systems patented by Pittsburgh Corning are shown in Figures 4.13 and 4.14. Both concepts employ a system of oil wicking and radiant energy capture.

Oil residues and emulsions floating on a body of water are burned by confining the layer of residue within a furnace chamber (Figure 4.13). The furnace is equipped with a combustion air inlet adjacent to the upper surface of the residue and a stack with inlets for combustible gas. The combustible gas burns the combustible material from pyrolysis of the liquid residue to provide a relatively smokeless combustion process. The furnace (Figure 4.13a) is fabricated from a refractory material having insulating properties so that a substantial portion of the heat given off by the combustion of the residue is retained within the furnace to propagate further combustion of the residue and aid in the complete combustion of the difficult to burn portions of the residue. The furnace is preferably fabricated from a material that permits the furnace to float (Figure 4.13b) partially submerged in the body of water and may be easily transported from one location on the body of water to another location thereon. The furnace may be supported (Figure 4.13c) from suitable pipings and the residue conveyed directly into the furnace chamber.

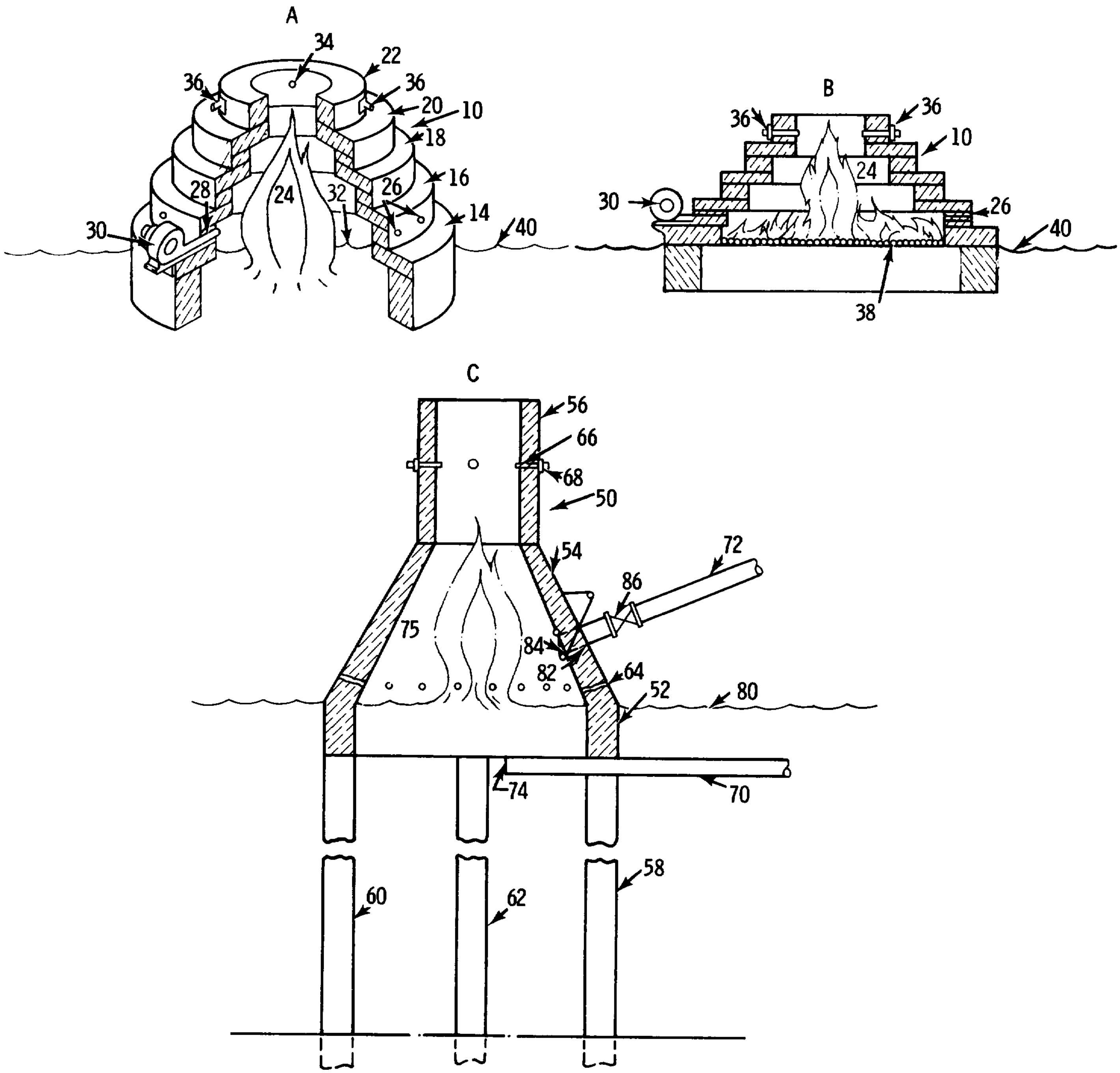


FIGURE 4.13. Floating Oil Spill Furnace

Source: U.S. Patent 3,695,810, October 3, 1972.

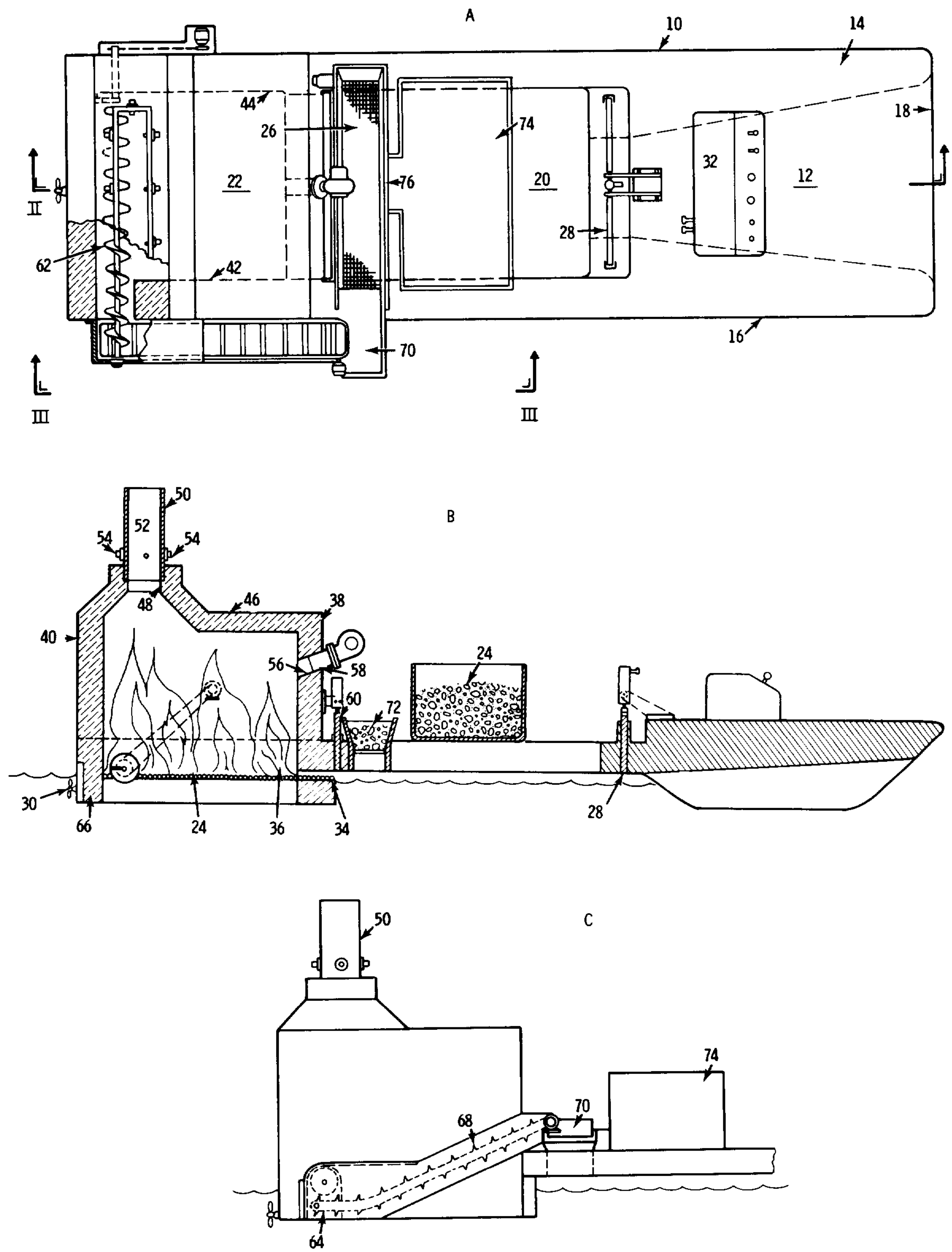


FIGURE 4.14. Oil Spill Incinerator Vessel

Source: U.S. Patent 3,663,146, May 16, 1972.

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

A generally U-shaped, buoyant, self-propelled vessel (Figure 4.14) floats partially submerged in a body of water and has a longitudinal channel portion with a front opening. The vessel has an open bottom portion beneath the longitudinal channel portion. As the vessel advances into a body of water, a band of water with the layer of combustible liquid floating thereon enters the channel of the vessel. The rate at which the combustible liquid, as a layer, enters the channel is dependent on the forward speed of the vessel. This speed is controlled so that substantially all of the layer of combustible liquid is removed by burning before the band of water passes under the rear or exit portion of the vessel. As the vessel advances, the band of water with the layer of combustible liquid moves through a mixing chamber within the channel portion where a monolayer of cellular ceramic nodules are positioned on the top surface of the layer of combustible liquid. The layer of combustible liquid with the nodules floating thereon moves toward the rear with the forward advance of the vessel. The oil moves into a combustion chamber where it is ignited and burned. The glass nodules within the combustion chamber are recycled to the mixing chamber where they are re-positioned as a monolayer on the upper surface of the layer of combustible liquid. Combustion air is provided for the combustion chamber and the combustion gases can be subjected to a secondary burning in the stack to remove the combustible materials in the gases to provide a substantially smoke-free waste gas. Apparatus is provided to seal the combustion chamber and mixing chamber if the burning of the combustible liquid tends to spread beyond the receiver.

Some of British Petroleum's oil burning investigations were conducted in the late 1960s when the burner called "Elijah" was created. This burner (Figure 4.15) drew oil into a concentrated pool within the lower part of the burner by a vortex forming submerged pump. The oil would get several inches thick and was continuously thrown as a spray up into the upper part of the burner in a stream of hot air. The burner which was 5 ft wide x 10 ft long x 7 ft high, consumed about 10 gal/hr in a highly luminous minimal smoke producing manner. Burning continued even though oil surrounding the burner was substantially less than 1 in. thick. British Petroleum wished to handle 100 tons/hr; therefore, this system was abandoned for other physical removal systems.

Another system which may have application when combined with skimming and pumping equipment is illustrated in Figure 4.16. This system illustrates a method which is particularly suitable to prevent oil pollution of water in the vicinity of an offshore drilling operation. Apparatus is provided for use on a ruptured oil and/or natural gas pipe where fluid is issuing under pressure from the pipe. A heat dissipating screen is disposed in the path of the fluid and raised to a predetermined position. The fluid is then intentionally ignited (thus preventing pollution), and the heat dissipating effect of the screen confines the flame to a region above the screen spaced from the open end of the well pipe. A thermal radiation shield can be provided in addition to water cooled members for the screen and shield.

The use of lasers for oil spill mitigation is being considered by several interested parties especially for severe winter conditions. The discussion in Section 3.7 on ignition potential should be kept in mind as this equipment is evaluated. The application of this technology is yet to be fully demonstrated. At present, one technique is reported[a] as using a carbon dioxide laser to successfully ignite No. 2 fuel oil in laboratory demonstrations. Laser pulses of up to 15 joules lasting several microseconds are used, and research is under way to determine optimal ignition patterns and uses of combustion promoters.

Combustion slick containment systems have been used in conjunction with oil burning tests (see "on water," Appendix B). During the 1969 sea tests of the combustion promoter, "KONTAX," a wooden barrier (small boom) was successfully used to keep the oil from spreading. This resulted in a rather complete oil burn, as reported, with little charring of the wood. Burning oil in ice

(a) Oil Spill Intelligence Report, 26 January 1979, p. 4.

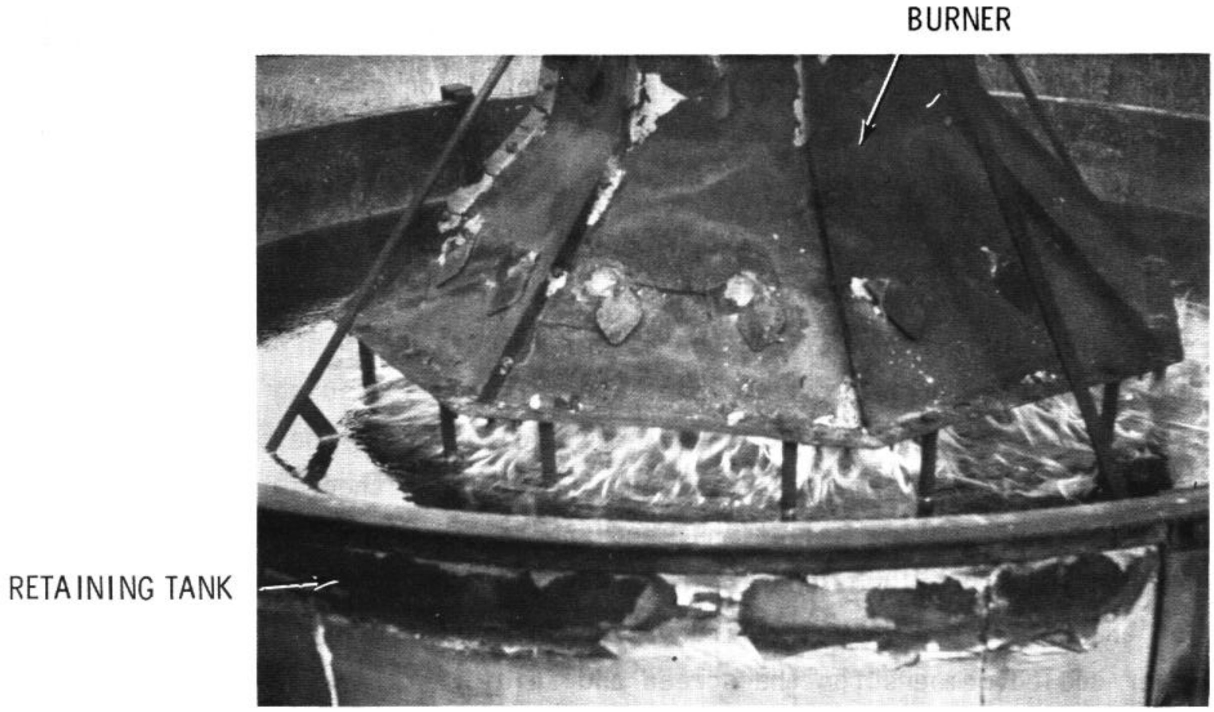


FIGURE 4.15. Oil on Water Burner

Source: British Petroleum Co., Ltd.

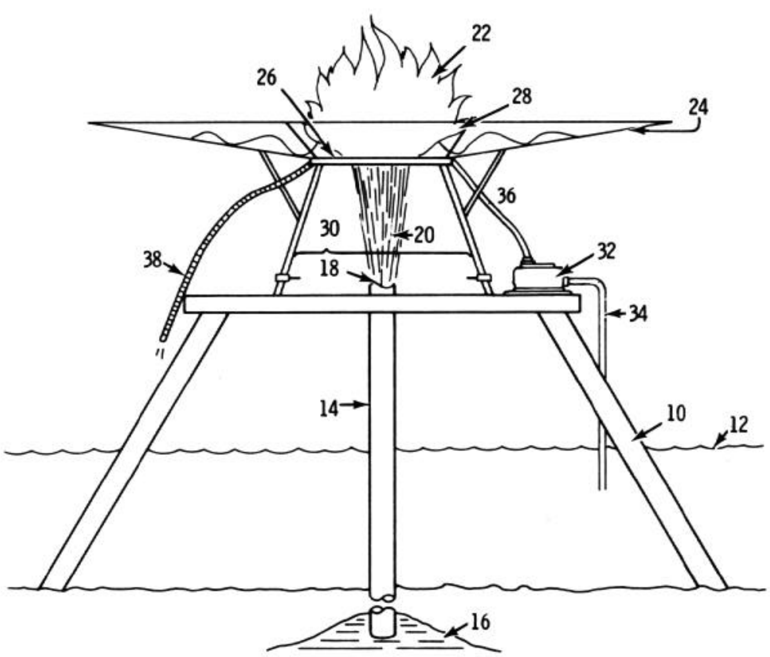


FIGURE 4.16. Combustion System for Pipeline Leaks

Source: U.S. Patent 3,602,299, August 31, 1971.

melt pools has been reported by the Canadian studies as successful due to the ice acting as a containment system (see Ice and Snow, Appendix B). Test experience cited in the U.K. (personal communication, J. A. Nichols) indicated that the use of a slick "herding" material or surface tension modifier has beneficial effects on retarding the spreading of the oil into an extinction thickness layer. Systems for booming or controlling the spreading of oil have received considerable attention almost exclusively with the purpose of oil recovery in mind. There appears to be no commercially available fire resistant or fire proof boom or containment system other than some type of onsite field rigging of 55-gal drums or wood.

4.6 OIL BURNING TECHNOLOGY - CONTAMINATED DEBRIS

The problems of disposal of oil-contaminated debris are extensive. An approximate 5-million-gal oil spill (EPA, 1972) produced 13,957 tons of debris. This required 220 railroad hopper cars to transport the debris for proper disposal. Acceptable disposal is dependent upon local conditions and, in the U.S., the desires of state and local authorities. The National Oil and Hazardous Substances Pollution Contingency Plan (40 CFR 1510) states at 1510.44(b):

> (b) Pollutants and contaminated materials that are recovered in cleanup operations shall be disposed of in accordance with procedures agreed to at the State or local level.

This authority plus the intended participation of state and local authorities in the Regional Response Teams operating under 40 CFR 1510 makes it clear that burning will not be undertaken for debris removed unless it is with full consensus of these agencies.

Local regulations, such as the Bay Area Air Pollution Regulation No. 3 (1976) which pertains to contaminating organics in waste oil, would discourage burning. Federal Technical Guidelines for other than incineration have been released, but it is clearly stated that, "incineration is often the most effective and desirable method of disposal." (EPA, 1977). The U.S. Coast Guard has sponsored separate studies in the "Feasibility of Disposal Systems for Oil Recovered from Marine Spills."

Attention will therefore be directed in the following text at use of incinerators, burners, and combustion aids and techniques which are considered of use in disposing of oil-contaminated debris. The sources of materials, sequence in gathering material and context of debris burning alternatives are illustrated in Figure 4.17.

An earlier U.S. Coast Guard study (Kim et al., 1974) concluded that incineration as a destruction method of potential pollution prevention was useful for quickly and permanently removing oil from the environment. Incineration is the only destruction technique with a technology developed to the point where equipment can be presently ordered from manufacturers. Incineration is a viable method of the ultimate disposal of oils and oil-soaked debris recovered from spill cleanup. Waste oil incineration is versatile and applicable to a wide range of waste oil types, compositions, and volumes. Incineration also has been used for the disposal of oily wastes containing substantial amounts of water emulsions and oil-soaked solids. In situations where the treatment and recovery of waste oils or disposal on land by landfilling or land burying are impractical because of unfavorable economics of environmental constraints, incineration is the only alternative method of ultimate disposal. Some municipalities and chemical waste disposal companies operate refuse incinerators. These incinerators, where available, may be used for the destruction of contaminated debris.

Municipal incinerators are not used in many areas of the country because they have difficulty meeting air pollution regulations and the costs are high. They are used in the few areas where costs for landfills are high and the reduction in volume effected by the incinerator becomes an important cost factor. As a consequence, few, if any, municipal incinerators have a capacity of less than 500 tons of refuse per day.

Municipal incinerators encounter several problems with recovered or oil-contaminated debris:

1. The heat of combustion of the oil is greater than that of domestic refuse, for which the facility was designed.

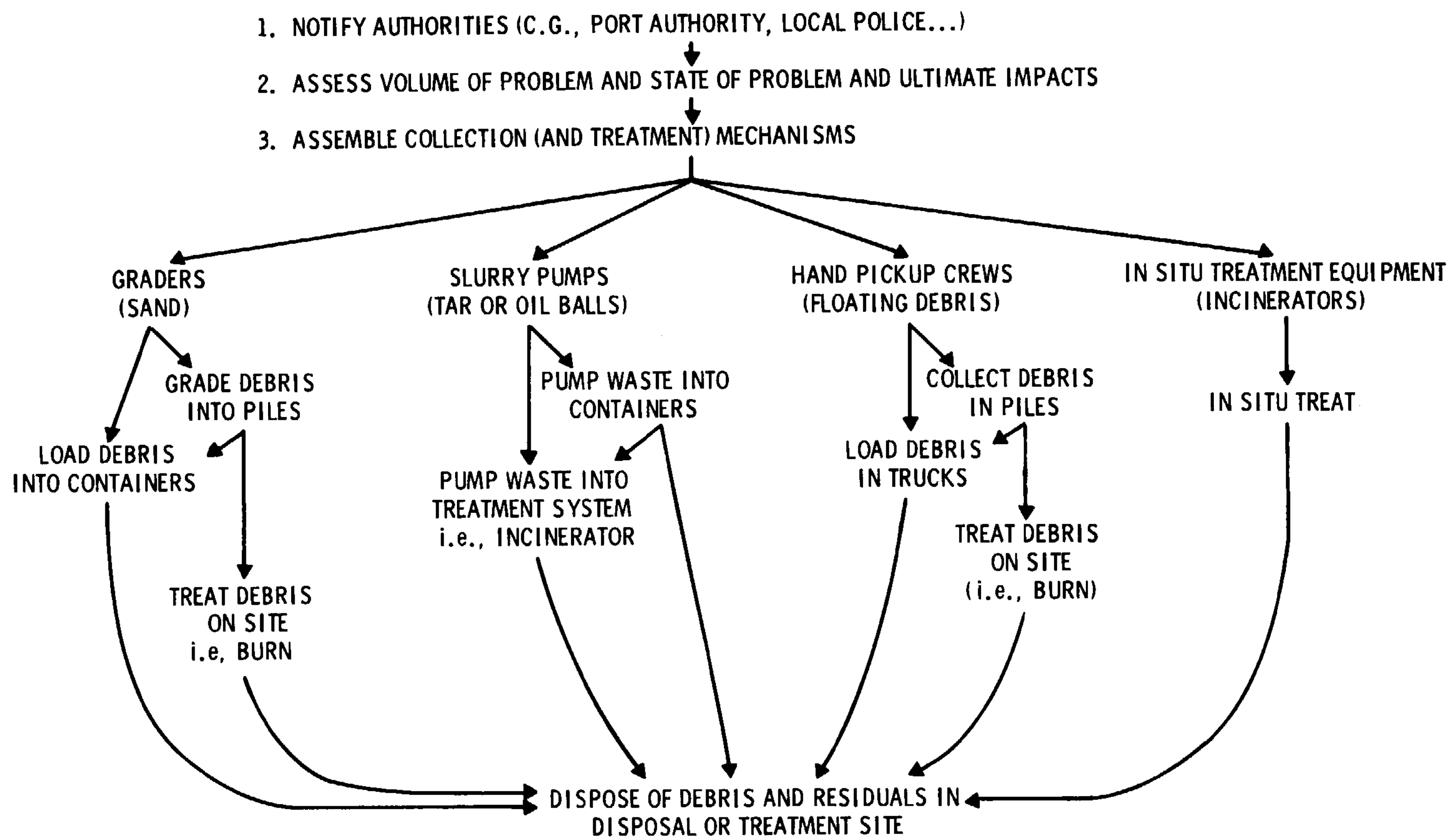


FIGURE 4.17. Options and Actions for Oil-Contaminated Debris Disposal

2. The sodium from salt water in the oil fluxes with the incinerator refractories and destroys them.
3. The chloride content corrodes the metal heat exchange surfaces in the incinerator.

The first problem can be managed if the oil content of the debris is controlled. A mixing limitation of recovered oil with refuse at about 5% to 10% appears workable. The slight extra heat will cause few problems. The second and third problems can be met by desalting the oil before incineration, but desalting is impractical for marine water spill debris disposal. An engineering evaluation of the effect on the facility for a "one shot" spill disposal could also aid in determining the practicality of burning oil recovered from a cleanup action.

Because of the burning rate, the capacities of many incinerators are limited for use in the case of a large spill. Most municipal incinerators burn 500 to 1000 tons of refuse per day. If only a 5% to 10% oil-contaminated debris were run through the incinerator, the incinerator capacity for the oil would be 25 to 100 tons/day or 7000 to 27,000 gal/day.

Refuse incineration costs about $5/ton (1973). Using escalation of 10% per year would be about $8/ton (1978). Since incinerator capacity is limited by heat released and oil has about three times the heat content of refuse, an estimated cost for oil incineration is $24/ton or 8 to 9¢/gal of oil spilled. This does not account for transportation costs and assumes that debris heat content is about the same as refuse.

Chemical waste disposal companies operate incinerators for the destruction of noxious chemicals. Plant capacities of 26,000 gal/day or more exist, with charges of 10 to 15¢/gal to incinerate (1973), the cost being more a function of oil properties than oil quantity. Seawater up to 50% is not a problem and no charge is made for the contained water. Since their incinerators are inland and salt in the oil would eventually drain into freshwater streams, they cannot incinerate if the seawater content is greater than 50%. Therefore, they cannot process a very wet oil. Oil-soaked debris could be burned in their incinerator. They charge slightly more on a weight basis to incinerate solids than liquids.

The study (Kim, 1974) concluded that incinerators for oil-contaminated debris are available in easily transportable units in sizes up to about 325 lb/hr of solids feed. If the solids contain 50% oil, the oil feed rate is 21 gal/hr. The cost of oil disposal in one of these units is \$185/ton of solids or about \$1.40/gal of oil if the incinerator is operated 300 days/year. If it is only 30 days/year the costs increase to \$550/ton of solids or \$4.00/gal of contained oil.

The current incinerator/burner systems and their commercial availability are listed in Table 4.6. It should be stressed that several of the systems are not commercially available. The technical feasibility of combustion of oil spill debris should be evaluated with full acceptance and of the approval of local authorities previously documented and discussed in Section 7 on ethics.

It should be recognized that over a prolonged period of repeated debris disposals, damage could occur in municipal incinerators, and skilled operators would be needed to blend oil-contaminated debris with normal refuse loads. This single event incineration alternative should be evaluated by the Federal Onscene Spill Coordinator and the assistance and cooperation of local authorities should be sought in advance of an incident. Three metropolitan counties were approached during this study and the reactions were so different they escape concise description.

By examining Figure 4.18 it may be noted that major U.S. oil spills (more than 1000 gal) during the period 1974 to 1977 generally occurred in three geographic areas. On the West Coast there were six spills in the 1000 to 10,000 gal range. All occurred off the Coast of California between San Francisco and the Mexican border. During this period of time on the East Coast there were six spills between North Carolina and Maine with three of the spills larger than 10,000 gal and one over 100,000 gal. Finally, there were 16 spills in the Gulf of Mexico off the coast of Louisiana. Two were over 10,000 gal and one was over 100,000 gal. There were also two small spills off the southern tip of Florida.

TABLE 4.6. Incinerators and Burners

Name	Manufacturer/Owner	Comments
Portable Beach Incinerator	Not commercially available	Could be manufactured locally -- mounts on standard 22 ℓ drum.
Brush Burner	Fleco	High capacity air supply and fuel oil sprayer.
Elijah	Not commercially available	Draws oil from water surface and sprays it up into combustion chamber.
Floating Furnace	Not commercially available	Closed burning chamber burns smoke free.
Self-Propelled Skimmer Incinerator	Not commercially available	Skims oil from the surface and incinerates it.
Homemade Incinerator	Not commercially available	55-gal drum fitted with propane burner.
Open Pit Burner	Kenting Oil Field Services Canada	Rectangular pit with high velocity over fire air supply.
Mobile Incinerator	Not commercially available	Operates similar to packer garbage truck but with self-contained incinerator.
Environmental Restoration Incinerator Complex	MB Associates San Ramon, CA	Truck mounted incinerator complex. Requires three tractor-trailer units.
Rotary Kiln Sand Cleaner	Envirogenics Co.	Designed for cleaning oil soaked beach sand.
Waste Paper Incinerator	Not commercially available	Smoke free sheet metal incinerator.
Mobil Oil Burner	Conceptual Design	Natural draft burner utilizing a hot air supply.

TABLE 4.6. (contd)

Name	Manufacturer/Owner	Comments
Vulcanus	Ocean Combustion Services The Netherlands	High efficiency incinerator ship -- handle liquids only -- up to 25 MT/hr.
LD 600	United Corp. Topeka, KS	Burns liquid wastes at 400 to 6000 gal/hr.
CAM Shipboard Incinerator	Vent-O-Matic North Quincy, MA	Burns liquid wastes up to 150 gal/day.
Trash Burners	U.S. Smelting Furnace Co. Belleville, IL	Will handle solid waste -- batch type.
Enviro-O-Pak	Sunbeam Equipment Corp. Lunsdale, PA	Complete self-contained mobile incinerator system.
Open Flame Liquid Oil Burners	Otis Engineering Co. Dallas, TX Baker Oil Tools Co. Houston, TX	Require large area to operate in, will burn relatively smoke free up to 12,000 barrels/day of liquid oil.

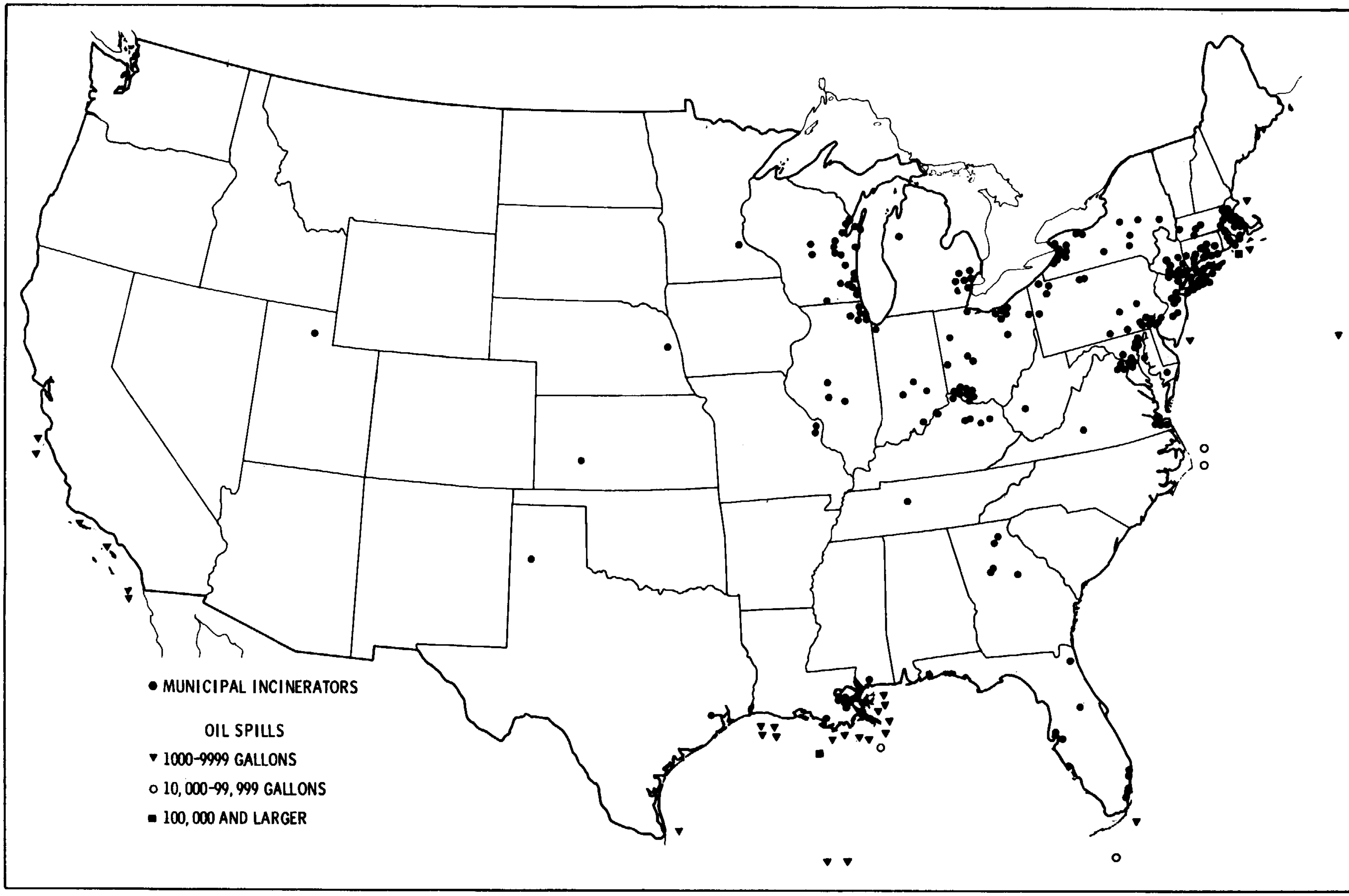


FIGURE 4.18. Municipal Incineration Sites (Weinstein, 1977) in Relation to Major Oil Spills (USCG 1974-1977)

Of these spills, those in California were the only ones with no municipal incinerators near the spill site. In the Northeast, there are many municipal incineration facilities and the two spills near North Carolina might possibly have used the four incinerators in the Hampton area of Virginia. The Gulf Coast, where the largest number of spills have occurred, has a number of incinerators in the New Orleans Baton Rouge area. The two spills off the tip of Florida were fairly close to the incinerators in the Miami area.

Other types of facilities which have been used are electric power plant coal piles. Cleanup contractors as well as the U.S. Army Corps of Engineers have found this option acceptable under certain circumstances. The procedure employs the coal pile and allows all debris and oil to be dumped upon it, later to be used as fuel.

Various types of incineration devices could be used to burn material recovered from an oil spill that for one reason or another are not amenable to open or surface burning. These materials would include snow/oil mulch, chocolate mousse (oil/water emulsions), oil-soaked beach debris, and sand and oil sorbents such as straw or sorbent pads. Incineration devices vary from one man portable beach incinerators to multi-ton stationary units capable of handling 100 tons/day of refuse (St. Clair, 1978).

4.6.1 Small Portable Incinerators

These units could be transported by one or two men and a standard pick-up truck. This type of burner will not maintain a high enough temperature to burn smoke free.

Portable Beach Incinerator

The portable beach incinerator unit was developed in England for burning beach debris and tar balls on remote beaches (Wayment, 1977). The unit (Figure 4.19) is designed to be placed on the top of a 22-liter drum and can be operated by one man. The unit is relatively simple and could be manufactured locally.

Brush Burner

The brush burner is a wheel-mounted fan, powered by an air-cooled four cycle Briggs and Stratton engine. The propeller has a rated capacity of

FIGURE 4.19. Portable Tar Ball Beach Incinerator Showing Size and Handling
Source: Warren Springs Laboratory, Stevenage, England

23,000 cfm at 2700 rpm and optional pumps and fuel nozzles which deliver 15 to 30 gal/hr of diesel fuel. This type of unit was used to dispose of 125,000 gal of contaminated black oil recovered from the shoreline of Chesapeake Bay in 1976 (Wise, 1977). The waste oil was collected in drums and transported to a central disposal site. The drums were placed on a layer of old tires and the tires were ignited. The burning tires, in the presence of the high air flow from the brush burner, cooked the water out of the oil and eventually ignited the oil. Except for large volumes of black smoke produced by the burning tires, this was felt to be a very economical disposal method. The authors felt smoke generation could be reduced by using brush and driftwood in place of tires.

Elijah (Section 4.5.2)

The Elijah is a floating burner developed by the British Petroleum Co., Ltd Research Center in England in the late 1960s. The burner uses a vortex forming submerged pump to draw the concentrated oil under the burner. The oil is then pumped through nozzles as a spray and burned in the upper part of the burner. A Provisional Patent was issued to British Petroleum Co., Ltd on the burner, but it has not been commercially produced.

Floating Furnace (Healger, 1972) (Section 4.5.2)

This unit was developed by the Pittsburgh Corning Corporation in 1970. The furnace was made of concrete containing cellular glass nodules to supply buoyancy. This furnace burned relatively smoke free when tested with a variety of crude oils and oil water mixtures.

In this furnace the burning zone is completely contained and the waste oil would have to be pumped into the burning chamber. The unit could be used in conjunction with a skimmer. This furnace is also not commercially available.

Self-Propelled Skimmer Incinerator (Heagler, 1970) (Section 4.5.2)

This incinerator was patented by Pittsburgh Corning Corporation in 1972. The unit consists of a self-propelled vessel designed as a skimmer to collect the oil and transport it to the aft section where it is burned in a forced draft incinerator. This unit is also not commercially available.

Homemade Type Incinerator

For small spills, 100 gal or less, 55-gal drums fitted with a propane burner should be capable of disposing of oil and oil-soaked debris (Peterson et al., 1975). This idea has been expanded upon by Pace, Inc. where a design for a fluidized bed, 55-gal drum, tractor wheel rotation-powered combustion chamber can be produced for about $600 and field fabricated (AMOP-Canadian Proceedings, 1979).

KONTAX

This material described in Section 4.5 has also been tested and employed to burn oil on beaches. Successful tests were reported (Rijkswaterstaat, 1969) on burning crude oil 3 cm deep which was allowed to age 24 hr. Fresh crude oil mixed into the beach sand was also reported as burning with this agent. At present, the Netherlands has stockpiled 200 kilos of KONTAX along with pneumatic guns for propelling KONTAX grenades safely into an oil spill area. Recent Canadian tests were not very positive pertaining to the use of this device (AMPO, 1979).

4.6.2 Large Portable Incinerators

This type of incinerator including commercially available rotary kilns will require a tractor-trailer or railroad flatcar for transportation and a trained crew to set up and operate the unit. The unit may require special charging to assure efficient operation.

Open Pit Burner

The open pit incinerator was developed by E. I. duPont in the mid-1960s. The basic design is a refractory lined open top rectangular pit with a high velocity curtain of air directed across the burning zone (Peskin, 1966).

Kenting Oil Field Services, Ltd. of Edmonton, Alberta, Canada, used the E. I. duPont idea and produced a pit type incinerator designed to burn oil off beach sand and gravel. The Kenting "Kleen-Up" incinerator was designed to permit easy transportation to oil spill cleanup sites. Test results indicate that a heavy crude with up to 40% water could be burned relatively smoke free. However, U.K. experts on beach cleaning advise that no combustion techniques are satisfactory for beach cleaning because of the resulting ash (at best) or residue.

It may be possible to construct a reasonably efficient pit burner in the field by excavating the pit in the earth. This would require transportation of only the duct work and blower for the air curtain. Peterson et al. (1975) suggested using a small turbojet engine for the air supply which would furnish combustion air at near 1200°F. This high temperature air would increase the combustion rate, especially in areas where the ambient temperature is low.

The U.K. is developing a heater/treater system using oil/water separation to clear sandy pebble beach to avoid the combustion residue.

Mobile Incinerator

Engdahl et al., of Battelle Memorial Institute of Columbus, Ohio designed a mobile incinerator to operate like a packer garbage truck. The unit has a moving grate that transports the waste through the combustion zone (Engdahl et al., 1968). The principles of this unit could be modified to burn liquid oil and oil-soaked beach debris. The truck could be modified to operate off-road with the possible addition of four-wheel drive.

Mobile ERIC (Environmental Restoration Incinerator Complex)

This unit is being designed and built for the Environmental Protection Agency (Tenzer, 1978). The ERIC, Figure 4.20, is designed to safely destroy most, if not all, organic hazardous chemicals. Compounds excluded would be those containing mercury or arsenic.

This hazardous materials unit could be criticized as being over designed and under capacity for most oil spills. The current design includes three tractor-trailer units which are interconnected at the spill site. The ERIC will handle 100 gal of oil per hour or 9000 lb/hr of dry sand. The unit will handle virtually any type of debris and would work for oil spill cleanup, but transportation and operation costs, when compared with other alternatives, would be high.

Rotary Kiln Sand Cleaner (Peterson et al., 1975; Scurlock et al., 1975)

This incinerator was developed by the Envirogenics Company for cleaning oil-soaked beach sand and debris. The unit is skid mounted and capable of processing 20,000 lb of sand containing 5000 lb of oil and 1600 lb of water

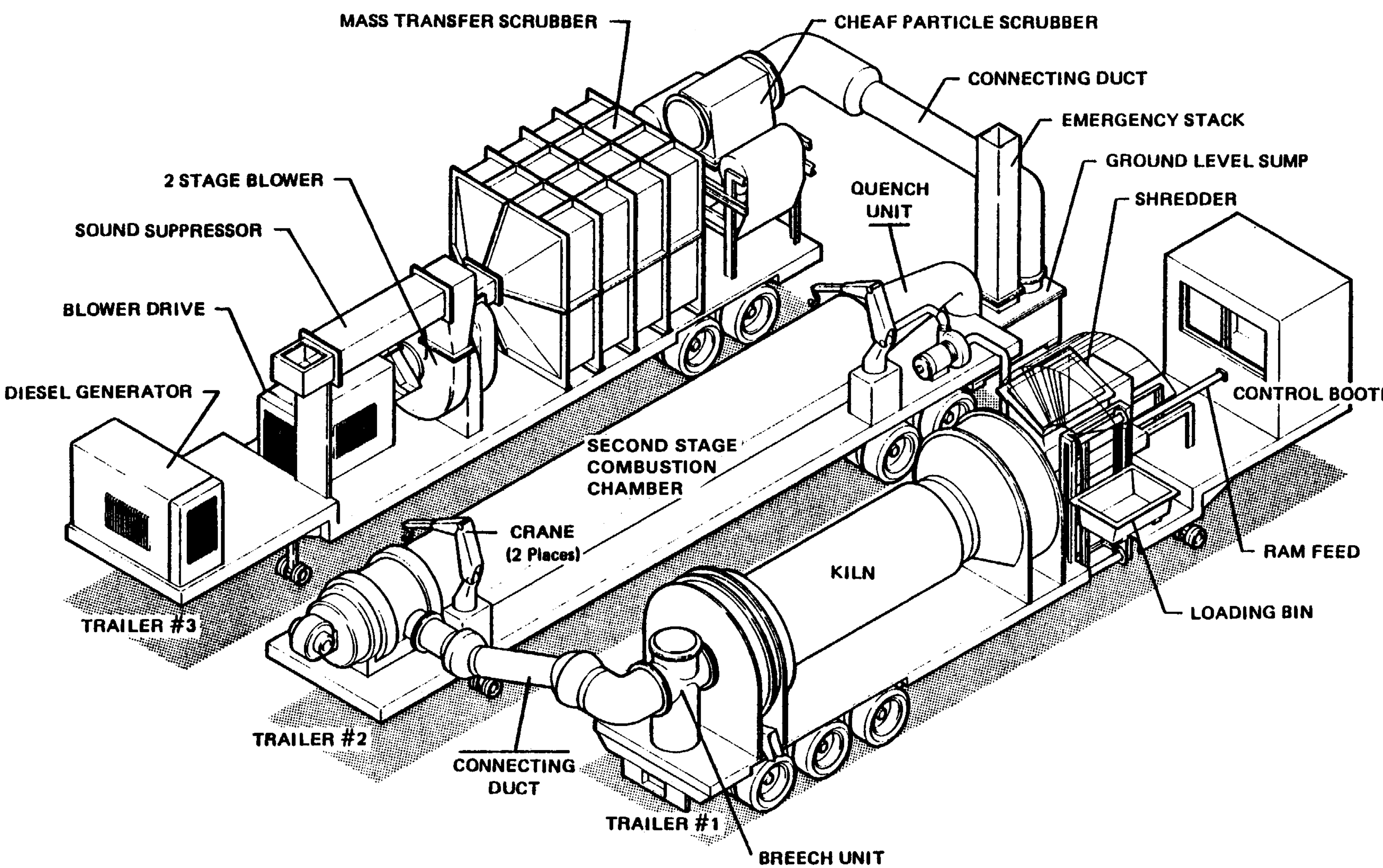


FIGURE 4.20. USEPA Mobile Environmental Restoration Incinerator Complex
Source: Tenzer et al., 1978.

per hour. Tests indicate the unit will require no additional fuel if the sand contains a minimum of 6% oil by weight. This unit can be transported by tractor-trailer.

Waste Paper Incinerator

This incinerator was developed at Battelle Columbus for burning classified waste paper. The unit is lightweight sheet metal and is air cooled. Current models are not large enough for burning large volumes of oil-soaked waste; however, a unit could be built which would handle much larger volumes of waste with very little smoke.

Mobile Oil Burner

This natural draft burner was proposed by A. A. Putnam of Battelle Columbus in 1969 (Peterson et al., 1975). The burner is a cylindrical sheet metal combustion chamber mounted on pontoons for water operation or wheels or skids for land operation. Hot (1200°F) air is supplied to the combustion chamber by a small turbojet engine. Although this type of unit was felt to have promise for burning spilled oil, development was not undertaken.

Vulcanus

The Vulcanus is a 102-meter cargo ship that was converted in 1972 to an incineration ship for disposal of hazardous wastes. The ship is operated by Ocean Combustion Services, B. V., of the Netherlands. In 1974 the Vulcanus incinerated a total of 16,800 metric tons of waste containing a mixture of chlorinated hydrocarbons for Shell Chemical Company's Deer Park, Texas plant. The burn took place in the Gulf of Mexico and the results of monitoring indicated more than 99.9% of the wastes were oxidized. The ship would handle oil as long as it was pumpable (Wastler et al., 1975). Feed rate is listed as 21 to 25 metric tons/hr.

Mobile Incinerator System

This incinerator is a single tractor-trailer conceptual design by Vent-O-Matic Incinerator Corporation of North Quincy, Massachusetts. The unit has primary and secondary combustion chambers and all necessary separator and scrubber equipment to operate smoke and ash free. It has a slurry pump for liquids and a ram feeder for solid materials. The tractor and trailer have floatation tires and are designed to operate in a wet, beach type environment.

LD 600 Liquid Destructor

This liquid incinerator, manufactured by the United Corporation, Topeka, Kansas, is designed to burn liquid waste materials at 400 to 600 gal/hr depending on the Btu content of the waste. It should adapt well to burning waste oil and/oil water mixtures and would be transportable.

Shipboard Incinerator

The Series CAM shipboard incinerator, manufactured by Vent-O-Matic Incinerator Corporation, North Quincy, Massachusetts, is designed to destroy shipboard oil/water mixtures and sewage plant sludges. The largest off-the-shelf model will handle 150 gal/day of waste oil and could be transportable on a tractor-trailer. This unit will also handle solid waste.

Trash Burners

A number of companies manufacture small to medium size incinerators similar to the Smoakatrol Incinerator manufactured by U.S. Smelting Furnace Company, Belleville, Illinois. This type of incinerator normally has a large charging door on the main burning chamber and is equipped with an after burner and spark arrestor. The unit requires electrical service and natural or LP gas fuel. Most burners of this type could be mounted on a flatbed truck and used onscene for burning oil-soaked debris.

Envir-O-Pak

The Envir-O-Pak is a trailer-mounted, self-contained incinerator system manufactured by the Comtro Division of Sunbeam Equipment Corporation, Lunsdale, Pennsylvania. The unit is completely self-contained including generator and fuel tanks. Models are available that are rated from 100 lb/hr to 2000 lb/hr solid waste. Some modification, including a feed pump, would be required for burning liquids.

4.6.3 Stationary Incinerators

Stationary incinerators are as follows:

Multiple Hearth

This furnace is a refractory lined steel shell containing a series of circular hearths placed one above the other. Solid waste is introduced on the top hearth where it is moved around by a rotating rabble arm until it reaches an opening and drops to the hearth below. Wastes are reduced to ashes by the time they reach the bottom hearth. Liquid wastes are injected through nozzles into the optimal zone of the furnace. This type of furnace is used mainly for sewage sludge incineration, (Peterson et al., 1975).

Rotary Kiln

The rotary kiln is a rotating cylinder mounted at a slight angle to the horizontal. The tumbling action improves efficiency of solid waste destruction. This type of incinerator exhibits considerable promise for disposing of large volumes of oil-soaked waste. Rotary kilns have been built that are transportable but most units to date are stationary.

Liquid Injection Incinerator

This incineration method utilizes a vertical or horizontal vessel into which the waste is atomized through nozzles to increase the rate of vaporization. Most units have an auxiliary fuel source for rapid warm-up and for burning low Btu wastes. Models are available that will burn solids which are fed to the furnace by a screw conveyor (Peterson et al., 1975).

Fluidized Bed Incinerator

The fluidized bed combustor utilizes a bed of sand or similar granular material which is fluidized by blower driven air flowing up through the bed. Waste material is fed to the top of the bed and burned as it flows down through the sand. The heat capacity of the bed is about three orders of magnitude greater than the flue gases in typical incinerators operating in the same heat range, which means the capacity is much higher per unit volume than other incinerators (Peterson et al., 1975).

Molten Salt Incinerator

In the molten salt reactor, waste is injected below the surface of a molten salt bath where pyrolysis of the feed occurs. The off-gases may be combusted in the reactor or in an afterburner. The unit will handle solids or liquids. This unit is being offered to dispose of chemically contaminated oils with little or no residue.

Beach Cleaners

Combustion was used as the primary oil reduction principle in beach cleaning systems developed by the predecessor agencies of the EPA. These systems operated either stationary on the beach where sand was carried to be cleaned and returned or, if soil conditions would permit, the beach cleaner could be moved along the beach (EPA, 1971). The commercial availability of these systems is doubtful or very limited. Experience in the U.K. has shown that combustion is totally unsatisfactory to clean beach sand, again because of the ash and residue of the oil.

4.6.4 Open Flame Liquid Oil Burners (Section 4.4 - Flares)

These burners (see Table 4.7) are designed to burn large volumes of liquid oil and oil/water mixtures. The burners are used to burn off unrefinable crude oil and waste gases during off-shore well tests. The burners require compressed air to atomize the oil and a large area to operate in as the flame on some models can extend 160 ft. Relatively smoke-free operation can be obtained by using a water spray in the rich part of the flame. The oil must be liquefied to a pumpable degree which may require an additional heat source. Models are available which will burn up to 20,000 barrels of oil per day. The application to disposal of oil-contaminated debris using these systems is questionable, but with wood chippers, shredders, or maserators it may be technically feasible.

4.6.5 Commercial Waste Processors

The number and distribution of commercial waste processors who employ incineration depends on the type and quantity of material to be disposed. Due to recent Federal action, many incinerators have been closed and some dismantled. The bulky waste incinerators which were common a few years ago in all port authorities to dispose of dunage were able to meet few of the fundamental air pollution standards. Organizations such as those listed in Table 4.8 appear to have the capability of handling the incineration of oil-contaminated debris.

TABLE 4.7. Selected List of Waste Oil Burners

Model and Manufacturer(1)	Capacity	Size
Developed by National Air-Oil Burner Company		
Sold by Otis Engineering Company Dallas, Texas		
Model CB-12	12,000 BOPD(3)	1175#
Model CB-4	4,000 BOPD(3)	
Developed by John Zink Company(1)		
Sold by Baker Oil Tools Company Houston, Texas	10,000 BOPD(3)	1288#
Flopetrol(2)		
Paris, France	6,000 BOPD(3)	1200#
Portatest	13,000 to 18,000	
Noralco	20,000	

(1) P. L. Peterson, "Temporary Storage and Ultimate Disposal of Oil Recovered from Spills in Alaska." Prepared for U.S. Department of Transportation, U.S. Coast Guard by Battelle, Pacific Northwest Laboratories.

(2) Company brochure

(3) Barrels of Oil Per Day

TABLE 4.8. Waste Treatment Combustion Facilities

Rollins Environmental Services, Inc. (Rotary Kiln)
Bridgeport, NJ
Baton Rouge, LA
Deer Park, TX

Hyon Waste Management Services, Inc. (Rotary Kiln)
Chicago, IL

Seymour Manufacturing (Liquid Incinerator)
Seymour, IN

American Chemical Service (Liquid Incineration)
Griffith, IN

Liquid Waste Disposal, Inc. (Liquid Incineration)
Louisville, KY

TABLE 4.8. (contd)

Petrolite Corp. (Rotary Kiln)
Calvert City, KY

Environmental Waste Control, Inc.
Inkster, MI

Liquid Disposal Co. (Liquid Incinerator)
Utica, MI

Monsanto Chemical Co. (Liquid Incinerator)
St. Louis, MO

Scientific Chemical Processing, Inc. (Liquid Incineration)
Carlstadt, NJ

Chemical Waste Disposal Co. (Liquid Incineration)
Elizabeth, NJ

Chemtrol Pollution Services (Liquid Incineration)
Model City, NY

Pollution Abatement Service (Liquid Incineration)
Oswego, NY

Recycling Laboratories
Syracuse, NY

Destructo Chemway Corp. (Liquid Incineration)
Belmont, NC

Systems Technology Corp. (Fluid Bed)
Franklin, OH

Browning-Ferris of Ohio (Liquid Incineration)
Warren, OH

Wasteplex, Inc.
Jonesboro, TN

Browning-Ferris
Houston, TX

Liquid Waste Disposal of Virginia
Richmond, VA

Waste Research and Reclamation Co., Inc.
Eau Claire, WI

Pollution Control, Inc.
El Dorado, AK

5. STATUS OF OIL BURNING RESEARCH

The following text describes the research undertaken by several countries in the field of oil burning.

5.1 INTERGOVERNMENTAL SURVEY

Since the spring of 1969 when the United States Federal Water Pollution Control Administration tested currently available combustion promoters, little research activity has been carried out in the U.S. on oil burning. Instead, research and development efforts have focused on the development of improved physical removal methods utilizing skimming, booming, and sorbent devices.

A brief summary of typical burning information which was available to the U.S. Coast Guard during the ARGO MERCHANT incident is found in Appendix H. The report, in essence, concludes that a basic study is needed to understand the conditions and limitations of using combustion as an oil spill mitigation tool. The following text describes the research undertaken by several countries in the field of oil burning.

While limited reserch on combustion has been carried out by other countries, extensive work conducted in the United Kingdom in the late 1960s and up to 1972 was dedicated to evaluating the combustion alternative. Currently the U.K. Department of Trade is reconsidering its position that burning is an infeasible tool and should be disregarded. Particular attention of U.K. investigators is anticipated to be directed toward enhancing systems of burning oil in situ in stricken tankers. The Marine Division of the Department of Trade in conjunction with the Department of Industry and the Ministry of Defense Research Establishments have been meeting since September 18, 1978 and are preparing a research program document. At present research has been commissioned on two subjects. A contract has been given to evaluate the effect of oxygen enrichment to sustain an oil slick fire. Also, efforts are being funded by the Shipping Requirements Board to establish what it takes to explosively cut open a vessel in preparation of an open burn. Researchers in the U.K. are still interested in the offloaded floating burner concept, but no work has been commissioned.

Dutch authorities responsible for the storage and use of the combustion promoter, KONTAX, appear to have had no experience or conducted any tests since the 1969 field experiments. The North Sea Directorate of Rijkswaterstaat is currently responsible for combating oil pollution at sea. Canada's test on the material were not encouraging.

Swedish research involves the reported experience of one use of burning in ice-filled waters. There appears to be some sponsored research on the use of combustion such as the work of Hägglund and Persson on Heat Radiation from Petroleum Fires, FAO, Forsuarets Forskningsanstalt.

Norway has budgeted funds for oil combustion research which has yet to be reported. The project is intended to investigate what conditions must be satisfied to cause ignition and to maintain combustion. Norway is interested in demonstrating the effectiveness of any combustion promoters. In addition, the needs of transporting oil which has been collected or cleaned up motivate the Norwegian authorities to develop arrangements for burning in the area of the oil fields.

Japan has experienced large-scale burning tests (two 85-ton spills of Iranian heavy crude in 1968) and burning an oil slick was one technique tried on >72 tons of slick. Ignition was with a 40-m range flame thrower within 6 min after oil was released. Oil burned for 14 min. Wind was moving at 7 m/sec. The slick spread beyond the flame front during burning. A residue was left on the surface after burning stopped. The flame thrower technique is commonly used on small spills in Tokyo Bay (Source Observation Report G. J. Beynon, British Petroleum, 1968).

Mexico, Spain, Philippines, South Africa, USSR and several other countries contacted indicated interest, but no experience or ongoing research. Unconfirmed reports of extreme success by USSR near Leningrad as well as success by South Africa indicate reason for optimism.

In North America, the United States has carried out little oil spill combustion laboratory or field research. However, program directors in Canada have initiated an extensive and comprehensive study into the cleanup of oil spills in the arctic terrain through the application of burning technology.

The use of such methods is particularly beneficial in Canada because of the logistical, environmental, and economical parameters peculiar to their situation. The cold weather serves to enhance the burnability of oil due to retention of volatile petroleum components, while exacerbating problems with other cleanup approaches. Furthermore, the remote location of the most probable spill areas precludes the use of conventional spill countermeasures.

5.2 ONGOING OIL BURNING RESEARCH

The Environmental Emergency Branch (EEB) was established in 1972 as a division of the Canadian Environmental Protection Service to oversee activities where an environmental threat is unforeseen because it comes in the form of an accident in which a hazardous chemical or substance such as oil is released to the environment. The major thrust of this research is governed under a program titled Arctic Marine Oil Spill Program (AMOP) and a series of seminars, reports, and other data exchanges have been conducted at the industrial and governmental levels. This program is ongoing, and progress and planning reports provide details of results and anticipated developments including burning of oil and gas under Beaufort sea ice. Several environmental impact assessments of burning have been prepared.

A brief account of ongoing research efforts by the EEB pertaining to oil burning is provided below. Proceedings of the AMOP projects status review meeting held March 1979 by the EEB contain additional studies.

Testing of Air-Deployable Incendiary Devices for Igniting Oil on Water (D. E. Thornton)

Research work carried out during the last 3 years, including field programs and laboratory studies, has concluded that the most efficient method of oil spill cleanup in ice-infested waters is in situ burning. It was further identified that the igniting of oil pools would be very dangerous, if attempted from ice level, because of the hazards associated with operation on the ice. As a result of these conclusions, the AMOP Management Committee directed that work be carried out to develop an air-deployable incendiary device. Earlier work, initiated in this field by the Environmental Protection

Service, revealed four promising candidate devices, namely: thermite, phosphorus flares, calcium hydride flares, and Kontax. More recently industry carried out experiments and selected another promising candidate including solid fuels and propellants.

The objective of this study is to develop further a suitable incendiary device and to test its effectiveness and air-deployability under simulated field conditions. The project is divided into several components, the first of which is the initial modification of the various candidates to maximize their effectiveness for the present purpose. Following this, the candidates will be thoroughly tested in order to determine statistically their ability to light oil in water. Once the optimal candidates(s) has been selected it will be again modified and tested to statistically determine its air-deployability. The final step will be recommendation of final modifications to the most promising candidate(s). The study has just recently been initiated and it is anticipated that the work will be completed by the end of the fiscal year 1979.

Development of a Wicking Device for Burning Oil Slicks (D. E. Thornton)

During an experimental oil spill, as part of the industry-government Beauford Sea Environmental Program, it was determined that crude oil spilled under first-year sea ice will migrate to the surface through brine-drainage channels in the Spring. At this time, over about a 4- to 6-week period, oil collects on the surface of melt pools in a combustible state. Field work to determine the porosity of multi-year ice indicates that similar behavior might also be expected in this case, although the migration of oil will perhaps occur later during the summer months.

In the event of a subsea oil well blowout in a zone of moving ice, a considerable area of ice could be contaminated. The primary oil spill cleanup tactic during the spring and summer would be in situ combustion of oil in melt pools on the ice surface. However, because oil is released gradually from the ice on a continuous basis over a lengthy period, a considerable number of burns in individual melt pools might be required to remove most of the oil. To minimize logistical efforts, then, it is desirable to have available a device which automatically will reignite a slick on a periodic basis when sufficient oil accumulates for uncontrolled in situ burning or which will continually wick and burn emerging oil in a controlled fashion. A contract was awarded in October 1977 to Energetex Engineering to develop and test a suitable device and draft results are available.

Characteristics of Smoke from in situ Crude Oil Fires (P. J. Blackall)

Research by both industry and the Federal government has indicated that in situ combustion of oil in ice-infested water is the primary cleanup method. There has, however, been very little research on the environmental impacts associated with the burning of massive quantities of oil. This lack of knowledge has raised various concerns and, as a result, the subject study has been initiated to determine the environmental significance of burning compared to leaving the spilled oil on the water and ice surface. The project requires that an initial review of available literature on the characteristics of smoke from uncontrolled ground level fires and dispersion characteristics of smoke under arctic weather conditions be carried out. Once the available information has been assessed, laboratory tests must be developed and carried out to determine the heavy metal and other associated pollutant concentrations released to the atmosphere during burning. Having established the quality and quantity of pollutants released to the atmosphere, the environmental impacts of burning will be assessed. This information, in turn, will be compared with the better-known effects of leaving the oil on the water and ice surface.

Design and Development of Equipment to Aid in the Burning of Oil on Water (K. M. Meikle)

One of the methods being considered as a countermeasure for an arctic oil spill is in situ combustion. This would involve burning of oil on the water surface. However, to achieve a successful burn the oil must be sufficiently thick to sustain combustion. Two ideas have been put forward to assist in the containment, ignition, and support of combustion of oil on the water surface. One of these ideas is a buoyant net which would trap the oil in its mesh and prevent it from spreading. The oil could be ignited and burned within the net's openings. The other is a lightweight, fireproof boom which would contain the oil for burning within it. The boom could be used in conjunction with the net.

Design of a Transportable Incinerator for Arctic Oil Spill Application (K. M. Meikle)

In the event of an oil spill in the offshore areas of the Arctic, cleanup operations will recover oiled combustible debris (used sorbents, sea weed, etc.) in addition to oily fluids and noncombustible debris. This material would be stockpiled for disposal. Because of the area's remoteness, one method of disposal would be to incinerate the material at or near the collection site. Therefore, it is desirable to have available the design of an incinerator with a proven capability of burning combustible oiled debris. The incinerator should handle 0.5 ton/hr of this material, be helicopter transportable, and be complete with readily obtainable ancillary equipment. Instead of stockpiling these incinerators, the plan is to construct them in the North as required.

Feasibility Study or the Cleaning of Oil-Contaminated Beach Sands by a Rotary Kiln Incinerator (K. M. Meikle)

During the past 2 years, Trecan Ltd., under contract to EEB, conducted investigations into various types of incinerators and their applicability to cleaning oil-contaminated beach sands. The rotary kiln was selected and pilot plant studies were undertaken using the Ontario Research Foundation's rotary kiln. Burnout was found to be essentially complete on tests of sand, with a 8 to 15% residual oil content. Using these results, a preliminary engineering design for a portable rotary kiln was prepared. Before proceeding with detailed design and fabrication, an independent study will be undertaken to establish the practicability and the cost-effectiveness of such a unit. This study will establish the capital, operating, and maintenance costs of the proposed kiln. The present techniques of cleaning and disposing of contaminated beach sands will be reviewed to ascertain the exact role of the kiln in these operations.

6. TECHNICAL FEASIBILITY ASSESSMENT OF OIL SPILL MITIGATION BY COMBUSTION

The preceding sections of this report were dedicated to providing descriptions of the oil spill problem, understanding the theory of combustion as it applies to oil spills, identifying equipment and materials of assistance, and providing insight into existing research programs in the field. This section provides an evaluation of the combustion techniques in the context of other available options. As background, Section 6.1 briefly gives some observations on case histories of particular interest to oil burning. Section 6.2 is dedicated to a brief review of options other than burning to address the oil aboard vessels, oil on water, and oil-contaminated debris disposal. Section 6.3 combines the above information in a technical assessment, while Section 6.4 summarizes oil burning conditions. The information guides have been presented in Section 6.5 in the context of the scope of this study given in Section 1.

6.1 ACTUAL INCIDENT TIME/EVENTS

Four case histories were analyzed and documented to illustrate what events took place over what period of time. The concluding observations are given below. The data on total effort, costs, and other significant factors are listed in Appendix C to serve as a factual basis for determining the technical feasibility of using combustion under similar circumstances.

1. ARROW - The ARROW was in a remote location teaming with wildlife. Access to the beach area was impossible due to the steep cliffs and shingle. The remoteness eliminated the possibility of response craft giving any true assistance to the vessel. The assist vessels which arrived on scene followed Maritime Law and permitted the Captain of the ship to command the situation. Unfortunately, the situation became more severe (see Appendix C, Page 27) - it was thought that the tide would lift the vessel off the pinnacle of rock onto which it was impaled; after waiting for high tide (a 12-hr delay); the tide

did not lift the ARROW off the pinnacle of rock; the crew was instructed to assemble on the stern of the vessel then ultimately to abandon ship, first securing the vessel (securing involves releasing steam, shutting down the boilers, and placing the vessel in a totally inactive status). It was later decided to return to the vessel, raise steam, and attempt a cargo offload. This action was abandoned when the vessel began to break up. A decision was made to cut the vessel in two leaving the forward section on the pinnacle of rock, salvaging only the stern half of the vessel. These decisions took a tremendous amount of time, during which oil was escaping from the vessel. Ultimately, the vessel broke up, thus releasing the majority of its oil cargo. The oil traveled for a considerable distance to Sable Island, another wildlife refuge. To protect the wildlife the Intervention Act could have been evoked and a cargo burn action considered. Attention is also drawn to the fact that this vessel was in excess of 21 years old which should be taken into consideration at the time of the "response action," since the American Bureau of Shipping rates present day tankers to a 25-year useful life span.

2. <u>IRENES CHALLENGE</u> - The IRENES CHALLENGE was in a similar situation (see C-28) as the ARROW. The vessel was located in an isolated area where reefs and wildlife refuges existed. The vessel was in excess of 20 years old; its back had broken; all but three of the crew had been removed from the vessel; and salvage tugs would not accept a salvage assignment. None of the Coast Guard vessels were capable of towing this stricken tanker for a deep water scuttling. No response equipment was available, such as booms, skimmers, etc. This situation would have readily lent itself to developing experience for a burn response action and greatly enhanced capabilities for the burn attempts made at the ARGO MERCHANT and other marine casualties.

3. <u>ARGO MERCHANT</u> - The ARGO MERCHANT, another vessel in excess of 21 years of age, wrecked in the vicinity of some of the most productive fishing grounds off the New England coast (George's Bank). The vessel was 21 miles from land, clear of any shipping lanes (see C-31). The entire crew was safely removed from the vessel. Weather conditions were hazardous for a response action.

Although attempts to control the spillage were ernestly made with little effect, the U.S. Coast Guard Strike Forces and other personnel were exposed to extreme danger. The vessel was well suited to a burn action due to oil type, weather, stability and location. Furthermore, smoke generation would not have been a problem since it would have been blown seaward by wind action which later proved strong enough to carry the oil out to the open ocean. The tremendous cost of response and equipment gathered is typical of what can happen during these incidents.

4. SANTA BARBARA - The Santa Barbara situation (see C-39) was one whereby after drilling through the overburden or unconsolidated materials, the drilling continued into bedrock until bedrock was used in lieu of pipestem. Normally, pipestem was put down into the bedrock a distance of 300 to 500 ft, following which the rock itself serves as pipestem. When the drill broke through the oil reservoir, the oil rose to the surface of its own gas pressure and gravity head. As the oil rose to the surface, leakage occurred through a rock fault. However, the majority of the oil was still going to the production platform. By Federal order, the production facility was shut down and, as a result, oil that would normally go through the production lines escaped through the fault. Copious quantities of detergent were used largely around the platform to protect the platform from possible fire.

The rig was located 3 miles off shore and would have been conducive to a burn action, although smoke would probably have gone into the residential areas along the Southern California coast. No response equipment was immediately available. Booms were inadequate in structural strength to withstand the elements. Attempts were made to fabricate booms from telephone poles or marine pilings (a very time-consuming procedure); in the process of towing these marine booms to the spill site they broke free and were later found on the coastal beaches. The use of detergents was abandoned and then restarted.

The response action continued 8 months into August 1969 by which time the spill collection rate increased to 51% of the gross spill. In mid-December 1969, the oil spillage increased again. A break occurred in a platform-to-shore pipeline. In order to repair the break, production from Platform A was suspended. By December 23, 1969, additional oil (estimated at 400 barrels) hit the coastline warranting additional cleanup action. Continued spreading of dispersant was undertaken to protect the offshore oil rig from oil accumulation and fire when fire at the leak source may have controlled the wide dispersal of released oil.

The entire response action showed a lack of preparedness, delayed decision making and a lack of suitable response equipment and experience. The resulting damage from the escaping oil exceeded the value of the production rig. Some form of containment and burn action with a boom that would withstand the temperatures of the burn might have been a more suitable response. The entire incident is indicative of limited capabilities in areas where numerous offshore rigs are evident and where the possibility of spills is a constant daily occurrence. Although the incident occurred in an area prone to oil spills from numerous producing rigs, oil response equipment was limited and unsuited to sea conditions.

6.2 SPILL RESPONSE ACTIONS AVAILABLE OTHER THAN BURNING

In this section generalized approaches are set out with the view of documenting the efforts and time required to mitigate oil pollution by means other than combustion. These observations will be used as a basis for assessing the feasibility of using combustion as an oil spill mitigation tool. Considerations will be made for in situ tanker burning, burning oil on water, and burning oil-contaminated debris. Since the thrust of this study is combustion, only brief highlights of these generalized approaches are noted. More details are given in Appendix D.

6.2.1 Alternatives to Burning In Situ Tankers

When a vessel runs aground, as has been the case in a number of marine casualties, i.e., TORREY CANYON (1967), OCEAN EAGLE (1968), GENERAL COLOCOTRONIS (1968), ARGO MERCHANT (1976), and AMOCO CADIZ (1978), and is unable to free itself by its own power, it is, in marine terminology, stranded. A number of techniqus can be instigated to release a tanker type vessel from its stranded position. These techniques are as follows:

- pumping/jettisoning the oil cargo overboard to lighten and refloat the vessel
- offloading the cargo into barges, or other tank vessels, to lighten ship and regain buoyancy
- ballasting the ship down onto the sandbank, shoal, or other obstruction to gain a stable situation to ride-out adverse weather until offloading can be implemented
- scouring the bottom with air, water, steam, or ships propellers until the stranded vessel is refloated
- cargo gelling to contain same within the vessel's hull and control leakage through structurally damaged areas
- pulling the vessel free from the bottom obstruction using beach gear and/or tugs
- dewatering the vessel if she has taken on water from bottom impact
- sinking in deep water.

6.2.2 Alternatives to Burning Oil on Water

It is not common practice to use combustion as a present oil spill mitigation tool for a variety of reasons as noted earlier in this reort. The techniques which are used are physical/chemical methods of recovery or dispersal and a few applications of biological degradation. The technical feasibility of these techniques is rather well understood by public officials as well as cleanup contractors. These methods include nontreatment, dispersing agents, gelling agents, sinking agents, biological seeding, skimmers, booms, and sorbents. Costs are included in Appendix D, Page D-15, from readily available information which was gathered in late 1970 to simply illustrate relative expenses of using one technique over another. The methods can be briefly described as follows:

- nontreatment which allows oil to disperse, apparently as a result of evaporation, biological decomposition, and photooxidation
- dispersing agents which form finely divided and stable oil-in-water emulsions that can enhance natural degradation
- oil gelling agents used to congeal the oil and allow it to be physically picked up

- oil sinking agents which are dense sorbent materials that bond to the oil and sink it
- biological degradation which involves microorganisms that decompose the oil
- skimmers that separate oil from water through gravitational and dynamic action
- floating boom devices that prevent spreading by containing the spilled oil riding on the sea surface
- physical absorption in which pads or loose material, made up of several organic/inorganic substances, are used to soak up oil from water.

6.2.3 Alternatives to Burning Oil-Contaminated Debris

Burning of oil-contaminated debris has been a widely used practice, but, due to public concern for air quality and the development of other technology, it is not now uniformly practiced. Each local jurisdiction can and often does pass controlling regulations pertaining to the use of open burning of oil debris or shoreline burning of collected oil and debris. The alternatives (see Page D-22) to burning involve a variety of approaches starting with non-treatment to physical removal and recovery for reprocessing materials, using the oily debris in some direct application or using various controlled land disposal techniques. The alternatives to burning are:

- nontreatment, which allows oil to percolate into the soil or be covered by sand; anaerobic or aerobic digestion may also occur
- physical removal of the contaminated sand and debris to a disposal site
- burial if contamination is not too extensive
- land farming in which material is thinly spread and tilled into the aerated portion of the soil to permit decomposition
- suction of very viscous or thick oils by a sludge or slurry pump with a storage-tank system
- chemical treatment to clean sand and debris and disperse oils.
- steam strip sand and debris of oil

6.3 TECHNICAL ASSESSMENT OF COMBUSTION AS AN OIL SPILL MITIGATION TOOL

This section draws information from throughout this report. The assessment of technical feasibility presented here is designed to provide justifiable guidance on the advantages and limitations of using burning. The types of oil that can be shown from theory and practice to be amenable to burning are noted. The comparison of alternatives to burning are given along with condition specifications demonstrating the state-of-the-art and the technical feasibility of using burning for:

- oil in tankers
- oil released on water
- oily debris disposal

6.3.1 Types of Oil Amenable to Burning

Oils may be classified as suggested in Section 3.6. This procedure employs net heat calculations by examining the total heat of combustion released back to a pool fire and the total heat required to vaporize and sustain combustion. Evaluation of the combustibility of various oils under weathering conditions (Section 3.7) demonstrated the effects of wind and temperature on the volatile fractions, burning rate, and ignitability. From those analyses it would appear that oil is readily amenable to burning when it can be characterized by:

- for a refined cut, having a positive net heat available throughout its boiling temperature range
- for a crude oil, having a "breakeven point" (point where the heat requirements just equal the radiated heat back to the pool) at greater than 67% by volume of the oil.

Oils that may be amenable to burning depending upon circumstances and some combustion promoters being used must be characterized by:

- refined products - having at least a positive net heat available at the upper boiling point of the fraction
- crude oil - having a breakeven point at greater than 40%, less than 67%.

Oils that will require considerable effort to make them amenable to burning by extensive and repeated use of combustion promoters, etc., must be characterized by:

- refined product - a negative net heat is available throughout the fraction boiling range
- crude oil - having a breakeven point at approximately 40% (below 30%) or less.

Information of this nature is available from the petroleum assay, but is not normally part of the shipping documentation. Options are, therefore, available to both the public and private sectors to determine the most cost effective way of making these data available to those persons who need the information to make a timely decision. The oils listed in Table 6.1 appear to be amenable to combustion under generalized conditions.

6.3.2 Technical Assessment of Oil Burning In Situ in Tankers

The alternatives to using combustion were reviewed in Section 6.2.1 and are suggested as effective in a range from: essentially total recovery of vessel and cargo to loss of both with resulting widespread pollution. Indecisiveness in the first few hours of a vessel's incident was observed to be of major consequence in review of actual case history time and event sequences (Appendix C). Burning oil in situ in tankers, following the guidance of Section 6.3.1 on types of oil, appears feasible as noted in Table 6.2, which lists conditions that appear to favor burning.

The major efforts which are employed upon a stricken vessel pertain to salvage and cleanup of spilled oil. This response, however, can be examined and several conditions become apparent which favor in situ burning.

It should be stressed that marine salvage is carefully planned action. Once crew members have been removed from a stricken vessel, the slow methodical procedure for saving the vessel from the elements commences. The safety

TABLE 6.1. Evaluated Combustibility of Selected Oils

Oil Type	Combustion Promoter Required	Expected Results
Kerosene	Doubtful	Good burn, little residue
Jet Fuel #3	Doubtful	Good burn, little residue
Fuel Oil #4	Under Most Conditions	Will burn
Bunker C	Definitely	Will burn, some residue
Spray Oil	Yes, plus additional care	Weakly burns, residue left
Resin Oil	Yes, plus additional care	Weakly burns, residue left
Tembungo, Malaysian crude	For ignition only	Good burn, little residue
Brass River, Nigerian crude	Ignition only	Good burn, little residue
Arabian Light, Saudi Arabian crude	For ignition and some sustaining	Will burn, light residue
Oriente, Ecuador crude	For ignition and some sustaining	Will burn, light residue
Bacherquero, Venezuelan crude	For ignition and continual addition and care	Doubtful burn, heavy residue
Pari, Indonesian crude	For ignition and continual addition and care	Doubtful burn, heavy residue

TABLE 6.2. Conditions and Circumstances Making In Situ Tanker Oil Burning Feasible

FEASIBILITY MUST CONSIDER Conditions or Circumstance	OPTION A Salvage and Cleanup	OPTION B In Situ Burning
Minimum response time available	Several weeks to a few months required	3 to 5 days required conceptually
Manpower involved	Up to 500 men from several vessels	Less than 50 in and vessels
Equipment exposed to risk	$100 million in ships and aircraft	$30 to $40 million in vessel and aircraft
Support facilities	Extensive involving several ships and aircraft	One vessel and one or two aircraft
Special expertise available	Salvors, cleanup contractors, most countries coastlines	Explosives, pyrotechnic, shaped change experts, few available in military organizations. No large commercial organizations.
Value of resulting vessel	$12 million for new to $960,000 for old vessel	$0 to $200,000 for old vessel and perhaps $340,000 for new vessel as scrap
Random locations of accidents	Salvage and cleanup equipment must be moved and set up often far from operations base	Accessible and safe provided 3 miles from population
Costs of response	Up to millions of dollars	A few hundred thousand dollars
Public regard for response	High costs, much preparation, and delay, confusing options - poor	Potential cost savings, rapid decision action demonstrated - good
All weather response	Inclement weather threatens safety and operations halt	Can be considered in all but most severe when equipment must remain at safe location
Civilian application of military technology	Little involvement except occasional Navy salvage	Defense agencies, equipment techniques; and personnel in full scale training increase return on military budget expenses, i.e., peaceful uses

of the salvage team is one of the foremost tasks of the Salvage Master (see Appendix I). Salvage equipment is carefully checked and positioned and whenever practical, oversized equipment is used to develop a high degree of safety, and to ensure that equipment failure does not worsen the position of the vessel under salvage. The USN salvage vessels fall under ARS, ATS, and ATF categories, i.e.:

ARS 251' OAL x 86' beam x 21.25' draft
Complement 115 (6 officers, 109 enlisted men)

ATS 282.66' OAL x 50' beam x 15.1' draft
Complement 102 (9 officers, 93 enlisted men)

ATF 205' OAL x 38.5' beam x 15.5' draft
Complement 80 (5 officers, 75 enlisted men)

It can be readily seen that the employment of one or more salvage vessels becomes labor intensive and costly. However, high speed tugs, working in concert with the ship's engine, have been effective in rescuing vessels when stranding is not too severe. This action can take place before the deterioration has a chance to do extensive damage.

The actual time to complete a salvage operation is controlled by weather, the type of casualty collision, stranding, beaching, and structural failure. The steaming time to reach a casualty site can be calculated at a maximum speed of between 15 and 16 knots. Since most casualties occur under adverse weather conditions, a speed of 10 to 12 knots would appear more practical. On the East Coast the vessels are largely berthed in Norfolk, Virginia. To arrive on scene in the New England area (scene of many wrecks, and the major oil ports on the East Coast, Table 2.6) could involve an elapsed time of up to 60 hr depending on location - New York, Boston, Portland, etc. These vessels have a new construction value of $12 to $200 million which should be considered when a salvage vessel (which has been designed and built for the purpose) is required to operate in a shoal area under adverse weather conditions. The worldwide commercial market suggests that higher performance vessels with smaller crews are available well below the $30 million figure. The daily operating cost of a large salvage vessel can also average $20,000/day, and as many as four such vessels may be needed at the casualty scene. Commercially, the ARS class vessel may be retained for about $500/day. Many aircraft are required for overflight purposes to observe the extent, direction, and dispersal of spilled oil, and for helicopter heavy lift and personnel transfer. In this respect, the 265 hr of flight time as used on the ARGO MERCHANT response can exceed $200,000.

The type of cargo must be given prime consideration before selecting a burn response action. This is defined in Section 6.3.1.

The age of the vessel deserves due consideration basing the average useful operating life of a tanker at 25 years. Most casualties have, for some unexplainable reason, involved tankers in excess of 20 years of age. The value of an aged tanker (22 years) using MARAD's straight line depreciation rate (which is subject to question) of 4%/year would be in the vicinity of $960,000[a] assuming a 1953 building cost of $8 million and a 25-year life span. Ship values vary significantly depending on the market and not only on their age. It is critical to note that sometimes the difference between the value of a vessel as experienced on the world market and that vessel's insured value can be far apart. In the aspect of the insured value, it is the underwriter who must bear the full price; there is no depreciation to insured value concepts. The face value of the policy is the value of the vessel in a preagreed matter.

The general stability and/or condition of the stranded vessel should be related to predicted weather conditions to determine if the vessel could survive increased wave and wind action. The remoteness of the casualty and the time elapse for positive assistance (other than to aid the crew) has considerable bearing on the ultimate decision to burn. An additional, important factor relating to a decision to burn involves the fish and wildlife known to be prevalent in the area of the stranding.

(a) If salvage for scrap is possible, this figure could, according to US/DOC/MARAD, be increased by a factor of 0.025 of original purchase cost ($200,000).

Parameters are noted below and summarized in Table 6.3 which are of importance in evaluating the burning alternative in light of other options other than ship strength considerations. The strength considerations are of such importance to the use of burning that a short examination is warranted.

Accident Exposure

With the exception of in situ burning and bottom scouring, all response actions require personnel to board and work aboard a stricken tanker, thereby developing high injury potential to response team members. In fact, unless the air access openings are made by an air to ground missile approach, in situ burning would demand personnel boarding the stricken vessel to position shaped charges on the deck. It is anticipated that this demand for manual service could be eliminated by research and development with innovative engineering.

Manpower Demands

With the exception of a burn action, all other response actions would require multiple ship and helicopter support with adequate crews to support the assisting ships or aircraft. These personnel would in turn be supporting the USCG Strike Force Teams which would increase the work population. By comparison, a burn action, if air activated, would demand only one or two flight crews once the stricken vessel is moored securely at the disaster site.

Weather Condition

High sea states have in the past restricted cargo jettisoning, offloading, and dewatering a vessel to regain buoyancy. Cold weather, coupled with loss of on-board power supply, has rapidly cooled heated oil cargoes to the extent that pumping for any reason became impractical. The positioning of beach gear in sea states above 3 (up to 4-ft waves) becomes exceptionally difficult, and according to USN salvage personnel impossible under sea state 4 (4 to 8-ft waves). The possibility of mooring an offloading barge into position near the stricken vessel would fall into a similar category as beach gear. On this basis, the rating would favor the overflight or overflights of fixed wing aircraft to fire explosive/pyrophoric missiles into the deck of the strander tanker.

TABLE 6.3. In Situ Combustion Compared to Other Techniques

Response Action	Accident Exposure H	Accident Exposure L	Manpower Demands H	Manpower Demands L	Weather Restrictions H	Weather Restrictions L	Equipment Demands H	Equipment Demands L	Time Demands H	Time Demands L	Success Potential H	Success Potential L
In Situ Burning		X		X		X		X		X	X	
Jettisoning Cargo	X		X		X		X		X		X	
Offloading Cargo	X		X		X		X		X			X
Ballasting Down	X		X			X		X		X	X	
Bottom Scouring		X		X		X	X		X			X
Cargo Gelling	X		X			X	X		X			X
Use of Beach Gear	X		X		X		X		X		X	
Dewatering Vessel	X		X		X		X		X			X
Sinking in Deep Water	X		X			X		X		X	X	

H = High
L = Low

Equipment Demands

There is little, if any, major equipment owned by the Federal government or private industry kept on standby solely for spill response purposes. At the time of the ARGO MERCHANT incident, USCG capital equipment had to be drawn from other daily tasks to serve in the emergency, i.e., 200 mile fishing limit patrol, aerial surveillance, etc. (note: the USCG was required to borrow equipment from Army, Navy, and Air Force in addition to gaining privately owned contractor equipment). On this basis any response that demands a fleet of vessels, helicopters, and the like, presents a major supply problem. Barges and pumping systems (other than the USCG ADAPTS pumps) also develop demand and supply problems, whereas military aircraft which could be equipped with a suitably developed air-to-ground missile firing capability are constantly on national defense standby. It is traditional for salvage equipment to be on standby and in matters of arbitration at Lloyd's where contract work is accomplished under the Lloyd's Open Forum, No Cure - No Pay, the lost time in standby costs of equipment is always taken into consideration as an expense to the salvor. The gelling of a cargo is also a new untested procedure, as is the missile use that can be costly and demand excessive quantities of the gelling agent that are not readily available with the U.S.

Time Demands

The accumulation of assist ships at a stranding site can be time consuming. The time involved to offload a vessel under heavy sea conditions with partially coagulated oil can in some cases involve days of pumping. At any time during the pumping the stranded vessel can become in grave danger, and release her cargo to the sea.

The ballasting or sinking of a vessel can also be time consuming. Ship side openings or sea chests are limited in diameter greatly restricting the flow of water into a vessel. It is in fact difficult to violate the buoyancy of a tanker type ship unless three complete compartments can be flooded. Here again the time factor favors a fast burn response using the envisioned missile carrying aircraft with a series of fast overflights and firings.

Ship Strength Considerations: Removal of Structure and Fire Effects

The subject of ship strength was reported by Rynecki[a] as being, under relatively normal operation, an engineering challenge; it is more difficult where structural damage has been encountered, such as associated with the removal of deck or scantlings and fire damage. The removal of scantlings generates the reduction of section and hull continuity - transverse or longitudinal. The primary factor to consider is the loss of section causing the net loss of midship section modulus, and thus the ability of the hull girder to carry the maximum longitudinal bending moments. This loss can be generated either from the physical removal of steel sections, as may be experienced from the cutting of main deck access areas, or from the effective damage caused to the structure by the burning of the cargo products. The solution to the resulting structural problem is complex at best. An overview of factors which must be considered is provided due to the importance of this subject in assessing the technical feasibility of burning oil in situ tankers.

The hull of the vessel is considered to act as a girder for determination of structural behavior. A hull girder may be defined as:

> the basic structure which resists longitudinal bending, consisting basically of the shell plating, decks, inner bottom, longitudinal bulkheads, and girders (Comstock, 1967).

It is the integrate steel mass composed of these elements that carries the longitudinal load and operates as a continuous structure within the ship. This creates many indeterminate structures and therefore precludes simple structural analysis. To obtain the full significance of the "hull girder" in structural terms, it is necessary to study the structural drawings of the specific vessel and determine the effective section modulus for locations under analysis (for example, see Figures 6.1 and 6.2). A section modulus can be determined by the typical, and continuous typical mid-ship section (Figures 6.3 and 6.4) illustrating their structural components of beams, cross braces, deck and other plates.

(a) Alex Rynecki, Inc., Letter Report May 1979 to C. Hugh Thompson, Battelle.

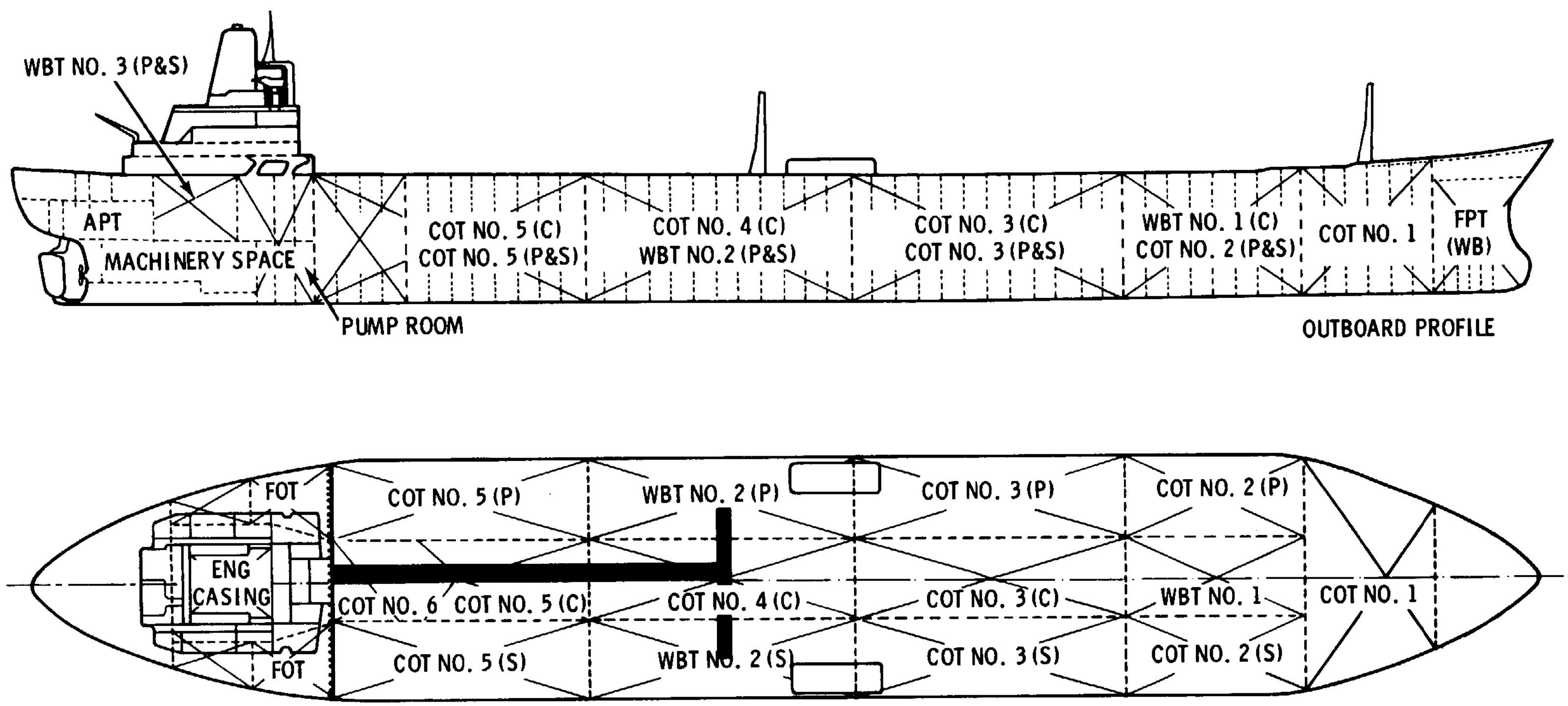
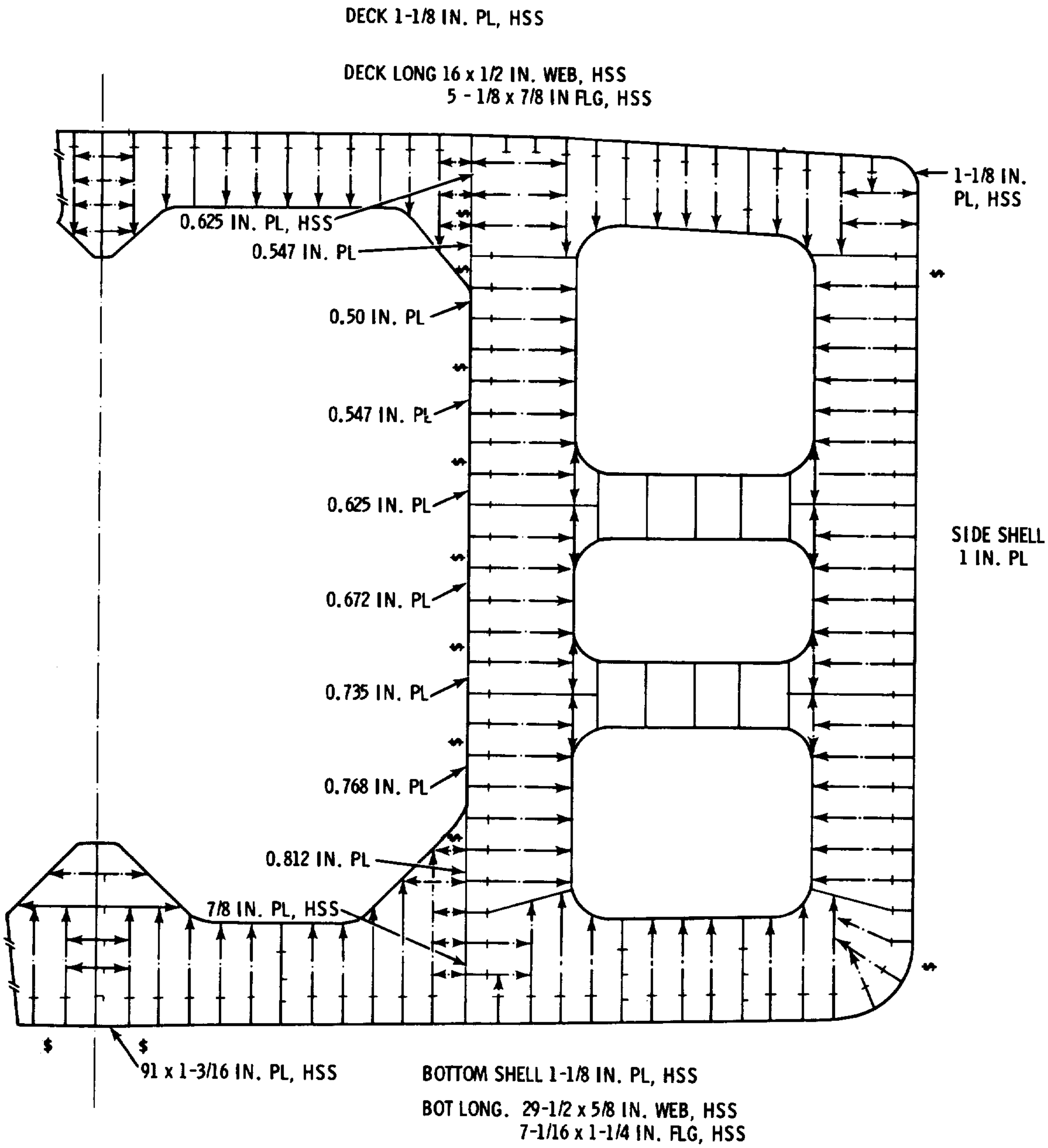


FIGURE 6.1. Tanker Profile and Deck Plan

Source: A. M. D'Arcangelo, Society of Naval Architects and Marine Engineers, Ship Design and Construction



L_{pp} = 1027'-0", L_{WL} = 1050'-0", B (MOLD) = 158'-0", D = 83'-8",
T (DSGN) = 54'-3", DWT (APPROX) - 175,000 LG TON

FIGURE 6.2. Midship Section of a Tanker of About 175,000 Tons DWT

Source: J. H. Evans, Ship Structural Design Concepts

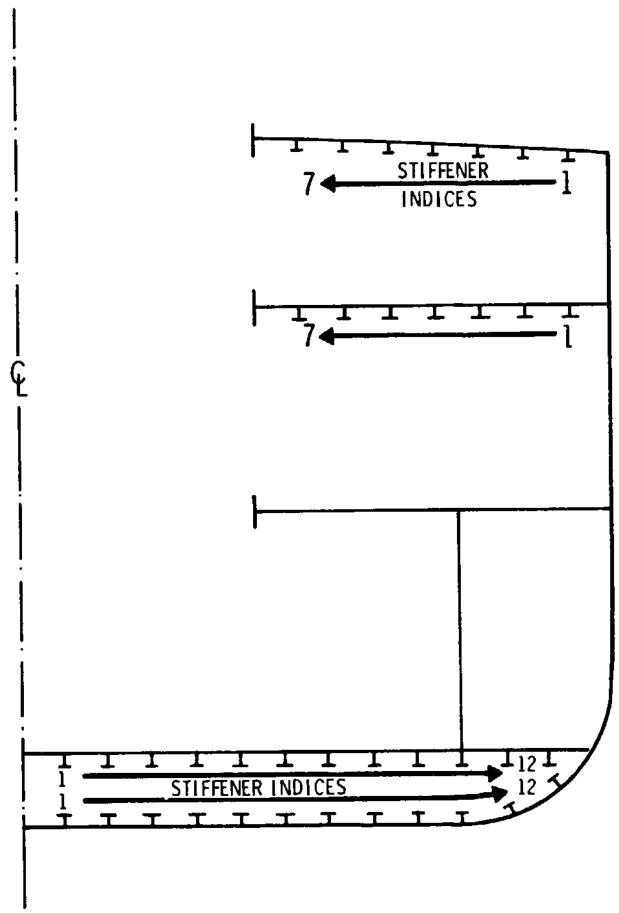


FIGURE 6.3. Typical Midship Section and Stiffener Indices

Source: J. H. Evans, Ship Structural Design Concepts

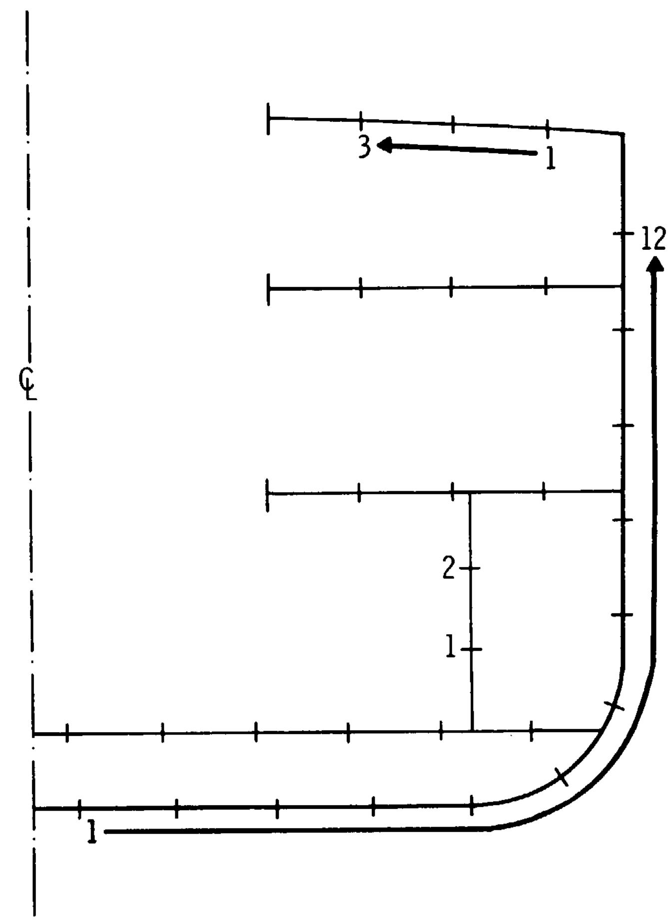


FIGURE 6.4. Typical Midship Section Plate and Indices

Source: J. H. Evans, Ship Structural Design Concepts

The mechanics of hull failure are many, and in some instances of failure difficult to delineate. With reference to burning of cargo, and the reduction of structural section in the hull girder, it is important to note the failure mode analysis, and thus attempt to prevent the occurrence of excessive structural strength loss. Single loads and loads which are repeatedly applied must be examined.

Several potential forms of catastrophic "collapse" have been identified (Evans, 1975) as responses to an excessive hull girder bending moment. These may take place, presumably, with but a single application of load so the possibility of their occurring must be weighed against the extreme or worst-likely load value. An exception is brittle fracture with which a threshold condition for almost instantaneous, absolute, and complete failure encompassing the total ship cross section may be set up with only a small stress component.

Based upon the "plastic hinge" concept of "limit design" theory, Caldwell (Evans, 1975, Chapter 13) has sought to define an absolute upper limit of hull girder strength which, though never physically possible of attainment, is readily calculable for any ship and most surely represents its ultimate load-carrying capacity as a beam. Muckle (1967) concluded that where buckling is likely to take place, as must inevitably be so in a plated structure such as that of a ship, some doubt must exist as to what is the ultimate strength of the structure, since the ultimate strength of plating in compression cannot really be defined exactly. It is clear that to approach the fully plastic moment, the design of the compression members should be such as to give as high buckling stresses as possible and certainly not less than the yield stress for the material. As Figure 6.5 illustrates the most severely stressed portion of the vessel is at the distance one-third down from the deck to the hull girder neutral axis, since this is the area of maximum compressive stress under simple loading. The deck is also in compression and, therefore, any cutting for side vents or top vents for burning must be regarded as dangerous. The relative contribution to hull strength and deck strength by the beams and surface plates must be determined. It is clear that the removal of side and top plates as well as any significant supporting members must be conducted in at least an alternate spacing in both plan and elevation view. This "checkerboard" pattern would also have to meet the ventilation location requirements of the tanks to be burned.

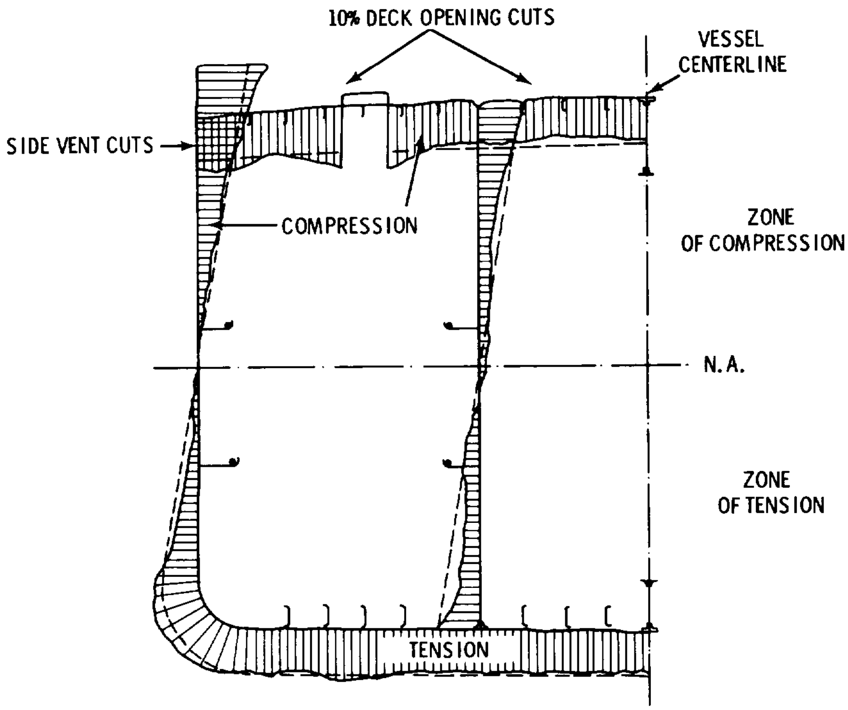


FIGURE 6.5. Half Cross Section of Tanker Hull with Longitudinal Stress Illustrated as Normally Sag Loaded (Supported on bow and stearn)

Source: A. M. D'Arcangelo, Ship Design and Construction, Society of Naval Architects and Marine Engineers

The loss of section modulus associated with deck removal, and that experienced with fire damage, must be taken into consideration for determining the ultimate strength of the ship after burning the cargo. In instances of ship casualty, and in those particular instances of marine salvage where time is available, complex calculations may be accomplished. Both the manual method, and the computer method can be applied to calculating the expected load and the yield points in hull girder loading in severe casualty conditions. It has been suggested that all ships at sea "be entered" into existing computer programs to allow for quick calculations. Marine salvors have made good use of "entered ships" in the computer systems of classification societies, and with building yards for salvage analysis. In the salvage of the OBO, T.V. IGARA much use of computers was made for strength analysis. Specific calculations have not been undertaken here; however, it is recognized that the technology is such that a comprehensive structural analysis could be readily made for several vessel classes under a variety of cutting conditions. Work currently being sponsored by the U.K. Department of Industry, Ship and Marine Technology Requirements Board may provide additional evaluation and guidance.

Generally, a structure is damaged if its original form has changed in a way that is detrimental to its future performance, even though there may be no immediate loss of function. Examples of damage include excessive permanent deformations resulting from local yielding or buckling, or the appearance of cracks due to fatigue or local brittleness. In such cases the structure may still be able to sustain its design loads, but because of the possible adverse effects on performance or appearance, and hence on the confidence of operators and users, repairs should be made as soon as convenient.

Collapse occurs when a structure is damaged so badly that it can no longer fulfill its function. This loss of function may be gradual, as in the case of a lengthening fatigue crack or spreading plasticity; or sudden, as when the failure occurs through plastic instability or through propagation of a brittle crack. In all cases the collapse load may be defined (Evans, 1975, Chapter 8) as the minimum load that will cause this loss of function.

Where main deck damage is contemplated, such as in the removal of main deck and other scantlings or because of fire damage, the shift of the neutral axis away from the damage area can be predicted just as it can in a conventional beam structural analysis. For a net longitudinal force equal to zero, the plastic neutral axis must be at the interface which divides the cross section into two equal areas (see Figure 6.5).

The argument has been made that once the yield stress is exceeded in either flange (main deck/bottom), the resulting excessive strain will overload the adjacent structure, thus triggering ultimate failure before the fully plastic bending moment can be achieved. It remains significant to note that calculated, design, and actual ultimate bending yield points may differ significantly because of the many unknowns in the hull's construction and experience loading. However, for simple vessel designs and loads, good agreement of theory and failure exists for longitudinal stress and shear. In salvage-related instances, the inability to perform exact calculations remains the rule rather than the exception; it is considered adequate to develop calculations in the "order of magnitude" scope.

What may be termed an "instability collapse" may occur at stress levels well below the yield strength even though, in general, good design practice will aim to stabilize the structural components so that stresses as near as possible to the yield stress can be attained before collapse takes place in order to realize the full strength potential of the material (Evans, 1975, Chapter 8). Such an ultimate failure (Rynecki suggests probably extensive in area), although conceivably brought about by a single excessive loading, may be instigated by buckling of a lesser kind affecting individual plate panels or individual stiffeners in primary, tripping, web buckling or some other secondary mode and under compression, shear or combinations of stress types. The need to examine for premature failure of stiffener elements in some of their minor modes may be obviated by the proper choice of proportions for the rolled section selected or by the subsequent addition of stabilizing devices, such as chocks. Fundamentally, the philosophy must be to anticipate trouble everywhere and in all elements. Instances of such collapse in service, with buckling functioning at least as the triggering mechanism are explained by Evans (1975) suggesting that once the deck or bottom flange structure buckled, the ship section modulus was reduced to such an extent that fracture or rupture of either flange inevitably followed as the wave bending moments reversed, although not necessarily immediately. It must be considered, therefore, that creation of top and side vent holes should be designed to avoid this collapse or the vessel could begin to fold like an accordian and then break up.

A second category of total hull failures is of the progressive type in which the ultimate collapse is prolonged but perhaps not sufficiently for a vessel to make port and effect repairs. Brittle fracture (a tension phenomenon) may, of course, occur also in stepwise fashion and so must be included in this group. With the very marked reduction in incidence of brittle fracture since the late 1940s, any appearance of macroscopic cracks now is being attributed almost entirely to high-stress, low-cycle fatigue. By itself, fatigue might be viewed (Evans, 1975) only as a costly and annoying nuisance form of damage, difficult to quantify.

Cyclic loading on a damaged hull may have implications far removed from the conventional engineer's ability to analyze. Where initial damage is induced, or where fire damage severely weakens the hull girder, the cyclic loading may have additional integral damaging contributions most difficult to estimate. Where salvage operations are undertaken in calm waters, and the ship is not expected to enter a seaway, the dynamic loading aspects may be ignored and only the static condition need be considered. With this outlook, which is common practice in salvage circumstances, approximately 50% of the bending moment normally considered limiting may be added to ship's assumed allowable bending moment. This "credit" is often relied upon as a convenient concept upon which to evaluate salvage operational plans.

Major importance was concluded by Evans (1975) on the foregoing processes of fatigue and progressive buckling with regard to collapse, where he suggests that their coupling can instigate brittle fracture. Therefore, cut points in scantlings, or those areas removed, may well also generate brittle fracture initiation. No matter how small the tension in the deck of a vessel in hogging[a] happens to be, it will be increased above the nominal value

(a) Deviation of the keel from a straight line resulting from upward force applied amidship, which may be of a permanent or temporary nature, or a combination of both, is known as a hog (Comstock, 1967).

locally along fore and aft stiffening members if panels are initially bowed. Before progressive buckling had been recognized, the thought was that a substantial loss of hull girder efficiency might be avoided so long as unfairness[(a)] did not exceed 0.30 times the plate thickness. Presumably, if it stopped there, this was acceptable (Rynecki). Whether or not any subsequent progressive buckling augments these cyclic tensile stresses, it does produce cold work and so increases the notch sensitivity (in our application - the vent cutting sensitivity) of the steel. Small though its effect, simultaneous progressive buckling in the bottom might enforce another increment in the deck stresses. Necessary and sufficient conditions for the formation of fatigue cracking may thus be set up. There is ample evidence of such cracks sometime in existence in both the decks and the bottoms. More than enough of the few ingredients which are necessary for brittle fracture could be present, including a slightly enhanced stress-strain rate, and only the severity of their total content will decide whether or not it takes place. The growth of unfairness is to be avoided in order to limit stresses, minimize cold work and reduce the possibility of forming fatigue cracks from which brittle fracture may emanate.

When the program is commenced to open the main deck for allowing burning of the cargo, and approximately 10% to 20% of the main deck must be opened, it is important to note the considerations of cyclical loading and those associated with ultimate bending moments that each ship may tolerate. These must be developed on a case by case basis.

Rynecki[(b)] has suggested that marine salvors must take full advantage of a vessel's strength and that their working plans may go beyond the traditional acceptable limits of "normal" practice. Figure 6.6 is a modified configuration to reflect the maximum bending stresses allowed in still water bending. These conditions may receive further credit, of up to 100%, in the

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(a) The loss of local or overall alignment of a structural member from the design axis is known as unfairness.
(b) Alex Rynecki, Inc. by letter report May 1979 to C. H. Thompson, Battelle.

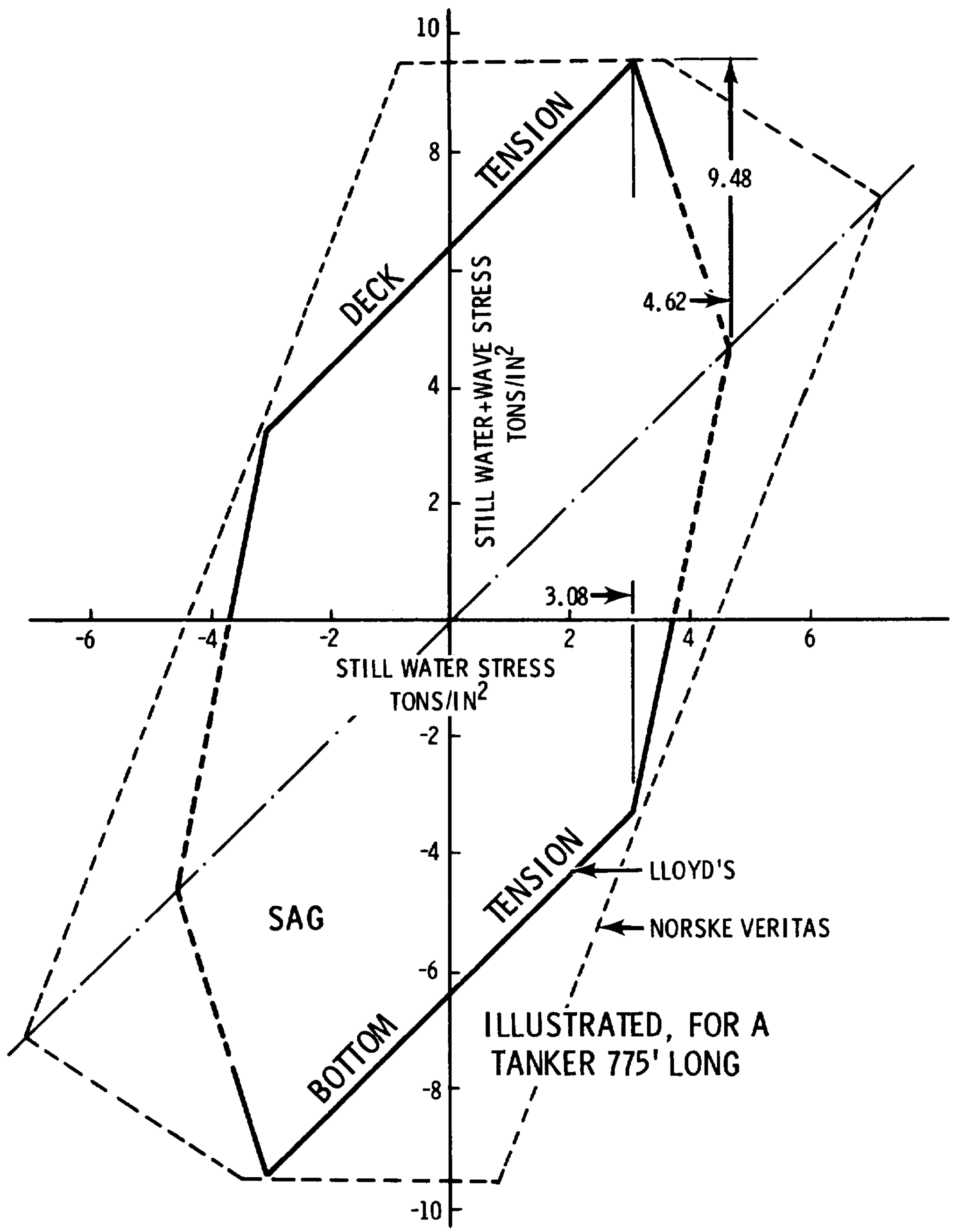

FIGURE 6.6. Allowable Total Bending Stresses as a Function of the Still Water Stress

Source: Evans 1975, Chapter 6, Ship Structural Design Concepts.

event that the ship is located in well protected waters where no sea waves may be expected, and where the full dynamic credit may be taken in the static condition. The classification societies use these estimates in establishing basic design classes for various types of ships and uses.

Success Potential

The decisions under this heading are based on past experience gained from an indepth study of response actions. Few of the major casualties have had a high degree of response success. Attempted burns have also had a low success factor; yet to be demonstrated are specially prepared and sophisticated weaponry. Technical contacts within the military suggest optimism for a high degree of success on conceptual ideas for opening up the vessel, igniting its cargo, and sustaining a burn action. Marine salvor experience indicates that any explosive cutting should be done only by careful onboard precise positioning.

By careful examination of the alternatives other than burning, it may be concluded, from a comparison with burning, that combustion offers the advantages and disadvantages as defined in Table 6.3 and that a most significant determinant is the ship's ultimate strength before, during, and after burning.

6.3.3 Technical Assessment of Burning Oil on Water

From this study it has been shown that oils may be categorized into groups illustrating their propensity to burn under various spill conditions. Using these categories (Sections 3.6 and 6.3.1), the assessment of burning oil on water can be made in comparison to other techniques.

The conditions which appear favorable to oil spill combustion are outlined in Table 6.4. The advantages and limitations of using combustion compared to other alternatives are then summarized in Table 6.5. Previously, a majority of public and private spill response resources have been dedicated to physical, followed by chemical actions to control oil released upon water. Therefore, the current status of commercially available equipment and techniques available for burning is rather limited to nonexistent. However, the concepts which have been or could be demonstrated should be assessed in light of other response options available.

TABLE 6.4. Conditions Favorable to Combustion as Oil Spilled on Water Mitigation Tool

CONSIDER Condition or Circumstances	OPTION A Other Options	OPTION B Burning
Limited Time Available	Extensive equipment and manpower deployment establishes some delays. Other methods require days to weeks.	Burning responses have been very quickly conducted with results immediately known. Burning is a response of hours and days.
Manpower Required	Physical removal is labor intensive, chemical dispersant is not too labor intensive	Limited staff is required to administer the burn - less than 50
Equipment Involved	Extensive equipment available and required for physical removal and expendable material is used	Can be limited to moderate, development needed - not much commercially available
Major Spills	Experience demonstrates that new tools are needed	Yet to be shown, but can be reasonably handled with only incremental resource increase
Light, Fresh or Oils With Positive Net Heat	Chemical techniques can be effective, but little gained by other techniques	Shown to be combustible and pollution minimized
Ice Conditions	Essentially inadequate	Very effective especially in confined areas
Moderate to Calm Seas	Physical and other materials feasible	Burning shown effective, but development needed
Safety of Response	More people, movement and handling. Potential for accidents rise. Moderate to severe weather, hazardous	Fewer persons, less immediate contact with oil or stricken vessel, remote burning feasible, but not demonstrated

TABLE 6.4. (contd)

CONSIDER Condition or Circumstances	OPTION A Other Options	OPTION B Burning
Costs	Can be high, but recovered oil reduces total cost	Potentially low cost if value of time and environmental danger is weighted more than recovered oil
Remoteness to Property	Can cause problems for equipment and personnel recovering oil	Allow free burning with minimal damage potential
Military and Related Technology Transfer	Other than Navy experience (published) little anticipated	Use of incendiary and delivery systems possible for civilian application

This assessment has been attempted from assumptions, using the limited evidence available on a variety of burning techniques and materials, as if the best of these techniques were available in the "burning" option. It must be clearly understood, therefore, that development is required to add validity to these evaluations.

The subjective evaluations were prepared with a range of spill sizes and oil forms in mind. A more quantitative approach is desirable, but the limited information available on burning makes this of dubious value at this time.

6.3.4 Technical Assessment of Burning Oil-Contaminated Debris

From this study and others, it has been shown that burning is an efficient and permanent method of disposing of oil-contaminated debris. A variety of equipment is available including field fabricated and manufactured units,

TABLE 6.5. Comparison of Combustion with Other Alternatives (Oil on Water)

RESPONSE ACTION	Field Personnel Experienced		History of Success		Permitted by Authorities		Equipment Locally Available		Effective in Severe Weather		Time Demands		Potential Costs		Oil Recovered		Disposal Required		Major Spill Effectiveness	
	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
Burning Using any Technology		X		X		?		X		X		X		X		X		X	?	
*Nontreatment	NA																			
Dispersants	X		X			X		X		X		X	X			X		X		X
Gellants		X		X	X			X		X		X	X		X		X			X
Sinking Agents		X		X		X		X	X			X		X		X		X	X	
Biodegradation		X		X		X		X		X	X		X			X		X		X
Skim	X		X		X		X			X	X		X		X			X		X
Skim/Boom	X		X		X		X			X	X		X		X		X		X	
Sorbents	X		X		X		X			X	X		X		X		X			X
Sorbent/Boom	X		X		X		X			X	X		X		X		X		X	

* **Not evaluated due to local authorities past reactions of unacceptability as a response.**

H = High
L = Low

as well as a limited number of permanent incinerator facilities. Controlling factors pertaining to debris burning are not always technical, but are related to local authority responsibilities and desires.

The conditions which appear favorable to using combustion for oil contaminated debris disposal are listed in Table 6.6. The advantages and limitations of using burning in comparison with other disposal alternatives are listed in Table 6.7.

Contrary to burning oil on water, the state-of-the-art for incinerators, portable beach burners, brush burners, portable incinerators, etc., is quite advanced. USCG and other recent sponsored studies provide quite detailed information. Quantitative comparison can nearly be made on a cost-effective basis. Until those cost data are available the following evaluation should be considered. The primary alternatives appear to be burial and land farming. The advantages of these techniques being simplicity and potential low first cost should not be considered without an awareness of the increasingly reported incidents of improper land disposal of oil and chemical wastes. Burning is regarded as a permanent solution to the debris disposal problem by most authorities.

6.4 SUMMARY OF OIL SPILL BURNING CONDITIONS

From the previous three sections, some generalized conclusions may be drawn pertaining to the use of combustion. Tables 6.1, 6.4, and 6.6 illustrate conditions favorable to burning. Section 6.3.1 defined qualifications to be placed upon the types of oil amenable to combustion spill mitigation. From these factors use of combustion as an oil spill mitigation tool becomes technically feasible if:

- The oil falls into the first or possibly the second category reviewed in Section 6.3.1.
- Response action is taken within hours after oil is released.

TABLE 6.6. Conditions Most Favorable to Burning Oil Contaminated Debris

CONSIDER Condition or Circumstances	OPTION A Other Options	OPTION B Burning
Land Availability	Requires extensive preparation land area for farming or burial and restricted access upon completion	Small site required can be existing facilities
High Ground Water Table	Burial unacceptable in some areas	Debris can be burned on site
Heavy Precipitation	Earth moving slow and difficult	Once burning is initiated only most severe would hamper disposal
Permanent Solution Needed	Land farming with time can be permanent disposal, but burial is potentially just storage	Regarded by all authorities as most permanent
Health and Safety	Odors, erosion, leaching, flooding or other changes can endanger health	Dead wildlife, other disease vectors, are handled and delayed hazards prevented
Energy Recovery	Only if oil is recovered and separate at much cost	Used as coal pile additive or in recovery incinerator advantages known
Bulky Debris	Not amenable to burial or land farming without preparation	With limited preparation can be handled even with portable equipment
Limited Transportation	Delays in reaching suitable burial or farming areas	Can be conducted on site
Beach Sand Needed in Place	Detergents can be used, but aquatic toxicity increased	Manual or automated equipment has been used to process sand on site

TABLE 6.7. Oil-Contaminated Debris Burning Compared to Other Alternatives

Response Action	Experienced Personnel		Local Authorities Permit		Success Potential		Need For Special Equipment		Equipment Available Locally		Costs		Time Required		Major Spill Application		Disposal Problem		Oil Recovered	
	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
Incineration (all types)		X		X	X		?			X		X		X	X			X		X
*Nontreatment	NA																			
Physical Removal	X		X			X	X			X	X		X		X		X			X
Burial	X		X		X			X	X			X		X	X			X		X
Land Farming		X		X	X		X			X		X	X			X		X		X
Chemical Treatment		X		X		X	X			X	X			X		X		X		X
Suction/Pools/Beach	X		X		X			X	X			X	X		X		X		X	
Oil Sorption in Debris	X		X			X		X		X	X		X			X	X		?	

* Not evaluated due to local authorities past reactions of unacceptability as a response.

H = High
L = Low

- Such imminent and substantiated danger exists that intervention is justified.
- The burning site is remotely located from the population.
- Weather is expected to change for the worse precluding successful completion of other alternatives.
- The volume of oil is beyond the capacity and capability of other response methods.
- Salvage operations are questionable or abandoned.
- Groundwater is too high to permit land fill burial of debris.
- Quantities and bulk characteristics of debris make land farming too costly.
- Local authorities will permit burning debris.
- Personnel experienced in oil burning plus necessary equipment and material are on the scene or available within hours.
- Because of age or damage the vessel is expected to be lost or at best scrapped.
- Vessel stability, weather, and cargo pose an unreasonable risk to responding personnel.

6.5 PROPOSED OIL BURNING DECISION INFORMATION

With the conditions being advantageous to burning, the following guidance is offered for use in the context of the "ethics of burning" (Section 7). The burning option could then be used if it is considered appropriate after evaluating the information elements.

The decision information elements for using combustion may be examined for an oil pollution incident occurring within U.S. authority where:

1. Potential for release from a vessel exists such that in situ tanker burning should be evaluated (Figure 6.7).
2. Release has occurred, this need not be limited to vessels, and burning should be evaluated:

   (a) for oil released upon water (Figure 6.8)
   (b) for oil-contaminated debris disposal (Figure 6.9).

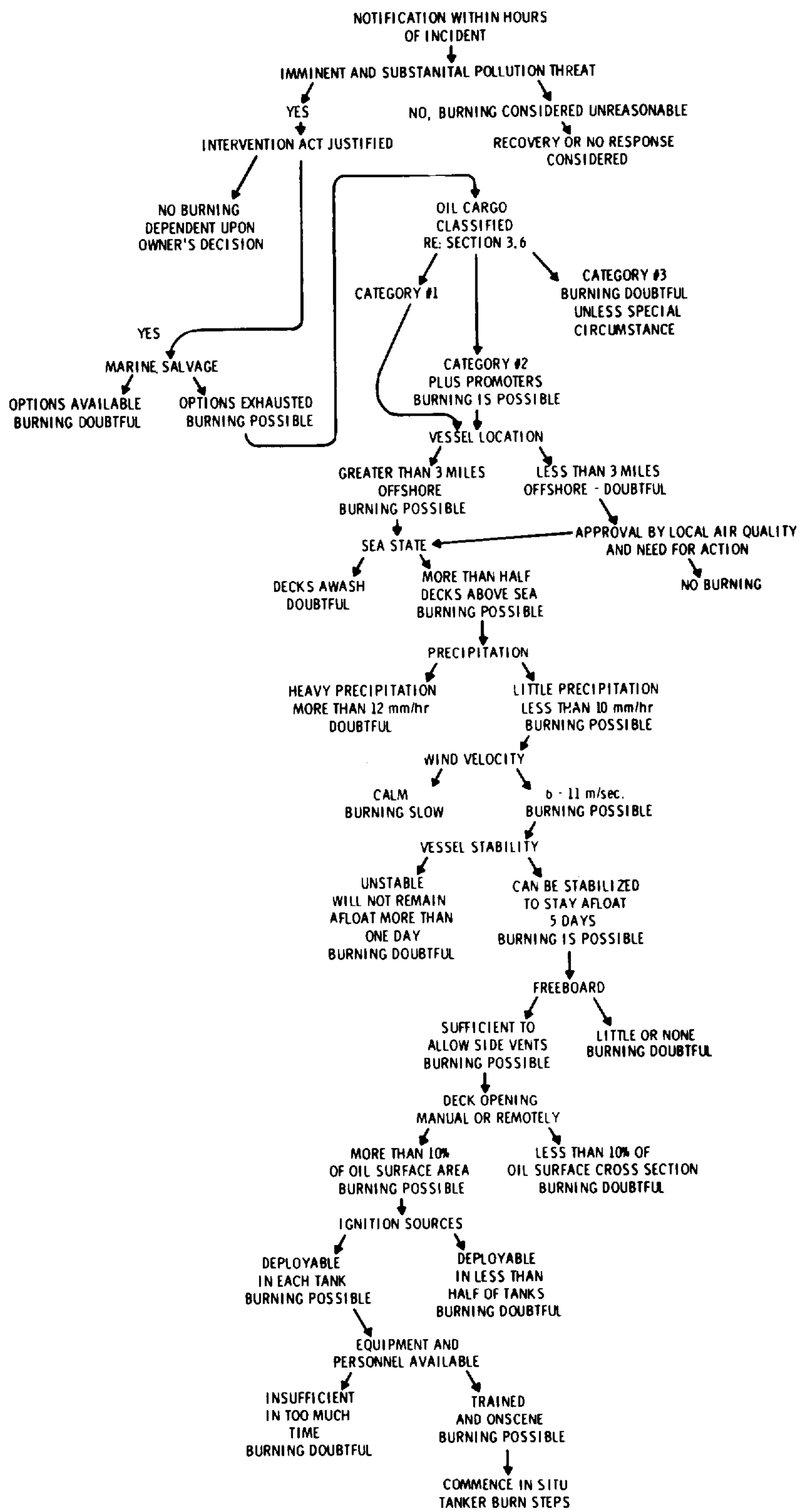

FIGURE 6.7. In Situ Oil Burning Evaluation

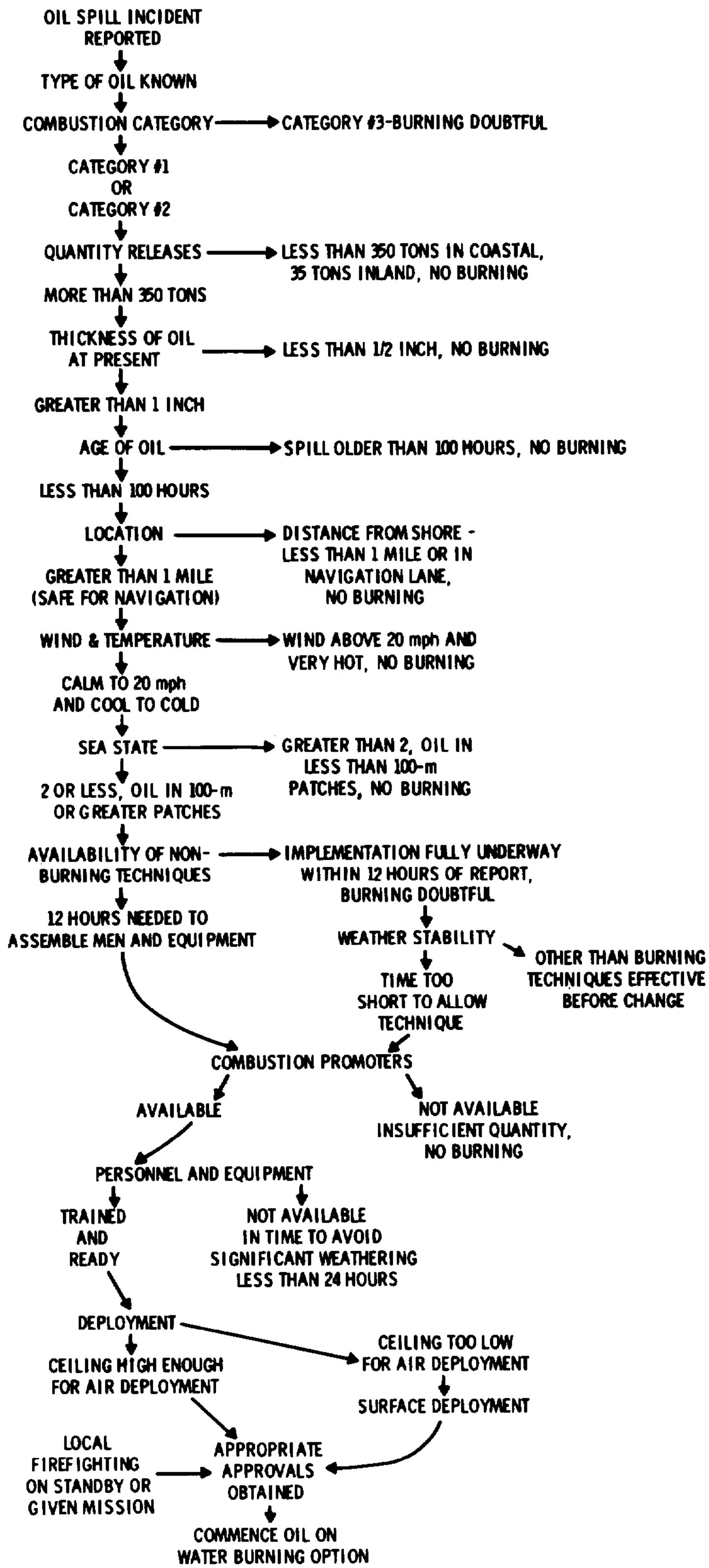

FIGURE 6.8. Oil on Water Burning Evaluation

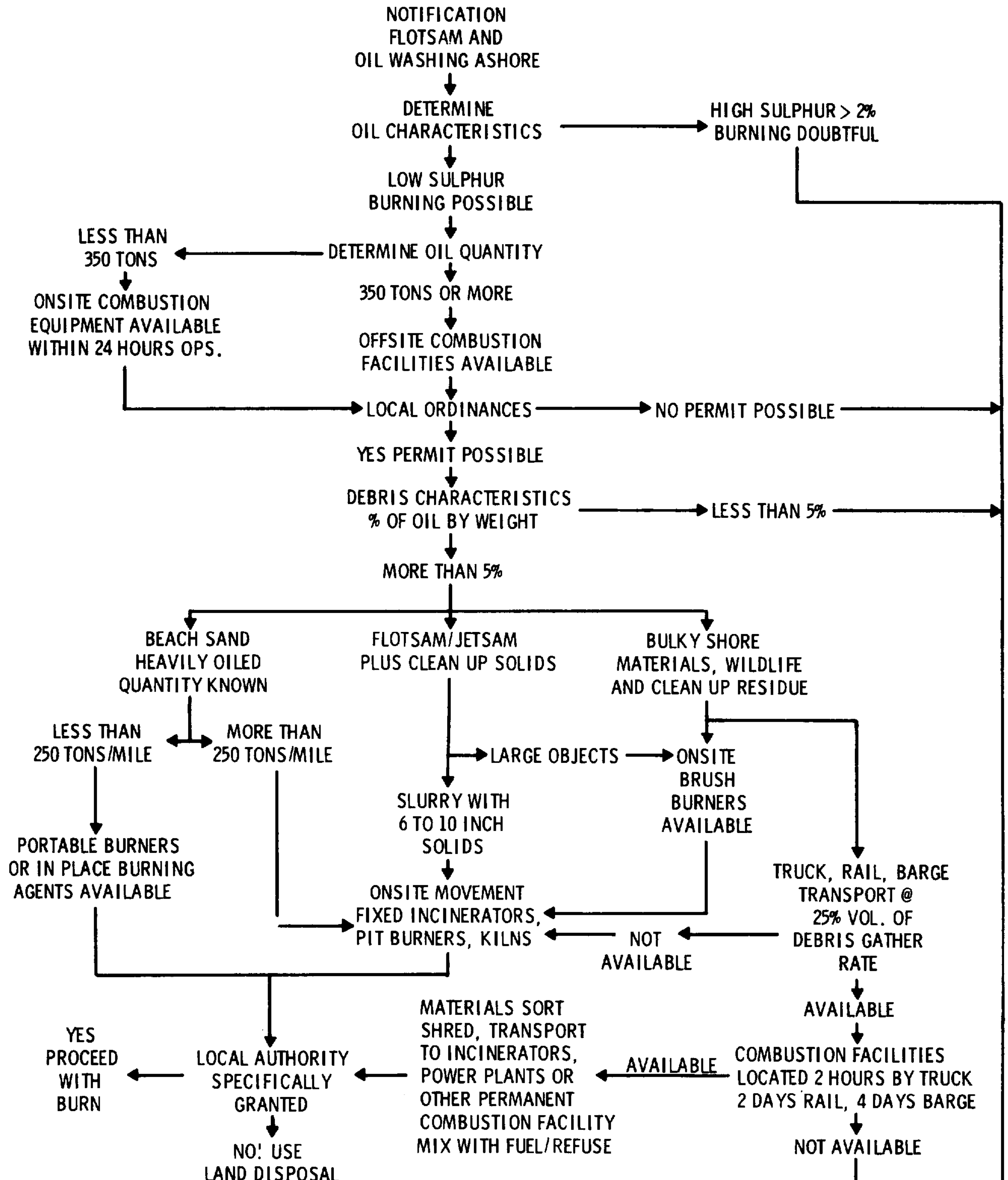

FIGURE 6.9. Oil-Contaminated Debris Burning Evaluation

6.5.1 Information Elements - In Situ Tanker Burning

As illustrated in Figure 6.7, the decision to burn oil in situ tanker is complex. From previous information in this chapter plus the information presented in the other sections such as 4.4, some quantitative guidance can be provided.

The information provided in Figure 6.7 can be explained beginning at the top of the figure. The rapid notification of the incident, within hours of happening, has been observed as being significant in assuring a successful response action. Oil burning in situ tanker is a significant undertaking and the decision maker bears an ominous responsibility. Therefore, a careful examination of the pollution threat must be made, and if it can be determined that the release is imminent and the damage would be catastrophic, burning may be justified. Under all circumstances where the Federal government decides to invoke the Act of Intervention, it must be adequately justified to not only authorities in the United States but also international authorities,if that is appropriate.

Tradition of the sea such as No cure - No pay has developed the manner in which the marine salvage operators conduct their activity. Recognizing that no salvage operation is conducted as an emergency response but rather as a carefully thought out plan, the appropriateness of in situ burning may hinge upon the salvor's expertise, his availability, and his desire for success. In those cases where the marine salvor has no plan, is unsure of the rate of success, has a modified basic contract form, or in fact has abandoned the salvage operation, burning may be considered a viable option. This consideration is not viable, however, if the personnel and equipment necessary to assure the in situ burn (Section 4.4) are either not on scene or will take days to reach the scene and assemble the materials.

If intervention is justified, an examination of the oil cargo is important. As discussed in Sections 3.6 and 3.7, the oils, both refined products and crudes, may be categorized according to their potential combustibility. It would be very conservative to conclude that a Category 3 oil is too difficult to attempt burning, and that a Category 2 oil would require considerable effort in the use of combustion promoters. Category 1 oils should provide a successful burn with limited effort dedicated to ignition, but with considerable attention directed to safety.

Vessel location becomes significant because of the potential for explosion and other safety considerations which may alarm populated areas. Based on the unfortunate incident occurring in Texas City (1947) where ammonium nitrate cargo exploded, to facilitate decision making it is reasonable to consider that burning should not be attempted in the U.S. closer to shore than 3 miles except under request by a state. If the vessel is in this location and the sea state is such that at least half of the decks are above water so that opening the tanks would not cause additional flooding, then burning may be possible.

Studies conducted in the United Kingdom indicate that burning is possible in precipitation up to 12 mm/hr and in a wind velocity of from 6 to 11 m/sec. Precipitation of more than 12 mm/hr and wind velocities dropping to calm will retard and complicate in situ burning.

Vessel stability and structural integrity should be assured and if the vessel is in a precarious situation or due to uneven burning the vessel would sink or capsize, burning is of doubtful value. Casualty work by salvors indicates that not too much attention is required to avoid capsizing. Improper ballasting or unloading in any particular seaway could cause vessel breakup and is therefore of great importance. Since the burning rate is limited, evaluation should be made which would assure that the vessel would stay afloat long enough for the in situ burn to take place. Studies on large-scale model tanks have indicated that it would be reasonable to assume that 5 days would be needed to burn oil cargoes in tanks which are the size being encountered in contemporary tankers. Experience of organizations such as British Petroleum has been that only under the most rare circumstances is a severely grounded vessel offloaded and successfully put back into service. This consideration should be included in the burning evaluation.

Freeboard is an important consideration for in situ burning based on studies indicating that side vents are necessary to maintain a high burning velocity. Information has yet to be produced which would demonstrate for the VLCC or ULCC sized tankers that multiple deck openings would be sufficient to provide the necessary oxygen to ensure combustion. Side vent openings may be a technique which will by necessity be delayed in its application until sufficient oil is burned to allow the vessel to rise in the sea and expose more hull area. The deck opening is an obvious requirement for any in situ tanker burn. At least 10% of the horizontal cross-sectional surface area of the oil must be exposed by deck removal. Techniques have been discussed for doing this manually with personnel aboard the vessel or remotely from vessels and aircraft. Procedures and materials have yet to be demonstrated for safe use aboard a tanker.

The ignition sources, assuming the cargo does not ignite upon deck opening or venting actions, must be deployed in a sufficiently large number of tanks to ensure the uniform and balanced burning. Recognizing that not all ignition sources can be guaranteed to operate, it seems reasonable that if ignition sources may be deployed in less than half of the tanks intended to be burned, the in situ burning option is questionable.

Reviewing again the elements in Figure 6.7, it is possible to construct the sequence of events which would assist an OSC in taking a decision to commence an in situ tanker burn.

6.5.2 Information Elements - Oil on Water Burning

As illustrated in Figure 6.8, the decision to attempt to burn oil which has been released on water requires an evaluation of several factors nearly simultaneously. Some quantitative guidance may be provided which has been previously described in Sections 3.6, 3.7, and 4.4.

From this study and others, it is clear that the oil spill incident must be reported in a timely manner for combustion to be a viable consideration for oil on water. As noted in Figure 6.8, questions which pertain to the type of oil as well as the environmental conditions must be evaluated in context with options other than burning to reach a justifiable decision. The type of oil usually will be known; however, its combustion characteristics may not be. Therefore, the information provided in Sections 3.5, 3.6, and 3.7 should be useful for categorizing the oil's propensity for combustion. The USCG CHRIS manuals for oil response could be revised to include these types of data. Category 1 and 2 materials are considered as combustible on water with the appropriate combustion promoters.

For oil spills involving a very small quantity, other techniques are probably more appropriate than combustion. Using guidance of the National Contingency Plan, quantities of more than 350 tons in coastal waters are considered major spills and would warrant aggressive action on the part of and age of industry and government including consideration of burning. The thickness of the oil, if it is 1-in. or greater thickness, and exposed less than 100 hr to the environment, may warrant burning. These data are suggested based on the review of the combustion properties in the analysis of weathering previously discussed in Section 4.

Considering the safety of populated areas, damage to shoreline, and threats to navigation, burning sites should be more than 1 mile from shore and appropriately regarded for safe navigation. Distances of 3 miles or more simplify the jurisdictional issues and can assist in reaching a decision to use burning. The wind may be variable from calm to 20 mph, and the air temperature may be cool to cold for burning considerations.

Nonburning techniques may be employed if they can be fully implemented within 12 hr and weather is stable enough to allow the nonburning techniques to be rather completely implemented. If the 12 hr are needed to assemble men and material and the weather stability is such that the nonburning techniques cannot be implemented effectively in that period of time, combustion promoters available and trained personnel and equipment available, deployment by air or surface should be considered. Depending on the safety of air delivery based on ceilings and other meteorological conditions, appropriate approval from Federal, state, and local authorities should be obtained to commence the exercise of burning the oil on water.

6.5.3 Information Elements - Oil-Contaminated Debris Burning

The equipment, techniques, and practical knowledge is much more available for the use of combustion for oil spill debris disposal than for the previous two applications. The information provided in Figure 6.9 can serve as guidance in the combustion decision.

Figure 6.9 illustrates that after an oil spill has been reported another element of importance is the direction in which the oil moves. If the oil is washing ashore or is anticipated to wash ashore, the debris disposal problem is created. Onscene observation during the ARGO MERCHANT incident demonstrated the concern for handling debris, as there was literally a small army of personnel standing by if the oil were to head for shore. At that point the type of oil becomes significant relative to the burning option. Because of local ordinances and Federal standards on air emissions and for reasons pertaining to the use of existing incinerator facilities, the sulfur content of the oil is important. The quantity of the oil is significant from the standpoint of the demands of men and material as well as logistics involving transportation and disposal areas which are required. Three hundred and fifty tons is a quantity of oil regarded as a major marine oil spill. It is reasonable, therefore, to consider that less than 350 tons would be an oil spill that would be amenable to onsite handling unless there were extenuating circumstances. Onsite combustion should be immediately initiated and, therefore, equipment should be available and in operation within 24 hr if that response is to be effective. The offsite combustion facilities such as municipal incinerators, power plants, commercial industrial incinerators, etc., are listed in other references and their availability should be determined. However, the burning option is of no value if there are stringent local ordinances which do not permit combustion. In these cases, as shown in Figure 6.9, land burial or farming must be the preferred method of disposing of oil-contaminated debris.

If local ordinances permit combustion, the decision may still be modified by the debris characteristics. If the debris contains less than approximately 3% oil by weight, the debris represents essentially the same type of disposal problem that flotsam recovered from a harbor presents. Land application may in that case be the most economical option to choose. If, however, there is more than 3% oil by weight, this oil-soaked debris poses problems not normally encountered in shoreline debris recovery programs.

Beach sand which has become heavily oiled poses a unique problem which can be handled both onsite and at another location. It is reasonable to assume on a per mile basis if something less than 200 tons of oil have come ashore that portable burners or in-place burning or other systems which use manpower and highly mobile systems may be employed. If, on the other hand, more than this quantity of oil per mile is discharged, then transportable or remotely located systems should be considered. None of these combustion systems can be fully satisfactory due to the resulting ash and oil residue if the beach is used for recreation. Work is under way in the U.K. to make available a steam stripper/oil-water separator which avoids this problem.

Debris that could be characterized as drift materials such as sorbent pads, broken booms, seaweed and other debris left behind after the oil spill cleanup activities are candidates for combustion by transportable stationary onsite combustion systems. If the material has a consistency of a slurry with solids no larger than 6 to 10 in., technology is readily available to handle it quite efficiently onsite.

Materials such as large objects in shoreline debris and dead wildlife may be handled using onsite brush burner type equipment, or for the large, concentrated quantities of materials, transportation and processing in existing combustion facilities may be the option. For the existing facility option to be viable, transportation must be carefully evaluated. To avoid delays in transport and reintroduction of oil from the contaminated debris gathered into the waters, a 25% excess volume in the transportation system should be available. It is desirable that the combustion facilities be located no further than 2 hr by truck, 2 days by train, and 4 days by barge. These times are significant because of cost and the transportation system's availability to have equipment tied up for periods of time. If this transportation system is not available, or the combustion facilities are not within that range, onsite combustion or transportation for local land applications should be strongly considered.

7. ISSUES AND ETHICS OF BURNING

Ethics as applied here are meant to discuss the principles of human morality and duty or nontechnical considerations which must be taken in making a decision to burn oil cargo in a stranded vessel, oil released upon water, or oil-contaminated debris washed ashore. The complexity of the issue and the dangers of over generalization are recognized. The intent is to answer significant points and to identify the potential tradeoffs involved when an oil burning spill response alternative is selected. As illustrated in Figure 7.1, ethics are evolved and defined from a series of specifications and subsequent evaluations which may be used by others for similar decisions; e.g., a Federal Onscene Spill Coordinator (OSC) using burning as an oil spill response will be better prepared if he understands how his actions will be perceived by others.

This discussion is offered with the assumption that the technology is presently available to implement an oil burning action. The narrative therefore focuses upon the decision-making issues. The issues were identified from surveys and meetings with state and local government environmental officials, industrial and governmental safety specialists including fire department personnel, maritime industry representatives, and Federal Onscene Spill Coordinators. The issues identified from this survey are discussed below, followed by a discussion of the economic considerations. The economics are most complex for situations involving the burning of a vessel, and, therefore, attention has been paid to this aspect. The ethics of burning can be formed in the mind of the reader upon review of the last section on issues and tradeoff options.

7.1 CONCERNS OF RESPONSIBLE OFFICIALS

The organizations contacted represent public and private officials who are responsible or could be held responsible for activities related to the use of combustion to mitigate oil spills. Particular attention was given to personnel at the state and local level of government. From a brief regulatory

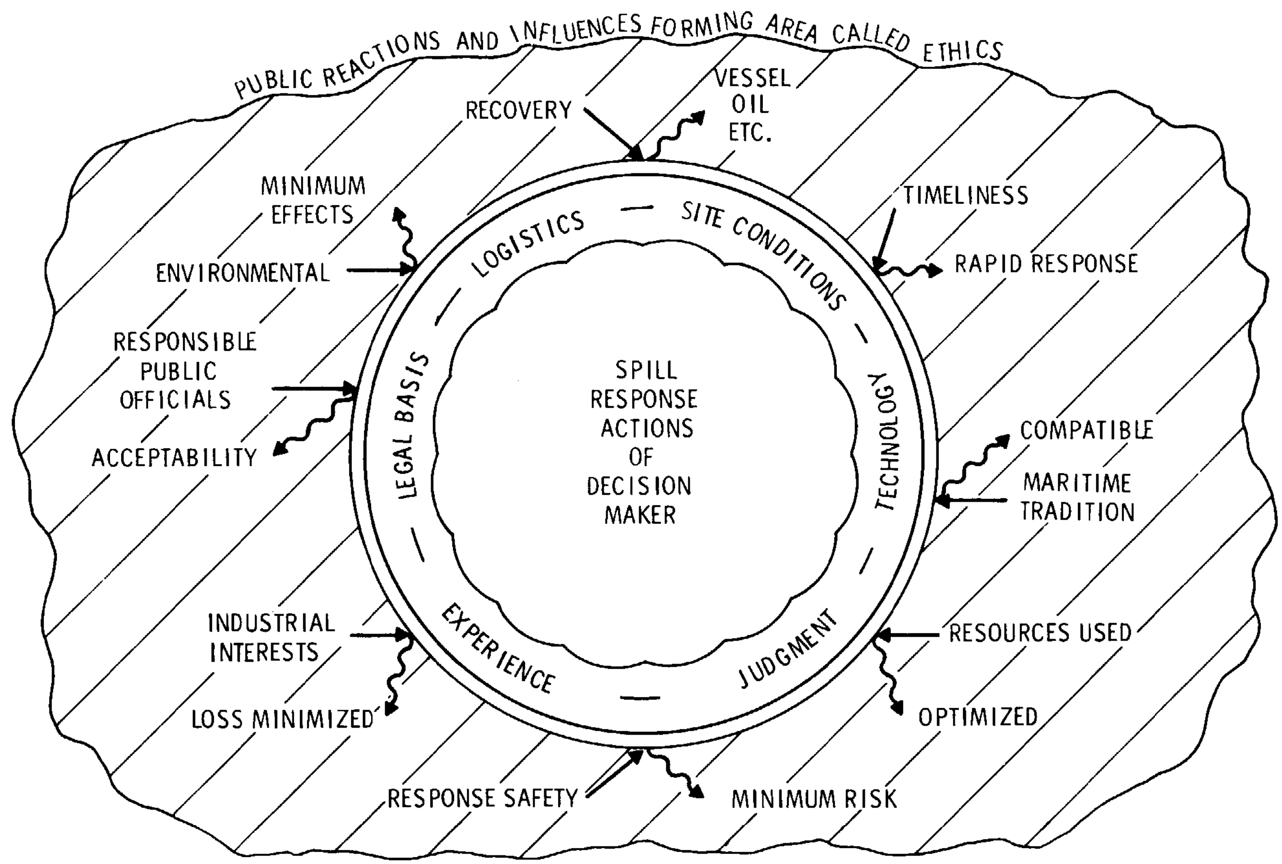

FIGURE 7.1. Ethics of Using Combustion as an Oil Spill Mitigation Tool

review it was concluded that the obvious air quality considerations pertaining to open burning of oil have not stimulated uniform standards or practices nor any "generally applicable Federal assessment or statement."

Organizations contacted that provided responses include those listed in Table 7.1. Additional groups were contacted and have either not responded or had little interest in the study. Efforts were also made to coordinate this study with those in Canada and the United Kingom. Copies of our Interim Draft of this report were also circulated to industry and different levels of government for review and comment. The interviews were generally conducted in the following manner:

- Introduce the oil combustion study and suggest initial findings for burning oil in vessels, on water, and in contaminated debris.
- Suggest that interviewees accept, for now, the premise that technology is available to allow burning of oil under these three conditions.
- Ascertain what background or experience the interviewee and his organization have had in burning oil as a spill response procedure.
- Determine what issues are of prime importance to the interviewees and what evidence they would need to satisfy them and those they represent that burning (under the right circumstances) could be considered a viable spill response action.

7.1.1 Concerns Raised (Answered in Sections 1 Through 6)

There are many concerns that were of common interest to all groups contacted. The concerns are summarized into 13 questions below and are generalized to cover the three conditions of oil burning, i.e., vessels, on water, and debris, and are placed in a descending priority order expressed by the public officials.

It is suggested that responses to most of these concerns are contained in the text of this study and therefore they are not repeated here. The importance of highlighting these concerns is to emphasize the clear need for education of the public and responsible officials and to demonstrate the advantages and limitations of the combustion tool.

TABLE 7.1. Organizations Contacted Which Provided Reactions to Oil Burning

STATE AGENCIES

Alaska	State Environmental Agency
California	Air Resources Board, Office of Emergency Services, Water Resources Control Board, State Lands Commission, Coastal Commission
Illinois	EPA Air Pollution
Maine	Department of Environmental Protection
Michigan	Energy Response Office, Air Quality Division
Minnesota	Emergencies and Spills Section
New Jersey	Office of Hazardous Substance Control
New York	Hazardous Material Spills Office
Ohio	EPA, Emergency Response Section
Oregon	Environmental Quality Division, Air Quality
South Carolina	Industrial-Agricultural Wastewater Division, Bureau of Field and Analytical Services, Division of Monitoring and Enforcement - Air Quality, Water Surveillance and Analysis Division
Texas	Air Control Board and Regional Offices
Washington	Department of Emergency Services Department of Ecology - Air Pollution Control Division Department of Natural Resources
Wisconsin	Department of Natural Resources, Air and Solid Waste Management Division

LOCAL OFFICIALS

Corpus Christi, Texas	Oil Spill Cooperative
Fairfax County, Virginia	Fire and Rescue, Public Works, Air Pollution Control, Comprehensive Planning
Loudoun County, Virginia	Health Department
Port of Charleston, South Carolina	Oil Spill Committee
Prince George's County, Maryland	Emergency Preparedness, Fire Department

INDUSTRIAL OFFICIALS

American Bureau of Shipping	Lloyd's Registry of Shipping
American Petroleum Institute	London Salvage Association
Atlantic Richfield Company	Murphy Pacific Marine Salvage Co.
Exxon Research and Engineering	

FEDERAL OFFICIALS

USCG Captain of the Ports: Charleston, SC; Miami, FL; New York, NY

USEPA Division of Oil and Special Materials; Region VIII, Region III; Edison Research Laboratory

US Maritime Administration

US Navy: Surface Weapons Facility, Dahlgren, VA
Indian Head, MD
Navy Base Ship Yard, Charleston, SC

US National Bureau of Standards

US Dept. of Interior Fish and Wildlife Service, Warren, PA

The 13 concerns are:

1. Does combustion really work to reduce the volume and environmental threat of oil pollution?

2. Assuming that burning does work, is not the air pollution problem posed by burning a more severe threat than the liquid oil itself to health, property (including items such as dwelling paint, clothes hanging to dry), coastal vegetation, and the attitude of a community toward governmental decision makers?

3. How safe to the response personnel is it to burn oil under the three conditions and what is the past experience to demonstrate this safety?

4. How fast can an oil pollution threat be mitigated by using the burning option and what residue is left?

5. Because of the perceived drastic nature of using burning, would not the decision maker need broad-based support locally as well as clear authority to initiate this alternative?

6. Is it not wasteful of resources to burn the oil, destroy the vessel, recover no heat or recycle material or salvage value? How can this be justified?

7. What are the effects of burning oil in the surrounding waters and shorelines, such as radiant energy, smoke precipitation, enhanced hydrocarbons released into the atmosphere, spreading of potentially dangerous materials onto food crops?

8. Does the burning option place more equipment and response personnel at risk than other possible actions available for implementation, especially during inclement weather conditions?

9. What is the role of the fire department or other fire control officials in a burn response and is the technology developed to where these personnel could employ combustion using conventionally available, or modified, firefighting equipment?

10. What would be the effects, when nonburning options cannot be used, of not using the burning option, i.e., doing nothing versus burning?

11. Cost is of no real importance locally or of great importance during a Federally directed response, but is there any savings if the burning option were used?

12. How far away from people or population centers does a burning operation have to take place in order to be safe and to cause a minimal amount of local public concern?

13. Who is presently available and technically competent to conduct the burning action under the three conditions studied in this report?

7.1.2 Experience Basis for Oil Burning Concerns of Selected States and Local Organizations

The range of experience which officials contacted have pertaining to oil burning is given below. No statistical significance or comprehensiveness could be given to this sampling.

Officials in Maine have had experience with burning oil-contaminated debris, but allow it only to be burned when it has been properly bagged and it is conducted under approved conditions. However, Wyoming has used the burning alternative particularly in remote locations such as production sites. Washington State has used burning for years to deal with oil-contaminated debris, tufted grass, and forest slash. Kansas, Iowa, and Missouri were indicated as states which have taken a rather liberal attitude to the use of burning particularly those conducted by railroads where releases have occurred on remote track locations.

Minnesota has frequently used burning for pipeline leaks where snow contaminated by oil mixtures exists, while Michigan has had experience in burning spills resulting from pipeline leaks involving crude oil. Michigan planned to burn a tanker which was foundering in the Great Lakes. Routinely, Ohio experiences approximately one crude oil burn per month on rivers and lakes under its jurisdiction and has had experience burning machine and cutting oil on ice-filled rivers. New York has engaged only in burning oil-saturated debris and conducting demonstration projects using portable pit incinerators which were moved to sites by flatbed trailers. A common practice, which was conducted in western Pennsylvania until recently, burned waste oil collected in waterfilled pits from exploration and production wells. The technique was to wait for calm weather and ignite the pool with a kerosene-soaked rag.

Alaskan industry uses burning for handling oil spills on land that result from pipeline operation and also in tundra areas where physical removal has been determined to be more environmentally destructive. Alaskan state control agencies are less optimistic for use of the oil burning tool. Texas has routinely used oil burning on land and especially for pipeline leaks in remote areas as well as oil releases threatening barrier island shorelines. Experience by the Texas oil spill cleanup cooperatives (industrial mutual aid groups) in using the burning spill response alternative has not been too successful. Similarly, Oregon was not successful in using burning techniques when attempts were made to burn oil off of rocks with propane torches. South Carolina, however, has had very successful experience using burning to quickly handle a large quantity of No. 2 fuel oil when threatening weather would not have allowed other alternatives to be used.

Both the Prince George's County, Maryland, and the Fairfax County, Virginia, fire departments have had experience in fighting oil fires and in using "burn-back" (where controlled fire is used) fire technology. Within the Charleston, South Carolina, Naval Yard, located in a urban area, more than 40 oil fires per week are ignited in an 800 ft^2 tank as part of a fire-fighting program.

7.1.3. Attitudes of Officials Towards Burning to Predict Probable Responses

The following selected comments are offered in a running narrative to illustrate a range of attitudes toward burning and do not constitute any statistical basis for comparison or decision.

States and Local Attitudes

In the State of Maine, burning will be reluctantly allowed, since they have an active program of landfilling and land farming oil-contaminated debris. Burning will normally be restricted to bagged oil-contaminated debris. Wyoming has a more liberal attitude toward burning but would prefer recovery techniques. Washington State takes the attitude that burning is prohibited, but exceptions can be granted on a case-by-case basis. Burning is, however, recognized by Washington as beneficial if it protects shorelines and marine resources (including fish and shellfish) in remote areas, or areas to which it is difficult to gain access. However, Minnesota is more concerned about generating black smoke usually associated with oil burning. It is therefore prohibited and exceptions would be granted only as a last resort.

Michigan looks at burning as a useful tool and would be guided by the recommendations of the Regional Response Teams (refer to 40 CFR 1510) as a most appropriate way to decide if this burning should be tried. Primarily, if the tool is considered as a last resort response, it is recognized as an appropriate action. This attitude is balanced by the air quality concerns which, for the most part, prohibit open burning especially in high population areas. Ohio is quite used to employing burning as one of several emergency response tools. Burning is used often enough that open burning criteria exist and a rather detailed procedure of field site inspection and permitting has been established. New Jersey, however, takes the attitude that open burning of oil could take place only at sea and not inland because of heavy opposition to resulting smoke and residue which might be created.

To use burning in the state of New York a top level policy decision is required since most of the debris disposal is conducted with licensed ultimate disposal facilities. Alaska recognizes that burning could be accepted outside the 3-mile limit when under Federal jurisdiction, but within the state jurisdiction (within 3 miles and on land and rivers) each case would have to be evaluated based on its circumstances. Some Alaskan authorities favor oil burning because of its minimal environmental effect compared to other alternatives in cold climates. The law totally prohibits burning within Wisconsin and only under rare exceptions would burning be allowed.

Texas allows burning, especially if it is in sparsely populated areas. Removal of the oil is preferred and, in some regions of Texas, burning is quite far down the priority list of spill response tools available. Recovery of oil from spills on water is common enough that an oil spill in Texas is reprocessed for approximately $0.10/gal. Illinois takes the attitude that if an oil spill is on private property it may be burned with a small spills permit; however, large spills can be burned only with approval of the Illinois authorities guided by the decision of the Federal OSC. Illinois is of the opinion that the OSC, especially the Coast Guard, would never authorize a burning activity without a State approval and the State often prefers a landfill or recycling disposal option.

Oregon would, if the technology were shown effective, use burning even though open burning is prohibited. Permits can be granted in an emergency on a case-by-case basis. The State recognizes that any burning activity beyond the 3-mile offshore limit is beyond its jurisdiction. California is so concerned that to encourage more rapid and advanced technology to be applied to oil spills the burning alternative would definitely be considered. Temporary smoke violations could be waived as long as safety, heat radiation, and other concerns were answered. California would require a generic environmental impact statement (which is required by state law). This pre-licensing step in California would also satisfy many of the questions and tradeoffs pertaining to the advisability and limitations of using the burning technology. South Carolina's concern was similar to California's except that effects of smoke and sulphur dioxide on people and coastal vegetation need to be identified. South Carolina has used the burning technology and it would appear that, if fact sheets were available, the oil burning spill response alternative could be used since proper disposal sites are limited in that state.

On the local level, Prince George's County, Maryland, considers oil burning to be acceptable, if the fire department were advised and were allowed to evaluate the situation and be on standby for any nearshore operations. Local air quality personnel are required to be consulted. The State Fire Marshall's

Office in Maryland need not be consulted. Fairfax County, Virginia, recognizes the usefulness of the burning technology, but is not particularly worried about any cost savings since those benefits would accrue to parties other than Fairfax County. The County visualizes situations where the OSC decision could be supported at the local level providing these authorities had been given appropriate fact sheets or decision trees analysis to understand the basis and status of the oil burning technique to be employed. Fire officials have authority during a conflagration to create a fire break using explosives, fire, and other means. Therefore, the use of combustion to mitigate an oil spill is an acceptable technological approach to these authorities. Both Fairfax County and Prince George's County as well as many other fire departments throughout the nation have had experience using "burn-back" firefighting strategies on grass fires and feel that these offensive firefighting techniques previously employed would be similar to those required for burning oil on water or open burning oil-contaminated debris.

OSC (Onscene Spill Coordinator) Attitudes

The attitude of the U.S. Coast Guard's OSC ranges from aggressive positive reactions for the oil burning option to negative hesitant thoughts of using the technology. The following thoughts were regarded as valuable for generally expressing the attitude of the OSCs. The USCG becomes involved in an oil spill usually after it has received notification of the spill. The timing of this notification is critical in evaluating the technical feasibility of using the burning alternative. Presently there is no Commandant Instruction or guidance directing USCG response personnel to proceed or not to proceed under dangerous situations such as inclement weather or an unstable vessel. Any additional safety afforded the response team by using fewer people working remotely from the stricken vessel or the oil spill site is therefore difficult to evaluate, including any savings due to use of the burning alternative.

USCG field personnel recognize the importance of having a complete environmental impact statement on file and available prior to specific consideration of using oil burning technology. A less concerned attitude towards the use of burning (10 to 15 miles offshore) was expressed by USCG personnel where, if need be, a unilateral action could be taken, but even then it is visualized for only a few cases. Remoteness of the burn is important to the USCG because of their responsibility to the locally affected populations. The USCG field personnel recognize that burning could be used if it could be clearly shown that nothing else could be done in the time frame necessary.

The USCG field personnel recognize that the responsibility for making the decision resides with the OSC; however, they feel that the Regional Response Team (RRT), or perhaps the National Response Team (NRT) must concur, if not decide, on the use of burning. Similar experience in deciding on the proper use of dispersants by the RRT has suggested that any unilateral decision on the part of the USCG, especially using the technology such as burning, would be most difficult. USCG field officers assigned to port areas look to the Coast Guard Strike Forces or to the personnel of the National Response Teams as experts in technology and would include burning in their areas of expertise. Once the decision is made on a course of response, the cost of implementing that response is of little operational concern to USCG. Costs are primarily considered during that response only from the tradeoff basis (Commandant Instruction 16450.1) when considering an alternative; then costs are important as record keeping. The decision to burn a vessel is recognized by USCG as being most difficult and for incidents involving collisions of vessels, the value of the vessels and cargo becomes extremely complicated to facilitate a quick decision to burn (e.g., ATLANTIC EMPRESS, AEGEAN CAPTAIN VLCC collision July 1979 off Tobago).

USCG field personnel reflect an attitude that they would be most hesitant to burn any light refined oils because of safety considerations. Field personnel could readily identify offshore locations where, if a tank ship were leaking in the summer, they could justify burning the vessel, but in the winter perhaps it could not be justified. Along the U.S. East Coast, tankers will be smaller, older, many with foreign flags and in marginal operating conditions. Such a situation poses a unique set of conditions for establishing the ethics of oil burning decisions. Certain coastal locations can be considered as candidate areas where stricken vessels could be burned regardless of season due to the high population and shoreline affected by oil coming ashore. Other areas can be identified where burning would be acceptable due to offshore prevailing winds, ocean currents, and spreading of the polluting oil with its associated localized effects on commercially harvestable marine resources. Controlled burning, rather than destruction of the vessel, seem most desirable to the USCG field personnel and the idea of using the offshore platform waste oil burner flares seem workable and appealing to the field personnel.

Industrial Attitudes

An industrial view of burning the oil cargoes of vessels at sea may be represented by ship classification groups and marine salvors. The classification groups are the surveyors who must be satisfied that a vessel is seaworthy and safe such that it may be insured. The marine salvor is the person engaged in time of incident to recover the ship and the cargo to the greatest extent feasible. The view of the burning option by this segment of industry is not positive.

The American Bureau of Shipping (ABS) prefers that an attitude prevail such that the first priority is to save the ship and crew and secondly to save the cargo. The age of the vessel as a factor in deciding to burn or not to burn is regarded by this group as unfounded. This group attitude is "there is much more assistance available to a stricken tanker than masters usually call for in sufficient time that it would do some good." The use of rapid cargo offload should take place as soon as possible after a tanker casualty. The information available to a master upon entry into United States waters is not adequate, e.g., the availability of emergency services and contact points.

The attitude reflected by this group is that grounded tankers can be readily stabilized by flooding. It was suggested that the number of groundings has reduced since vessels began complying with the 1978 Load Line Convention instead of operating under the 1966 Convention which permitted vessels to carry more cargo and ride lower in the water.

The American Bureau of Shipping contends that 10% to 20% of deckplate being removed for initiating an oil burning action in situ vessel combined with the intense heat of combustion would affect the stability of the vessel since the deck is one of the vital structural members of the tanker vessel. These deckplates are considered as vital to the vessel strength just as the hull bottom plates. An extensive periodic inspection program is conducted by ABS to ensure vessel deckplate thickness meets standards. The attitude of the ABS pertaining to use of flaring aboard a tanker was rather positive as long as a certain amount of testing and control was undertaken.

Statements from Lloyd's Register of Shipping personnel indicated that they agree with the American Bureau of Shipping on the structural problems of vessels whose oil cargo was burned. However, they disagree that the vessel age and depreciation value was not an important consideration in a burning decision. Lloyd's suggested that the vessel value is most dependent upon age, equipment on board, and vessel maintainance. Lloyd's expressed the opinion that the Protection and Indemnity Clubs (see Section 7.2.4) are the groups with the largest financial stake in the vessel burning decision.

The London Salvage Association and the Murphy Pacific Salvage Company (no longer in business) provided additional insight into the attitude of the marine salvor pertaining to burning oil in situ vessels. Both organizations are negative to the burning alternative. They are motivated to saving the vessel and crew first and the cargo second. They are proud of their salvage expertise and their records of success. The London group suggested that changes in the deck configuration or cross section would certainly accentuate the breakup potential of the vessel.

The salvors indicated that they are routinely not contacted early enough in the tanker casualty to fully render all salvage assistance possible. Even with the apparent wide disagreement on the ease of sinking or ballasting and stabilizing a vessel, the salvage organizations are confident that they can stabilize most grounded vessels. The London Salvage Association expressed concern that a "military man" might be in a position to make the decision to burn a vessel without having intimate knowledge of that specific vessel or of salvage procedures. Organizations such as London Salvage have detailed characteristics and prints on most vessels. The attitude of Murphy Pacific is that the role which a salvor could play in a burning response would be to stabilize the vessel by ballasting, towing, or other techniques which would enable others to implement the burning action.

The attitudes of this segment of industry towards burning may be summarized as a traditional marine salvor's way of doing business as noted above. Risk is such that the salvor gets paid if he succeeds. While flaring off oil in sufficient quantities to lighten a grounded vessel may be a tool that a marine salvor could employ sometime in the future, burning the entire content of the tanker would require a considerable readjustment of the thinking of this segment of industry. The attitude has been, and will probably continue to consider tanker vessels which might be valued at about $1 million per 10,000 DWT are worth jeopardizing $15 million worth of salvage vessel and equipment because the ethic established by this industry is to recover resources in the form of vessel and cargo.

7.2 ECONOMIC CONSIDERATIONS

This topic is a major study in itself and therefore only qualitative statements may be made to suggest trends and items which may be considered by responsible officials. Of the three conditions (burning oil in situ vessels, on water, and debris) the vessel burning is by far the most complex economically and consequently is treated in more detail below.

7.2.1 Generalized Observations

Oil can be valued at 20 U.S. dollars per barrel and still escalating. Oil tankers have values from a few million to more than 50 million dollars. Oil aboard the large tankers can be thought of to be valued at $0.50 to $1/gal ($130 to $261/ton). Many countries now have oil pollution control laws, the violation of which can cost thousands of dollars. Released oil cleaned up by conventional means can cost from $840 to $6720/barrel recovered[a] which might be reprocessed for $4 to $5/barrel. This would place the value of the recovered oil at an extreme market value if all costs were included. The pollution cleanup liability is placed at not to exceed $147/gross ton or $16.8 million, whichever is greater, by IMCO international agreement, and domestic law in the United States. The U.S. Congress is continuing to evaluate a "Superfund" bill which would establish a $300/gross registered ton and $30 million limit. However, these claims do not limit the ability of third parties to claim damages resulting from the oil release and/or subsequent inept cleanup attempts. Suits pending from the loss of the AMOCO CADIZ amount to $1.5 to $3 billion.

Those of the opinion that recovery of the released oil should have the top priority must accept the fact that technology for recovery is limited by its availability at the spill site and by weather and casualty conditions. The ARGO MERCHANT case is most illustrative of these limitations. As response costs are compared, the burning alternative should only be compared with other "non-oil-recovery" techniques, e.g. gelling, sinking, and dispersing. The costs of these techniques have been suggested in Appendix D. The costs of recovery should include not only those personnel paid to clean up but also value lost due to the quality of oil which is recovered and the additional costs of disposal of oil-soaked material and cleanup of equipment. It would appear that by using the conventional physical removal and trying to reuse the oil collected, it would be impossible for boiler quality oil (heavy residuals)

(a) Source: USEPA, Oil and Special Materials Division, Washington, DC, July 1979.

to be delivered to a user at any reasonable cost per barrel where all costs are included ($ for original oil + $ for skim type recovery + $ for reprocessed or cleaned + $ for handling, storage and transportation).

Since the consumer will ultimately pay these costs (regardless of liability claims decisions) by increased oil prices, the cavalier attitude of some that we must protect the environment from oil release by physical cleanup at all costs is subject to question. That question would quickly lead into a comparison (see Figure 7.2) of costs of cleanup versus environmental damage prevented or lessened which is beyond the scope of this study.

It should be of interest to note that the recent decisions in the United States courts have found the Federal government's case wanting to prove that cleanup costs beyond those limits noted above should be paid by the discharger. This and other factors place another burden upon the OSC to choose the most cost-effective cleanup technique which would not cost more than that for which the discharger is liable, unless the OSC intends to obligate the Federal government to pay for the cleanup. If the latter were true, then taxpayers in a distant western state could be paying for the oil discharge caused by a vessel, possibly not even a U.S. vessel, on the East Coast. These economic considerations would be argued by some as exceeding the intent of Congress which has been suggested as the "polluter pays." Therefore, the OSC must become more keenly aware of the economic considerations pertaining to each discharge and the most appropriate mitigation alternatives.

7.2.2 Economic Subtleties of Vessel Casualty and Liability

If all the economic effects of an oil spill response action were known to enable the OSC to make a clear and economically justifiable decision, it would be desirable to understand which party, if any, would benefit by the response decision. Actual spill costs will have to be more carefully accumulated for a range of spill incidents to be most meaningful. However, it is not clear from this investigation that burning a stricken vessel would be of economic benefit except in that rare instance where: the tanker and cargo were owned by the same party; that party is self insured; and the pollution potential (cleanup costs) plus property claims (damage) is predicted to be so large that this

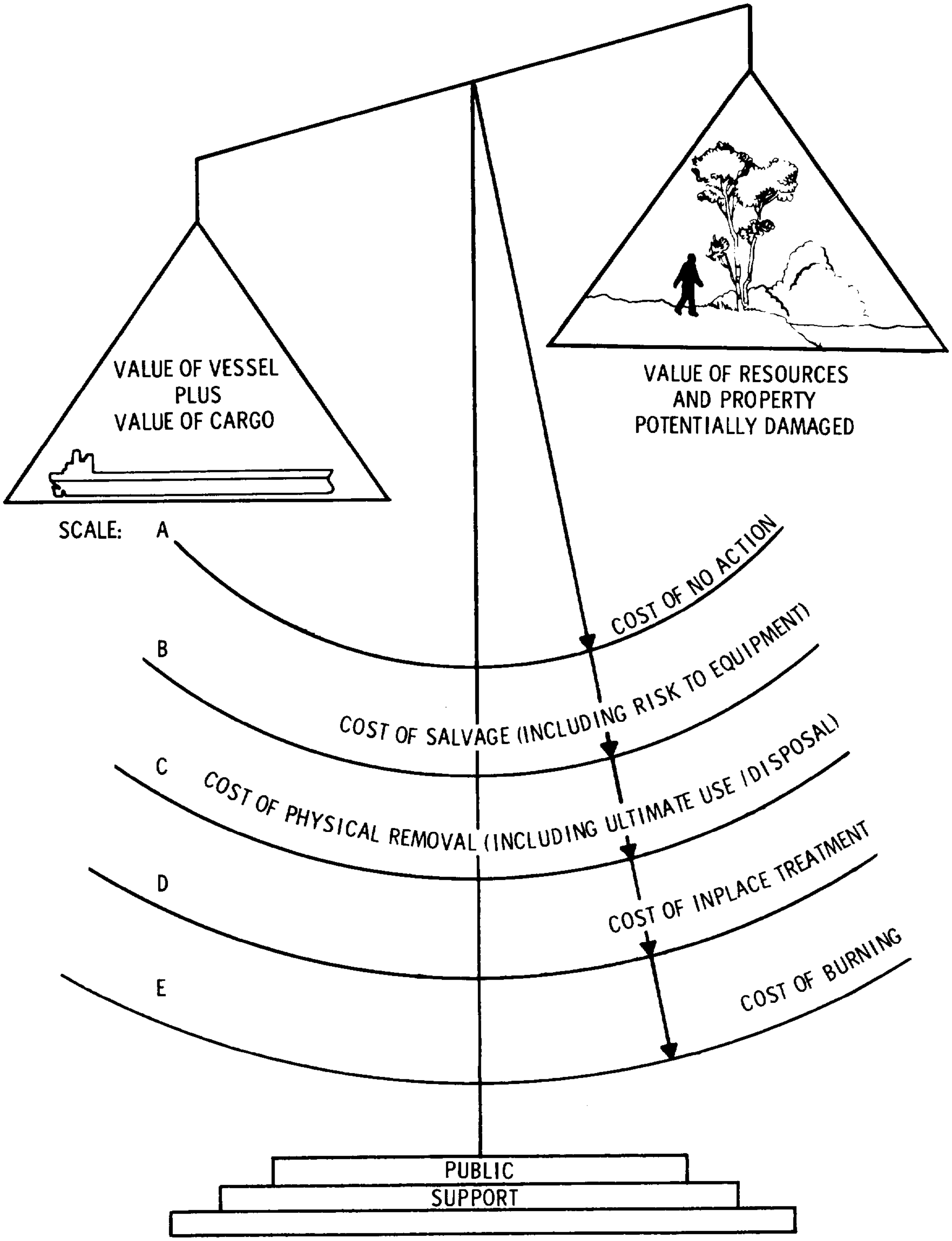

FIGURE 7.2. Comparison of Values and Cleanup Costs

sum will definitely exceed the value of the vessel and cargo. The following discussion illustrates the common economic considerations to which an OSC must be responsive in a marine casualty.

Among those with a direct interest in the casualty can be listed the shipowners, various hull and cargo underwriters, shippers, consignees, surveyors representing widely separated interests, and the numerous representatives of governmental bodies. It is not uncommon to prepare a program of those in attendance because it may be difficult to keep track of the participants and their various interests. The following discussion explains the liability situation from an operational viewpoint; it does not cover the ultimate legal question of liability.

Shipowners

In the occurrence of a marine casualty the immediate actions vary greatly; much depends on the experience and station of the shipowner. A strong and suitably experienced shipowner will generally take the initiative and do what needs to be done. He will remain cordial to all the interested parties but will behave in the great tradition of "an uninsured shipowner," acting in his best interest to protect his property and limit his liabilities. This is a good workable approach but one rarely undertaken; unfortunately, few owners have the experience, strength, and self confidence to proceed without due consideration to the other parties.

While a strong shipowner is well aware of his hull, machinery, and cargo coverages, and what protection and indemnity protection he has, he will proceed to mitigate the casualty in accordance with his best judgment at the time of the casualty. The various financial interests just mentioned will normally be represented at the casualty site mainly to advise the owner and not to direct operations.

Variation of opinions is common among those at the casualty site. A secure guiding hand is always necessary to minimize financial loss in terms of hull, machinery, cargo, and the potentially costly pollution aspects. Since the introduction of the Sue-And-Labor provision in hull policies, the owner need not concern himself excessively with the recovery aspects for his efforts to save the vessel and cargo. The underwriters will usually reimburse the owner for reasonable legitimate actions required to minimize ultimate loss. If the entire vessel were lost, as may be experienced in a constructive total loss, the owner can recover the insured value of his vessel plus costs incurred in trying to mitigate what becomes apparent as a total loss. This widely accepted provision allows the owner to proceed, without delay, to undertake such salvage actions as are considered necessary. However, the decision to burn the oil cargo and the vessel would be such a drastic action that much time would be spent determining if the action were necessary.

This traditional approach of owner responsibility for immediate action has carried over into casualties associated with mitigating pollution-related incidents, but still in the context of protection of vessel and cargo. Section 7.2.4 briefly outlines the characteristics of Protection and Indemnity (P&I) Clubs in casualty instances, but the ship, regardless of the general characteristics of the casualty, remains the owner's responsibility. With the possible singular exception of seizure/abandonment, it is the owner's responsibility to act in the best interests of all his underwriters. The IMCO Intervention Convention of 1969 allows coastal states to take measures as necessary to prevent grave and imminent danger to their marine resources resulting from oil spills. Therefore, if a coastal state is unsatisfied with the actions of the owner/salvor/pollution mitigation actions, the Act of Intervention is declared and the state assumes responsibility for the actions, including steps toward cargo and vessel destruction.

The "Owner-Always-In-Charge" concept is idealistic and, realistically, the interested parties can bring significant force to bear in most instances of ship casualty. While few have the direct courage to threaten loss of insurance coverage, the implication nevertheless is quite clear: "play by our rules or we won't pay your bill." With the exception of the large and financially secure shipowner, most shipowners are quickly aligned into the myriad of desires of the pressure groups associated with the casualty.

Brokers

American and London insurers for Hull and Machinery have traditionally maintained their business distance from the policy holder. The shipowner's insurance broker sits between the policy holder and the insurance underwriters; direct communication is generally maintained through the broker (as an invisible link in the chain). The designated marine surveyors for the underwriter are also linked into the system. The owner, by tradition and policy coverage, should take such actions as are deemed reasonable and necessary at the time of the casualty and immediately following. Eventually the owner prepares his claim which his broker presents for payment by his underwriter. If the actions taken by the owner are deemed proper (often as evaluated by the marine surveyors), and within the apparent coverage of his insurance, the claim for payment will be settled in due course.

Leading Underwriter

In the London market one underwriter within a group or insurance pool takes the sponsorship role, for example for hull coverage, to prepare to insure. Other underwriters within the group share the risk by percentages and the broker is then advised of the policy, premium and any special conditions.

Scandinavian and German underwriters have a somewhat closer relationship to their assured shipowners. Perhaps this relationship stems from the tradition of mutual associations for insurance, wherein the shipowner is his own underwriter on a mutual cooperative basis with other shipowners. It is common to observe the leading underwriter and shipowner working together for the protection of their mutual risks.

The OSC and other advisors should note these market differences to perhaps better understand the ethical relationship associated between varied owners and their further dispersed underwriters. These relationships are often the cause of nonuniform delay, evaluation and lack of decisiveness. In addition to the abovementioned markets, there are self-insured ships operated by governments, the participation of a very large Japanese hull market, and the further distribution of insurance coverage within varied and often complex reinsurance treaties and direct placements.

In Norway, the leading underwriter is the insurer appointed by the shipowner to take the lead in the handling of casualties and to make decisions and claim adjustments with binding effect on co-insurers. The leading underwriter also calculates additional premiums and returns. The system to appoint one of the insurers to take the lead in these matters is used chiefly in Scandinavian countries. The leading underwriter is authorized on behalf of the co-underwriters to make decisions regarding salvage, repairs, and legal proceedings; to provide security to third parties regarding collision, contact damage and salvage; and to make arrangements for and prepare statements of claims which are binding on the co-underwriters, providing they are in accordance with the insurance conditions. He handles all matters relating to a casualty from the time it is reported to him until the claim adjustment has been drawn up and settlement effected.

This system of only one claim handler works efficiently when decisions have to be made and there is little time for discussion; e.g., collision in American waters requires decisions on which salvors to hire, which guarantees to post, which jurisdiction to agree upon, and whether to repair the ship in the U.S. or to tow it to Europe. The owner of the casualty need only confer with his leading underwriter to discuss all questions regarding action to take. It is the leading underwriter's responsibility to see that the owner gets what he is entitled to.

"Chain of Liability"

The instance of a singular shipowner, his hull and machinery underwriter, and one Protection and Indemnity Club is rare. A common configuration would illustrate a distant nonoperating shipowner under the management of a separate marine services company with the vessel initially chartered and subsequently subchartered to other parties or interests. With consideration to tankers, particularly those in the parcel trade, a significant number of cargo underwriters and reinsurers can be identified together with their principals. Immediately following a marine casualty it is often difficult to identify all the interested parties to solicit their varying opinions and desires. For this reason all parties look to the owner for suitable action. The general presumption is that the shipowner will act in the best interest of the voyage; this includes, saving passengers, crew, the ship itself, her machinery, and cargo.

In a tanker stranding, where the master decides to jettison or burn a portion of the cargo consigned to his vessel, in the interest and safety of the voyage, it would not be unreasonable to assume that the vessel owners would have a prorata responsibity to the cargo owner. It would further be reasonable to assume that the cargo owner would be reimbursed for his total insured loss to the extent that his cargo may have been destroyed. It is particularly significant to note in considering time and probability of cargo loss claim settlements, that only in the most unforeseen circumstances will hull and cargo underwriters be the same. A divided economic and chain of liability interest can always be assumed in a tanker casualty.

7.2.3 Oil Pollution Compensation Funds

In response to expensive oil spill cleanup and damage costs incurred by the TORREY CANYON spill in 1967, various programs were initiated to ensure that spilled oil is cleaned up quickly and that persons and governments are promptly compensated for cleanup costs and damages. Several review papers and graphic illustrations have been prepared on this subject and reference should be made to the proceedings of the USCG/USEPA/API National Oil Spill Control Conferences (Craven, 1979) (also see Appendix E, Decade Capsule).

Inter-Governmental Maritime Consultative Organization (IMCO)

Under the auspices of a specialized agency of the United Nations Organization the maritime agency, IMCO, has created an international regime to pay for cleaning up oil spills. Under two combined IMCO programs, about 60 million U.S. dollars are currently available with further increases to 72 million under review. The funding programs are the Convention on Civil Liability and the International Oil Compensation Fund, which were created in 1969.

Under the Liability Convention, shipowners have strict liability for pollution caused by their vessels up to $16.8 million per incident. This

Convention also covers third party damage, an effort advanced by IMCO and ratified by 33 countries. Its application is limited to an oil spill from a loaded tanker affecting the territory of a contracting state. The Liability Convention came into force in 1975 when the required number of countries ratified the agreement requiring tanker owners to pay a certain sum per gross registered ton of the ship's tonnage into the oil pollution cleanup fund.

The limitation of liability to shipowners established by the Liability Convention featured in the matter of oil damage suffered along the coast of Brittany in 1978 by the grounding and breakup of the tanker AMOCO CADIZ. France, as a signatory to the Civil Liability Convention, is limited to a maximum damage claim of $16.8 million. Estimates of the damages claimed are varied but are believed to be in the range of $200 to $300 million representing the French Republic, French municipal governments, fishermen, hoteliers, and the citizens of Brittany. Law suits totaling nearly $3 billion[a] have been brought in the United States, not a contracting member of the Civil Liability Convention. U.S. courts granted a temporary injunction on claims against Amoco and considerable discussion resulted on proper location for court proceedings. Under the Liability Convention ground rules, France could have brought suit in a French court or in Liberia which has ratified the Liability Convention agreement. French officials chose not to sue Amoco Transport, the Liberian-based shipowner, but Standard Oil Company and Amoco International, the subsidiary that manages the company's fleet.

Despite the immense outlay in man-hours and money for the AMOCO CADIZ cleanup, the effectiveness of the cleanup is questionable. It has been noted by pollution experts that in spills of this size and catastrophic consequence, no insurance or indemnity is good enough. From this particular case, the OSC or others considering the ethics of a response type should understand that the ultimate liability for pollution is not well defined in terms of the parties and financial scope.

(a) Oil Spill Intelligence Report, March 23, 1979, p. 13

The International Oil Compensation Fund Convention (also sponsored by IMCO) provides prompt payment to victims of oil pollution damage beyond the limit of the shipowner's liability. Companies importing by sea over 150,000 tons of oil into ratifying countries are required to pay a specified amount of money to the Fund for every ton of oil imported. The Fund's obligation to pay compensation is confined to pollution damage in the territories and territorial seas of contracting states and in respect of measures taken by contracting states outside their own territory. The terms outlined in the Fund Convention will be kept under constant review and raising the limit of compensation is regarded a prime concern. In order to come into force, the Fund required (and achieved this late in 1978) signatures from 10 countries importing over 750,000 tons of oil each year. Where under the Liability Convention limited oil damage compensation is paid by the shipowner, the adoption of the Fund enables further compensation to be shared by the oil companies, the shippers, or consignees. The Fund can also supply assistance to contracting states which are threatened or affected by pollution and wish to take preventative or corrective measures against it.

In the interests of cargo owners the Fund Convention is designed to supplement the Liability Convention (for the interests of shipowners) for oil pollution damage, cleanup and third party claims. The Fund also indemnifies tanker owners subject to the Liability Convention for a portion of their liability. The Liability Convention compensation funds are maintained by tanker owners who pay a certain sum per GRT (gross registered ton) of the ship's tonnage. The Fund convention is maintained by cargo owners who pay a certain sum per ton of oil imported into ratifying countries.

The Fund Convention increases the amount of compensation payable to victims of oil pollution from ships, effective with oil spill incidents occurring on and subsequent to February 16, 1979. Fifteen countries ratified the Fund Convention by 1979. They include Algeria, the Bahamas, Denmark, France, the Federal Republic of Germany, Ghana, Indonesia, Japan, Liberia, Norway, Sweden, the Syrian Arab Republic, Tunisia, the United Kingdom and Yugoslavia.

Voluntary Shipowners' Funds

TOVALOP and CRISTAL are voluntary agreements establishing compensation funds maintained by tanker owners and oil companies to ensure that prompt action is taken to contain and clean up accidental oil spills. Both programs were designed to precede and eventually supplement the IMCO regimes, the Liability Convention, and the Fund Convention. Tanker Owner's Voluntary Agreement Concerning Liability for Oil Pollution (TOVALOP) was adopted in 1969 by shipowners to provide compensation for oil spill cleanup until the Liability Convention came into force. Under TOVALOP, the tanker owner compensates national or local governments who either clean up a spill or remove the threat of a spill to any coastline. The shipowner's liability for such government cleanup cost is $100/GRT of the tanker involved, or $10 million, whichever is less. The shipowner is also encouraged to respond promptly and to undertake cleanup or threat removal action with assurance that costs incurred for such actions will be promptly reimbursed.

TOVALOP is administered by an organization called the International Tanker Owners Pollution Federation Limited. In 1978, the agreement was amended to include compensation for pollution damage in addition to cleanup costs. Protection and Indemnity Clubs (discussed later) protect shipowners for similar costs up to a limit of $125/GRT or $10 million, whichever is less. TOVALOP provides that the owner has no liability if the ship is not at fault. However, negligence on the part of the tanker and its owner is presumed, and the owner has the burden of proving lack of negligence. TOVALOP does not apply where liability is imposed under the terms of the Civil Liability Convention, and is now viewed as a supplementary financial regime for compensating both public and private persons suffering damage in countries where the terms of the Liability Convention do not apply because the nation has not ratified it.

TOVALOP is applicable to a spill that occurs anywhere if the owner is a participant in the TOVALOP regime. Oil spill compensation under the Civil Liability Convention is limited to an incident by a loaded tanker within or affecting the territory of a contracting state. TOVALOP covers both loaded and ballast voyages, while the Civil Liability Convention covers oil spilled from a loaded tanker (lesser of $147/GRT or $16.8 million).

The Contract Regarding an Interim Supplement to Tanker Liability for Oil Pollution (CRISTAL) is a compensation fund supported by oil companies to supplement tanker owners cleanup costs after certain limits and third party damage claims from other sources have been exhausted. CRISTAL will probably remain in effect until the IMCO Fund Convention, now in force, becomes widely effective. The parties to CRISTAL are oil companies and the Oil Companies Institute for Marine Pollution Compensation Limited. The Institute, which administers CRISTAL, receives funds through contributions from member oil companies. In 1971, the Institute made an "initial assessment" on members for $5 million ($0.0635/barrel received by its members via sea). A second assessment of about $3 million was collected in 1976. The Institute will reimburse the shipowner for costs incurred in pollution cleanup, or in the removal of the threat of pollution, in excess of $125/GRT or $10 million, whichever is less.

CRISTAL provides for third party pollution damage. The Institute will pay a maximum of $30 million, (less the amount of the owner's cleanup costs), any liability of the owner under TOVALOP, and any liability of the owner or anyone else toward the claimant. CRISTAL does not apply where a shipowner is not or would not be liable under the Civil Liability Convention, e.g., ballast voyage.

Since inception, both TOVALOP and CRISTAL have been improved by amendments. Both schemes were changed to include provisions which encourage action to remove the "threat" of a spill. TOVALOP was amended to eliminate both TOVALOP and the Civil Liability Convention from being available concurrently to compensate government claimants in a Liability Convention spill. Cargo-related compensation plans such as CRISTAL and the IMCO Fund Convention involve a monetary fund into which specified contributions are made based on oil tonnage imported by oil companies and transported by sea. The maximum available compensation per incident, prior to February 1979, when supplemented by CRISTAL was $30 million, after remedies from other compensation plans had been exhausted.

During the AMOCO CADIZ casualty in 1978, the owner Amoco Transport established a fund of $16.8 million, its limit as a contracting member (Liberia) to the Civil Liability Convention for pollution liability. Under the terms of CRISTAL, an additional $13.3 million would be available to bring cleanup and third party damage compensation funds to a combined limit of $30 million. By comparison with the TORREY CANYON casualty involving a cleanup cost of about $7 million, the above available compensation would have been comfortable. However, as stated previously, AMOCO CADIZ pollution costs are estimated at $300 million, rendering even the recently doubled Fund Convention inadequate.

A significant effort has been made to compensate innocent parties for pollution damage. The availability of the several multi-million dollar funds has created immense claims on this compensation system. There is liability and financial limits confusion in today's regimes. Each pollution claim may vary from the last, and only final interpretations will determine the limit of the various compensating funds.

Proposed Compensation Funds

In addition to the voluntary and intergovernmental programs described, a "Superfund" proposal is under consideration in the United States Congress, which is designed to eliminate the burgeoning individual state and national schemes. Superfund would cover resource (wildlife) damages, as well as third party or property damage plus cleanup costs. Superfund would be the only regime to impose a minimum liability on the shipowner in advance of fund availability in the amount of $250,000. The proposed Superfund itself would have unlimited liability. Shipowner liabilities under proposed Superfund legislation would be the lesser of $300/GRT or $30 million and would apply to both persistent and nonpersistent oils. One amendment contains a minimum shipowner limit of $250,000. Another amendment would lower inland barge owner liability to $150/GRT with a limit of $150,000.

Superfund would impose liabilities on nontanker operations such as offshore oil production. In such circumstances the operator's liability would be $50 million. This would be of particular value if situations like Santa Barbara, Timbalier Bay or Bahia de Campeche platform blowouts happened in U.S. waters. Superfund legislative proposal preempts application of other state and national oil spill compensation statutes which is a significant factor for U.S. oil industry interest.

The United States Coast Guard has proposed regulations to implement the oil spill liability and compensation provisions of the Outer Continental Shelf Lands Act (OCSLA) Amendments of 1978 (September 18, 1978). These amendments establish a $100 million to $200 million fund for payment of cleanup costs and damage compensation in case of oil pollution resulting from an Outer Continental Shelf (OCS) operation. Owners or operators of OCS facilities are required to provide a $35-million guarantee of financial responsibility. The USCG has designed its regulations so that OCSLA fund and financial responsibility mechanisms can easily fit into the Superfund legislation (should that bill become law). To establish the fund, the proposed regulations authorize collection of a fee of $0.03 per barrel from the owners of oil produced on the OCS. A certificate of financial responsibility has been proposed which allows the applicant to select either insurance, surety bond, guarantee, or self-insurance to establish financial responsibility.

7.2.4 Protection and Indemnity (P&I) Clubs

These clubs function as a shipowners group or cooperative insurance organization. The P&I Clubs (Table 7.2) cover liabilities not insurable in the ordinary marine insurance market. Compensation regimes such as TOVALOP and the Civil Liability Convention generally require proof of financial capability to cover liability limits. Shipowners normally do this through insurance coverage with a P&I Club.

London P&I Clubs

English maritime customs and laws have influenced all worldwide ocean marine insurance. In the 1800s ships could, by law, be insured in England only by Lloyd's underwriters and two other companies. This tight control

TABLE 7.2. P&I Clubs with Interest in Oil Tankers

Assuranceforeningen Gard (Gjensidig)
Arendal, Norway

Assuranceforeningen Skuld (Gjensidig)
Oslo, Norway

Britannia Steam Ship Insurance
Association, Ltd.
London, England

British Marine Mutual Insurance
Association, Ltd.
London, England

Canadian Shipowners Mutual Assurance
Association
Quebec, Canada

The Chartered Shipbrokers' Protection
& Indemnity Association, Ltd.
London, England

Danske Rederers Retsvaern
Copenhagen, Denmark

International Shipbrokers' & Agents'
P&I Club, Ltd.
London, England

The Japan Ship Owners' Mutal Pro-
tection & Indemnity Association
Tokyo, Japan

The London Steam-Ship Owners' Mutual
Insurance Association, Ltd.
London, England

Newcastle P.&I. Assocation
Newcastle upon Tyne, England

The North of England Protection
& Indemnity Association, Ltd.
Newcastle upon Tyne, England

The Oceanus Mutual Underwriting
Association (Bermuda), Ltd.
Hamilton, Bermuda

The Shipowners' Mutual Strike
Insurance Association (Bermuda), Ltd.
Hamilton, Bermuda

Schutzverein Deutscher Rheder V.a.G.
Hamburg, West Germany

The Standard Steamship Owners Pro-
tection & Indemnity Association, Ltd.
London, England

The Standard Steamship Owners Pro-
tection & Indemnity Association,
(Bermuda), Ltd.
Hamilton, Bermuda

The Standard Shipowners Mutual Freight,
Dead Freight, Demurrage & Defence
Association, Ltd.
London, England

The Standard Mutual War Risks Asso-
ciation, Ltd.
London, England

Shipowners Mutual Insurance
(Seamens Benefit) Association, Ltd.
London, England

Steamship Mutual Underwriting
Association (Bermuda), Ltd.
Hamilton, Bermuda

Steamship Mutual Underwriting
Association, Ltd.
London, England

Sunderland Steamship P&I Association
Sunderland, England

Sveriges Angfartygs Assurans Forening
Gothenburg, Sweden

The Transmarine Mutual Strike Assurance
Association, Ltd.
London, England

United Kingdom Mutual Steam Ship
Assurance Association (Bermuda) Ltd.
Hamilton, Bermuda

West of England Ship Owners Mutual
Protection & Indemnity Association
(Luxembourg)
Luxembourg

International Shipowners Investment
Co. S.A.
Luxembourg

The West of England Mutual Insurance
Association (London) Ltd.
London, England

The Shipowners' Protection & Indemnity
Association Ltd.
London, England

drove the cost of insurance so high that shipowners organized in groups to pool their losses. The owners leaned to groups of similar ships as a unifying factor, but their underlying purpose was a need to provide cooperative aid and to voluntarily share their losses with other owners. These mutual associations are centered in London and have now branched out to include the international shipping world. The fellowship generated from these nonprofit groups led to referring to them as "clubs" and today they are generally known as P&I Clubs.

P&I protection covers property damage and ship salvage; loss of life or personal injury; fines incurred for damage to property on another ship; or damage to fixed or movable objects such a dock, cable, bridge, wharf and the goods thereon. Liability for damage to cargo on board the ship itself is covered. P&I coverage was extended to include structures at sea, such as oil drilling platforms. P&I coverage usually equals ship insurance which normally is adequate when the shipowner is permitted to limit his liability to the value of the ship. P&I Clubs indemnify the owner in certain instances of pollution in addition to the regimes previously discussed. Other P&I insurance provisions have higher limits, e.g., a wreck removal order made upon the shipowner.

Scandinavian P&I Clubs

The Scandinavian P&I clubs work closely with their members because of the long tradition of the hull market risk being handled mutually by all interested parties. Scandinavian clubs generally accepted members from their own home waters. Recently these clubs are using the "London approach" accepting shipowners far from their homeland.

The central organization of the clubs is the Mutual Hull Clubs' Committee, with four members representing:

- the Unitas Club in Oslo
- the Arendal and Christiania Club in Arendal
- the Christianssand Club
- the Bergen Club

Other clubs include the Mutual War Risk Insurance Club and the P&I Clubs Skuld and Gard.

The clubs normally handle claims from the time an accident occurs until the settlement is made. The clubs advance the settlement amount to ease the member's cash flow. Reserve funds are invested with benefits passed on to the members by reduced premiums. The clubs supply other services and benefits such as consultative advice in preparing claim statistics, insured value, special conditions, rate quotations, and assistance in the handling of casualties.

Japan Shipowners Mutual P&I Association

The Association provides similar coverage as other international clubs, with two exceptions:

- No coverage is offered against one-fourth collision liability which is automatically included in Japanese hull policies.
- No coverage is offered for hospital, medical, maintenance, etc. expenses for the Japanese crew as they are insured by the Japanese Government under their National Insurance Scheme.

This club handles, through legal representatives in 250 ports, over 2,000 worldwide claims each year. In 1978 over $10 million (U.S.) were paid for about 1,700 property damage claims. Claims from oil spill pollution cleanup have now escalated to the point that they exceed claims rising from U.S. longshoremen injuries.

7.2.5 Salvage Associations

The London and U. S. markets have created the need for salvage expertise. The Salvage Association (nonprofit) was founded in 1856 by a group of underwriting members of Lloyd's and other marine insurance companies practicing in London who were experiencing difficulty dealing with the demands of worldwide ship casualties. The Association investigates damaged vessels and cargo, and provides surveyor assistance and advice to eliminate fraudulent claims. The Association, working for any employer, will accept instructions from shipowners, P&I Clubs, claim adjusters, attorneys (acting for interested parties), governmental agencies, merchants, or manufacturers. The surveyor assignments (20,000 cases per year) may be classified as in the area of salvage, ship repair, oil industry, cargo, and loss prevention.

The United States Salvage Association was founded by New York underwriters to perform similar functions as those outlined above but to concentrate in the American market. In a marine casualty, where underwriting interests are involved, a surveyor representing these interests can be expected at the casualty site.

In addition to these two principal surveying groups (London and United States), there are other associations and a large international body of independent surveyors that may from time to time represent any of the outlined interests.

7.2.6 Hull Underwriters

The hull underwriters are responsible for losses associated with the ship (hull and machinery) itself, not for losses associated with cargo or pollution liability. While some hull and machinery insurance cover is somewhat broader, the limited liability as outlined is generally ruling.

Major spills may invoke a combination of insurance and protection and indemnity coverage or self-insurance. Different coverage is available for tanker owners, refineries, drilling platforms, pipelines or other petroleum-related facilities. The insurance coverage for a potential spiller can be quite complex. A Cargo Risks clause under P&I coverage extends protection to the loss or damage to cargo. This would arise from unauthorized deviation, unseaworthiness, or improper navigation or management of the vessel and negligence in the care and custody of the cargo for which the shipowner is liable in respect of the insured vessel. Liability should be speedily determined following a spill as the degree of liability determines which course of action to pursue in meeting claims for cleanup and damage. However, many claims cannot be resolved as long as oil remains on the water or entrapped on coastlines or beaches as the threat of further pollution and liability lingers with this oil. While the liability picture may be a bit cloudy at the time of the casualty, it remains important for the shipowner, and cargo interests, to act "as though uninsured," and take those actions deemed necessary to minimize damage and ultimately limit the total liability. The OSC or responsible official must be aware of these principles to evaluate "adequate response" and make an ethical judgment. In the wake of a major oil spill, three types of claims may arise: class action claims, state and municipal claims, and individual claims. The most costly are class action claims filed by one person on behalf of himself and others who are similarly affected.

The direct avenue to recovery is not any easy one to outline, but, with the exception of the rarest of insurance cover, the hull and machinery underwriter cannot be directly linked to the pollution liability under his cover. The shipowner must look to other underwriters for this third party liability insurance.

7.2.7 Liabilities if the Ship is Deliberately Destroyed

The owner is usually required to clear difficulties resulting from his vessel's predicament. This liability involves pollution abatement and wreck removal. The owner may be called upon to pay the expenses of wreck removal when a ship is sunk or stranded in a navigation channel or sea lane. In the case of a collision, this can apply to either ship and if the insured vessel is held to be responsible for the collision liability, responsibility for the expenses of removing the other ship could fall on the insured.

Economic factors frequently determine casualty responsibility. The CHRISTOS BITAS, bound for Belfast in October 1978 with 35,000 tons of heavy crude oil, grounded on rocks halfway between the Welsh and Irish coasts. She was off course and out of the designated sea lane. The tanker was Greek-owned, internationally insured and partially covered by Lloyd's, and chartered to a partially Government-owned British oil company. Salvage was accomplished through the combined efforts of United Towing and BP Tanker Co. Ltd.

Complicated offshore cargo lightering operations dispelled major oil pollution risks, but the owners faced heavy costs in gas freeing, cleaning, and repairing the tanker. Furthermore, both countries were aware of pollution threats should the vessel enter port for repairs. No offer to present a port of refuge was forthcoming from any government. The cost to gas free and repair the ship was more than its total worth ($3.5 million). The decision was made to sink the CHRISTOS BITAS in deep Atlantic water. The resulting oil slick was contained to a few hundred feet.

Safe haven for casualty tankers has become a serious problem, and in a number of recent instances ships have not been able to make port until exhaustive pollution prevention measures had been accomplished. The traditional port of refuge for a maritime casualty seems to have disappeared when a threat of pollution is expected. This attitude should be carefully borne in mind by responsive officials directing response efforts to be limited to physical oil spill cleanup and ship salvage.

The 275,000 DWT Liberian tanker OLYMPIC BRAVERY ran aground in ballast on her maiden voyage in January 1976 and broke in two. A French-based scrap dealer offered to break up the wreck for ownership of the hull. The OLYMPIC BRAVERY was settled as a Constructive Total Loss, and one of the largest recorded marine casualties. The insurance underwriters declined to accept notice of abandonment and the ownership remained with the assured, along with the obligation to remove the gradually disintegrating wreck off the Brittany coast.

Governments have in the past made demands on owners to remove wrecks and to go to lengthy measures to limit the threat of pollution. Where in the past owners have attempted abandonment, it may be appropriate for responsible officials to note that this avenue seems closed as an ethical behavior -- certainly in the United States and in much of the maritime world outside the U.S. coasts.

7.2.8 Cargo Underwriters Liabilities if the Cargo Spill is Totally Lost or Causes Damage

Ocean marine insurance on cargo is written separately from hull insurance. Even in the case of large petroleum companies who own and operate their own fleets of ships, hull and cargo insurances are written separately under specially designed policies. As the liability of a shipowner or operator for loss of cargo may be limited to the value of the ship, the shipper's chances of collecting from the carrier for a cargo lost or damaged are limited unless he takes insurance on the cargo elsewhere. Loss from strikes, riots, civil unrest, or war is usually excluded but may be added by endorsement.

The concept of general average is outlined in the following section, and it is particularly important to note here that there is no general average contribution in the instance of total loss to all parties. Even where a limited recovery can be made, the sacrifice may be prorated on a percentage basis far below that of any related to lost values. Most cargo policies are subject to a Free of Particular Average (franchise or deductible) clause. This may provide that the insurance is free of particular average except loss from stranding, sinking, or burning or it may provide free of particular average above a specified percentage of dollar amount. Cargo insurance policies usually provide a method of determining the value of the cargo for insurance purposes. The tanker ANDROS PATRIA, as an example, suffered an explosion off the coast of Portugal in 1979 and lost 50,000 tons of oil cargo. Two British Petroleum tankers were used in a cargo lightering operation under adverse weather conditions. Subsequently, the ANDROS PATRIA was arrested at Lisbon and her Greek owner informed he must provide security against the oil lost and expenses incurred in salving the remaining cargo. The value of lost oil was about $4.6 million; the vessel at the time of arrest was scheduled to be scrapped. The German barge carrier MUNCHEN, lost in the Atlantic December 1978, was valued at $34 million with a cargo of 83 barges containing steel products and general cargo, valued at $23 million. The United States marine market was actively involved in the total loss from both hull and cargo risks and reinsurance undertakings.

A unique settlement for oil pollution damage involved the M/V POLY-COMMANDER and a "black rain" phenomenon at Viga, Spain, 1970. Subsequent to grounding, a fierce fire developed from the escape of crude oil and generated two whirlwinds. One of these whirlwinds developed a base diameter of approximately 200 yards and formed over a free floating oil area, causing oil in tiny droplets to be lifted to high altitudes. The black rain came down on farmland, destroying the crop, although the farmland was not rendered useless for future cultivation. The total amount paid in compensation for damage caused by black rain was approximately 300,000 Norwegian Krona.

7.2.9 Liabilities if Cargo is Deliberately Destroyed

A general average arises when a sacrifice is deliberately made in time of peril by one of the parties involved for the benefit of all concerned. A situation might arise when the master considers it necessary to jettison part of the cargo for the safety of the crew and ship. In the case of the ZOE COLOCOTRONIS, aground off Puerto Rico in 1973, the ship's master directed a deliberate discharge of 1.5 million gallons of oil to lighten the ship in an effort to become clear of the strand. The discharge resulted in extensive damage to mangrove swamps on the island. The court granted relief to the Commonwealth of Puerto Rico on several counts including the sum of $75,000 in cleanup costs, $500,000 for pollution damage, and $5,526,583.20 for damage to marine organisms.

Where the ship's master may wish to jettison cargo to lighten the vessel or for purposes of ship stability, he will in fact remain responsible to the cargo owner for his loss. This adjustment is generally accomplished, on a prorata basis from totaling the salved and lost properties. This adjustment is performed within the established rules of a general average. In most instances of cargo loss, the cargo owner must look to his underwriters for payment of the loss. These underwriters may in turn look to third parties for further liability assessment and financial recovery; in the instance of deliberate destruction of cargo, it may seem certain that recovery will be attempted by the cargo underwriters.

7.3 ETHICS OF BURNING

In Sections 7.1 and 7.2, selected concerns of responsible officials and economic considerations were discussed. Elsewhere in this report are discussions pertaining to the technological feasibility of burning oil under the three study conditions. This discussion is based upon the premise that it is technically feasible to use combustion to mitigate oil spills and therefore the pragmatic question: should burning be used. Eight issues summarize the tradeoffs, or advantages and limitations of using oil burning instead of other spill response techniques. These issues include: authority; action; logistics; safety; environmental/health; cost and property value; energy recovery; and permanent solution.

Issue 1 - Authority: For success in an oil spill response, there must be leadership which is clearly recognized, accepted, and justified as technically and administratively competent by all parties.

- For Burning: The legal authority for burning oil in situ vessels and elsewhere exists for the USCG in the High Seas Act - Intervention Act (PL 93-248) and in Section 311(d) of the Federal Water Pollution Control Act as amended. This authority is delegated to the Federal OSC as documented by Presidential Executive Order and the National Contingency Plan 40 CFR 1510. Three National Strike Forces are maintained by the USCG to technically assist OSC activities pertaining to oil spills. The USCG administers the revolving fund, Section 311(k), to enable commitment of spill mitigation expenses. The USCG Research and Development Program has invested in fundamental burning feasibility studies, use of flaring techniques and use of portable incinerators for debris disposal. Liberal use of RRT and NRT by the OSC would minimize criticism and should optimize the success of the burn option.

- Against Burning: The U.S. Navy may be recognized and accepted as a competent authority for salvage operations, but neither the USN or USCG are accepted by the shipping community as having experts capable of burning oil in situ vessels, or burning released oil. These organizations or the marine salvage or cleanup contractor organizations have little, if any, recognized competence using combustion to mitigate oil spills. The private sector's leadership is therefore equally lacking in this authority, and during an incident this lack of accepted authority would make the decision to use combustion difficult for the OSC. Even with portable incineration technology available, local air pollution authorities may legitimately block burning.

Issue 2 - Action: The speed of implementing activities should meet or beat the time required for the adverse effects to take place.

- For Burning: Conceptually, the burning option may be implemented in a matter of hours. The burning option in situ tankers can be visualized, using weaponry, as taking place very rapidly, but manually placing explosives will take time. Rates of burning would suggest that successful burns could be completed in 4 to 5 days. Burns on oil in open waters of ice-filled waters can be completed in 2 to 4 hr. Burning the debris (oil-soaked flotsam) which was washed ashore reduces the handling and disposal, time and therefore reduces the time of oil exposure to other wildlife. Effects of oil spills include toxic action, but most of the widespread and lasting effects are physical contact related. These effects are most dependent upon physical forces moving, spreading, and emulsifying the oil in time frames of hours to days. The decision maker could demonstrate rapid and deliberate response in taking the decision to use combustion.

- Against Burning: The decision pertaining to a response course of action to follow is often evolved by the OSC and his advisors in the first few hours or even days after a release. This type of delay works against the success of burning: in situ vessel - because of reduced stability and structural integrity of the stricken vessel; on water - because of weathering and oil spreading and emulsification; oil-soaked debris - because of spreading and increasing the volume of debris requiring disposal. The traditional considerations of salvors, cleanup contractors, and public officials for recovery of oil will have to be exhausted to the OSC's satisfaction before burning could be considered "as a last resort." The likelihood of success using burning is reduced with time.

Issue 3 - Logistics: Experienced manpower and reliable equipment and supplies with appropriate backup support must be readily available.

- For Burning: When compared to other response alternatives the size and quantity of equipment and supplies can be quite small. Conceptually, burning oil in situ vessels could require only five to ten people, an aircraft, and a response vessel. Equipment could range from sophisticated guided weaponry to shaped charges, igniters, and combustion promoters being hand deployed from the deck. Burning released oil can require only a few people, combustion promoters, primers, igniters and experience on their proper deployment. Burning oil-contaminated debris can be conducted onshore with fewer or the same people as required for landfilling or landfarming. Use of portable pit burners or incinerators can further reduce manpower but increases the need for equipment. Much of the combustion-related equipment is visualized as air transportable with the exception of rotary kilns, etc. Many combustion promoters and primers will be found locally. Firefighting personnel experienced in use of "burn-back" or "fire-break" techniques can be found locally in U.S. coastal cities and surrounding areas to aid in the implementation. Manufacturers of some combustion promoters have stockpiled materials as have a very few response authorities. Arctic experience is successful to the point that practical tools are nearly available to industry from Canadian-sponsored oil burning developments and investigations. Severe weather conditions place existing removal techniques in a standby mode, creating the need for new technology to be demonstrated.

• Against Burning: Neither the OSC, the USCG Strike Forces, nor any other element of the Federal Response community have any identifiable combustion experience equipment or materials. Few, if any, mutual aid cooperative or cleanup contractors have any stockpile of combustion promoters and possess little, if any, skill in their use. Uses of offshore oil/water exploration flare burners are only now being evaluated for potential response deployment in Arctic or ice-filled waters. No designated combustion promoters clearly stand out as rendering spilled oil as susceptible to burning. Physical removal equipment already exists and can be deployed at strategic locations. Personnel are available to operate the equipment, or else because it is so uncomplicated, local labor pools can be hired to operate it. The public, industry, and the courts are familiar with the nonburning spill response alternatives and can make accommodations locally to assist the OSC. If burning were to be attempted, excellent results, better than those from conventional cleanup, would be expected along with additional monitoring, e.g., air quality or effects on vegetation.

Issue 4 - Safety: The personnel responding should be provided the maximum safety and health protection under the circumstances.

• For Burning: Conditions of inclement weather and a foundering vessel are common with the result being an oil spill. The loss of life attempting to offload cargo or attempting other conventional techniques must be a questionable risk. Conceptually, the burning alternative could be implemented risking a minimum of men on the deck of the stricken tanker. Salvors have had experience with explosive cutting and use of igniters, and Navy firefighters have had experience controlling petroleum fires aboard ship. Burning released oil could be conducted remotely from a vessel or aircraft. Conventional removal, storage, and transfer of released oil carries with it an unknown degree of risk from explosion or fire which is anticipated when employing burning. Since there are no guidelines advising USCG personnel when a situation is too hazardous for the public to expect them to pursue using conventional techniques, the burning alternative employing fewer people at greater distances may be safer. Safety of using burning for debris disposal can be assured by drawing upon local firefighting leadership and resources.

• Against Burning: Tradition and safety codes do not mix oil tankers, open flames, and igniters, etc., because of the unpredictable results. The techniques of putting men on deck a stricken vessel with explosives, igniters, and combustion promoters in weather or conditions which do not favor conventional offloading or other alternatives would be argued by many as not safe. If the burn in situ tanker was only a partial success, the safety of personnel reboarding would be questionable. Gas inerting systems on new tankers would have to be overcome by additional venting or reversing the flue gas flow. Unless carefully timed and remotely operated, this venting could allow the tank space above the oil to go through the explosive zone while personnel were working on deck. Use of weaponry on the stricken tanker by surfacecraft or aircraft, while extreme, would be dangerous until operational experiece were gained. Burned out hulls cannot remain a hazard to navigation and, therefore, still require disposition.

Limited experiences have shown that burning oil released upon water can pose a safety threat to surface craft. Confined bodies of water (harbors) or areas of heavy vessel traffic pose additional safety problems to responding personnel by reducing their mobility. Onshore debris burning may be argued as posing additional safety hazards due to multiple shoreside fires being propagated and therefore requires special control. Heavy sooting from most of the combustion techniques, except well-operated incinerators, applied to released oil creates the additional safety problems of navigation visibility and smoke inhalation which must be considered.

Issue 5 - Environmental/Health: Wildlife, property, and human health must be protected.

- For Burning: Oil releases or the potential for oil releases are of such notoriety that noticeable discharges are against the law in several countries regardless of degree of environmental harm. Typical physical oil handling techniques of offloading, skimming, or burial of debris are slow, and from experience are known to leave environmental problems. Burning can be fast and relatively complete. Areas of ice-filled waters, frozen land, and inclement weather hamper the conventional techniques and demonstrate superior uses of oil burning. Areas of physically delicate tundra cannot stand the displacement of the soil column or much other conventional cleanup disturbance. Burning is the environmentally "gentle" way of removing an oil layer over the tundra. Marshes that have important breeding grounds can be quickly cleaned using burning and consequently allow more time for recovery to provide necessary natural habitats.

Oil allowed to remain in areas of harvestable fish and shellfish presents a temporary effect which may be avoided by the use of burning. Oil slicks attract wild fowl if left in remote areas with the resultant black agglomeration of bird life so often published. Residue from oil slicks which have been burned lose some of this adhesive property. It would appear that the environmental effects from burning are very localized. Heat is not radiated great distances in the air or water. Mobile life forms can avoid the area. Refertilization of a nearshore or onshore burn site allows rapid recovery even under Arctic climates. In temperate climates open burning of oil and the associated soot fallout nearshore may not be as severe on crops as the evaporated and unburned hydrocarbon vapors. Some effects have been known to last one season with the following season yielding a greater crop than the preceding season of the burn. It is not known if the burning increases the volatilization of polynuclear aromatics (PNA) or partially combusts them.

- Against Burning: Health effects on man caused by oil discharged into or upon the waters have yet to be conclusively shown. However, airborne polynuclear aromatics are a source of concern to many as are atmospheric distributed metals. The health effects of both of these types of materials are usually related to prolonged intermittent or chronic exposure. The concern is great enough, however, that an action such as open burning of a crude oil is looked upon skeptically. Very limited studies have been conducted in this field, yet enough doubt exists to keep the air pollution and human health effects issues highly visible. Burning oil on water usually produces a residue which many officials would regard as still requiring removal and disposal. Use of burning in any confined air shed basin would have reported, if not imagined, health effects. Burning an oil tanker at an offshore location can still be criticized if the prevailing winds cross populated areas. Soot fallout on crops can make them unmarketable due to taste and odor and fear of health effects. The possibility of induced human health effects from open burning of oil is argued by some as not worth the speed, economy, safety, or any other advantage which burning proponents might have.

Issue 6 - Costs and Property Values: Greater attention must be given expenditures in the context of values of property to be protected (including total environment) and values of property to be lost.

- For Burning: The conventional cleanup costs are rising due to other costs plus additional labor required to meet the quality of work demanded to minimize remaining oil. Rather minor weather shifts completely shut down most oil spill cleanup jobs with the result, upon weather breaking, that the effort must resume as if just beginning. Vast armies of hand labor are being replaced, in part, by machines, but the conventional oil spill cleanup is still labor intensive (estimates from less than $1,000 to more than $6,000 per barrel of oil recovered). Burning released oil can be accomplished with few people, little equipment, and rarely any disposal, handling, or transport. Costs for burning a vessel whose cargo is being lost or will be lost are unknown, but compared to salvage and cleanup operations these costs appear very high. Air deployable missiles and weaponry are conceptually available, as well as personnel trained in their use; experts in use of shaped charges and controlled burning can assist to keep costs down. Costs for these systems are in the several thousand dollar range. As the spill pollution liability increases, the return for saving the vessel and cargo becomes less significant.

Even with vessel and cargo saved, the trend is that coastal states, even some flag states of the vessels, will not permit safe passage of a ship with a high pollution potential. If the vessel is to be burned or sunk after the initial salvage and towage to attempt safe harbor it may be cheaper and safer to burn the vessel in place. The value of the vessel and cargo is rarely discussed by the OSC as cleanup strategies are being formulated. Otherwise, it would be an understandable reaction not to risk a $15 million salvage vessel and an equal value in cleanup equipment for a vessel and cargo worth only a fraction of that total. The costs of replacing property, e.g., wildlife habitats or cleaning marine shorelines, can be so high that even drastic steps such as burning may appear justified. In Arctic areas, the costs of using technology other than burning are very high due to high maintenance and down time.

- Against Burning: The demonstrated success of burning is so poor that any cost figures which would appear favorable to burning should be carefully evaluated. If similar persons in numbers and skill used in a vessel burning operation could be employed in a salvage operation, the cost savings is not obvious. Development costs or other hidden costs may shift the suggested low cost of aerial applied missiles and weaponry. Assuming a successful vessel burn, salvage costs would still be incurred for towage and scrapping. Reliability of a response system can require additional costs and since burning released oil has only sporadic success, additional costs should be anticipated. The insurance interests, liability and compensation interests must be educated to accept the costs and results of burning. The time involved would be argued by some as not worth the savings. Some would also argue that (assuming burning really works) if the technique is too simple, too fast and too economical, then the incentive to prevent oil spills is diminished. The costs of incineration of debris may be higher than land disposal because of the equipment transport, maintenance and personnel. Also, costs for monitoring and evaluating effects of smoke plumes due to burning must be included in the burning costs.

Issue 7 - Energy Recovery: The oil should be recovered, reprocessed, and used in response to petroleum shortages and conservation policies.

- For Burning: Most of the conventional oil spill cleanup technology is proudly hailed as conserving a resource that was almost lost (spilled oil). However, the hundreds of persons flying, driving, moving in and around the spill site by boat, helicopter, truck, etc. are all using energy. If the quantity of oil recovered and actually put back into productive use were placed on a per quantity of fuel-electrical-and-manufacturing-energy-use basis, it may be wiser to do nothing. Burning has little if any redeeming value pertaining to oil or energy recovery, but the energy spent implementing that alternative could be significantly less than conventional countermeasures. Energy recovery by incineration of oil-soaked debris in municipal incinerators or coal pile fired powerplants should be noted.

- Against Burning: A rather professional industry has evolved over the past decade who is dedicated to containing, removing, and reprocessing discharged or spilled oil. The oil spill cleanup industry was doing the job in this manner before concern for energy conservation became widely publicized. While the techniques employed were not developed with energy conservation in mind, the successful end result is recovered petroleum. Burning a vessel or released oil on water cannot provide that benefit. Burning oil-soaked debris in certain incinerators has only limited value since many of these incinertors are for waste disposal and not power generation or other beneficial use. If the residue left from burning oil on water is required to be removed, the savings in originally not using the boom, skimmer, transfer, and ultimate disposal would be minimal.

Issue 8 - Permanent Solution: No secondary problems in treating, handling, or disposing should arise.

- For Burning: Oily debris once burned provides the most stable, reliable form of disposal with no odor, leaching, or other secondary problems. Oil burned on water is often reduced to a viscous matted substance which breaks up and sinks to the bottom. Oil burned in a tanker is oil that cannot pollute the sea. The completeness of combustion and the extent to which burning continues prior to extinction are variable, but inversely proportional to the degree of secondary problems anticipated. Unlike some other nonrecovery technologies, e.g., sinking or dispersing agents, burning oils makes them predominantly not available in the water column even over long periods of observation.

- Against Burning: The few known secondary problem cases from employing conventional technology can be argued as acceptable. The permanent loss of the spilled petroleum through open combustion or portable incineration can be argued as creating a secondary problem as a resource lost and as airborne contamination.

APPENDIX A

CONTRIBUTORS AND INVITED REVIEWERS

APPENDIX A

CONTRIBUTORS AND INVITED REVIEWERS

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APPENDIX B

BIBLIOGRAPHY

APPENDIX B

BIBLIOGRAPHY

This Bibliography is designed to provide a foundation for more indepth review of the many facets of oil combustion technology. Abstracts are provided for several documents. A subject index is also included, as well as a list of additional relevant publications.

ANNOTATED BIBLIOGRAPHY

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.

Akita, K. 1972. "Some Problems of Flame Spread Along a Liquid Surface", Fourteenth Symposium on Combustion, Pennylvania State University, Pittsburgh, Penn., August 20-25, 1972, The Combustion Institute.

Flame spread is classified into three groups of uniform, pulsating, and pseudo-uniform spread, depending on the temperature of the liquid. The mechanism of spread in each region is discussed. Surface tension and buoyancy force were found to be the main controls of flame spread in the temperature region below the flash point of fuel.

Ahlstrom, S. W. 1975. A Mathematical Model for Predicting the Transport of Oil Slicks in Marine Waters. Battelle, Pacific Northwest Laboratories.

This computer simulation of oil slick transport predicts location, areal extent, and chemical composition of a slick as a function of time. It is coded in FORTRAN IV and may be programmed for either deterministic or stochastic mode.

Alger, R., S. R. C. Corlett, A. S. Gordon, and F. A. Williams. 1976. "Some Aspects of Structures of Turbulent Pool Fires," Proceedings of the 1976 Fall Meeting of the Western States Section of the Combustion Institute, UCSD, Oct. 18-20, 1976, LaJolla, Calif. 92093.

Burning of JP-5 and methanol pools were studied. Measurements made included radiant energy fluxes outside and within the fire, temperatures and chemical compositions within the fire, and rates of weight loss in the pool. The results emphasize structural differences between JP-5 and methanol fires and the importance of radiant feedback of energy to the pool surface in controlling rates of burning.

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.

Battelle, Pacific Northwest Laboratories. 1969. Review of the Santa Barbara Channel Oil Pollution Incident. Department of Interior FWPCA. 15080 EAL 07/69. Section 11-1. USCG Contract No. 14-12-530.

Debris from the Santa Barbara oil spill was incinerated with a diesel fired brush burner. This was discontinued after local residents complained about the air pollution and concern grew over excessive sulfur emissions. More efficient combustion methods need to be developed for in situ burning.

Battelle, Pacific Northwest Laboratories. 1970. Oil Spill Treating Agents: A Compendum. American Petroleum Institute Project OS-6.

The compendum lists the materials available in 1970 to treat oil spills. Dispersants, sinking agents, sorbents, biological degrading agents, gelling agents, and beach cleaners are listed with appropriate chemical property and experience data. Combustion promoters and wicking agents are also discussed.

Beach, R. L. et al. 1978. Investigation of Extreme Weather Oil Pollution Capabilities, Seaward International, Inc., prepared for Dept. of Transportation, U.S. Coast Guard, Contract No. DOT-CG-80372-A.

This report presents the state of the art in response to oil stranding and spills. Off-loading, cargo jettisoning, and tanker stabilizing were recommended in cargo stranding, and dispersing and skimming recommended for cleaning up spills.

Becker, H. A. and S. Yamazaki. 1978. Entrainment Momentum Flux, and Temperature in Vertical Free Turbulent Diffusion Flames, Dept of Chemical Engineering, Queen's University, Kingston, Ontario.

Jet-spread rate, mass entrainment rate, and momentum growth rate can be predicted for vertical free turbulent diffusion flames. The Richardson ratio, which determines the transition between forced and natural convection, governs the system's behavior. The eddy structure changes dramatically in this transition, leading to further changes in other flame characteristics.

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.

Blackshear, P. L., Jr. and A. M. Kanury. 1965. "Heat and Mass Transfer to, from and within Cellulosic Solids Burning in Air." Tenth Symposium (International) on Combustion. Pittsburgh, Combustion Institute, pp. 911-923.

Free convection heat and mass transfer coefficients were determined for fuel-soaked wicks of various sizes and shapes. The data suggest that the burning rate depends on the rate an isotherm penetrates the solid. Detailed studies of temperature-time histories of burning cylinders were used to determine local heat source and sink strengths.

Blackshear, P. L., Jr., and A. M. Kanury. 1967. "Some Effects of Size, Orientation, and Fuel Molecular Weight on the Burning of Fuel-Soaked Wicks", 11th Symposium (International) on Combustion, Pittsburgh, Combustion Inst. pp. 545-552.

A literature review and experimentation point to convection as the major control of burning rates. Mass transfer coefficients for horizontal and vertical wicks are determined as well as the influence of radiation for different size fuel soaked surfaces.

Blinov, V. I. and G. N. Khudyakov. 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 22.9 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.

Blinov, V. I. and G. N. Khudyakov. 1961. Diffusion Burning of Liquids, Moscow, Academy of Sciences.

This book extensively covers the experimental and theoretical material on the physics of combustion of liquids in tanks. The first part concerns the flammability and ignition of liquids, including a description of the properties of liquid mixtures. The second part covers the actual burning of liquids, including flame shape and dimension and temperature distribution in burning liquids. The third part discusses flame extinguishing by various means.

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.

Brackley, P. G. and P. D. Holmes. 1976. "Oil Spill Clean-Up - Application of Equipment and Methods," Prevention and Control of Marine Oil Pollution, Proceedings of the Regional Marine Oil Pollution Conference, Australia, University of Queensland, Brisbane, Australia, Nov. 8-10.

The three methods presented for dealing with oil spills offshore, inshore and onshore are to do nothing to corral and recover and to disperse. Coordination of efforts and contingency plans are needed.

Burgess, D. and M. Hertzberg. 1974. "Radiation from Pool Flames", Heat Transfer in Flames, Ch 27, John Wiley & Sons.

Radiation data from pool flames are summarized. The revised correlation of mass burning rate with Hc / Hv is fundamentally derived.

Burgess, D. S., J. Grumer, and H. G. Wolfhard. 1961a. "Burning Rates of Liquid Fuels in Large and Small Open Trays". (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.

Burning rates of butane, n-hexane, benzene, and methanol in a quiet atmosphere have been measured. The results agree with rates found by Blinov and Khudyakov for gasoline and less volatile hydrocarbons. Heat transfer was predominantly radiative. When burning rates are extrapolated to large tray dimensions, these extrapolated values are inversely proportional to the fraction of the flame's heat of combustion which is fed back to the liquid to maintain a steady evaporation rate.

Burgess, D. S., A. Strasser and J. Grumer. 1961b. "Diffusive 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.

Burwood, R. and G. C. Speers. 1974. "Some Chemical and Physical Aspects of the Fate of Crude Oil in the Marine Environment," Advances in Organic Geochemistry, Tissor and Bienna, Paris, France.

Weathering processes which assist the dissolution of petroleum components are studied. Abundantly oxygenated surface waters accompanied by intense photo illumination may help oxidize the crude oil. Oxidation mechanisms are discussed.

Caskey, J. C. 1970. Experiment Notes of Sea Beads on Arrow Spill. Interoffice Memo. April 15, 1969.

In this application of Sea Beads, some small burns were successful, but high winds and freezing temperatures hampered larger burns. Oil in some pools foamed due to mixing with water.

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.

Castellucci, Nicholas T. 1969. Trip Report to FWPCA Meeting to Discuss Burning of Oil. Interoffice Memo. October 13, 1969.

The FWPCA met to discuss and demonstrate oil burning technology. Sea Beads burned the oil effectively with little residue. Pyraxon required a much thicker slick and left 70% as residue, Cab-O-Sil needed a 5mm thick slick and left 50% as residue.

Cerkanowicz, A. E. and J. G. Stevens. 1978. "Radiative Augmentation of Combustion: Modeling," Chemical and Physical Processes in Combustion, Eastern Section of the Combustion Institute, presented at the 1978 Fall Technical Meeting, Nov. 29, 30, and Dec. 1, Miami Beach, Florida.

Preliminary results of a model of photochemical initiation and enhancement of combustion are presented. Photochemical enhancement results in combustion at smaller temperature increases than thermal ignition. A comprehensive model of radiative initiation and enhancement of hydrogen-oxygen-nitrogen mixtures is being developed.

Chansky, S. et al. 1974. Waste Automotive Lubricating Oil Reuse as a Fuel, EPA-600/5-74-032.

This study evaluates the technical, economic, and environmental feasibility of automotive waste oil reuse as a fuel. Physical and chemical properties of waste oil are presented. Various treatment methods are discussed.

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-2-0. 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.

Cohen, Y., W. Cocchio and D. Mackay. 1978. "Laboratory Study of Liquid-Phase Controlled Volatilization Rates in Presence of Wind Waves." Environmental Science and Technology. American Chemical Society, 12(5):553-557.

Liquid phase mass transfer coefficients are determined by volatilization of hydrocarbons from aqueous solution in a laboratory wind-wave tank. Wind velocities range from zero to 11.6 m/sec with and without gentle stirring to simulate turbulence. Implications of predicting environmental volatilization rates are discussed.

Cole, C. R., H. P. Foote, and J. R. Eliason. 1973. Oil Spill Drift Forecasting Model, Battelle, Pacific Northwest Laboratories , Presented at the 4th Joint Chemical Engineering Conference, American Institute of Chemical Engineers and Canadian Society for Chemical Engineering, Vancouver, B.C., Sept. 9-12, 1973.

This forecasting model of the movement and spread of oil slicks is based on transport due to permanent ocean currents, tidal currents, and winddrift. This initial spreading phenomena is simulated by surface eddy diffusion with an appropriate time varying diffusion coefficient chosen as a function of the type and volume of oil spilled. The eventual breakup and dispersion of the slick is also modeled.

Corlett, R. C. 1968. "Gas Fires with Pool-like Boundary Conditions", Flame, 12:19-32.

Burning rate is controlled by heat transfer to the liquid from the gaseous reaction zone. Important heat transfer mechanisms were studied and the dependence of heat transfer on fuel-vapor properties was determined. Results showed that fuel consumption rates are determined primarily by non-radiative rather than radiative heat transfer.

Corlett, R. C. 1970. "Gas Fires With Pool-like Boundary Conditions. Further Results and Interpretation". Combustion and Flame, 14:351-360.

Radiative and convective heat transfer to the cooled burner surface were studied. This paper presents data for a wide variety of simple fuel gases. The convective transfer was of primary interest.

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.

Cowan, E. 1968. Oil and Water - The Torrey Canyon Disaster. J. P. Lippencott Company, New York.

This novel details the Torrey Canyon disaster. Approximately 20,000 tons of oil was successfully burned from the holds of the vessel with 41,000 lbs of bombs and 10,000 gal of aviation fuel. The total cost was $560,000.

Day, T., D. Mackay, S. Nadeau and R. Thurier. 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., D. Mackay, S. Naudeau and R. Thurier. 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.

Deepwater Ports Project Office. 1976. Analysis of the Risk of Damage to the States of Florida and Louisiana from the LOOP, Inc. Proposed Deepwater Port and Analysis of the Risk of Damage to the States of Florida and Texas from the SEADOCK, Inc. Proposed Deepwater Port. National Oceanographic and Atmospheric Administration, Dept. of Commerce.

This model of oil spill transport was summarized in Stolzenbach et al.

deRis, J. N. 1968a. "Spread of a Laminar Diffusion Flame," Twelfth Symposium (International) on Combustion," Poitiers, France, July 14-20.

A model for laminar diffusion flame spreading against an air stream over a solidor liquid-fuel bed is presented. The model considers both a thin sheet and a semi-infinite fuel bed. Chemical stoichiometry, heat of combustion, gas-phase conducive heat transfer, radiation, mass transfer, fuel-bed thermal properties, and fuel vaporization are included in the model.

deRis, J. 1978b. "Fire Radiation - A Review, "paper presented at the Seventeenth International Symposium on Combustion, University of Leeds, England, August 20-25.

This paper reviews: 1) some early experimental flame radiation findings, 2) important theoretical developments for understanding and predicting flame radiation, 3) recent experimental data on flame radiation with emphasis on pool fires, and 4) limited knowledge available on the influence of fuel chemistry on diffusion flames and their radiative characteristics.

deRis, J. N. 1978c. "Recent Advances in Radiation From Fires," Chemical and Physical Processes in Combustion, Eastern Section of the Combustion Institute, presented at the 1978 Fall Technical Meeting, Nov. 29, 30, and Dec 1, Miami Beach, Florida.

Flame radiation is the dominant mode of heat transfer inducing fuel gasification and is controlled by the flames' "absorbtion-emission coefficient". This coefficient is related to the amount of soot and other flame constituents releasing radiant energy. Radiation from hot homogeneous soot clouds can be analytically predicted.

deRis, J. N., A. M. Kanury and M. C. Yuen. 1973. "Pressure Modeling of Fires," Fourteenth Symposium (International) on Combustion, Pennsylvania State University, University Park, Pennsylvania, August 20-25, 1972, The Combustion Institute.

Both theoretically and experimentally, laboratory-scale fires at high pressure were shown to accurately model large scale fires at atmospheric pressure. Steady burning, solid-phase heat and mass transfer, fire spread, and other transient phenomena are modeled. Evidence supports the model's accuracy for free burning and spreading fires. Its applicability to complex fire phenomena needs to be assessed.

Diederichsen, J., A. R. Hall and P. T. Hinde . 1972. Ignition and Combustion in situ of Oil from Wrecked Tankers: Small Scale Burning Tests Carried Out at the RPE. Rocket Propulsion Establishment. Westcott, England.

Size and position effects of venting apertures and wind speed effects on burning rates are discussed. Empirical relationships have been developed. The most serious practical problem is in cutting the vents in wrecked tankers.

Diederichsen, J., A. R. Hall and A. T. Jeffs. 1973. The Burning of Oil in Wrecked Tankers: Large Scale Burning Test. Rocket Propulsion Establishment. Westcott, England.

With the results from a large scale burning test (175 tons of oil), conditions for wrecked tanker burning and burning rates can be specified. Two vents, one in the roof, and one in the side, were used. The optimal operation size is 10% of the tank surface.

Donahue, J. 1951. "The Boundary Tension at Water Organic Liquid Interfaces." Journal of Petroleum Engineers. 6:480.

Reciprocal solubilities were determined for various water-organic liquid systems (toluene, benzene, pentane, hexane, etc.). Interfacial tensions at water-organic liquid interfaces are a linear function of the log of the "degree of miscibility" of the water with the organic liquids. The behavior of the interfacial tension was similar to that of the surface tension at the critical solution temperature.

Dorrler, S. J. 1972. "Use of Sorbents for Oil Spill Cleanup," Offshore Technology Conference, paper #1552, 2:403.

Six basic unit operations are being investigated: 1) sorbent broadcasting, 2) oil-sorbent harvesting, 3) oil-sorbent separation, 4) vessel or platform configuration, 5) oil storage or disposal, 6) sorbent reuse or disposal. Sorbent systems are able to effectively recover floating oil without contributing to solid waste or air pollution problems.

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

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.

Emmons, H. W. 1959. "Some Observations on Pool Burning." (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.

Acetone and methyl alcohol fires in small open pools have been studied. Pool sizes range from 1/4 inch to 10 inches. It was found that radiant heating of the surrounding area has a large effect on convective disturbances. A proposed method of separating burning rate into more tractable pieces has been shown to be effective in analyzing the data presently available.

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 fuse wire 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

Engdahl, R. B., H. R. Hazard and G. M. Hein. 1968. Mobile Incinerator. U.S. Patent No. 3,371,629.

A mobile incinerator was developed for collecting and incinerating refuse. A description of the incinerator follows.

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

Commerically 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.

Ethyl Corporation. 1951. Aviation Fuels and Their Effects on Engine Performance, Dept of the Navy, Bureau of Aeronautics Contract No. 52-202. USAF T.O. No. 06-5-4, Naval No. 06-5-501.

This report contains important data on the properties of aviation fuel and fuel components. Its intended use is for jet engine operation, design and development.

Fallah, M. H. and R. M. Stark. 1976. "A Probabilistic Approach for Dispersion of Oil at Sea," Ocean Engineering, 3:145-6.

This paper considers the volume of "lost" oil due to dispersion in a rough sea. Probabilistic descriptions are derived for the volume of oil dispersed in sub-surface water as a function of time, physical properties of the oil slick and the random environmental characteristics.

Fannelop, J. K. and G. D. Waldman. 1971. The Dynamics of Oil Slicks--or "Creeping Crud," AIAA Paper No. 71-14, AIAA 9th Aerospace Sciences Meeting, New York, New York, Jan. 25-27.

Oil slick spread is quantified for gravity-inertial and gravity-viscous flow regimes. Approximations for viscous drag are suggested. For both two-dimensional and radial slicks, similarity solutions are obtained for the two flow regimes that agree with experimental data.

Faure, J. 1959. "Study of Convection Currents Created by Fires of Large Area," (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.

For a fire storm (with respect to city fires) the following conditions may be required: a high heat loading (fuel), a high density of initial fires within a wide area (2-3 km^2), a high density of construction (at least 40 %), and an absence of wind and humidity. Convection currents arising from combustion are quantitatively analyzed.

Fay, J. A. Physical Processes in the Spread of Oil on a Water Surface, Research for U.S. Coast Guard under Contract No. DOT-CG-01-381A, Dept of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Based on analytical and theoretical studies of physical processes that accelerate or retard the spread of a film, formulae have been developed to predict the extent of oil slick spread. Both one dimensional and two dimensional slicks are considered. Comparisons are made with field observations.

Federal Energy Research Center. 1978. Western LNG Project Final Environmental Impact Statement, FERC/E1S-0002F, Vol. III (Draft), pp. C45-C-53.

This section of the EIS appendix discusses results of empirical studies of LNG pool fires of 6, 20 and 80 foot diameters. Observers considered pool size, wind velocity, and radiation feedback measurements.

Felske, J. D. and C. L. Tien. 1973. "Calculation of the Emissivity of Luminous Flames," Combustion Science and Technology, 7:25-31.

The total emissivity of luminous flames can be easily determined with the analytical basis developed here. The analysis considers flames whose dominant emitting species are water vapor, carbon dioxide, and soot. The relative importance of gas and soot emission under typical flame conditions can be calculated.

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

Currently available commerical 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 D. Mackay. 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 Environmental 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.

This contains a brief description of Cab-O-Sil and 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 G. P. Vance. 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 can then be conducted where no other oil disposal capacity exists. The burner is designed to protect the platform from the heat given off during combustion.

Gundlack, E. R. 1977. "Oil Tanker Disasters." Environment, 19(9):16.

This article briefly discusses the history of petroleum spillage with detailed reports on recent disasters such as the Arrow, Metula, Jakob, Maersk, and Urquiola spills. It addressed the inadequacy of present cleanup techniques and stresses prior planning.

Gundlack, E. R. and M. O. Hayes. 1977. "The Urquiola Oil Spill: Case History and Discussion of Methods of Control and Cleanup." Marine Pollution Bulletin, 8(6):132.

Large scale environmental damage resulted from this spill. About 100,000 tons of oil burned, but 30,000 tons washed ashore. Over 2,000 tons of dispersants were applied to the oil at sea. Land based cleanup was inadequate to combat the spread of oil, and 215 km of coastline was affected.

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, Environmental 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.

Heagler, R. B. 1972. Method and Apparatus for Removing a Layer of Combustible Liquid from the Surface of a Body of Water. U.S. Patent 3663149.

A self propelled floating incinerator has been patented which recycles ceramic beads used to aid combustion and subjects combustion gases to secondary burning in the stack. The speed of the vessel controls the contact time in the incinerator and thus, the efficiency of burning.

Heagler, R. B. 1970. Method and Apparatus for Burning Combustible Liquids Within a Confined Burning Area. U.S. Patent 3695810.

A partly submerged floating incinerator is insulated to maintain a high temperature within the furnace for complete combustion. An outside gas source is used to burn the combustible gases from the incinerator.

Hearst, P. J. 1974. The Fate of Spilled Navy Distillate Fuel, Prepared for Naval Sea Systems Command, Project No. 52-028.

Laboratory weathering studies of 4 Navy distillate fuels showed thick films (5 mm) to be relatively persistent. Physical properties did not markedly change. Distillate fuels did not form mousse; the Navy special fuel oil did. Weathering characteristics were related to the distillation range.

Hellman, H. and H. J. Marcinoroski. 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.

Henager, C. H., P. C. Walker, J. R. Blacklaw, and N. D. Smith. 1971. "Study of Equipment and Methods for Removing a Dispersing Oil from Open Waters." Prevention and Control of Oil Spills. TD 427P4, p. 405.

A cost effectiveness analysis was performed for equipment, materials, and techniques for removing or dispersing oil. Criteria included completeness of removal, removal rate, hazard and pollution, etc. The 3 most cost effective systems were burning, dispersing, and mechanical skimming. Dispersing was the best; burning was less favored because of its limited applicability.

Herschmiller, D. W. and R. D. Revel. 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 oil 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.

Hillyard, H. E. 1968. "Recovery of Waste Oil Using Floating Type Skimmers." Iron and Steel Engineer. August 1968, p. 77.

Waste oil that eventually flows into the plant sewers is recovered by floating type skimmers in a lagoon. The waste oil is used as a fuel in the plant boiler house, providing an economical as well as ecological means of disposal.

Hirano, T. and M. Kinoshita. 1975. "Gas Velocity and Temperature Profiles of a Diffusion Flame Stabilized in the Stream Over Liquid Fuel," Proceedings of the Fifteenth Symposium (International) on Combustion. Tokyo, Japan, August 25-31, 1974, The Combustion Institute.

A diffusion flame was used to study gas velocity and temperature profiles across the laminar boundary layer. Methanol and ethanol were used. Measurements were made with the free stream of air parallel to the liquid-fuel surface. The flame stabilizing mechanism and fuel consumption rate are discussed.

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.

Hottel, H. C. 1959. "Fire Modeling," (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.

The author lists some of the importants relationships in fire modeling - forces, mass rates, and energy rates. He then develops a radiation model for natural convection jets using the basic relationships. Forced jets are also discussed.

Hoult, D. P. 1972. "Oil Spreading on the Sea," Annual Review of Fluid Mechanics, 4:341.

Theoretical and experimental data pertaining to inertial, viscous, and surface-tension spreading are presented to explain oil slick spreading behavior. Fay's work on spreading is supported. The mechanism by which an oil slick ceases to spread is unclear at present, but a hypothesis is presented to explain this phenomena.

Houston, B. J. 1968. Investigation of Materials and Methods for Use in Removing Surface Layers of Oil and Water. U.S. Army Engineer Waterways Experiment Station. Miscellaneous Paper C-8-5.

Special emphasis is on floating and sinking oil absorbing materials for oil spill cleanup. Silicone-treated flyash, high adsorptive swelling clays, and synthetic silica were tested. Some laboratory testing of burning oil on water was conducted.

IMCO Oil Manual. 1973.

Oil is difficult to burn because it spreads rapidly to a thin layer, the cooling effect of the water deters combustion, and the volatile fractions evaporate quickly. Igniters and wicking agents have been used with variable success.

Inter-Governmental Maritime Consultive Organization. 1973. Manual of Oil Pollution. London, England.

Burning from the holds of a vessel is presently considered the only viable burning option. Igniters and wicking agents can be effective. Combustion is unlikely to be complete, so unburnt residue and air pollution are potential problems.

Isakson, J. S., J. M. Storie, J. Vagners, G. A. Erickson, J. F. Kruger, and R. F. Corlett. 1975. Comparison of Ecological Impacts of Postulated Oil Spills at Selected Alaska Locations, NTIS AD-A017 600.

This model of oil spill transport and spread was summarized in Modeling Methods for Predicting Oil Spill Movement, 1977, by the Oceanographic Institute of Washington.

Jeffery, P. G. 1971. "Large Scale Experiments on the Spreading of Oil at Sea and its Disappearance by Natural Factors." Prevention and Control of Oil Spills, API.

This paper describes important considerations in large scale oil spreading experiments. Blokker constants are calculated from the spreading of the slick, and graphical data are presented as a function of time.

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.

Johnston, William D. 1972. Process for Burning a Combustible Liquid Using Cellular Ceramic Nodules. U.S. Patent 3661495.

Cellular ceramic nodules can be used as a wicking agent to sustain oil combustion.

Kanury, A. M. 1974. "Modeling of Pool Fires With a Variety of Polymers", Fifteenth Symposium (International) on Combustion, Toski Center Hall, Tokyo, Japan, August 25-31, The Combustion Institute.

The experiments reported in this paper deal with steady burning of 8 different polymers. The burning rates, history, and thermal radiation emitted were measured under various ambient air pressures up to about 40 atm.

Kim, B. C., H. Carlton, T. J. Cooke, J. H. Hancock, R. A. Mendelsohn, and W. J. Sheppard. 1974. Support Systems to Deliver and Maintain Oil Recovery Systems and Dispose of Recovered Oil, Battelle-Columbus, Contract No. DOT-CG-23223-A.

This report focused on three problem areas: (1) to determine optimal transfer systems for use in oil recovery at sea, (2) to determine oil tanker traffic patterns, and (3) to study the effectiveness of ultimate oil disposal techniques.

Kim, Y. C. 1974. "Oil Spreading on Coastal Waters", Proceedings of 14th Conference on Coastal Engineering, Copenhagen, Denmark, III:2260-7.

A predictable model of oil spreading on coastal waters has been established. Experimental work focused on the relationship between the oil slick and the Reynolds, Froude, and Weber numbers; the influence of wind, currents, and waves on the spread area; and effects on the changes in water depth and alteration of the net spreading coefficient on oil spreading capacity. Field measurements were compared.

Kinbara, T. and K. Akita. 1959. "On the Self-Ignition of Wood Materials." (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.

An approximate solution is postulated for the differential equation for self ignition. The solution is independent of the sample size and has been tested experimentally. The solution is applicable to the self-ignition of spherical samples of large size placed in a constant uniform temperature field.

King, F. 1978. "Oil Spill Debris: Where to Put the Waste." Environmental News. April, p. 8.

EPA representatives recommend burning oil debris where air pollution standards permit. The oily wastes are difficult to dispose of properly, even if buried in a landfill, because of possible seepage and groundwater contamination. EPA studies suggest that only debris should be reclaimed, burned, land cultivated, and buried.

Lamp'l, H. J. 1969. "Beach Cleanup." Prevention and Control of Oil Spills. API. 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.

Leary, J. F. 1975. Ultimate Disposal of Oil and Hazardous Materials. NTIS AD1A-035 137.

Equipment costs and capabilities are analyzed for both fixed and portable incineration of liquid and solid wastes. If oil is free of heavy debris when burned, burning efficiency can match that of present oil recovery systems.

Lissauer, I. M. 1974. A Technique for Predicting the Movement of Oil Spills in New York Harbor, NTIS AD-786 627.

This model of oil spill transport and spread was summarized in Modeling Methods for Predicting Oil Spill Movement, 1977, by the Oceanographic Institute of Washington.

Lissauer, I. M. and J. C. Bacon. 1975. Predicted Oil Slick Movement from Various Locations Off the New Jersey-Delaware Coastline. Prepared for the Dept. of Transportation, U.S. Coast Guard, Report No. CG-D-137-75, June 1975.

Projections of oil slick movement and impact location were determined from 3 potential deepwater port sites and 3 potential oil drilling sites. Average monthly wind speeds, wind directions, and current patterns were used.

Lissauer, I. M. and J. P. Welsh. 1975. Preliminary Projections of Oil Spill Movement for Three Potential Deepwater Port Sites in the Gulf of Mexico. Prepared for the Dept. of Transportation, U.S. Coast Guard, Report No. CG-D-19-176, Dec. 1975.

Oil slick movement and impact location were projected from 3 potential deepwater port sites. Average monthly wind speeds, wind directions, and current patterns were used to assess drift and probable areas of impact along the shoreline.

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. and P. J. Leinonen. 1977. Mathematical Model of the Behavior of Oil Spills on Water with Natural and Chemical Dispersion. Economic and Technical Review Report EPS-3-EC-T1-19. Canadian Environmental Impact Control Directories.

The mathematical model yields data on the oil slick size, thickness, properties, and composition; the amounts of oil evaporated, dissolved, and dispersed; and the concentration history of dissolved hydrocarbon in the water column. The model permits variation in oil composition, sea state, wind speed, temperature, and time. Thirty four model spills are presented with a discussion of the most important factors.

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.

Markstein, G. H. 1977. "Scaling of Radiative Characteristics of Turbulent Diffusion Flames". Proceedings of the 16th Symposium (International) on Combustion.

Radiative characteristics of a fire for given dimensions and geometry were studied. Equations were derived to model the burning process.

Markstein, G. H. 1978. Radiative Properties of Plastics Fires, Factory Mutual Research, FMRC JI 7AOR3.Gu, RC 78-BT-20.

Radiative properties of plastics pool fires were measured by a variation of the Schmidt method. Two models, a gray-emitter homogeneous model and a model that assumed a spectral absorption coefficient inversely proportional to wavelength, yielded comparative radiation data. The correlation between emissivities and burning rates suggests that for large fires burning rate is controlled by radiative transfer.

Marshall and W. Kosman. 1978. "French Oil Spill: Cleanup Proves Tough." Chemical Engineering. 85(11):112.

Use of presently available oil removal techniques during the spill of the Amoco-Cadiz was largely unsuccessful due to sea conditions and equipment failures. Although several dispersant chemicals were used, natural wave action proved to be the most effective. New research and development is necessary to meet the growing need for cleanup techniques.

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.

McAlevy, R. F. III, and R.S. Magee. 1968. "The Mechanism of Flame Spreading Over the Surface of Igniting Condensed-Phase Materials", *Twelfth Symposium (International) on Combustion*, Poitiers, France, July 14-20, 1968.

This paper discusses an experimental and theoretical approach to explain the mechanism by which a flame spreads over the surface of a condensed-phase material. Predicted flame-spreading characteristics were well supported by experimental data.

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.

McLeod, W. R. and D. L. McLeod. 1972. "Measures to Combat Offshore Arctic Oil Spills," *Offshore Technology Conference* paper #1523, 2:14.

Statistics on 15 Arctic and subarctic oil spills and combatant schemes are presented to analyze the effectiveness of spill mitigation techniques. The best cleanup method must be weighed against peculiar environmental conditions and effects on wildlife. Legislative and insurance considerations are mentioned along with contingency plans.

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

McMinn, T. J. 1973. "Oil Spill Behavior in a Winter Arctic Environment", Offshore Technology Conference paper #1747, 1:233.

Arctic field tests were conducted to quantitate oil spreading on and under ice, oil aging on ice, unique interaction characteristics between snow and oil, and the effectiveness of existing oil recovery techniques and treating agents. This is part of a comprehensive Coast Guard study.

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.

Milgram, J. 1977. "Being Prepared for Future Argo Merchants," Technology Review. July, p. 15.

The Argo Merchant spill showed how unprepared we are for dealing with offshore and tanker accidents. Research effort should be put into oil removal and combustion as well as re-evaluation of tanker construction and regulation.

Miller, M. C., J. C. Bacon, and I. M. Lissauer. 1975. A Computer Simulation Technique for Oil Spills Off the New Jersey-Delaware Coastline. Prepared for the Department of Transportation, U.S. Coast Guard, Report No. CG-D-171-75.

Predictions of the movement of oil slicks and their impact locations along the shoreline of New Jersey and Delaware were determined for two potential deepwater ports and two potential drilling sites. A hydrodynamical-numerical model for the New York Bight Area was coupled with a wind generating model to produce temporal patterns of concentration of oil. Shoreline impact determinations are included.

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.

Modak, A. T. 1977. "Radiation from Pool Fires - Analytical Solutions," presented at Fall Technical Meeting, Eastern Section, The Combustion Institute, Nov. 10-11.

Solutions to radiation calculations from polymethyl methacrylate pool fires show that use of a cone model slightly overestimates values at the pool surface and the fire's leading edge.

Morton, B. R. 1965. "Modeling Fire Plumes," Tenth Symposium (International) on Combustion, The Combustion Institute, pp. 973-982.

Equations for weakly buoyant plumes were modified to develop theoretical treatments for turbulent diffusion flames and for the strongly heated regions of fire plumes in a still environment. Some of the modifications are discussed. The effects of large variations in density on the plume dynamics and heat transfer by radiation are also presented.

Munday, J. C., Jr., W. Harrison and W. G. MacIntyre. 1970. "Oil Slick Motion Near Chesapeake Bay Entrance," Water Resources Bulletin, 6(6).

A study of Bunker C oil revealed that slick motion was due mainly to surface currents. The slick wind factor varied with wind speed. Wind and published tidal-current data were insufficient for accurate prediction of slick motion; extensive wind and surface-current time-series data are necessary.

Murgai, M. P. and H. W. Emmons. 1960. "Natural Convection Above Fires", Journal of Fluid Mechanics, 8:611-624.

This paper presents solution curves which are used to compute natural convection over a fire of arbitrary size in an atmosphere with arbitrary lapse rate variation. These independent parameters: fire size, energy release rate (buoyancy), momentum release rate, and atmospheric lapse rate, are given over a range of values. The arbitrary variation of lapse rate can then be calculated.

Murgai, M. P. 1962. "Radiative Transfer Efffects in Natural Convection Above Fires," Journal of Fluid Mechanics, 12:411-448.

This paper examines the influence of radiative heat transfer on turbulent natural convection above fires in an atmosphere of constant potential temperature. Both the "opaque" and "transparent" approximations are used. Solution curves are presented which cover various fire sizes, energy release rates, and absorption coefficients.

Murphy, T. A. 1970. The Sinking of the Tanker "Arrow." Edison Water Control Laboratory. EPA.

The use of Sea Beads cellated glass nodules is critiqued. On small scale burns the promoter proved effective in 15 knot winds. Although combustion was incomplete, the slicks could be reignited. Large scale tests are recommended with development of dispersal ignition techniques.

Murray, S. P. 1975. "Wind and Current Effects on Large-Scale Oil Slicks," Offshore Technology Conference, May 5-8, Houston, Texas.

The relative effect of local winds and near-surface currents in determining oil slick movement in coastal and shelf waters was studied by a helicopter survey. Local wind direction closely controls oil slick orientation. A simple regression model is presented that determines slick area and orientation as a function of wind velocity and local conditions.

Murray, S. P., W. G. Smith and C. J. Sonu. 1970. Oceanographic Observations and Theoretical Analysis of Oil Slicks During the Chevron Spill, March, 1970, Coastal Studies Institute, Contract No. N00014-69-A-0211-0003, Project No. NR 388 002.

Oceanographic observations of an estuarine system revealed the relative roles of physical factors on oil slick behavior. Surface stress from wind, tidal currents, and fresh water incursion were a few of the factors investigated. A statistical theory of spill movement is developed.

Murty, T. S. and M. L. Khandekar. 1973. "Simulation of Movement of Oil Slicks in the Strait of Georgia Using Simple Atmosphere and Ocean Dynamics", Proceedings of the Joint Conference on Prevention and Control of Oil Spills, Washington, D. C., 13-15 March, pp.541-6.

Hydrodynamical techniques were used to investigate the movement of oil slicks by assuming that the oil moves with the current and not with the wind. The interaction of several slicks is important in determining trajectories. Stratification of the water causes the oil plume to bifurcate.

Nair, K., H. C. Shah and W. S. Smith. 1974. "Cargo Spill Probability Analysis - A Bayesian Approach," Offshore Technology Conference paper #1980, 1:435.

A probability model for predicting the occurrence of cargo spills was developed and quantified using Bayesian statistics. The results of the study allow definition of probable size, cause, and location of cargo spills. Decisions on regulatory measures should also consider spill consequences.

Nielsen, H. J. and L. N. Tao. 1965. "The Fire Plume Above a Large Free-Burning Fire", Tenth Symposium (International) on Combustion, The Combustion Institute, pp. 965-972.

This model describes the variation with altitude of the composition, temperature, and velocity of the gases within a plume above a large free-burning fire. It includes the effects of combustion, composition variation, and radiation losses. A set of differential equations is derived for the upward flow of gases and their combustion products. Burning rates are assumed to be controlled by oxygen entrainment from the surrounding air.

Oceanographic Institute of Washington. 1977. Modeling Methods for Predicting Oil Spill Movement; A Report to the Oceanographic Commission of Washington.

This report contains a literature review and an overview of the present state-of-the-art in oil spill movement modeling. Oil spreading, drift, transport, and trajectory models are assessed and verified.

Oran, E. S, 1978. "Detailed Modeling of Reactive Flows," Chemical and Physical Processes in Combustion, Eastern Section of the Combustion Institute, presented at the 1978 Fall Technical Meeting, Nov. 29, 30, and Dec. 1, Miami Beach, Florida.

The fundamental processes involved in a model of realistic combustion are discussed. The modeling approach was to model each fundamental process individually, then to couple them by considering the interactions between them. "Asymptotic" techniques are required when there are small space and time scales. A one-dimensional relative shock model is discussed in detail.

Orloff, L., A. T. Modak and G. H. Markstein. 1978. "Radiation From Smoke Layers," paper presented at the Seventeenth International Symposium on Combustion, University of Leeds, England, August 20-25, 1978.

This well-defined model quantifies nongray, nonhomogeneous and nonisothermal effects in calculating radiant heat transfer from smoke layers. Input parameters include vertical distributions of temperature, product species, and enclosure dimensions. Radiative flux can be evaluated by making simple approximations.

O'Rourke, C. 1976. "Oil Spill Cleanup in the Beaufort Sea." Spill Technology Newsletter, 1(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-emusified heavy oils burn readily without promoters in the Arctic waters. Studies are underway to improve ignition techniques and fireproof booming.

Orthlieb, F. L. 1971. Forecasting Oil Slick Behavior - A Preliminary Guide, Prepared for Commandent (DAT), U.S. Coast Guard HQ, Report No. 724107.1.

This model predicts oil spreading and transport from both sudden releases of oil and continuous flow. Slick drift due to wind and currents is estimated from empirical observations. The result is an approximate forecast of slick size and position versus time.

Parker, R. O. 1974. "Calculating Thermal Radiation Hazards in Large Fires," Fire Technology, 10:147-152.

A method has been developed to assess thermal radiation hazards to objects from fires. A comparison of the method to actual experience indicates that the method is reasonably accurate but somewhat conservative.

Peskin, L. C. 1966. "The Development of Open Pit Incinerators for Solid Waste Disposal," Journal of the Air Pollution Control Assoc., 16(10).

An open pit incinerator has been developed for safe destruction of potentially explosive chemical wastes. Closely spaced nozzles admit a screen of high-velocity air over the burning zone resulting in high burning rates, high flame temperature, and complete combustion.

Peterson, P. L., R. A. Yano, and M. M. Orgill. 1975. Temporary Storage and Ultimate Disposal of Oil Recovered From Spills in Alaska, Battelle, Pacific Northwest Laboratories, prepared for DOT under Contract No. DOT-CG-23223-A.

This report identifies alternative methods for temporary storage and ultimate disposal of oil recovered from postulated spills in Alaska. Representative sites and spill sizes were considered. The types of spills evaluated were crude oil, distillate fuel oil, residual fuel oil, and gasoline. Environmental effects specific to Alaska are discussed.

Pipkin, O. A. and C. M. Sliepcevich. 1964. "Effect of Wind on Buoyant Diffusion Flames," I&EC Fundamentals, 3(2).

Buoyant diffusion flames of natural gas were observed in wind tunnel experiments to determine the extent of bending by wind. Flame buoyancy was varied while nozzle velocity was kept constant. A single straight line correlation was obtained.

Pittsburgh Corning Corporation. 1970. Sea Beads for Oil Spillage Removal. SB-1 1.5M 3/70. B6.

This is a product report for cellulated glass beads which act as an effective wicking agent for oil. Capillary action draws the oil to the surface, insulating it from the sea water for enhanced burning. The non-toxic lightweight beads degrade in a moderate time period by wind/wave action.

Premack, J. and G. A. Brown. 1973. "Prediction of Oil Slick Motions in Narragansett Bay," Proceedings of the Joint Conference on Prevention and Control of Oil Spills, Washington, D.C., Mar. 13-15.

A model was developed which incorporated Fay's work on spreading characteristics and Teason's work on drift motion under wind and current action. The model of Narragansett Bay was in good agreement with the actual conditions in the Bay.

Putnam, A. A. 1965. "A Model Study of Wind Blown Free-Burning Fires", Tenth Symposium (International) on Combustion, The Combustion Institute, pp. 1039-1046.

Both pointand area-source flames and line fires were exposed to cross winds to study free-burning fire modeling. With pointand 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.

Rasbash, D. J., Z. W. Rogowski, and G. W. V. Stark. 1956. "Properties of Fires of Liquids," Fuel, 35:94-107.

Temperature, rate of burning, and compositional changes of alcohol, petrol, benzole, and kerosene were measured. Flame data included the dimensions, upward velocity, temperature, and emissivity. For hydrocarbon liquid fires, heat transfer to the surface was mainly by radiation.

Remick, E. M. and K. E. Torrance. 1978. "Small Pools Burning in a Crosswind," Seventeenth Symposium (International) on Combustion, at the University of Leeds, Leeds, England, August 20-25, The Combustion Institute.

A numerical study of transient and steady burning of small shallow pools is presented. A two-dimensional diffusion flame model was used which incorporated the effects of surface-tension driven flows, surface evaporation, and radiant heat transfer. Parametric studies focused on the effects of surface tension and airspeed. Radiation, the inert/oxidizer ratio and thermal boundary conditions were also considered.

Roberts, R. M. and T. S. Hoyt. 1970. A Feasibility Analysis of Incinerator Systems for Restoration of Oil Contaminated Beaches, U.S. Environmental Protection Agency, Contract No. 14-12-595.

This study concluded that incinerators were an attractive method, both technologically and economically, to clean beach sand. Different incinerator designs were analyzed and a three-effect combustor based on the rotary kiln principle was recommended.

Rose, V. C. and G. C. Soltz. 1971. "Removal of Oil from Sunken Tankers," Prevention and Control of Oil Spills, API. p. 205.

The most economical and effective solution to eliminating the oil threat from sunken tankers is pumping the oil out. This design includes searching and buoying procedures, penetrating of the oil tank, pumping oil out, capping the holes, and innoculating each tank with oil eating bacteria.

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.

Schatzberg, P. and K. V. Magy. 1971. "Sorbents for Oil Spill Removal," Prevention and Control of Oil Spills, API, p. 221.

Effective sorbents must float on water, attract and absorb oil, and be easily removed from the water. Three classes of materials: inorganics, natural organics, and synthetic organics, are evaluated. Polymeric foams were the most effective sorbents tested. Inorganics and natural organics were generally less effective.

Schwartzberg, H. G. 1970. Spreading and Movement of Oil Spills, Water Pollution Control Research Series, U.S. Dept. of the Interior. Program No. 150 80, Contract No. WP 01342-01A.

The spreading and movement of the oil spills on water were investigated. Equations were developed which describe spill areas that forms lenses or films. Spreading rates for small spills were measured and correlated with spill volume, oil density, and water viscosity. Wind drift and current drift were roughly correlated.

Scurlock, A. C., A. W. Lindsey, T. Fields, Jr., and D. R. Huber. 1975. Incineration in Hazardous Waste Management, EPA/530/SW-141.

This report presents an overview of the state-of-the-art, summaries of data on various types of incinerators, and a list of general considerations to be addressed when evaluating hazardous waste incineration questions.

Sivadier, H. O. and P. G. Mikolaj. 1971. "Measurement of Evaporation Rates from Oil Slicks on the Open Sea," Prevention and Control of Oil Spills, API, p. 475.

Gas Chromatography is applicable to all types of petroleum products to measure time dependent oil evaporation on the sea. This method has been calibrated to within 1% of the actual evaporative weight loss. Testing in Santa Barbara showed that volatile components are lost within 1-2 hours and the resulting residue can then enter the water column.

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

Evaporation and dissolution are the main mechanisms 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, J. W. 1976. "Oil Pollution of the Sea - The World-Wide Scene," Prevention and Control of Marine Oil Pollution, Proceedings of the Regional Marine Oil Pollution Conference - Australia, University of Queensland, Brisbane, Australia, Nov. 8-10.

This general article covers the sources of marine oil pollution, an outline of the International Agreements to limit oil pollution, costs of cleanup, cleanup methods, environmental damage, and the need to develop contingency plans.

Spalding, D. B. 1962. "The Art of Partial Modeling," Ninth Symposium (International) on Combustion, Cornell University, Ithaca, New York, August 27-Sept. 1, The Combustion Institute.

Similarity theory requirements are so numerous and restrictive that complete modeling of combustion processes is practically impossible; all successful modeling so far has involved deliberately ignoring many of the similarity rules. This paper reviews some of the more notable examples of partial modeling and discusses physical facts underlying their success.

Steward, F. R. 1964. "Linear Flame Heights for Various Fuels," Combustion and Flame, 8:171-178.

Flame heights for several different fuels have been correlated with a single parameter derived from a model assuming mixing controlled combustion.

Steward, F. R. 1978. "Fundamentals of Radiative Transfer in Combustion Systems." Chemical and Physical Processes in Combustion, Eastern Section of the Combustion Institute, presented at the 1978 Fall Technical Meeting, Nov 29, 30, and Dec 1, Miami Beach, Florida.

A summary of the development and state-of-the-art mathematical methods for predicting flow and concentration patterns of combustion systems is presented. Problems related to naturally occurring fires are also treated mathematically. Radiative heat transfer is discussed.

Stewart, R. J., J. W. Devanney, III, and W. Briggs. 1974. Oil Spill Trajectory Studies for Atlantic Coast and Gulf of Alaska, Massachusetts Institute of Technology, Report No. MITSG 74-20.

This model of oil spill spread and transport was summarized by both Stolzenbach, et al., and the Oceanographic Institute of Washington.

Stewart, R. J. 1977. "Tankers in U.S. Waters." Oceanus, 20(4):74.

Modeling of tanker traffic and spillage is difficult because of the random timing of tanker groundings. This model predicts one spill per day and a 50% chance that the largest U.S. spill in a given year will be less than 5000 gallons. Cleanup of spills in unprotected waters need close investigation.

Stolzenbach, K. D., O. S. Madsen, E. E. Adams, A. M. Pollack, and C. K. Cooper. 1974. A Review and Evaluation of Basic Techniques for Predicting the Behavior of Surface Oil Slicks, Report to the Marine Assessment Division Center for Experiment Design and Data Analysis, Environmental Data Service, National Oceanic and Atmospheric Administration, MIT, Dept. of Civil Engineering Report No. 222.

This major work reviews the state-of-the-art in basic modeling techniques for surface oil slicks. The hierarchy of modeling levels is evaluated with regard to assumptions and sophistication. Wind fields, advection, and physical phenomena that transform oil slicks are discussed. A review and evaluation of existing models is presented along with a comprehensive bibliography.

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

Swift, W. H. 1974. Logistic Requirements and Capabilities for Response to Oil Pollution in Alaska, Project for the U.S. Coast Guard, Battelle, Pacific Northwest Laboratories.

Fourteen key Alaska locations were selected as having relatively high potential for oil spills. Response requirements for the various locations and environmental scenarios were produced. The logistic support capability for each site is analyzed on the basis of available manpower and equipment.

Tarifa, C. S. and A. M. Torralbo. 1966. "Flame Propagation Along the Interface Between a Gas and a Reacting Medium," Eleventh Symposium (International) on Combustion, University of California, Berkeley, August 14-20.

Flame propagation and heat transfer mechanisms in air are discussed. An analytical solution to the heat transfer problem is calculated using a boundary-layer approximation and solving a heat-balance partial differential equation.

Tayfun, M. A. and H. Wang. 1973. "Monte Carlo Simulation of Oil Slick Movements," Journal of the Waterways Harbors and Coastal Engineering Division, ASCE. 99(WW3):309-324.

Two stochastic models - a random walk analogy and a time-series model are developed to simulate oil slick movement by the Monte Carlo method. The motion is simulated by the random movements of a large number of particles where each time step takes into account the combined effects of a deterministic current drift and a random wind drift. The distribution of the slick, probability of reaching shoreline, and trajectory statistics can be estimated.

Tenzer, R. 1978. Characteristics of the Mobile Field Use System for the Detoxification/Incineration of Residuals from Oil and Hazardous Material Spill Clean-Up Operations, USEPA, Edison, N.J., EPA Contract No. 68-03-2515.

The mobile detoxification/incineration system is designed to clean debris, soil, and water from oil, hazardous materials, viscous liquids, chemical and petrochemical sludges and pesticides. The system consists of a primary incinerator, an excess air afterburner, and gas stream processor (gas scrubber). Design details are included.

Thew, M. T. 1968. "The Formation and Stability of Emulsions of Water in Crude Petroleum and Similar Stocks," Institute of Petroleum Journal, 54(539).

The formation and stability of oil/water emulsions are dependent on the chemical composition of the oil. Stability is due to complex chemical components in the nonvolatile residue, particularly asphaltenes, porphyrins, and vanadium complexes. Nominal amounts of emulsion-breaking additives with agitation result in oil dispersion.

Thomas, P. H. 1963. "The Size of Flames From Natural Fires," Proceedings of the 9th Symposium (International) on Combustion, pp. 844-858.

Flame heights were studied in terms of both a dimensional analysis and the entrainment of air into the flame. Then they are compared with other experiments on the flow of hot gases. Wind effects on flames are also reported.

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

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

Tom, G., and W. F. Purves. 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 inadequated 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.

Torrance, K. E. and R. L. Mahajan. 1974. "Fire Spread Over Liquid Fuels: Liquid Phase Parameters," Fifteenth Symposium (International) on Combustion, Pittsburgh, Pennsylvania, The Combustion Institute.

Fire spread over liquid fuels at sub-flash temperatures is controlled by flows induced in the liquid. Liquid flows are driven by surface tension and buoyancy forces. The effect of Prandtl number, fuel depth, and flame speed are obtained from numerical solutions of the equations governing the liquid phase.

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.

Tully, P. R. 1971. Process for Burning Oil Spills. U.S. Patent 3,556,698.

The invention (particulate solids) is applied to the spill to aid ignition and enhance burning. Combustion is more complete and the residue can be more easily removed.

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, Environmental 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.

U.K. Institute of Petroleum. 1971. In Situ Burning of Cargo Crude Oil in Stricken Tankers - Consideration of Need for Further Investigation, Rocket Propulsion Establishment.

This is a state-of-the-art analysis following the Torrey Canyon experience. Further combustion research is recommended, both in the lab and on old tankers going to scrap. However, tanker burning is not presently considered feasible for oil spill mitigation.

Under Sea Technology. 1973. "Improving the Capability to Cleanup Oil Spills in U.S. Waters."

This short article suggests that new research and development technology is not applied because small oil cleanup companies cannot afford to invest in new equipment. It encourages spending by government agencies to create their own spill cleanup capacity.

Vagners, J. and P. Mar. 1972. Oil On Puget Sound, University of Washington Press, Seattle.

This general reference critically evaluates the current status of oil spill prevention and control in Puget Sound. Oil spread and traffic control models are discussed. Crude oil characteristics in the environment are qualitatively presented.

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

Waldman, G. A., R. A. Johnson and P. C. Smith. 1973. The Spreading and Transport of Oil Slicks on the Open Ocean in the Presence of Wind, Waves, and Currents, Coast Guard Report No. CG-D-17-73, NTIS # AD-765926.

This model of oil slick transport and spread was summarized by Stolzenbach et al.

Walkup, P. C., et al. 1971. Oil Spill Treating Agents: Test Procedures: Status and Recommendations, Battelle, Pacific Northwest Laboratories.

This section discusses effectiveness parameters for beach cleaners including ease of agitation and mixing, temperature effects, spill material type, and contact time. The quantitative analysis of dosage ratio and completeness of oil removal gives the best indication of effectiveness.

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.

Walkup, P. C., et al. 1969. Study of Equipment and Methods for Removing Oil from Harbor Waters. Battelle, Pacific Northwest Laboratories. Report No. CR 70.001.

Behavior characteristics of spilled oil are discussed. Spreading models that take wind and water currents into account and product properties are included.

Wang, H. and W. C. Yang. 1976. "Modeling of Oil Evaporation in Aqueous Environment." Water Research, 11:879.

This numerical model predicts the changes of oil characteristics, specific gravity, and percentage of weight and volume remaining during evaporation. Major driving forces are air temperature, wind speed, and slick size. Lab experiments resulted in developing empirical relationships for determining the diffusion coefficient in the first-order decay formula. The effect of temperature on oil weathering is very significant in early stages. The effect of wind speed is more uniform over time.

Wang, S. and L. Hwang. 1974. A Numerical Model for Simulation of Oil Spreading and Transport and Its Application for Predicting Oil Slick Movement in Bays. Tetra-Tech Inc., Report No. TT-P-345-74-1.

This computer model predicts oil slick transport in harbors and bays as well as spreading and movement on the ocean surface. Physical properties of the oil and behavior at the interfaces characterize the spreading process, which is then superimposed on the drift motion caused by wind and tidal currents. The model can predict oil slick size, shape and movement as a function of time.

Warner, J. L., J. W. Graham and R. G. Dean. 1972. "Prediction of the Movement of an Oil Spill on the Surface of the Water," Proc. Offshore Technology Conference, Dallas. Paper No. OTC 1550.

This model of oil slick transport and spread was summarized in Stolzenbach, et al.

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.

Wastler, T. A., C. K. Offutt, C. K. Fitzsimmons and P. DesRosiers. 1975. Disposal of Organochlorine Wastes by Incineration at Sea, Oil and Special Materials Control Division (WH-448), Report No EPA-430/9-75-014.

This report describes the monitoring activities undertaken to evaluate ocean incineration as a disposal method. Gas emissions indicated that 99.9% of the wastes were oxidized and no measurable increases in trace metal and organochlorine concentrations could be detected in the water and marine life. Results indicate that ocean incineration is a viable means of disposal.

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.

Wayment, E. C. 1977. Portable Beach Incinerator, Warren Spring Laboratory, England, Crown copyright ISBN-0-85624-100-8.

A portable incinerator was developed for onsite beach cleaning. Tar balls are put on a perforated plate resting over a drum and ignited from beneath. Molten residue drips into the drum and is subsequently burned. Combustion was more rapid in windy conditions.

Webb, L. E. R. Taranto and E. Hashimoto. 1970. "Operational Oil Spill Drift Forecasting," Paper presented at the 7th U.S. Navy Symposium of Military Oceanography, Annapolis, Maryland, May 12-14.

An operational method of forecasting oil spill drift is presented. Surface current parameters used are tidal, permanent, geostrophic, and wind drift currents. Each parameter is discussed and its contribution to the forecast method explained using vector sums. The method can be modified for use in restricted or open waters.

Weinstein, N. J. 1977. Municipal - Scale Thermal Processing of Solid Wastes, Office of Solid Waste, Report No. EPA/530/SW-133c, Contract No. 68-03-0293.

This report covers the state-of-the-art of incineration. It is an updated version of Municipal - Scale Incinerator Design and Operation, which was made obsolete by developments in resource conservation through thermal processing. This report includes site selection, design and cost data, utilities, weighing, handling, furnace design, energy recovery, pyrolysis, air pollution control, and resource recovery systems.

Welker, J. R., O. A. Pipkin and C. M. Sliepcevich. 1965. "The Effect of Wind on Flames," Fire Technology, 1(2):122-129.

This paper provides a simplified and improved correlation for the drag coefficient of windblown natural gas flames. Experimental results were obtained in a low speed wind tunnel.

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 Spartina marshes.

Williams, G. N., R. Hann and W. P. James. 1975. "Predicting the Fate of Oil in the Marine Environment," Proceedings of Joint Conference on Prevention and Control of Oil Pollution, San Francisco, California, 25-27 Mar, pp. 567-572.

The modeling presented here was developed to predict the impact of an offshore oil spill on the environment to aid SEADOCK on their oil spill contingency program. Extent of spread versus time was modeled. Information on the response time available for control at sea, sections of the coast which might require protection, and concentration of the soluble oil fraction in the water column was provided.

Wise, N. 1977. "Black Oil Disposal Techniques," Oil Spill Conference, API, publication No. 4284, p. 277.

Burning is considered a "limited application technique" which may be feasible depending on local problems. Given the requisite circumstances - a relatively isolated and unpolluted area, a high water table which precludes pit-burning or burial, and very large quantities of recovered oil the brush burner is an efficient, convenient, and high cost effective disposal technique.

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 a 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 98% 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.

SUBJECT INDEX

Burning

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APPENDIX C

CASE HISTORIES - TIME AND EVENT SEQUENCES

Case Histories Pages C-1 through C-25
Time and Event Sequences Pages C-26 through C-44

APPENDIX C

CASE HISTORIES

The purpose of including case histories is to establish events where combustion was or could have played a significant role in the pollution mitigation. Some of the events may call to reviewers' attention additional facts which are not available in the literature which will shed light on the oil burning question. These brief statements are documented to facilitate discussion and feasibility evaluation. Other documents, including the annotated bibliography (Appendix B) in this report, provide details on the events which are noted below.

The more than 60 oil spill incidents and 12 examples of use of burning as a mitigation tool were prepared from:

- U.S. Coast Guard Onscene-Coordinator files, Washington, DC
- "Oil Spills and Spills of Hazardous Substances" U.S.EPA
- USN "Manual for Open Sea and Ship Salvage Oil Pollution Abatement" OPNAVINST 6240.3D(1973)
- "Water Pollution by Oil" P. Heppel, Editor Elsevier Publishing Co (1971)
- "The Amoco Cadiz Oil Spill" NOAA/EPA Special Report (1978)
- "Measures to Combat Offshore Arctic Oil Spills," McLeod and McLeod Offshore Technology Conference (1972)
- "Oil Spill Intelligence Report," Center for Short Lived Phenomena, Cahners Pub. Co.

The cases reviewed as examples of oil combustion or circumstances where combustion may have been used as a spill mitigation tool are summarized below.

ANNE MILDRED BROVIG

On February 20, 1966, the Norwegian tanker ANNE MILDRED Brovig (24,454 GRT) loaded with 39,000 tons of Iranian crude oil, collided with the British MS PENDLAND (876 GRT) in the North Sea. The tanker caught fire and several explosions occurred. The following day the ship drifted to 54° 22.6' N, 6° 50.0' E, grounded and settled down by her stern in 120 ft of water. The floatable fore-section was cut off on May 2, 1966, and towed to Heligoland and then to Wilhelmshaven. A total of 21,300 tons of oil was offloaded (1,975 tons at the accident scene and 19,325 tons from the fore-end after towing), leaving approximately 17,700 tons discharged into the North Sea or burnt during the tanker fire. Only 2,200 tons could have burned, so that at least 15,500 tons were released to the sea. In spite of the amount of oil which escaped, German beaches did not report much oil pollution. Chemical dispersants (emulsifiers) were used to control the spill at sea. Drifting of the oil was kept under constant observation by planes, vessels and dead reckoning of the German Hydrographic Institute. It was reported that by calculations, using a drift of 4.2% of the wind velocity and allowing for inshore currents, the time of oil appearing near Blaavands Huk and Fano was predicted in advance with great precision.

TORREY CANYON

The TORREY CANYON, loaded with 118,000 tons of Kuwait crude oil, ran aground on the Seven Stones rocks off the coast of Cornwall, England on March 18, 1967, and released approximately 95,000 tons (26,000,000 gallons) of Kuwait crude oil over a period of about 12 days. The ship eventually broke into several sections and was finally bombed with incendiary devices in an attempt to burn the oil remaining in the ship. The oil released caused widespread contamination of the Cornish Coast of England, the Brittany Coast of France and the island of Guernsey. Cleanup methods employed by the British and French included chemical dispersing, sinking, burning and physical removal. The British relied largely on chemical treating agents, whereas the French used physical removal methods to avoid damaging shellfish and other marine life with chemicals. Cleanup costs have been unofficially estimated at $8 million to the British Government and $2 to $7 million for the French Government.

OCEAN EAGLE

The 12,065 ton tanker OCEAN EAGLE, carrying 5,700,000 gallons of Leona crude oil, grounded at the entrance to San Juan Harbor, San Juan, Puerto Rico, on March 3, 1968. The ship broke into two parts about two hours after grounding. Approximately 3 million gallons of oil escaped from the ship; the remainder was offloaded into barges. The two parts of the ship were removed from the harbor and sunk in early April in 600 fathoms of water about 8 to 10 miles north-northwest off El Morro. About 2 million gallons of the spilled oil spread throughout the harbor and the remainder drifted offshore as far as 30 miles east and 40 miles west due to unusual weather conditions. Slicks were reported up to a distance of 10 miles offshore. Some of these offshore slicks drifted back later and recontaminated beaches. Unofficial estimates of cleanup and salvage costs totaled $2 million.

Damage from the oil was to sea birds (primarily pelicans), holiday beaches outside the harbor, harbor structures and beaches, fishing boats and equipment, and small craft. Most of the recovery or treatment operations were in the harbor or on beaches.

GENERAL COLOCOTRONIS

The GENERAL COLOCOTRONIS, carrying 18,000 tons of Bunker C fuel oil, grounded on a coral reef about one mile off Eleuthera Island, Bahamas, on March 7, 1968, spilling about 2,600 tons of oil. The remainder of the cargo was off-loaded to another ship, the ESSO MARGARITA. Chemical dispersing was used to treat oil on the sea. Little damage occurred from this spill. About 3 to 4 miles of undeveloped beach and inaccessible shore were polluted out of some 2,000 to 3,000 miles of holiday beaches which might have been affected by a heavier spill or unfavorable winds.

SANTA BARBARA CHANNEL INCIDENT

On January 28, 1969, Union Oil Company well A-21 on Offshore drilling platform A in the Santa Barbara Channel blew out and a leak of mixed gas and crude oil occurred.

The released crude oil was driven ashore by south-easterly winds, resulting in contamination of beaches, harbors and rocky coastline, and initiating perhaps the largest oil cleanup operation that has occurred in the United States. Estimates of the rate of release at any one time varied considerably and it was impossible to measure the flow rate or cumulative volume. They estimated the cumulative total was 77,000 barrels after 100 days. This is equivalent to about 12,000 tons.

The principal damage from the oil spill was contamination of beaches and rocky shores, piling, wharves and ships in harbors, and birds. Total known bird losses through March 31 in the area affected were determined to be 3600. Marine mammals such as sea lions, seals, and whales were not affected adversely by the oil. Nor were there any serious acute kills among intertidal species, as determined by general ecological surveys and independent observations by biologists. Cleanup methods used or experimented with on the sea in the Santa Barbara incident included chemical dispersants, absorbents, skimmers, and booms.

HAMILTON TRADER

On April 30, 1969, at 03.48, the German coaster HANNES KNUPPEL (490 tons) collided with the British tanker, HAMILTON TRADER (12,718 tons) while the latter was anchored near the Bar Light Vessel in Liverpool Bay, England. The HAMILTON TRADER was bound for the Dingle oil terminal with fuel oil and was on charter to the Esso Petroleum Company. The tanker was holed about 3 ft below the waterline on the starboard side just forward of the bridge. Early estimates put the amount of oil spilled at around 2000 gal, but later it was reported that the quantity was more likely to be in the region of 600 tons. The oil escaped from one cargo compartment which had a capacity of 700 tons and spread over a wide area of England's Northwest coastal zone.

MV. EIRA

On December 9, 1969, this 5,860 DWT Finnish cargo ship went aground and sank in Ajax Shallows, 17 km southeast of Hanks at the entrance of the Gulf of

Finland. As a result of the sinking the vessel released some 15,000 liters of diesel oil with a resulting slick 18 km in length and 20 to 30 m in width. Booms could not contain the slick and a burn action was initiated using paraffin oil as an ignition source.

MV. RAPHALE

On December 15, 1969, this Russian flag ship of 50,000 DWT went aground west of Emasalo, Finland. The casualty resulted in the release of over 60 tons of crude oil which formed a slick 10 km long and several meters wide. Booms could not contain the spilled oil; however, the use of peat, fuel oil and petrol as fire promoters reslted in 90% of the spilled oil being burned.

STEAMTANKER ARROW

On February 4, 1970, the ARROW was proceeding into Chedabucto Bay, Nova Scotia, Canada, at a speed of 12 knots. Visibility was 5 to 6 miles; wave lengths were around 4 to 6 ft; and temperatures were near freezing. The vessel was laden with 16,010 tons of Bunker C oil; the No. 5 wing tanks were empty; and No. 5 center tank contained 79.5 tons of a lighter grade fuel. The cargo was maintained at a temperature of 135°F. The vessel was about to take on a pilot when at about 9:35 a.m. the bow struck a rock pinnacle. The vessel remained impaled on the pinnacle until the vessel broke in two and sank, (February 12) releasing all of her cargo to the ocean.

CHEVRON OFFSHORE OIL RIG MP-41C

On February 10, 1970, this oil platform caught fire off the coast of Venice, LA. The oil spill was first estimated at 8,000 barrels/day; however, this was later revised to 2,400 barrels/day. The crude oil involved was paraffin based 35/API gravity crude. By March 10, (28 days) the oil collection rig fire was extinguished.

SHELL PLATFORM FIRE

On December 1, 1970, a major offshore facility (Shell Company's Platform B Block 26, seven miles offshore of South Timbalier Bay) suffered a blowout, caught fire, and resulted in 4 million gallons of oil being lost. Oil was discharged into the Gulf of Mexico, but the platform was allowed to burn while relief wells were drilled to minimize the water pollution.

OCEANIC GRANDEUR

On March 3, 1970, this tanker hit an unchartered rock pinnacle in the Torres Strait near Brisbane, Australia. The 58,062 DWT ship, filled with an oil cargo, was within the 3-mile limit. The ship's bottom was severed for a distance of 186 ft. There were two main oil spillages, one upon impact and another on March 10, 1970. It was estimated that 5050 tons was spilled on impact and a similar amount escaped on the second occasion.

OTHELLO AND KATELYSIA

On March 20, 1970, the OTHELLO collided with the KATELYSIA in Tralhavet Bay, Sweden, and between 60,000 and 100,000 tons of Bunker C fuel oil were spilled. The oil formed large "blobs" 0.45 to 0.6 in. in diameter which sank except for a few centimeters showing at the surface. Ice flows in the area (ice was in spring thaw process) contained the oil somewhat and some oil was drawn up into the ice by capillary action. A burn action was implemented.

ALASKAN PENINSULA SPILL

On April 25, 1970, diesel oil from two Japanese ships which sank in a storm April 22, 1970, formed a slick 10 miles wide. The slick washed ashore polluting 700 miles of coastline.

ATHABASCA RIVER, ALBERTA, CANADA

On June 6, 1970, a break in a 16-in. pipeline released 17,000 barrels of oil into the river. The oil was rapidly transported downriver into the Athabasca Lake.

DECEPTION BAY, QUEBEC, CANADA

On June 6, 1970, a snow slush avalanche moving through a tank farm damaged 5 storage tanks which released 369,000 gallons of Arctic diesel fuel and 58,000 gallons of gasoline. The affected areas were the permafrost just below the tank farm, the shorefast ice, the tidal crack network and sea ice.

OIL BARGE IRVING WHALE

On September 7, 1970, the barge IRVING WHALE sank in the Gulf of St. Lawrence near Prince Edward Island. The barge carried some 4,000 tons of Bunk C fuel oil, pour point 12°C. Within 3 days, leaking oil formed lenses occupying an area 30 km long by 15 km wide.

ARIZONA STANDARD AND OREGON STANDARD

On January 18, 1971, both tankers collided in heavy fog in San Francisco Bay, CA, about 1/2 mile from the Golden Gate. The OREGON STANDARD spilled 5,000 barrels of Bunker C oil and a beach cleanup action was immediately instigated. The tide was in flood and there was little wind action. The spilled oil was first carried into San Francisco Bay then when the tide changed, the oil was carried through the Golden Gate for a distance of 7 miles seaward. By January 20, 1971, the oil had spread to its maximum limit and by January 27, 1971, beach cleaning and restoration was completed.

POLYCOMMANDER

On March 17, 1971, this 28,945 GRT tanker carrying 40,000 tons of light Arabian crude oil grounded when leaving Port of Vigo, Spain. Fire developed and it was reported that the crude oil took fire easily. After the fire was brought under control and extinguished, 33,000 tons of cargo were lightened from the vessel at a rate of 140 tons/hr. A total of 16,000 tons of crude were spilled into the ocean and could not be collected even though the tanker was boomed. The spilled oil contaminated 4 kilometers of beach and it was estimated that if the entire cargo had been lost some $30,000,000 of damage would have been experienced in the fishing grounds.

USN TOWLE

On the evening of July 14, 1971, this USN supply ship (T-AK240) was transferring Bunker C fuel. Due to a mishandling of flow valves the oil was discharged overboard into the harbor for a period of 3 hr. It was first estimated that only a 200 barrel (840 gallon) spill was involved. This was later revised to 900 barrels (37,800). The cleanup contractor actually recovered some 32,500 gallons of oil and the cleanup cost was $470,000.

AMERICAN OIL COMPANY, PLATFORM FIRE

On October 16, 1971, Platform B of Block 215, Eugene Island area, 40 miles offshore in the Gulf of Mexico, was involved in a fire. Three wells are gas and oil and two are oil only. Relief wells and surface shut down procedures were used to control the problem by November 27, 1971. Approximately 2000 bbl/day of crude were lost, most being consumed by fire.

TIEN CHEE

In May 1972 the tanker TIEN CHEE, carrying about 2 million gallons of crude oil, burned and spilled oil after she was rammed by the cargo vessel, ROYSTON GRANGE southwest of Montevideo, Uruguay. Oil spread in a fan shape to the southeast covering an area of about 300 square miles.

M/V SIDNEY E. SMITH JR. AND M/V PARKER EVANS

On June 5, 1972, both vessels collided in the Great Lakes and the SIDNEY E. SMITH, JR. carrying 49,000 gallons of Bunker C oil sank in 8 min at 1:56 a.m. At 3:00 a.m. a response action was initiated after the PARKER EVANS had lost 11,000 gal of No. 2 fuel oil, 9,000 gallons of which were recovered. By June 6, 1972, 34,000 gallons of cargo were offloaded and lightened and by June 15, 1972, 45,000 gallons had been lightened from the damaged vessel.

OIL BARGE SPILL

In January 1973 an oil barge struck a bridge pier on the Mississippi near Helena, Arkansas, spilling 800,000 gallons of diesel fuel. This was one of four oil barges which broke loose during a wintry accident resulting from flood conditions and fast current. The other barges stranded nearby, with two leaking. The leaking barges were offloaded after booms were placed near them.

M/V JACOB MAERSK (DE)

On January 29, 1973, while proceeding through the entrance to Leixoies, Portugal (Port of Oporto) this vessel grounded on a sandbank. A series of explosions occurred, followed by a fire which lasted until January 31, 1973, when it died naturally. The vessel finally sank after loosing 26,775,000 gallons of Persian Gulf crude oil.

ZOE COLOCOTRONI

In March 1973 the tanker ZOE COLOCOTRONI, with its cargo of 7.5 million gallons of crude oil, ran aground near the southwest coast of Puerto Rico. Her captain quickly discharged over 2 million gallons of crude oil into the sea to lighten and free the vessel, instead of waiting to offload it into a barge. With only minor damage, she proceeded to port, after causing the most serious oil spill in Puerto Rico since the OCEAN EAGLE incident in 1968.

The oil, driven by the wind, headed toward Bahia Sucia and Cabo Rojo. Floating oil covered a wide area, moving about with the wind and water currents.

An estimated 1 million gallons of oil hit the shore and beach areas; 400,000 gallons reached the island's mangrove swamps, where there was major damage to plant and animal life. On the beaches the oil penetrated as deep as 12 inches.

The damage by the oil was considerable, but the percentage of oil recovered was larger than in previous cleanup operations of oil tanker spills at sea. An estimated 700,000 gallons were collected in the first 6 days of recovery operations.

HILLYER BROWN

On March 8, 1973, the tanker HILLYER BROWN (US) ran aground on Kelp Point, Cold Bay, Alaska, outbound from Cold Bay, rupturing several tanks and flooding both pump rooms. The vessel was carrying diesel oil and light, straight-run gasoline. An accurate estimate placed the total cargo discharged into the sea at 1082 barrels (45,444 gallons) of gasoline and 4,511 barrels (189,463 gallons) of diesel. The escaped oil and gasoline dissipated due to high winds, and no heavy concentrations were immediately located. No further leakage of cargo was discernible after the initial discharge, and the vessel was refloated after transferring the outboard cargo into another tanker. The transfer of cargo commenced March 15 and was completed by March 18, 1973. The vessel was at all times quite close to land.

SS C.V. SEAWITCH AND SS ESSO BRUSSELS

On June 2, 1973, the SEAWITCH lost steering in New York Harbor and rammed into the ESSO BRUSSELS laying at anchor and laden with 31,000 bbl of crude oil. Three cargo tanks were ruptured; the oil cargo was ignited; and fire engulfed both vessels. The SEAWITCH's Master and 2 crew members died aboard the vessel. The Master and 10 crew members of the ESSO BRUSSELS died after abandoning ship, one crew member died on the vessel; and one crew member was listed as missing. The incident occurred about 400 yards from shore and the ship damage above was assessed at $23 million.

OIL BARGE SPILL

In December 1973 a towed barge spilled 336,000 gallons of crude oil after an accident on the Atchafalaya River west of Baton Rouge. Much of the oil was contained within a one-mile stretch of the river. There were an estimated 50,000 ducks in the marshes along the river, but the oil was prevented from reaching them by protective booms placed by response personnel.

ELIAS

In April 1974 the oil tanker ELIAS exploded and burned while offloading Venezuelan crude oil in Philadelphia. The blast was felt for 35 miles.

IMPERIAL SARNIA

On April 15, 1974, this tankship grounded on Whale Bank Shoal in the St. Lawrence River, Canada. Three cargo tanks were ruptured releasing 147,000 gallons of crude oil. A total of 130,200 gallons of crude were recovered from the water. An estimated 17,000 gallons of crude were spread by the water currents. The latter amount of oil affected the marine environment and contaminated 65 miles of coastal shoreline. The vessel was offloaded and refloated on April 16, 1974. However, shoreline cleanup and restoration was notcompleted until May 31, 1974.

ESSO GARDEN STATE

In August 1974 a broken submerged pipeline caused the tanker ESSO GARDEN STATE to spill a large quantity of oil into the South Atlantic Ocean at Rio Grande do Sul, Brazil. She was moored five kilometers off Tramandai Beach, discharging about 15 million gallons of crude oil when the spill occurred. The terminal serves the refinery at Canoa, near Porto Alegre.

OIL BARGE SPILL

In June 1974 a barge struck the Huey Long Bridge on the Mississippi near New Orleans, spilling an estimated 157,000 gallons of crude oil. Ribbons of the oil reached 30 miles downriver and oil was collected at the outside of each bend on the river.

ULCC METULA

On August 9, 1974, this 206,000 DWT, 1,067 ft OAL tanker carrying 193,673 tons of Arabian light crude grounded in the Straits of Magellan (Lat. 52°34'S; Long 69°48.48'W). By August 11, the vessel lost all power and by August 15, had lost 1,52,000 tons of her oil cargo. On August 19, additional hull damage occurred and another 40,000 tons of oil were discharged into the sea. On August 29, cargo offloading was commenced and 15,000 tons of oil were lightened. During the month of September another 50,000 tons of oil were off-loaded and the vessel was refloated September 25, 1974 (48 days after the grounding). The vessel was then moved to a safe anchorage where the rest of the crude cargo was offloaded.

TRANSHURON

In September 1974 the tanker TRANSHURON ran aground on the north shore of Kiltan Island in India and spilled about 900,000 gallons of heavy fuel oil.

TOKYO BAY SPILL

In November 1974 about 12.5 million gallons of naphtha and liquefied petroleum were spilled into Tokyo Bay when a tanker and freighter collided and exploded.

MIZUSHIMA, JAPAN SPILL

On December 18, 1974, about 11 million gallons of crude oil were spilled into the Inland Sea from a large storage tank at Mizushima, 300 miles south-west of Tokyo.

Damages to fisheries were extensive in this first large oil spill into the Inland Sea. Winds and current pushed a slick 80 miles long and 15 miles wide. Payments by the oil company for damages soon reached $6.1 million, with $3.3 million more promised.

BANTRY BAY IRELAND OFFSHORE OIL PORT SPILLS

Early in January 1975 a supertanker spill occurred in Bantry Bay at the southwest corner of Ireland. It was the second spill there in a short time. In October 1974, crude oil was spilled at a terminal on Whiddy Island in Bantry Bay when a valve on the 92,000-ton tanker UNIVERSE LEADER failed to close.

During the 1974 spill over 750,000 gallons of oil escaped, clogging Irish fishing ports and fouling coast and beach areas. Seagoing tugs sprayed detergent on the slick along the coast to sink it. Removal of the oil was hampered by lack of manpower and suitable equipment.

The Bantry Bay is rich in marine life. On the south shore of the bay, all life was reported virtually destroyed a month later. Fishermen claimed that the entire southern end of the bay, where oil was accumulated by northerly winds, had become unfishable.

TOSA MARU AND CACTUS QUEEN

In April 1975 the tankers TOSA MARU and CACTUS QUEEN collided south of St. John's Island in the Strait of Singapore. The Tosa Maru burned and sank.

CORINTHOS

In January 1975, the tanker CORINTHOS, while offloading crude oil at Marcus Hook below Philadelphia, was struck by the tanker EDGE M. QUEENY. The CORINTHOS exploded and burned, leaving three dead and 27 missing. The CORINTHOS carried approximately 13 million gallons of light crude. The QUEENY, with its cargo of phenol, gasoline, paraffin, and vinyl acetate monomer, suffered relatively light damage.

Flames from the fire reached 500 feet into the air and could be seen for over 15 miles in the heavily industrialized and populated area. Favorable winds kept the flames from reaching the tank storage area near the unloading terminal. The oil slick immediately began to spread down river. The cost of cleanup was over $1,000,000.

SHOWA MARU

In January 1975 the supertanker SHOWA MARU, with over 67 million gallons of crude oil, ran aground on rocks and coral reefs in the Strait of Malacca. Coastal and beach areas of Singapore, the Malay Peninsula, and adjacent islands were threatened after three of her 12 tanks released about 1 million gallons of light oil. A 10-mile slick moved onto several islands in the western section of the port of Singapore, as well as resort and dock areas. Large-scale measures to combat the slick had to be organized and put into service almost immediately.

OIL BARGE SPILL

In March 1975 one of four barges being towed by the tug, JOHNNY DAN wrapped around a bridge pier on the Mississippi near Helena, Arkansas (site of a 1973 barge spill described elsewhere in this listing). A total of 770,000 gallons of crude oil were spilled. The spill was carried downstream for a distance of 40 miles.

TARIK IBN ZIYAD

In March 1975 the tanker TARIK IBN ZIYAD, carrying about 28,000,000 gallons of light crude oil, ran aground and spilled about three million gallons of oil into the Guanabara Bay at Rio de Janeiro, Brazil. Some of the oil was carried out of the bay by tides and wind. A portion of the South Atlantic shore area was affected.

EPIC COLOCOTRONIS

In May 1975 the tanker EPIC COLOCOTRONIS, carrying about 16.5 million gallons of Venezuelan crude oil, spilled and burned near the Dominican Republic.

GLOBTIC SUN

In August 1975 the oil tanker GLOBTIC SUN caused an oil spill after it ran into an offshored drilling rig at night and caught fire. The platform had no working wells and was being built in 175 feet of water in the Gulf of Mexico, 120 miles southeast of Galveston, Texas. The tanker was carrying almost 15 million gallons of light crude oil and was abandoned by the crew at the time of the accident because of the fire. The drifting and leaking ship was later salvaged and offloaded of remaining oil after the fire went out.

SINGAPORE HARBOR

In October 1975 a 123,484 ton tanker was struck by lightning and broke into three parts after catching fire in Singapore Harbor.

OIL BARGE SPILL

Late in December 1975 a 240 ft barge pushed by the tug PETER CALLAHAN in dense fog, hit a pier of the Tappan Zee Bridge over the Hudson River. More than 90,000 gallons of No. 2 home-heating oil were spilled.

Because of the cold water, scientists from the Woods Hole Oceanographic Institute estimated that 25% of the spill went to the bottom. They indicated that the effects of the spill would persist in the river and its sediments for years.

TRANSPORTATION BARGE STC-101

On February 2, 1976, while in tow this barge partially sank in a vertical position (bow down) 3.5 miles south of Smith Point Light, VA, in the Chesapeake Bay (Lat 37°49'N; Long 76°11'W). Some 45,265 gallons of No. 6 fuel oil reached the Western Shore of Virginia, while 79,965 gallons reached the Eastern Shore, 251,496 gallons were unaccounted for. A later tabulation revealed that 5,959 tons (249,838 gal) had actually been spilled in the casualty. The incident happened in relatively calm water, clear of any off-shore structures, some 5 miles from the nearest point of land.

URQUIOLA

On May 12, 1976, the tanker URQUIOLA exploded and broke open after it struck a reef near the mouth of La Coruna Bay in Spain, spilling about 4.5 million gallons of light crude oil. The fire was extinguished May 15, and the remaining oil was pumped into another tanker. Oceanographers advised that there was a possibility that prevailing ocean currents could carry some of the oil to the Caribbean area in the months following the spill.

OIL BARGE NEPCO 140

On June 23, 1976, the barge NEPCO 140, with almost 7 million gallons of heavy fuel oil, went aground at 1:35 a.m. in the American Narrows near the Thousand Islands Bridge. Three tanks ruptured and spilled about 500,000 gallons of oil.

The spill moved 80 miles downstream and covered 30 miles the first day. Hundreds of miles of beaches, shorelines, inlets, covers, marshes or wetlands, and waterfronts were covered with the tarlike substance, requiring over $6.5 million for cleanup.

Over 700 people, 50 vessels, several booms, seven skimmers and 14 vacuum trucks were involved in cleanup. Oil containment booms were placed in an effort to keep oil from entering critical areas. In spite of this the No. 6 oil penetrated more than five feet into 16 miles of wetlands.

SINGAPORE SPILLS (MISC)

In July 1976 five ship collisions and a major oil spill were reported in the crowded Strait of Malacca near Singapore.

RYOYO MARU

In September 1976 the 96,000-ton tanker RYOYO MARU broke in half during a typhoon off southern Japan, east of Kyushu.

OLYMPIC GAMES

In December 1976 the tanker OLYMPIC GAMES ran aground, spilling 134,000 gallons of oil into the Delaware River near Marcus Hook, Pennsylvania. Within a few weeks of the spill about 80,000 gallons of the oil had been recovered. Some of the oil remained trapped under the ice along two shorelines and could not be reached until warmer weather.

T.S.S. ARGO MERCHANT

In December 1976 the ARGO MERCHANT ran aground on the Nantucket Shoals about 35 miles southeast of Nantucket Island. Efforts to free the vessel were unsuccessful and she broke up, spilling 7.6 million gallons of heavy oil. Some of the slick moved into the fishery area of the Georges Bank.

Containment booms and skimmers were impractical because of the high winds and waves. Burning of the thick oil on a cold and choppy sea was tried but combustion could not be sustained.

The ARGO MERCHANT spill threatened the humpback whales, gray seals, and a large fishing industry. Twelve groups of fishermen, from the local fishing industry which employs about 30,000 people, sued for $60 million in damages.

SANSINENA

On December 17, 1976, the tanker SANSINENA, after unloading a cargo of crude oil, exploded and burned at San Pedro, CA. During the cleanup operations oil was recovered from the vessel and surrounding water.

GRAND ZENITH

In December 1976 the tanker GRAND ZENITH sank at sea with all hands and a full cargo of over 6 million gallons of oil. The casualty occurred in the Atlantic Ocean several miles south of Nova Scotia at a time when the U.S. Coast Guard was fighting the ARGO MERCHANT oil spill.

BARGE B-65

In January 1977 this barge ran aground in Buzzards Bay, Massachusetts and spilled 100,000 gallons of heating oil. The response action included a successful burn of oil on the surface of the water.

IRENES CHALLENGE

On January 21, 1977, this tanker, carrying over 64 million gallons of gasoline, broke up and sank near the Midway Islands in the North Pacific Ocean.

EXOTIC

In January 1977 the tanker EXOTIC exploded and burned in southern Morocco.

EXXON SAN FRANCISCO AND BARGE EXXON 119

Late in January 1977 the tanker EXXON SAN FRANCISCO and barge EXXON 119 exploded and burned in the Houston Ship Channel. A loading arm failure had sprayed heating oil and a nearby tow boat started its engines, which may have caused the fire. Several people were killed or injured in the incident.

ETHEL H

On February 4, 1977, the oil barge, ETHEL H, while under tow ran aground on Con Hook Rock in the Hudson River, NY. Ice conditions were evident in the river which to some extent helped to contain the spilled oil. The resulting response action finally involved the removal of 103,000 gallons of No. 6 fuel oil, 2000 yd^3 of solid waste, and 300 drums of oil soaked from the vessel. The response action was completed at a cost of $1,115,000.

AMOCO CADIZ

At approximately 11:30 p.m. on Thursday, March 16, 1978, the supertanker AMOCO CADIZ went aground on a rock outcropping 1.5 km offshore of Portsall on the northwest cost of France. The vessel contained a cargo of 216,000 tons of crude oil and 4,000 tons of bunker fuel. At 6:00 a.m. on Friday, March 17, the vessel broke just forward of the wheelhouse and thus started the worst oil spill in maritime history. During the course of the next 15 days, the bunker fuel and contents of all 13 loaded cargo tanks, which contained two varieties of light mideastern crude oil, were released into the ocean. The oil quickly became a water-in-oil emulsion (mousse) of at least 50% water, and heavily impacted nearly 140 km of the Brittany coast from Portsall to Ile de Brehat. At one time or another oil contamination was observed along 393 km of coast-line and at least 60 km offshore. Impacted areas included recreational beaches, mariculture impoundments, and a substantial marine fishery industry. The time lapse of events was clearly shown by Hann et al., in the NOAA Preliminary Scientific Report on the AMOCO CADIZ, Figure 3-D (see Figure C.1).

BETELGEUSE

In January 1979 while unloading Saudi Arabian crude oil at the Gulf Oil terminal at Whiddy Island in Bantry Bay, Ireland, the French Tanker, BETELGEUSE (built 1968) suffered 2 explosions. From initial and information reports, fifty people were killed, the vessel sank, and the terminal was significantly destroyed.

About two-thirds of the cargo had been offloaded from the 119,514 DWT vessel's 18 tanks which were capable of carrying 893,000 bbls. Approximately 40,000 tons of crude oil could have been discharged into Bantry Bay. Flames ($\sim$600 ft high) burned for most of a day (approximately 20 hr) before a light rain and efforts by response personnel resulted in the fire dying out. A significant amount of oil leaking at about 5 tons per hour did remain aboard the vessel which sank in 30 meters of water. Initial informal reports indicated that spilled oil did burn, primarily in the wreck's vicinity, but flaring patches drifted 600 to 1000 yards to shore. Oil washing ashore was observed as viscous, possibly due to partial combustion and heating. The case pends full reporting.

CASE HISTORIES OF BURNING ATTEMPTS

Burning attempts of oil involved in releases or spill incidents have been recorded and are referenced in detail in the annotated bibliography (see Appendix B). As was shown in Table 2.10 there have been many successful uses of burning. However, careful attention should be paid to the environmental conditions and types of oil which are so reported. Many of the reports are inconclusive and many have such little scientific data that the results may not be extrapolated. A few case histories follow to provide a little more detail. This information was gathered from the literature and from personal knowledge of the incidents gained from direct contact with the spill response participants.

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 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 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. Environmental conditions during the tests were: ice temperature, 0.3°C; water temperature, 1 to 2°C; air temperature, 1 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 patchs. 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 to cigarette 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 disbursed 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 pounts 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 burning was considered, but there was opposition expressed by local vegetable farmers.

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 C.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. objections. The owner was attempting throughout the incident's early days to locate pyrotechnic specialists.

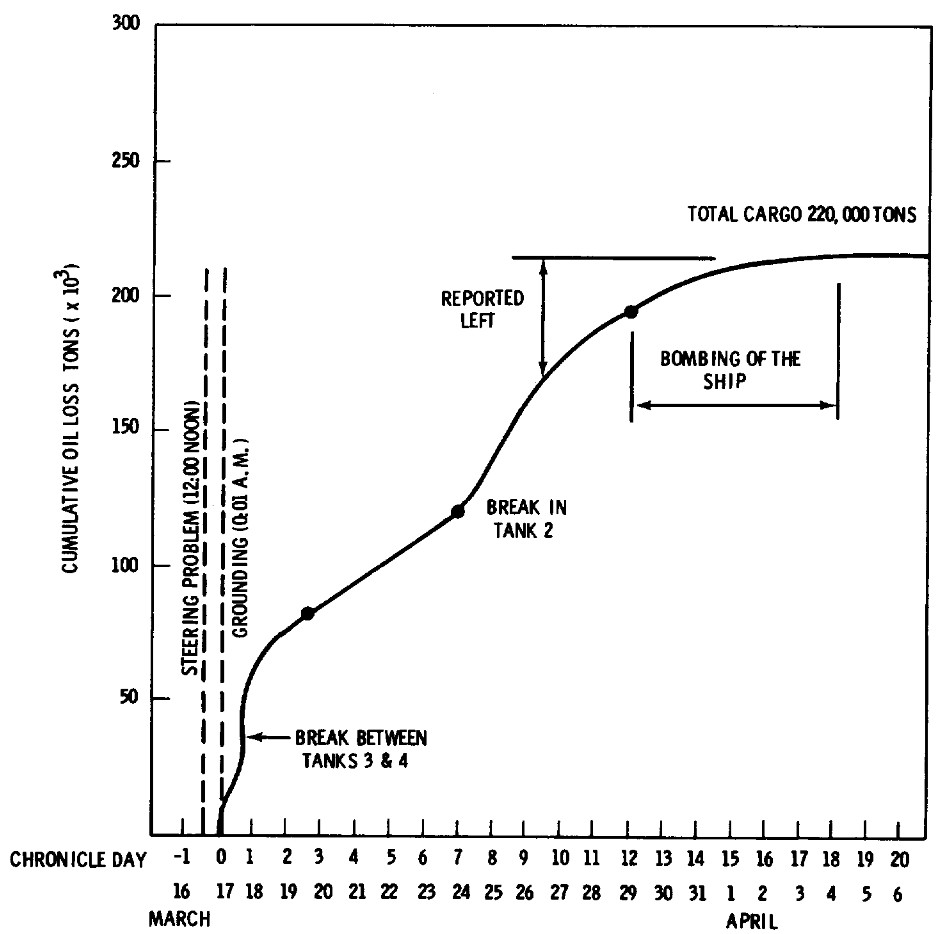


FIGURE C.1. Estimated Cumulative Oil Release from Amoco Cadiz Spill

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

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 98% 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.

To explain, in part, the reasons for the different observations and the reported variable success of burning, the theory of combustion and oil must be examined (see Section 3).

TIME AND EVENT SEQUENCES

STEAM TANKER "ARROW
LOST CHEDABUCTO BAY
NOVA SCOTIA, FEBRUARY 4, 1970
THROUGH FEBRUARY 12, 1970

1. Cargo

Venezuelan Bunker C fuel oil
Lighter grade fuel oil

2. Environmental Conditions (2/4/70)

Water temperature 0-1 C (33.8°F); air temperature much lower; wind SW at about 20 knots; waves SW significant height 20 to 22 feet, significant period 11 seconds. Water depth about 100 feet. Visibility 5 to 6 miles.

3. Oil Quantity

A. 16,010 tons Bunker C at 135°F
B. 79.5 tons lighter grade fuel oil at 135°F

Note: No. 5 wing tanks empty
No. 5 center tank held light crude

4. Other Casualty Features

- Vessel was proceeding at 12 knots through Chedabucto Bay heading to the Straight of Canso
- Vessel was 22 years old
- Vessel had 27 cargo compartments
- Casualty site was remote, lacked spill response resources, shores were inaccessible, rocky/shingle shoreline.
- Vessel was preparing to take on pilot

5. Sequence of Events

Day 1: February 4, 1970, 9:35 AM, vessel's bow struck Cerberus Rock and became impaled. Captain expected to be released by next high tide, indicated that he did not want assistance. 9:00 PM, vessel still aground - rolling on rocks. 10:30 PM, crew leaving forward part of vessel moving aft.

Day 2: February 5, 1970, 4:00 AM, vessel still trying to pull off rock with own power. 6:17 AM, ship's boilers shut down, crew abandoned ship.

Day 3: February 6, 1970, partial crew returned to ship, attempted to raise steam on boilers to heat oil cargo (oil now almost solid and offload. Engine room began to flood. Heavy oil slick escaping from vessel.

Day 4: February 7, 1970, ARROW broke back.

Day 5: February 8, 1970, bow and stern only attached by deck plates. Decision made to separate damaged sections of vessel due to movement of stern. Arguments ensued between crew and response personnel on who should be aboard during separation procedure. Partial crew returned to the vessel and vessel separated in two, aft of No. 5 tanks.

Day 6: February 9, 1970, preparation underway to float stern section.

Day 7: February 10, 1970, equipment readied aboard vessel.

Day 8: February 11, 1970, riding out storm.

Day 9: February 12, 1970, vessel sank releasing total of 70,000 barrels to Chedabucto Bay. Several slicks were formed and 190 miles of coastline were polluted.

Day 26: March 1, 1970, oil slick from ARROW reached and contaminated shoreline of Sable Island some 110 statute miles southeast of casualty site.

Results: Vessel total loss, major loss of cargo, extensive environmental degradation in otherwise undegraded area heavily populated with wildlife.

T/V IRENES CHALLENGE LOST 200 MI SOUTHEAST OF MIDWAY ISLAND, PACIFIC OCEAN, JANUARY 17, 1977

1. Cargo

API 17 crude oil
API 16.5 raw petroleum oil

2. Environmental Conditions

The first weather report indicated wind to be bearing 240° at 15 knots, seas bearing 290 with 6 to 8 ft waves. (This report provided by M/W Pacific Arrow first vessel to reach casualty site).

3. Oil Quantity

228,571 barrels, or 9.6 million gallons, or 34,000 long tons.

4. Other Casualty Features

- Vessel was located in the Pacific Ocean at a location 26°-53'N, 73°-52'W
- Three crew members lost their lives as a result of ship sinking; however, 28 crew members were rescued by the M/W Pacific Arrow
- Casualty occurred near U.S. National Wildlife Refuges-Lisianski Island, Pearl and Hermes Reef, Laysan Island and Maro Reef. Rare and endangered birds and wildlife species included:

  Hawaiian Monk Seal, Laysan Finch, Laysan Teal, Laysan Albatross and Blackfooted Albatross (latter two being the largest colony in the world).

- Vessel was 21 years old (ABS rates 25 years as useful life)
- Casualty occurred on high seas (57 miles from U.S. coastline). To legalize response action, and again reimbursement of costs, Intervention on the High Seas Act (33 USC 1471 et seq.) was invoked. Section 1472 of Act allows action when there is grave imminent danger to coastline or other U.S. interests from threat of pollution. Section 1486 of Act makes available revolving fund [33 USC (1321)(k)] for reimbursement.
- Vessel suffered structural failure in area of No. 5 cargo compartment.
- The federal response action cost $300,182.11, exclusive of time lost by commercial shipping that responded to SOS of stricken tanker.

5. Sequence of Events

Day 1: January 17, 1977, at 10:00 AM, the Master of the T/V IRENES CHALLENGE discovered a structural failure and at 12:30 PM a cracking sound was heard and the ship bent amidships.

Day 2: January 18, 1977, T/V IRENES CHALLENGE sent an SOS at 12:38 AM. USCG aircraft and two rescue craft dispatched to scene. M/V PACIFIC ARROW arrived at casualty site and rescued 28 crew members. First USCG vessel on site 4:14 AM reported two mile long oil slick. M/V RONA RIVER arrived on scene 8:00 AM. Both merchant vessels continued to standby stricken vessel. Salvage plans instigated.

Day 3: January 19, 1977, regional response team (RRT) convened 7:00 PM, planning commenced to dispose of stricken vessel, protect wildlife and instigate cleanup action. Plans discussed included:

a. sinking vessel in place (2700 fathoms)
b. towing away from wildlife refuge islands and sinking vessel
c. burning the oil cargo while still contained in the vessel

Item a. was considered the best alternative even though oil sunk with the vessel may pose future threat.

Oil cleanup procedures under consideration included:

1. Chemical dispersion (last resort)
2. Mechanical dispersion (preferable action)
3. Skimmers and absorbent material (skimmers out due to high seas; sorbents possible on shorelines)
4. Diversion booms (possible if found available for high sea use)

General conclusion reached to sink in place trying to keep oil cargo in vessel permitting oil to seep out slowly from depth (2700 fthm/16,000 ft)

Day 4: January 20, 1977, at 10:00 AM, OSC proposed towing vessel to open sea location to sink vessel. Attack on slick suggested as sinking and use of dispersing agents, also use of booms and sorbents if needed. Suggestion of on-water burn of oil slick ruled out due to futile attempts to burn at ARGO MERCHANT - and another marine spill near Spain. Magnitude of slick now in triangle 70 mi x 60 mi x 30 mi (50 mi to nearest island). All stern tanks of vessel now submerged with deck at 30-degree angle. Attempt to tow section not practical by USCG cutter, MALLOW; with available 5-in. hawser. Stern section vanished presumed sunk in 2800 fathom.

Day 5: January 21, 1977, large hole in bow section of 10 ft above waterline releasing oil. The bow was visibly settling and sank at 8:57 AM in 2800 fthm. No upwelling of oil observed after sinking. Light streaks of oil observed in 12 x 20 mile area during overflight.

Day 6: January 22, 1977, scheduled aerial overflight cancelled due to 30 to 40 knot wind storm front which apparently dispersed the slick away from islands and reefs.

Day 11: January 27, 1977, oil slick sighted 4 miles long x 1/2 mile wide.

Day 12: January 28, 1977, case closed when no apparent threat to wildlife refuges was evident.

STT. ARGO MERCHANT LOST
FISHING RIP SHOAL SE. OFF
NANTUCKET ISLAND, MA.
DECEMBER 15, 1976 - JUNE 1977

1. Cargo

No. 6 Bunker C fuel oil - Venezuelan

2. Environmental Conditions

On the day of the casualty offshore winds were blowing 230 T/10 feet seas, visibility 8 miles, air temperature below freezing. These conditions were fairly consistent during the entire spill response action except for certain days when a northeaster caused response vessels to proceed to safe harbor and the wreck was broken in two. Icy deck conditions were frequently evident on the response craft and the wreck itself.

3. Oil Quantity

27,500 long tons (7.5 million gallons)
No. 6 Bunker C fuel oil
$\pm$ 2076 tons of bunker fuel for ship's use

4. Other Casualty Features

- Vessel was 23 years old

- Due to mechanical/electrical malfunctions the vessels' navigation instrumentation was confined to a magnetic compass

- Vessel was 12 "lost" nautical miles inboard of normal traffic lane used for access in port of Salem, MA

- Radio message received at 0710 by USCG from vessel indicated that ship's "position was unknown" (ship grounded at 0700 hr)

- Casualty site was in charted shoal waters having a mean low water depth of 21 feet. Vessel draft at time of impact onto shoal was never determined by response/investigative personnel. With the engine and pump rooms flooded, after grounding, the vessel's draft was observed to be 36 feet aft and 34 feet forward.

- Vessel had 30 cargo compartments (1,359,000 bbls), two bunker fuel tanks (total 2076 tons), 2 oil/water settling tanks and a dirty oil tank.

- Shipboard pumping capacity was 4,000 tons/hr. On this basis the ship using her own pumps could have offloaded her cargo in about 49 hours based on 6.9 barrels equaling 1 metric ton.

- At 0830 (1 hr, 20 min after grounding) the Master of the ARGO MERCHANT requested permission to pump fuel cargo overboard to control the draft and lighten the vessel. At 0900 the engine room began to flood; power was secured leaving the ship with only an emergency generator. If offloading into the ocean was commenced immediately on grounding, the maximum amount of cargo that could have been offloaded in 2 hr prior to losing power would have been 8000 tons or 50,000 barrels. As the vessel was taking on water at a rapid but undetermined rate it appears doubtful if the offload would have compensated for the flooding or materially lightened the ship to ride free off the shoal.

- At 0915 (2 hr, 5 min after grounding) the Master was denied permission to lighten ship, but was advised to standby for U.S. Coast Guard assistance.

5. Sequence of Events

Day 1: December 15, 1976, vessel ground on Fishing Rip Shoal. Request to offload cargo refused, engineer room flood ship lost power and steam to heating coils which maintain cargo in fluid state at about 90° to 120°F (32°-48°C); seawater temperature 43°F(6°C); air 46°F(8°C); winds 230 T/25 knots; seas 230 T/10 ft; visibility-8 miles. USCG damage control party reported 19 feet of water in engine room and water in fuel tanks. Stability charts indicated vessel could float with engine room flooded. Act of Intervention invoked and U.S. response budget of $500,000 established.

Day 2: December 16, 1976 - all hands removed to forward deckhouse, salvors and salvage equipment aboard vessel. Engine room flooded to around 40 feet. Weather conditions greatly reduced. Pumps lowered water in engine room by 7 feet. Flooding out of control 1830. Crew evacuated from vessel 2100.

Day 3: December 17, 1976 - vessel listed from 5°-10° on fluctuating basis, vessel settling into shoal, stern deck awash, heavy oil leakage.

Day 4: December 18, 1976 - cooling of oil reduced spillage, plans underway to reheat oil and offload.

Day 5: December 19, 1976 - oil leakage estimated at 1.5 millions gallons. Response funding of $486,000.00 spent; additional $1M requested.

Day 6: December 20, 1976 - vessel now has 15° list, weather conditions quite satisfactory winds, 11 knots, seas negligible, visibility and ceiling limited.

Day 7: December 21, 1976 - bow pitching up to 10 feet, ship split aft of kingpost bow and stern grinding together. Additional $500,000 requested for salvage-response operation.

Day 8: December 22, 1976 - deck awash under 3 feet of water, bridge house totally underwater, icy conditions on wreck and response craft. Oil slicks observed for 90 nautical miles from wreck.

Day 9: December 23, 1976 - condition of vessel basically unchanged, water surface around wreck covered 100% with oil, oil clumps, and tar balls.

Day 10: December 24, 1976 - no change in vessel, initial tests to burn with wicking agent were instigated at onshore location, seagulls heavily oiled in wreck area.

Day 11: December 25, 1976 - weather conditions not too severe, barometer falling, 55 mile wide S shaped slick sighted.

Day 12: December 26, 1976 - 200 yard wide oil slick originating from ARGO MERCHANT heading away from vessel at 250 T. Condition of vessel unchanged.

Day 13: December 27, 1976 - stern section remained unchanged, with deck awash. Bow section laid over to starboard and sunk approximately 10 feet. Tilt to starboard, 40 degrees; keel laid 50 degrees above horizontal. Waterline ran from 10 feet astern of forefoot to 35 feet aft of forecastle break, port side, to 6 feet forward forecastle break, port side. Occasionally bow section moved as much as 3 feet with the seas. Due to 60-degree inclination of deck, any operations aboard were considered extremely dangerous. Pollution sheen tended 270 T, breaking up within one-half mile due to sea action.

First burn tests instigated using Tulanox 500 in plastic containers (11 lb) with thermite ignition charge. Later in day, stern section turned over and sank.

Day 14: December 28, 1976 - no major changes, decision made to use surface platform for burn tests after helicopter test conducted this day gave negative results.

Day 15 and 16: December 29 and 30, 1976 - monitoring and response activities continued, no change in vessel.

Day 17: December 31, 1976 - bow section sunk with shell fire 520 rounds of 20 mm ammo, 30% hits caused bow to settle on bottom. Burn tests from surface craft were unsuccessful due to high winds (8 knots) dispersing powdery wicking agent, and propulsion turbulence breaking up oil slick, unable to sustain burn.

Day 18 through 51: January 1 to June 15, 1977 - continued overflights, on scene monitoring with divers and surface craft, oil and water sample collection. Case closed June 15, 1977.

5. Results

- Vessel was total loss, all cargo lost to ocean, other than oil trapped in sunken sections of the vessel.

- The following equipment was deployed at the spill site, or at beach areas threatened by spilled oil:

BEACH CLEANUP EQUIPMENT

Nantucket Island

Ten 16-foot boats
Twenty motors
One commercial van
Three 40-foot box trailers
Utility van life-saving equipment, etc.
5500 feet of 36-in. metropolitan boom
Two box trailers
One flatbed
Two tank trucks
One tractor
Two bail pumps
6,000 ft of 36-in. boom with anchors
Absorbents
Hand tools
One truck
500 ft of 1-1/4-in. discharge hose
Forty-five shovels
Two boxes of rain gear
Thirty pitchforks
Thirty racks
Four personnel

Woods Hole:

One tractor trailer
Oil snare
Absorbent No. 6
One 40-foot box trailer and gear
Additional equipment was available (on an as needed basis) at:
A. Stoughton, MA (1-hour response)

B. Subcontracted:

(1) Local contract for diking;
(2) Two local boats on standby;
(3) 100 personnel from island.

Fifteen hundred feet of 36-in. coastal booms
Three hundred 18-in. coastal booms
Three hundred and fifty 18-in. metropolitan booms
One hundred and eighty sausage booms (10-foot sections)
One thousand and forty coastal packs
One spill trailer
Assorted tools
One 2-inch suction hose
Three boats

Personnel: Nine trained personnel available on-scene.

ADDITIONAL CONTRACTUAL EQUIPMENT

Four pressure vacuum trucks, plus 10 as needed
Twelve pumps - air/electric
Three air compressors
Five tank trucks -- 5,000, 8,000, 10,000 gal.
One industrial tractor
Two trailers-equipment-box-low-bed
Four boats
One water blaster
Five hundred feet of 36- and 13-in. booms
Grefco booms
Grefco pillow bags
Sea Serpent boom
Petroleum - trap bags 5 pack
Conwed blanket-booms-pads
Fifty-inch hauling barge, water-proof vessel, plus 10,000 gal. tank
Fifty-six LCN barges
Two truck - spill trailers, Chatham area
One truck - spill trailers, Orleans area

Cannons placed on alert A.M., 15 December 1976, and hired by Coast Guard at 1900, 25 December 1976, to deploy equipment at Chatham and Orleans.

ADDITIONAL RESOURCES: FEDERAL AND CONTRACTUAL

Vessels:

CG UNITS

1. CGC VIGILANT
2. CGC SHERMAN
3. CGC BITTERSWEET
4. CGC EVERGREEN

RESEARCH	Released
1. R/V DELAWARE II	December 23, 1976
2. R/V OCEANUS	December 21, 1976

COMMERCIAL

1. Tug SHEILA MORAN	December 22, 1976
2. Tug MOIRA MORAN	December 22, 1976
3. Tug MARJORIE B. MCALLISTER	December 22, 1976
4. Tug CURB	December 26, 1976
5. CALICO JACK (alerted 16 Dec. 1976)	
6. Barge NEPCO 140	December 16, 1976
7. Barge NEW JERSEY	December 22, 1976

NATIONAL STRIKE FORCE:

Personnel:

Atlantic Strike Team - maximum assigned personnel 23
Gulf Strike Team - maximum assigned personnel 10

EQUIPMENT

Five ADAPTS pumping systems (two lost on ARGO MERCHANT)
One command post Trailer with five insulated phone lines
One trailerized communications center (TCC)
Five boxes High Seas skimmers
One Lockheed skimmer
Dive equipment
Public Affairs Trailer with four installed phone lines.

COAST GUARD AIRCRAFT - Air Station Cape Cod

Three HH3 helicopters
Four H52 helicopters
Three HU16E albatrosses
CGAS Elizabeth City, N.C.
Three ---- C130

ARMY EQUIPMENT

One C-141 aircraft
Two CH54 Skycrane helicopters
Two UH-1 helicopters
Five 5-ton tractors
Four 12-ton trailers
One low-bed trailer
One 1/2-ton jeep
One 5-ton wrecker
One 500-gal. water trailer

AIRFORCE EQUIPMENT

One C-141 aircraft

AIR NATIONAL GUARD

Two UH-1's
Crane Service
Fork Lifts
Lowboys

De-icing equipment
Aviation Fuel trucks
Hangar Space for A/C

UNDER CONTRACT TO NAVY

One 450 hp steam generator
Two Framoi pumps
One 4-leg mooring system
Four ADAPTS pumping systems

NAVY

Four Marco Mark V skimmers
Four 30-kW generators
Four light towers
Two beach gear legs
One reel 5/8" x 1200' wire rope
Seven exposure suits
Two boom vans
One boom roller
Two 600 CFM air compressors
One 2000 foot, 1-1/4 in. air hose
Two hot tap kits
Four 125 CFM air compressors
Two 600 CFM air compressors
One 2000-ft 1-1/4" air hose
Three 55 cubic ft. volume tanks

COST OF ARGO MERCHANT RESPONSE ACTION

The total direct cost of the response action was calculated at $1,826,609.10. The financial accounting can be summarized as follows:

1.	Equipment Costs	$ 419,441.54
2.	Contract Costs	979,717.86
3.	Purchase Orders	19,399.14
4.	Regular Personnel Costs	54,251.05
5.	Reserve Personnel, Travel and Per Diem	20,345.83
6.	Strike Team Costs	220,548.15
7.	Other Federal and State Agencies	85,646.49
8.	Miscellaneous Unit Costs	27,260.19
		$1,826,610.25

However in any accidental circumstance it has been proven that the hidden cost of a casualty exceeds the direct costs by a factor of 4.[a] The total cost of the incident could therefore be in excess of $7.3 million.

- The vessel presently remains in two halves on Fishing Rip and future plans for salvage have not yet been formulated.

- The entire crew was safely evacuated from the stricken vessel, and the only injury suffered involved a member of the response team who suffered a broken leg.

(a) H. W. Heinrich, Industrial Accident Prevention, McGraw Hill Publication

SANTA BARBARA, CALIFORNIA
UNION OIL COMPANY OF CALIF.
OFFSHORE DRILLING PLATFORM "A"
JANUARY 28, 1969

1. Oil

Santa Barbara Crude

2. Environmental Conditions

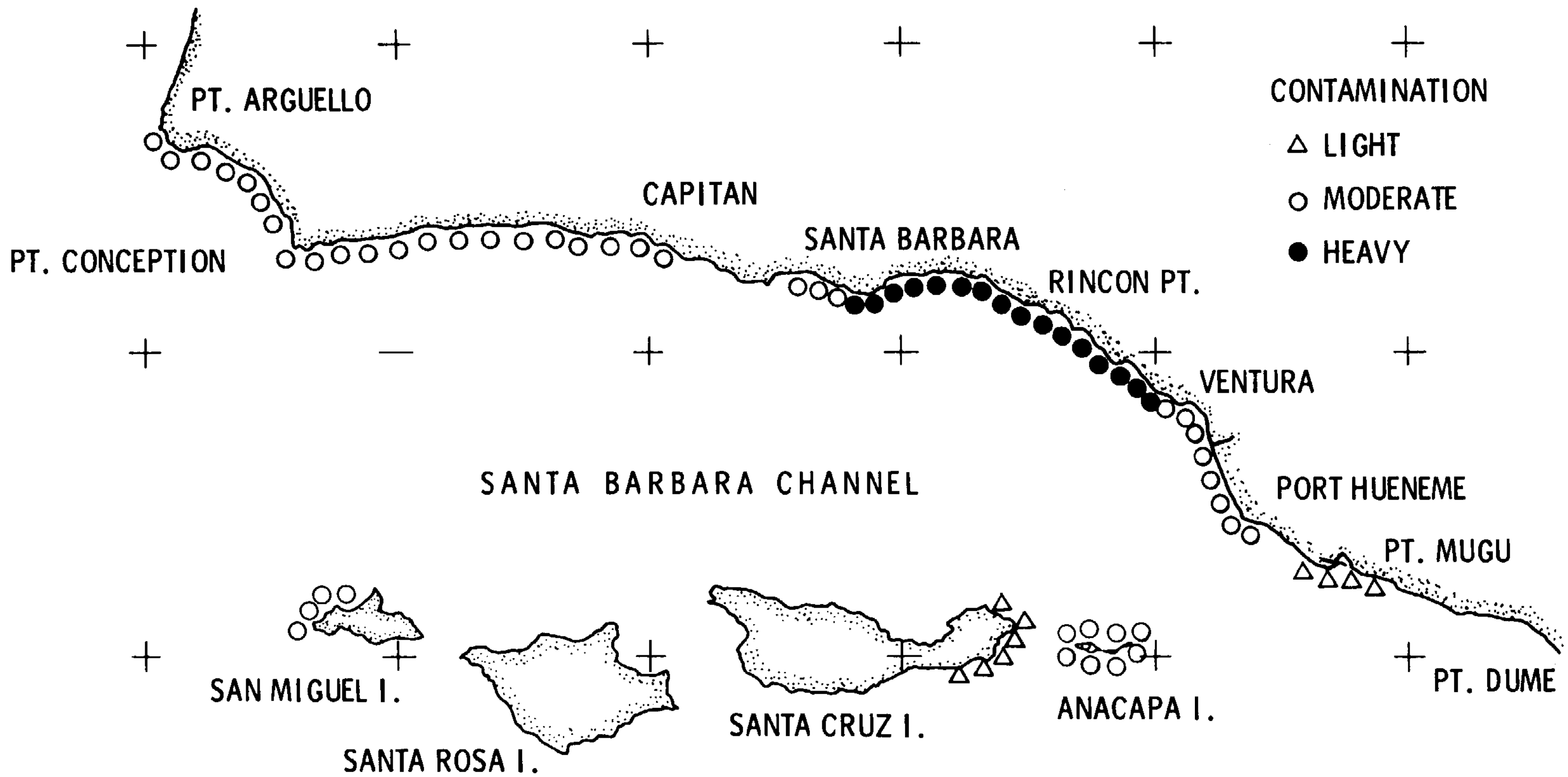
Area normally sheltered by offshore islands of San Miguel, Santa Rosa; Santa Cruz and Anacapa. Offshore platform in federal waters in excess of 3 miles off Santa Barbara, Calif. Prevailing winds usually blow from northwest. Weak littoral current normally along coast in northly direction. Immediately after leak developed two severe storms came into the area, one immediately after the other, accompanied by gale winds from the southeast.

3. Oil Quantity

Total estimated quantity of crude oil spill has been subject of many estimates; however, a U.S. FWQA (now EPA) sponsored study estimated the spillage to be in the vicinity of 4,500 metric tons (31,050 bbl).

4. Other Casualty Features

- Leakage occurred from the oil reservoir through fissures or seismic faults in the bedrock through which the oil well was drilled.
- The flow of oil was for all purposes stemmed within three weeks of the initial flow, but an estimated 400 gallons per day continued to seep to the surface.
- Most of the mainland beaches were oil contaminated by March 31; the islands of San Miguel, Santa Cruz and Anacapa experienced some contamination (Figure C.2) additionally, 1000 boats required exterior hull cleaning.
- Extensive oil contamination of kelp beds resulted along with extensive damage to marine vegetation. Numerous marine animals were either oil covered or killed by the oil slick.
- Some $27 million (API Petroleum Information Package, June 1, 1978) was spent in pollution prevention and the restoration of property and the environment. The majority of the response costs resulted from use of the following equipment and salaries for a task force of 1000 persons:



AREA CONTAMINATED WITH OIL FROM PLATFORM A BY MARCH 30, 1968.
(DATA SUPPLIED BY COAST GUARD)

FIGURE C.2. Illustration from "The Santa Barbara Study," Dale Straughn, Proceedings Joint Conference on Prevention and Control of Oil Spills, 1969

BOATS

	Name	Owner	For Use As
1.	Coast Tide 76'	Tidwater Marina	Straw spreader
2.	Sea Truck 65'	General Marine Transport	Straw spreader
3.	Zelma 54'	General Marine Transport	Boom tending
4.	Pike I 135'	WODECO	Spraying and skimming
5.	Pike II 30'	WODECO	Boom tending
6.	Oil City 100'	Port Hueneme Ind. Serv.	Spraying
7.	Trojan 100'	Pacific Towing	Spraying
8.	Petrel		Tug
9.	RS-23 135 x 45'	Crosby and Overton	Boom tending - Ventura
10.	Mary K	Private fishing boat	
11.	Mary K Skiff	Private fishing boat	
12.	Genes Folly	Private fishing boat	
13.	Pieface	Private fishing boat	
14.	Bonanza	Private fishing boat	
15.	Sea Mistress	Private fishing boat	
16.	Six Pak	Private fishing boat	
17.	Gaviota	Private fishing boat	
18.	Skiffs (2)	Rental	

BOOMS

1. 6' Foam float with 6" skirt at 1800' - Hutchison
2. 28" Inflated sea curtain - 30" curtain at 1000' - Union Oil Co.
3. Log boom at 2000' - Union Oil Co.
4. Union Oil Co. 1000' plastic boom from Marine Terminal
5. Union Oil Co. 4 x 4 wood boom - 200'
6. Crosby and Overton - 3100'
7. U.S. Navy - 900'
8. Log boom 2000' - due 2/5/69
9. Plastic boom - 500' - due 2/5/69

HEAVY CLEANING SPECIALISTS

1. Crosby and Overton

CHEMICAL SERVICES

1. Enjay Chemical Co.

CHEMICALS

1.	Corexit 7664	120 drums	Santa Barbara
		99 drums	Stanton
		80 drums	Stanton (due 2/5/69)
		72 drums	Oakland
		800 drums	Houston, Texas
		650 drums	Bayonne, N. J.
		400 drums	Misc. U.S. Cities
		10 drums	Santa Barbara
2.	Polycomplex A-11		

AIRCRAFT

1. Durden Bros. - Fish spotting service (for positioning boats)
2. Rotor Aids - Observation and transportation

MISCELLANEOUS EQUIPMENT

1. Baker tanks (2) mounted on barge RS-23
2. Haliburton pumps (2) 1 on Pike I - skimming; 1 on RS-23 - skimming
3. Crawler Crane (5) Ton mounted on RS-23
4. Essick pump 6"
5. Welding machine (rental)
6. Pickup truck (6) (rental)
7. Food stores for U.S. Navy YO-223
8. 5000-lb anchor - General Marine Transport
9. 1000-lb anchor (2) - General Marine Transport
10. 250-lb Danforth anchors (2) - Ocean Science and Eng.
11. 200-lb Danforth anchors (3) - Ocean Science and Eng.
12. 150-lb Danforth anchors (3) - Ocean Science and Eng.
13. 60-lb Danforth anchors (6) - Ocean Science and Eng.,
14. Round buoys 35" (3) - Ocean Science and Eng.
15. Round buoys 72" (3) - General Marine Transport
16. Can buoys 24" dia x 30" (6) - Ocean Science and Eng.
17. Polyform buoys 30" dia (4) - Ocean Science and Eng.
18. Polyform buoys 18" dia (2) - Ocean Science and Eng.
19. Polyform buoys plugs (6) - Ocean Science and Eng.
20. Galv. chain 1/2" (343")
21. Wire rope - misc. sizes - 10,000'
22. Shackles - misc. sizes (100 est.)
23. Cable clamps - misc. sizes (2000 est.)
24. Shovels (200)
25. Rakes (180)
26. Nylon line 1-1/4" (400')
27. Manilla line - misc.
28. Snow shovels (100)
29. Pitch forks (150)
30. Fibre drums (1000)

MISCELLANEOUS EQUIPMENT (contd)

31. Buckets, 5 gal (100)
32. Fertilizer spreaders (for talc)
33. Hand cleaner (100 gal)
34. Push brooms (100)
35. Straw (100 tons/day)
36. Mulch spreaders (3) - boat mounted
37. Flat bed truck, 3 ton (3) - Crosby and Overton
38. Talc (3 tons)
39. Ekoperl (600 bags) - due 2/5/69

5. Sequence of Events

Day 1: January 28, 1969 - During normal well drilling operation at about 11 AM an oil leak was observed from the drilling platform and Federal and state regulatory agencies were notified along with Union Oil management.

Day 2: January 29, 1969 - Aerial overflight revealed crude petroleum breaking the water surface three-quarters of a mile from the emission point. Slick extended 25 sq. miles in area extending easterly from the platform. At 3:30 PM FWPCA gave authority for the use of chemical dispersants. Workboat was adapted to spray dispersant through fire pump and two crop dusting aircraft ordered.

Day 3: January 30, 1969 - Dispersant applied by aircraft at rate of 40 gallons/acre

Day 4: January 31, 1969 - Dispersant applied by both airplane and boat. Two additional vessels were being equipped to apply chemicals.

Day 5: February 1, 1969 - Oil in one-mile isosceles triangle with apex at platform. Some oil observed 15 miles distant from Platform A and a thin, grey film covered a 150 sq. mile area. Chemicals not considered effective and use was discontinued. At 3:00 PM, same day, FWQA decision was rescinded and chemicals were again used to protect platform. Air application no longer used. Containment booms ordered and a floating skimmer was under construction.

Day 6: February 2, 1969 - Straw and mulchers ordered from as far afield as Arizona. First inflatable boom section arrived and was assembled.

Day 7: February 3, 1969 - Boom proved inadequate for sea conditions, action commenced to construct boom from wooden pilings.

Day 8: February 4, 1969 - Attempts to deply booms not practical due to heavy seas. Boom broke free under tow along with two of five pontoons intended for pumping platform.

Day 9 and 10: February 5-6, 1969 - Storm scattered oil slick. Beaches covered with oil, sea walls, cliffs and home sprayed with oil carried by strong winds. Use of dispersants discontinued.

Day 11: February 7, 1969 - Leak source stemmed - over 1000 men and supervisors involved in cleanup action.

Note: Cleanup continued at beach locations; however, dispersants not used except around platform until February 25, 1969.

Day 29: February 25, 1969 - Significant quantities of dispersants again used to combat spill.

Day 36: March 4, 1969 - On this day, USCG extended the use of chemical dispersants outside of the immediate platform area (one mile circle). Oil collection considered to be only 10% successful.

Note: Cleanup continued and was increased on March 4, 1969.

APPENDIX D

ALTERNATIVES TO BURNING

APPENDIX D

ALTERNATIVES TO BURNING

This appendix expands the information given in Section 6.2.

ALTERNATIVES TO IN SITU BURNING

Pumping/Jettisoning the Oil Cargo

Under International Law when a vessel and her crew are in danger, the master of the vessel can offload or jettison cargo to control the draft and lighten the vessel. This would normally be undertaken with the ship's own cargo pumps and the pumping would continue until the vessel could pull off the bottom obstruction under her own power. Care must be exercised during the offloading procedure to ensure that the movement of the vessel during the lightening procedure does not worsen the grounding situation. In short, the vessel should be pulling astern toward deep water while offloading.

Shipboard power being available,[a] the illfated ARGO MERCHANT, for example, could have discharged 4,000 tons of cargo (24, 922 bbl) an hour directly into the ocean. At the time of her demise, the vessel was laden with 27,500[b] long tons of fuel oil. On this basis the vessel, using her own pumps, could have been fully offloaded in about 7 hr. With each hour of pumping the vessel could have gained, according to the "Registry of Tankers," about 43 in. of freeboard. In hindsight the stranded vessel by continued pumping could have lightened her draft by almost 10 ft before losing power due to the engine room flooding. The adverse aspect would be the discharge of 12,000 tons of oil cargo into the open ocean. It would have been better, however, than the ultimate result when 27,500 long tons of oil were finally released into the ocean by the foundering.

An alternative to using ship's pumps would involve the use of portable pumping systems such as the Air Deliverable Transfer Pumping and Storage System (ADAPTS) as developed by the U.S. Coast Guard. The pumping units are

(a) This was not the case; the vessel within 3 hr of grounding lost power.
(b) 189,750 bbl

prepositioned at selected U.S. Coast Guard Air Stations for delivery by helicopter to casualty sites. The system has the capability of unloading 20,000 tons of cargo within 24 hr of a reported ship pollution incident. The intent of the system is to offload cargo into temporary oil storage containers; however, should the use of the containers be impractical, due to adverse weather conditions, a direct discharge to the sea could be accomplished. At a rate of approximately 833 tons/hr a ship similar to the ARGO MERCHANT could be lightened at a rate of 9 in./hr of ship displacement or draft. This is considered a slow rate of jettisoning cargo and could result in the vessel becoming more severely stranded during the offloading operation.

Consideration might be given to using more than one ADAPTS pumping system to refloat the vessel. At all times during the pumping, if the vessel's propulsion system is inoperative, tugs or other craft capable of undertaking the tow of a fully or partially laden tanker must be available. The tow line, or lines, should be deployed and maintained in a taut position ready to pull the lightened vessel free from the submarine obstruction. An additional but important problem associated with offloading oil cargo is the condition of the oil. A number of crudes and heavy fuel oils require heat to maintain them in a pumpable condition. Upon heat loss the oils eventually cool to ambient water and air temperature. Since most marine casualties occur during the winter season, near freezing temperatures can be anticipated demanding a fast offload action before the oil develops the consistency of molasses.

The day has probably passed where the ship's master will take this dramatic action, when great liablity may be incurred by his owners, without instructions from his owners or managers. Communications systems have afforded the master opportunity to discuss matters with his owners and managers and because of this much of the initiative on the part of the master has been lost and usurped. The deliberate decision to discharge cargo overboard is risky and is not known to have been undertaken by any master in recent years. The fear of liability of pollution and the hope that something can be done to save the ship and cargo have prevented such dramatic action. Unfortunately, deteriorating conditions, as they cascade from one set of circumstances to another, do not allow an opportunity to go backwards. During marine casualties there is always the feeling that something else can be done and it is only with great hindsight that these cases can be restructured along different operational lines.

Offloading the Cargo Into Barges or Other Tank Vessels

The traditional elements required for offloading consist of pumping capacity, receiving capacity, transfer methods and fendering. It takes an element of good weather and favorable geometry to allow the transfer. In some instances, long hoses might have to be floated to the wreck where navigation by barges to the site is not reasonably accomplished. Probably the greatest element of offloading is good weather. During good weather it is possible to deliver equipment and personnel to effect the required transfer. When the weather deteriorates, as seems to have been so often the case in large tanker strandings, the situation deteriorates and there is little or nothing that can be done away from the ship.

Using ship's pumps or portable pumping systems such as the ADAPTS and flexible hose line connections it is possible to transfer oil from the stricken vessel to another towed or self-propelled tank vessel. Pumping rates and times almost duplicate those anticipated above, the deciding factor being the diameter of the flexible transfer hose and the receiving line aboard the receiving vessel. It is recognized that during actual incidents no single offloading system is continuously employed; therefore, time estimates are most difficult to establish. The deployment and hook-up of the lines under adverse weather and sea states demands high standards of seamanship, and develops a high rate of personal injury exposure. Even so the USN has developed systems for fueling vessels at sea, while under way, and this is now considered a standard naval procedure.

Problems include: 1) locating barges or tank vessels capable of receiving the cargo. Normally, operating vessels would be in active service, fully or partially laden, or under ballast; 2) having the ability to safely approach the stranded vessel and to standoff, in a fixed position, in close proximity to the casualty site; 3) locating and connecting lengths of flexible hose line. Flange sizes differ greatly from one vessel to another, as does flange bolt spacing. Pipe spacers and/or reducers may be needed and may be difficult to readily locate at the time of an emergency located some distance offshore. Flexible hoses are normally furnished by the onshore facility (refinery, marketing terminal or other) and many of the marine terminals are rapidly converting to fixed position (dockside) metal loading/unloading arms. On this premise, problems could occur locating hose lines. Once located, helicopter transport and lift actions can greatly aid hose installation.

A master salvage plan for offloading oil cargo from the ARGO MERCHANT is worthy of description even though the plan could not be implemented due to adverse weather (Figure D.1). A steam boiler was welded to the open deck of an available supply ship. The vessel was also to be equipped with a large, heavy-duty Framo hydraulic pump system. Steam generated in the boiler was to be transferred from the supply ship through a flexible steam line connected to a portable steam coil inserted in the ARGO MERCHANT's Center Tank No. 4 (the tanker had portable steam coils aboard at the time of the grounding). The plan was to transfer the heated oil from the center tank, by using the Framo pump system, into either of two lightering barges (the on-board Framo pump obtaining power from the prime mover on the supply ship).

During the cargo transfer the exhaust steam from the heating coils was to be directed into other cargo tanks to raise the temperature of the oil to a desired level for transfer pumping. During some salvage operations a safer procedure is followed where the cooler more viscous oil is pumped at a lower rate. Using ADAPTS pumps the oil from the other cargo tanks into Center Tank No. 4 for further transfer into the lightering barges. In this manner the entire cargo could have been offloaded and transferred to an onshore reception area in two loadings and trips of the lightering barges. The equipment was being assembled when the ARGO MERCHANT broke up under heavy weather conditions and the plan was aborted.

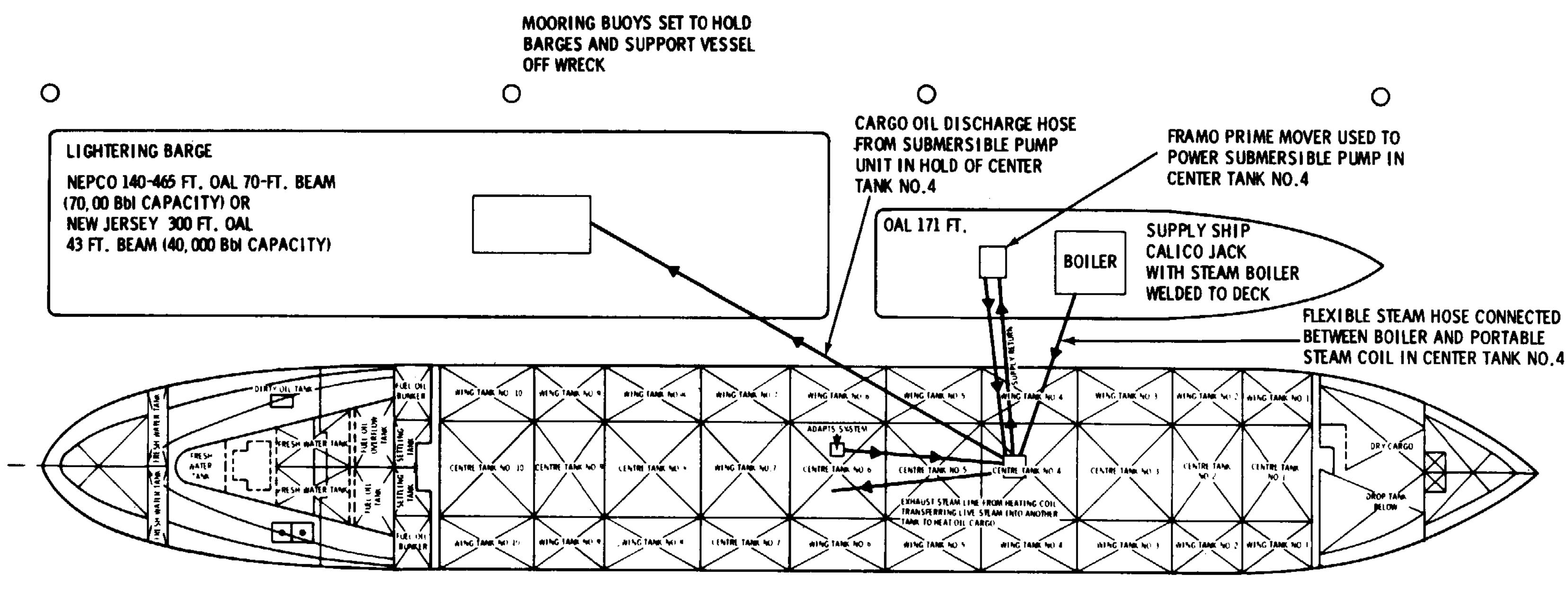


FIGURE D.1. Proposed Method of Transferring Oil Cargo from ARGO MERCHANT

Ballasting Down

If for any reason the above techniques should not be practical, an alternative action involves ballasting the stranded vessel down on the bottom to stabilize her, and prevent buoyant movement from wind and sea actions. This requires flooding the vessel's engine and pump rooms and any other below water compartments that could take on water such as the forward and aft peaks. The process is time consuming and quite difficult. All overboard discharge valves (sea valves) would have to be opened and covers removed from pumps (ballast and bilge pumps) to permit the entry of seawater into the engine room and possibly the pump room. The inlet of water would, however, be quite restricted and considerable time could elapse during the flooding process. Flooding could be expedited by the use of portable pumping systems pumping seawater into any available openings leading into storage, accommodation, and engine-room and pumproom compartments.

The detonation of limpet mines attached at strategic locations onto the underwater hull could further expedite the flooding or ballasting process. The mines are, however, of limited diameter and multiple detonations would be warranted for rapid ballasting. The placement, of necessity, would be conducted by divers coping with freezing waters and heavy wave action during the winter months. Once in the water, few problems would be experienced. Since the divers could dive beneath the wave action, recovery of the divers would definitely result in operational and general safety problems. Once in position there are a number of techniques for detonating the mines such as acoustics and remote servo mechanisms. Where possible salvage work is often accomplished from within the vessel to minimize weather considerations. Once the feasibility of ballasting is positively assessed the actual time involved in this action would vary greatly by the size of the vessel, the residual buoyancy, the size of the water inlets (ship side openings-natural, and explosive formed) and their underwater depth. The action would optimistically involve at least 2 days of activity to prepare the vessel for the ballasting, to acquire and install water pumps and the limpet mines, and to activate.

Recovery of the vessel after the ballasting down would require underwater patching and dewatering of the vessel using pumps, compressed air, or inplace foaming to gain buoyancy. The use of limpet mines on the bottom can create significant bottom damage and prevent the refloating of the vessel without great repair to the bottom and side shell. Experience is known where a bottom piece of coral was explosively removed from underneath the stranded destroyer FRANK KNOX, South China Sea, 1965. The explosive created very severe damage to the bottom because consideration was not made for the significant hydrostatic water tamping. The strategic use of very small explosive shape charges can be made under some circumstances, but the use of limpet mines is quite severe and excessive to the ballasting down considerations normally used by commercial marine salvors. Consideration of recovery of the ship by pumping out the ballast water should be made well in advance of the ballasting down and flooding, and should be an integral part of the plan. It would be of little service to flood down certain spaces and then have to go through lengthy and difficult procedures for dewatering them. Traditional salvage pumps do not have great capacities. When consideration is made of the thousands of tons that may be required to ballast the vessel down, it might be better to use conventional flooding, but associated with controlled entry rather than the concept of using limpet mines.

Scouring the Bottom

A stranded vessel can be grounded on many types of seafloor such as mud, sand, gravel, hardpan, coral or rock. Combinations of soils are also possible. Once bottom sediment conditions are known scouring techniques can be used to deepen the water depth and thereby release the ship from its grounded conditions. The procedure is best suited to mud, sand, or silty bottom conditions (see Appendix J).

Scouring can be a useful method in soft conditions, but great care is required not to induce further sagging or broaching of the vessel, particularly where the bottom materials are highly unconsolidated and can be quickly moved. It is also important to carefully determine the significant point of grounding and try to work on that area as a primary position. Scouring will not work in consolidated rock, coral, granite or similar materials or where the vessel may be impaled on an underwater structure such as an old wreck. Movement of bottom materials can sometimes be induced from inside the ship as was done in the salvage of the tanker CORINTHOS to break the bottom suction where air and water were alternately discharged through the bottom plating to break the bottom friction.

The USN Ship Salvage Manual (NAVSHIPS 0994-000-3010) states that:

> ...scouring can be accomplished with the use of tugs, harbor craft, or the ships own propellers; to properly cause the movable soils to shift, it is necessary to create a laminar flow of water past the hull. Sufficient velocity and amount of water will move large quantities of soil from the ship; the scouring action is continued until the ship is freed. Scouring can be used in conjunction with beach gear (discussed later), weight removal, pumping of water, and other applicable salvage techniques...

The problems associated with this response action involve adverse weather conditions for which shallow draft vessels as described above may not be suited; bottom conditions not suited to scouring; length of time to bring scouring vessels to casualty site; or shallow rough water on site preventing entry of vessels into scouring area.

The time associated with a scouring action is a wide variable. The amount of material to be moved can be readily calculated by comparing soundings to the known draft of the vessel. In this manner an hour of scouring can readily determine if the selected approach is progressing in a satisfactory manner to warrant continued scouring action.

The alternative to propeller scouring involves the use of air, steam, or water jets which would be diver operated. With this type of action, visibility on the bottom is quickly deteriorated, and since a team of divers would be needed, the safety problems associated with entering, working, and leaving, turbulent seas are developed.

<u>Cargo Gelling</u>

The solidification or partial solidification of an oil cargo within the confines of a vessel's hull to effectively control or reduce leakage appears an attractive alternative response action. A USCG report developed by Seaward International, Inc., "Investigation of Extreme Weather Oil Pollution Response Capabilities," indicates that:

...the oil must be gelled to a self-supporting shear strength approximately 1.2 psi in order to prevent extrusion through all but very large holes. Gel forming reagents must be used at about 3 to 10% of the oil weight to be effective. These quantities would be logistically overwhelming if the entire cargo was to be gelled. A main tank on a 100,000 DWT tanker might contain 7,700 tons of oil and could require as much as 770 tons of gelling agents.

To form the gelled mass, thorough mixing is required. The mixing energy required for the above example is equivalent to the output of one ADAPTS pumping unit. Heating the cargo to 15°C for 8 to 24 hr is also required to complete the reaction. The presence of water is undesirable; only 2% water will reduce the shear strength by about 40%. Hold tanks that are spilling oil and have allowed some water to enter them would therefore not be gellable...

One of the newly available reagents is a powdered polymer, which rapidly gells oil to rubber upon mixing and agitation and in some cases by simply settling through the oil. Presently the material sells at about $1.15/lb which would result in a total cost of around $1.77 million to gel a single cargo compartment of an average tanker in U.S. waters. The manufacturer anticipates that revised and increased production will materially reduce the price per pound to about $0.85. Presently, the main problem appears to be the high cost factor and acquisition since no production facilities are evident in the U.S. and production is a French process. However, 300,000 lb of the polymer was used for beach cleanup during the AMOCO CADIZ casualty off the coast of Brittany, France. There is one alleviating factor to the extent that if the ship was later salvaged the rubberized oil, once removed, could be used for production purposes with some financial remuneration. The need to heat the oil to 15°C (59°F) may also produce operational problems since the action to gel the cargo must begin promptly before steam heating is lost, and the oil temerature drops to ambient oil and water temperatures. Additional equipment required to implement this response action would be a portable pump system for oil circulation, or a supply of compressed air for agitation mixing of the oil. Both items are air transportable, and can be lifted into position by helicopter.

Pulling the Vessel Free from the Bottom Obstruction

To release the ship from her stranded position a wide arrangement of beach gear is necessary. Beach gear is a system of anchors, pulling wire rope and purchase tackle used to develop the necessary force needed to free the vessel from its fixed position. Marine salvors view this technique more as an art than a science. The maximum pulling force of U.S. Navy beach gear is approximately 60 tons; the value of 45 tons is used as the effective total pull that can be expected from one set of beach gear. The number of sets employed can be anywhere from one to thirty. They can be used singularly or in conjunction with tugs and the ship's engine.

A grounded ship is supported by the remaining buoyancy and the ground reaction. The ground reaction equals the weight of the vessel (ship and cargo) minus the force of buoyancy. This effectively indicates the ground reaction is equal to the weight of water, whose volume is equal to the change in underwater volume of the vessel, going from the floating to the stranding condition. An intimate knowledge of mathematics and naval architecture is needed to estimate the pull needed to free the vessel and the number of sets of beach gear needed to accomplish the task, and it is still not precise engineering calculations.

The rigging of beach gear is complicated and time consuming; however, the initial rigging of the gear could be accomplished on the salvage ship when proceeding to the casualty site. Beach gear is normally maintained on USN, ARS, ATS, and ATF type vessels as follows:

East Coast	Sets of Beach Gear	Naval Command
3-ARS	12	Norfolk, VA
1-ATS	4	Norfolk, VA
2-ATF	2	Norfolk, VA
1-ATF	1	Mayport, FL
West Coast		
6-ARS	24	Pearl Harbor
3-ATF	3	San Diego, CA

There are, however, some commercial salvage organizations that would have beach gear on both coasts and it should be recognized that many of the Navy salvage ships are entering the Merchant Marine command of the U.S. Navy.

Discussions with USN salvage personnel revealed that to rig beach gear in sea states and wind forces as evident during the ARGO MERCHANT casualty would not have been possible. On the basis of salvage operations being a slow methodical process, rather than a fast emergency operation, under normal conditions two sets of beach gear could be rigged in one day. Weather permitting, a beach gear action on a project similar to the ARGO MERCHANT incident would have required six legs of gear and at least three service vessels to provide the necessary assist. Possibly under high wind conditions one or more tow type vessels might also be needed to hold the assist ships on station, against wind and sea conditions.

Additional factors that would be taken into consideration by USN salvors during an action of this type include the following:

- character of the bottom under the ship (rock, mud, sand, uneven terrain)
- slope of the bottom
- depth of water under and around the ship
- particular area of underwater hull in contact with bottom
- condition, character and type of ship
- ship's draft and loading
- ship's structural strength
- damage sustained in stranding
- period necessary for assistance to arrive
- distance from drydocking facility
- value of ship and/or cargo, cost of salvage, cost of repair
- damage anticipated during salvage and refloating
- change in list and trim caused by stranding
- ship's position with respect to shore
- ship's position with respect to tides
- presence or absence of swells
- prevailing waves and weather conditions
- currents
- underwater visibility.

Although there are a number of methods for using beach gear for both pulling and lifting a stranded ship, Figure D.2 depicts one typical example layout of its use.

The problems associated with a beach gear response action largely involves time (3 to 4 days) to bring the equipment on site, and deploy the ground tackle and other equipment on the stricken vessel. Naturally, the hazards to personnel and restriction of use in adverse weather further deters from its use.

The need for multiple vessels and crews, coupled with the fact that the vessels are always on call and must respond to a USN emergency also detracts from its use for a pollution control project. The USN advises that replacing salvage vessels which would be used would be:

ARS Class - \$190 to 200 million

ATS Class - \$110-120 million

T-ATF Class - \$30 to 40 million

These 1981 dollars do not report the value of the ships presently in use; an over-simplified observation is that it is clear that they are far in excess of the value of most of the aged tankers needing salvage assistance. Even if 10% of the above values are suggested as current commercial prices with the T-ATF being in the \$12 to \$15 million range and the salvage vessel amortized over many years, the potential exposure cost of the response equipment is high for what is salved.

Dewatering the Vessel

A stranding in adverse weather frequently results in underwater hull damage, release of cargo, and entry of seawater into the vessel. Once the size of the damaged opening has been determined the probability of dewatering with pumps to regain buoyancy can be assessed. Pumping is the usual and more favorable method to dewater a ship since pumps are easier and lighter to handle than air compressors, and pumping is normally a faster salvage operation than blowing. Air can create large overpressured differentials which are sometimes difficult to accommodate particularly in a damaged ship. It is, however, necessary to patch underwater damage to the fullest watertight integrity prior to a pumping action. The USN considers a good patch one that resists the

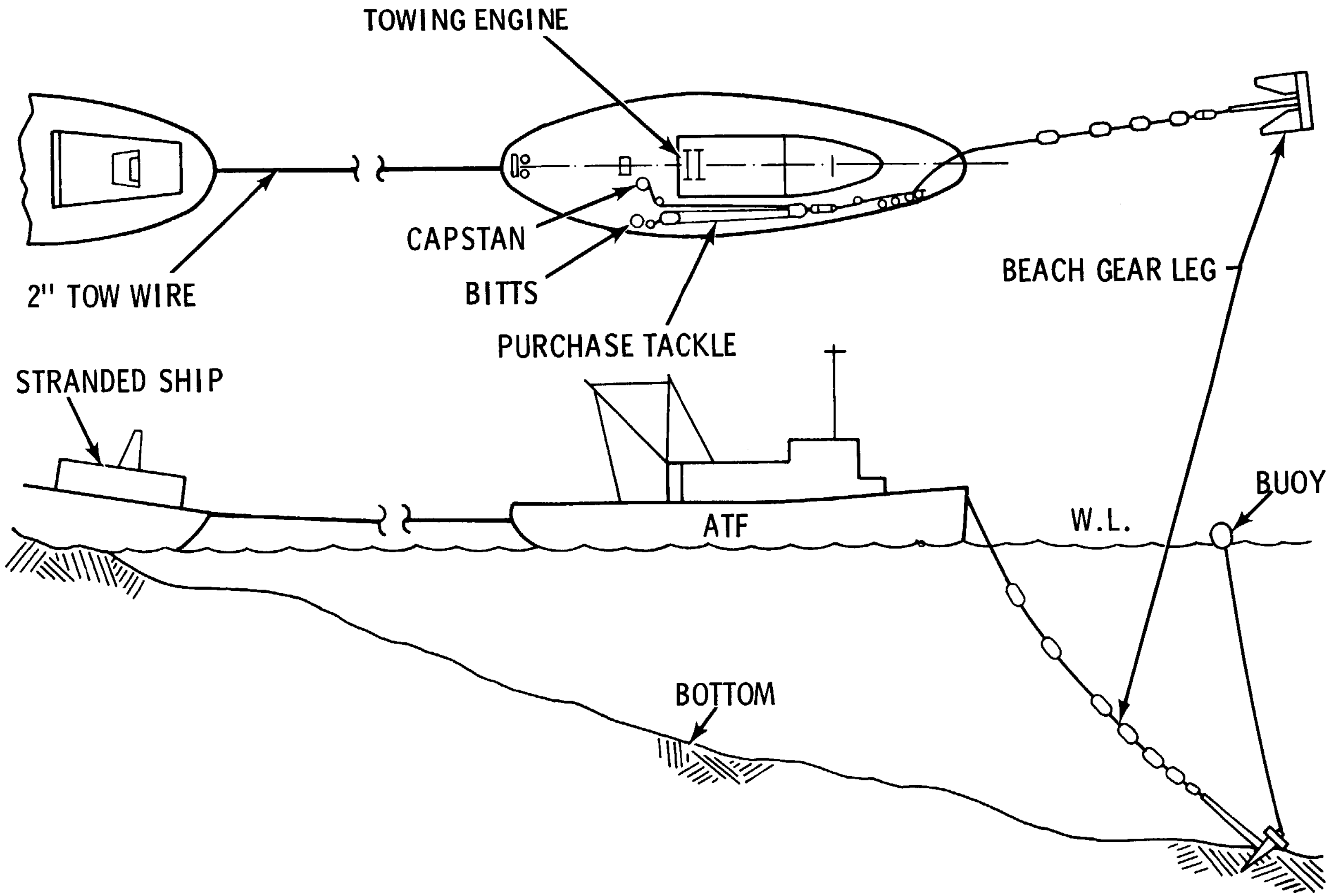


FIGURE D.2. Example of One Configuration of ATF Beach Gear/Tow Wire Heaving Arrangement

Source: U. S. Navy

foreseen hydrostatic pressure and uses ambient external water pressure to aid in seating the patch. Regardless of size, all patches must be mechanically watertight. The patches ultimately can be fastened with bolts, steel studs detonated into the metal, or by welding. Welding is not used extensively since close tolerances are needed between the plates being welded. Most often multiple pumps are used to dewater a vessel to reach capacity and provide backup equipment. This should not present too much of a problem since suction hoses can be inserted in the ullage openings of the tanker; the "Butterworth" openings (used for tank cleaning with high pressure water jets); and in the 4 ft x 4 ft hatches used for tank access and tank bottom cleaning. Care must be used to determine that these openings are properly sized, in the right configuration during the incident and compatible with systems which will be employed for salvage.

The major problem involves patching under adverse weather conditions, unless patching from inside is feasible. Large concrete patches have been poured from the inside and much steel work can be undertaken inside the vessel in addition to timber, shoring and the other methods traditionally available. It is not always necessary to work from the outside. Outside patching requires divers to enter turbulent waters and be subjected to heavy lift operations when steel patch plates are being lowered from a gyrating surface craft. The design, acquisition, and fabrication of the patch, be it wood or steel, would be time consuming. Installation would be difficult since openings of more than 50 ft in length have been torn in a tanker's underwater hull. In some cases, the damage could be in the bottom of the ship where it is not accessible for a patch operation. Another problem is developed from divers working in an area of oil release where they are subjected to a continual annoyance and restricted visibility. Attempts made to dewater the ARGO MERCHANT with five ADAPTS pumping systems, without patching, proved unsuccessful. It would appear that this type of response action would be best suited to good weather conditions following a ballasting down situation.

Sinking in Deep Water

Following a circumstance other than stranding, such as a two ship collision or the physical breakup of a ship, a possible response would be to sink or scuttle the ship in deep water. In 1977 the T/V IRENES CHALLENGE sank in 2800 fathom (16,800 ft) from where the oil was slowly released and dispersed at depth greatly reducing damage to a number of wildlife refuges (Appendix C). By this approach, the oil within a stricken tanker is gradually released and dispersed by submarine currents. In a recent (1978) action off the coast of Ireland, a tanker was purposely sunk, then bombed to release the oil at a time when it could be collectd by mechanical means (booms, skimmers, and vacuum pumps). Considerable experience and confidence exists with marine salvors in scuttling ships. A tanker type vessel, when fully laden with an oil cargo, can be difficult to scuttle. The vessels are designed not to sink and to make them negatively buoyant at least three compartments must be water flooded by opening the sea valves and ballast and bilge pumps. There is also a need for the use of limpet mines as described under Ballasting Down. Even with the engine and pump rooms flooded, it is doubtful that the integrity of the ship's buoyancy could be violated enough for the ship to sink unless there was an empty cargo compartment in the vessel. Should the collision, impact, or physical breakup of the tanker structurally damage one or more cargo compartments, the sinking response action may be materially simplified.

The sinking action would be selected when no other response action can be used. The sinking would reduce the threat of a massive oil slick being transported by wind and waves to endanger a land area or a bountiful marine resource location - such was the case with the illfated T/V IRENES CHALLENGE.

ACTIONS OTHER THAN BURNING OIL ON WATER

Nontreatment Alternative

Natural oil weathering and degradation are the principal mechanisms in the nontreatment alternative. When petroleum is spilled it immediately begins to undergo changes through evaporation, dissolution, spreading, emulsification, air-sea interchange, biological degradation and uptake, and sedimentation. The composition of the petroleum and the characteristics of the environment (temperature, bacteria, sea state) determine the rate at which petroleum is altered. The ultimate fate appears to be a combination of evaporation and decomposition in the atmosphere plus oxidation by chemical and biological means to CO_2. In addition, some portions of the residues will become incorporated into the sediments of both the oceans and the marsh and tidal flats.

When oil becomes incorporated in beach sands it becomes protected from the full weathering effects of sun and wind; consequently, its residence time may be measured in years or decades. All feasible steps are therefore normally taken to reduce the input to a level that can be assimilated in a reasonable time.

Dispersing Agent Addition

Quite a variety of nontoxic oil dispersants have been developed for breaking up petroleum spills on water. The purpose of the agent is to disperse the oil into a stable oil-in-water emulsion which will eventually degrade naturally in the body of water. Most dispersing agents contain three constituents: surfactants, solvents, and stabilizers. A typical dispersant is about 70 to 80% solvent, 10 to 15% surfactant, and 10 to 15% stabilizer.

The surfactants are generally nonionic compounds which effectively alter the surface tension and cohesive properties of the oil such that oil tends to spread and form a very fine colloidal suspension which becomes widely dispersed. Stabilizers are employed to preserve the dispersed oil and thus inhibit recoalescence. Solvents allow the surfactant to penetrate into the slick and mix with the oil.

The dispersion of an oil slick by emulsification or complexing is done to enhance a more rapid natural degradation. The amount of oil emulsified with a given amount of dispersant varies widely among products. Manufacturers claims generally report from 5 to 100 parts of oil per part of dispersant. The amount dispersed varies with the type of oil treated, nature of the application, slick thickness, temperature, and environmental factors. However, a reasonable assumption for typical spills in ports and harbors is that about one part dispersant is required to disperse five parts of oil (Walkup et al., 1969). Recent developments may allow this dosage to be considerably reduced. Dispersants are applied by hand, from vessels, or from aircraft. Chemical dispersants can range in cost from \$3.60 to \$10.00/gal and depending on their application rates will cost around \$1.20/gal of oil treated. Small spills in the range of 1000 to 10,000 gal will require approximately 0.003 manhours labor per gallon of oil treated. As spills get larger (100,000 to 300,000 gal) the manhour requirements drop to 0.00012 manhours per gallon of oil treated. Total treatment costs including chemicals, labor, pumps and spray equipment, and maintenance range from \$3.20/gal of oil treated for small spills to \$1.30/gal of oil treated for large spills (Naval Civil Engineering Laboratory, 1970). Dispersing agents are commercially available throughout the world from chemical and oil companies as well as specialty manufacturing organizations.

Oil Gelling Agents

Oil gelling agents are generally applied around the periphery of an oil slick and are intended to absorb, congeal, entrap, fix, or make the oil mass more rigid so as to facilitate subsequent cleanup steps. Gel agents include molten wax, soap solutions, lanolin, liquid solutions of fatty acids, soaps of alkaline metals, treated colloidal silicas, and various synthetic polymers. The gel is applied to the surface of the water by a high-pressure spray system to provide agitation and mixing of the gel-oil mix.

The gelling approach for treating oils on water, although promising, must provide greater attention to application and distribution, lower materials and operational costs, and suitable means of picking up the amorphous oily masses. Bunker C, heavy crude oils, and some gel agents by themselves may clog intakes, pumps, and suction lines. The major difficulty is the ability to harvest the congealed mixtures since gelled oils cannot be easily collected by mechanical or manual means. Necessary improvements are needed in the gelling approach in line with a total operational system cleanup (Struzeski, 1969).

Gelling agents cost much the same as chemical dispersants (approximately \$6.00/gal). Application rates range from 1:1 to 1:3. A conservative cost estimate is \$6.00/gal of oil treated while an optimistic cost estimate for chemicals is \$2.00/gal of oil treated. In small spills (3000 gal of oil) the labor requirement will be about 0.01 manhours per gallon of oil treated, while in large spills (300,000 gal of oil) the labor requirement drops to 0.003 manhours per gallon of oil treated. Total treatment costs including gelling chemicals, labor, equipment, energy, conveyor collection, and maintenance will range from $21/gal for small spills to $8/gal for large spills (Naval Civil Engineering Laboratory, 1970).

Oil Sinking Agents

Oil sinking agents are designed to attract oil and repel water. They are sorbent materials which sink oil slicks out of sight rather than agglomerate on the water surface. The use of these agents is advantageous in deep water locations where heavy fishing zones would be unaffected. Such areas are generally off the continental shelf where adverse effects upon biological bottom life may be held to a minimum. In turbid waters such as many inland rivers and coastal areas, much of the oil will naturally adsorb onto clay, silt, and other particulate matter normally suspended in the water thus causing eventual sinking of the oil.

A variety of natural and commercial materials are effective in sinking oil. These agents include sand, dust, flyash, clay, volcanic ash, coal dust, cement, stucco, slaked lime, spent tannery lime, carbonized-siliconized-waxed sands, crushed stone, vermiculite, kaolin, Fuller's earth, and calcium carbonate. They have been most effective in treating thick, heavy, and weathered oil. To be effective they must be evenly distributed over the surface of a slick with a certain degree of mixing, agitation, and time interaction. The particle-coated and agglomerated mass eventually becomes heavier than water and sinks to the bottom of the water body.

The major problem in sinking oil is that the bonding of the oil and the agent is not permanent. In instances where the oil is not tightly bound to the agent the oil can become resuspended and ultimately refloat. Increasing the application rate or applying the agent over a long period of time may serve to minimize the re-release of oil to the environment.

The cost of sinking agents is very much the same as chemical dispersants. They can range from $4.00 to $10.00/gal and depending on the application rates will cost around $1.50/gal of oil treated. Small spills (3000 gal) will require approximately 0.003 manhours per gallon of oil treated. Larger spills (300,000 gal) will require approximately 0.00012 manhours per gallon of oil treated. Total treatment costs including chemicals, labor, pumps, spray equipment, and maintenance range from $3.50/gal of oil treated for small spills to $1.50/gal of oil treated for large spills (1970 data).

Biological Degradation

Hydrocarbons naturally degrade when exposed to microorganisms in the marine environment. Because of the toxicity potential of oils, most higher forms of life organisms cannot thrive on it. A number of different microorganisms have been shown to be capable of degrading the oil through assimilation and metabolism. An oil removal technology based on bacterial seeding and fertilization of the oil slick has been considered and tried for several years. The technique has been partially successful due to basic microbiological reactions of preferential energy sources and sequential substrate removal.

To completely degrade an oil spill, many different bacterial species are needed and more easily degraded materials than the oil must be denied the organisms. Normal paraffin fractions in crude oil are very readily attacked by bacteria because they are the least toxic. On the other hand, the toxic aromatic hydrocarbons are not rapidly attacked and require an acclimation period for adaptive enzyme systems to predominate. Oxidation may also be slow in locations where the temperature is low, oxygen balance off, or other environmental factors. Some commercial activity exists in this area but reliable success is yet to be accepted by many authorities.

Skimmers

The mechanical surface skimmer is usually designed to be self-propelled and capable of separating a small amount of oil from a large amount of water. These systems generally skim the top layer of oil and water from the water surface by the use of suction pumps, overflow drains, or scoops. In doing so they separate the oil from the water by gravitational action. To date these systems have demonstrated most success in calm water and their effectiveness for open sea separation is variable.

The effectiveness of all skimmers is limited by the thickness of oil on the water surface. It has not been demonstrated that these systems can remove a very thin film of oil from water surface in anything but calm water. It is thus necessary to first concentrate the oil on the surface through the use of booming devices and to second develop systems in which the oil inlet responds rapidly to changes on the surface and conforms to the shape of the wave field or is insensitive to changes in water level. Costs of these systems are estimated at $100,000 capital and $12,000/yr operational for a 2000 gpd skimmer and requires 2 men to operate. The recovered oil can have a recovery value of up to $0.26/gal although the recovery value will likely be much smaller (1970 data).

Booming Devices

Oil containment by confining the oil at a source includes a variety of methods to prevent spilled oil from spreading. Spilled oil can be contained by floating booms which extend downward into the water and upward into the air to retard the oil's flow either under or over the boom. The booms have a flotation chamber filled with air, foam, or other types of flotation material. They also have a skirt which is weighted to keep the boom upright and can act as a barrier between wave troughs and provide for oil tight joints between joined sections. Booms can be used as permanent barriers for constant spill protection or can be mobile for spill response activities.

Most booms have been designed to contain oil in calm waters such as harbors and around oil tanker loading docks. Their successful use for open sea containment is sporadic. The difficulties associated with open sea boom such as heavy-duty connectors, anchoring systems, etc. have received considerable attention from both public and private sector resources. Booms are not too effective above sea state 3 to 4. When conditions permit use of booms the costs are in the range of $54/ft of boom. Booms are also made for calmer water applications which cost approximately $10/ft of boom (1970 data).

Physical Absorption

Absorption is a physical method of removing oil from the water surface. The process can be broken down into a four-step process: 1) application of the absorbing material to the oil-covered area; 2) absorption of oil by the material, including any necessary agitation or time required for efficient absorption; 3) collection of the saturated sorbent material and removal from the water surface; and 4) disposal or regeneration of the sorbent material. In most cases the sorbent material is made up of a compressed pad which is hand distributed and collected. Some mechanical systems have been developed to collect pads by these are still basically in the experimental stage of development. These have also been continuous belt-type sorbent collection systems developed but these also are mainly in the experimental stage. If the sorbent material is not regenerated, burning and burial are the main disposal options utilized.

The sorbent material must be selected such that it preferentially collects oil and leaves the water behind. Desirable characteristics of a solid sorbent are to have a critical surface tension greater than the vapor-liquid surface tension of the oil, but less than the comparable surface tension of sea water, and have a large, open-ended pore structure. Many naturally occurring fibrous materials, as well as synthetic plastic foam materials appear to have these desirable properties. There are four basic categories of absorption materials which are in use. The four categories are:

1. solid inorganic - such as silica and talc
2. lightweight porous inorganic - such as expanded perlite, glass wood, mineral wood, Fuller's earth, and vermiculite
3. natural organic - such as peat, tannery waste, bark, sawdust, cotton waste, paper, rope, bagasse, and straw
4. polymeric - such as polyurethane and polyethylene foams, polypropylene fibers, rubber shavings, and organic co-polymers.

The efficiency of each method is greatly affected by both oil and water temperature, and viscosity. Higher oil viscosity generally decreases the mobility of the oil and thus decreases the rate of movement of oil into pores in the absorbent. Temperature also affects viscosity and surface tension but to a lesser extent than the weathering impact on the oil or type of crude.

Materials such as lightweight porous inorganic and solid inorganic range in cost from $200 to $500/ton and can absorb about three times their weight in oil. Therefore, the cost per gallon treated would be about $0.60. Polymeric materials can cost as much as $2000/ton but can absorb more than the inorganic materials (as much as five times). Therefore, the cost to treat is about $0.20/gal of oil treated. Natural organics and particularly straw are by far the least expensive absorbent to employ. Straw can also absorb up to 5 times its weight of oil. At $60/ton to buy, the cost for oil treatment is approximately $0.06/gal of oil recovered (Department of the Navy, 1970).

It is estimated that it takes 3.25 man hours to collect a ton of oil-soaked straw. Assuming the waste is 5 parts oil to 1 part straw, this converts to 3.9 man hours per ton of oil recovered.

ALTERNATIVES TO BURNING OIL-CONTAMINATED DEBRIS

Nontreatment

When oil spilled on water reaches the shore it generally impacts the beachline area. Oil left on the beaches by falling tides and wave action tends to permeate into the beach sediments. Sediment porosity and permeability are the two factors which most affect subsurface oil flow. Oil flowing through a column of sediments is best characterized by Darcy's Law:

$$V = \frac{Ph}{L}$$

where V = velocity of fluid through the sediment
P = permeability coefficient
L = reference length of sediment column
h = differential head across the column

The permeability coefficient is a function of the shale of sediment media, viscosity of the permeating fluid, friction factor, and void spacing of the media. If it is assumed that soil is saturated to the extent that hydraulic flow commences then the porosity, hydraulic gradient, and permeability of the soils are the principal parameters defining the movement of oil into the sediments.

Percolation is not the only means for oil to disappear from the beach surface. Wind blown sand and the seasonal movement and turnover of beaches have a tendency to cover up the oil-contaminated zones.

Regardless of mechanism, as the oil is worked into beach sands it comes into intimate contact with microbial populations. Oil, which is dispersed as a fine film on small particles, should be ideally suited for microbial attack. Aerobic degradation is generally much more rapid than anaerobic degradation. For aerobic microbes to be most effective they must have abundant oxygen. Wave action can provide adequate mixing of the upper layer of sand to maintain sufficient exposure of the oil to air. It is generally known that most sediments and soils provide excellent environments for microbial destruction of organic matter with more than 1000 different species of microorganisms found in the soil that are known to attack and decompose many of the hydrocarbons contained in the petroleum (Dotson et al., 1970). Studies have shown that oil mixed in 6 to 8 in. of topsoil followed by the addition of fertilizer nutrients resulted in oil degradation of up to 56% after 41 months for initial concentrations of 4 to 8% oil in soil. This constitutes an annual degradation rate of 7 to 16 g oil/kg of soil, or 60 barrels of oil/acre/year (Cresswell, 1977).

Biodegradation of oil and oil-contaminated debris can occur under anaerobic conditions; however, it will degrade very slowly requiring possibly many decades. If biological degradation does not take place, the oil can persist for long periods depending on the severity of the contamination. Other debris such as physically removed material, dead animals, etc., will not be effectively treated by the nontreatment alternative.

Physical Removal

Physical removal refers to any of a variety of methods of picking up oil-soaked and contaminated sand, sediments, and debris from the beach and removing it to an alternate site for disposal. Depending on the size of the spill, its location, and its accessibility, physical removal may involve the use of crews hand picking with rakes and shovels, as well as heavy earth moving equipment such as bulldozers, graders, front end loaders, and dump trucks. The decision about which methods to use is made based on an assessment of the environmental impacts of the existing spill and on the potential impacts of the spill mitigation process.

In some locations the replenishment rate for beach sand is very low. If sizeable amounts of sand are contaminated and must be removed, it will not rapidly be replenished by natural means. Detrimental effects such as surface erosion can reverse the flow of sand on the beaches.

Generally only the upper few inches of sand will be contaminated and have to be removed. Two options have been practiced in the past for replenishing beach sand: 1) clean the excavated sand and replace, or 2) replenish with uncontaminated sand. There will be approximately 0.11 cubic yards of sand contaminated per gallon of oil that reaches the beach. For example, if 100,000 gal of oil reach the beach as a result of a spill, there will be about 11,100 cubic yards of sand saturated with oil. This much sand would likely have to be replaced after excavation in order to maintain the beach stability.

The sand removal process can be very inexpensive if the beaches are accessible to heavy equipment. Such equipment as scrapers, bulldozers, and graders are designed specifically for earth moving and hauling tasks. This means that there are no special design requirements that have to be met in order to move large amounts of sand.

When large amounts of oil-soaked wood, vegetation, and other miscellaneous debris must be removed, scrapers can be used to collect the debris in piles or rows on the beach. A crane-operated clam shell bucket can then be used to load the material into dump trucks.

Beach-restoration costs associated with the Santa Barbara, California, and Grand Island, Louisiana, oil spill incidents were calculated by Sarton and Foget (1971). At Santa Barbara it was stated that a work force of 50 men using 4 front end loaders, 2 bulldozers, and 10 dump trucks could clean 1 mile of beach per day. Extrapolated costs show that a 75-ft-wide beach would cost \$325/acre and a 50-ft-wide beach would cost \$500/acre. At Grant Island a work force of 20 men using 4 rubber-tired front end loaders and 1 grader cleaned 15 miles of beach in 4 days. The cleanup costs were \$140/acre for a 20-ft-wide beach and \$170/acre for a 15-ft-wide beach.

In addition to these removal costs, there is also a transportation cost incurred for hauling the waste to a disposal site. These costs range from \$0.05 to \$0.14/cubic yard/mile hauled.

By assuming that the oil penetration in the beach is no more than 6 in. and that the oil fraction of the beach is 38%, the amount of oil that can be contained in an area of beach is about 200 tons. Therefore, recovery costs will range from \$0.70 to \$2.50/ton of oil removed and will require approximately 0.01 man days/ton of oil removed.

Burial

When the oil contamination of the beach sand is not very extensive, the oil-soaked sand and debris can be buried by either plowing it under or by collecting large volumes for burial in central locations. This can usually be accomplished very quickly and at a low cost. A problem may arise in that beach sands are constantly in a dynamic mode and the constant migration of the sands could cause resurfacing of the contaminated material. In addition, when the oil is buried in a horizontal layer it will hinder the percolation characteristics of the sand, thus destroying the stability of the sand and promoting erosion from tidal influences. While the oil is buried, anaerobic degradation will take place, thus liberating odorous gases and potentially toxic by-products. This could eliminate any other use of the beach area.

If burial is to take place on the beach itself, there will be no expense incurred for hauling. The major expenses will involve opening up a burial site and moving the contaminated material to the site. Scrapers, earth movers, and bulldozers are well suited for these tasks. Removal and burial costs will range from \$0.70 to \$2.50/ton of oil removed assuming that the oil fraction of contaminated sand is 38% and the oil lies in the top 6 in. If the burial site must be covered, an additional \$0.35 to \$1.25/ton of oil burned will also be needed.

If burial is to take place at a remote site from the contaminated beach, additional costs will be incurred in hauling the debris. These costs will range from \$0.05 to \$0.14/cubic yard/mile hauled depending on the distance hauled. By assuming the debris is 38% oil, this changes from \$0.19 to \$0.55/ton of oil disposed/mile hauled. Once the transportation mileage is determined, these costs can be combined with the collection and burial costs to arrive at the total disposal cost.

Land Farming

With land farming, materials are usually dispersed evenly as a thin veneer over a parcel of land. They are then tilled into the aerated portion of the soil. The purpose of the tilling is to provide intimate contact of the waste materials with active microorganisms in the soil. The waste material will then undergo bio-oxidation and destruction. In this manner, waste materials can be treated and disposed of without extensive treatment systems and high capital and operating costs. On the other hand, land farming generally requires a sizeable amount of land area. Care must also be taken to ensure that the applied waste is not toxic to the soil bacteria, thus sterilizing the soil.

When the wastes to be applied are either liquids, soils, or sludges, common farm equipment can be used to spread and till the wastes. When bulky materials and debris are contaminated by the wastes, the wastes must either be removed from the debris or the debris itself must be reduced in size so as to be compatible with the land spreading technique. Size reduction can be accomplished by shredding, chipping, maseration, or other systems which will render the oil and debris into a slurry type consistency.

In order to provide for adequate degradation, the tilling operation must be repeated a number of times. Additional tilling breaks up zones where an anaerobic environment has developed. It also provides for more intimate mixing of the soil-waste mixture. The greater the contact of waste with organisms, the greater will be the waste decomposition.

Land farming can be performed on the contaminated beaches if there is no alternate use of the beach. Usually the impacted beach area is utilized as a recreation area or other high use activity which precludes its use as a land farm. Normal land farm operations take place on low use lands adjacent or close to the contaminated beach area. Because of this, the oil, oil-soaked sand, and contaminated debris must first be collected (basis: oil-soaked sand at 38% oil). Transportation costs of the oil and debris will range from $4.00 to $8.00/cubic yard of total waste handled (EPA, 1977). The total operation will require between 0.12 and 0.16 man days/cubic yard of total debris disposed of.

Absorption

Many of the same materials used for absorbing oil on water can likewise be used for absorbing oil on beaches. Materials such as straw, rags, and specially designed sorbent pads have been used in the surf area of the beach to soak up the oil as it first meets the beach area. The absorbents almost exclusively remove oil which remains on the surface of the beach before it has a chance to soak in. Unless they are tilled into the beach sand, they have little chance of extracting oil from the interstices of the beach. The absorbents are generally hand deployed and manually collected. It becomes an expensive treatment procedure because the distribution and collection is so labor intensive.

Absorbents are most useful when applied to floating oil either just behind or in the surf zone. They are less effective on the beach itself because of the oil transport problem. The most useful absorbents are those that are easily collected with standard implements such as pitch forks, shovels, or rakes. Straw has been shown to be particularly effective in absorbing oil as well as being easily retrieved by these standard implements. Absorbents can limit the degree of contamination but not eliminate it. Physical removal of some contaminated sand will still be required as part of the total restoration procedure.

Sorbents can be grouped into three basic categories: 1) bulk materials; 2) polymer foams; and 3) straw. The bulk materials are comprised of materials such as perlite, vermiculite, talc, shredded bark, and shredded paper. Polymer foams are comprised of materials such as polyurethane, polypropylene, and polyethylene. Bulk materials typically range from $200 to $500/ton and can absorb about three times their weight in oil. Therefore, the cost per gallon treated would be about $0.60 (EPA, 1977). Polymer foams cost more than bulk materials (as high as $2000/ton) but can generally absorb more oil. A 5 to 1 absorption ratio is common. Therefore, to treat oil is only about $0.20/gal of oil treated (Department of the Navy, 1970). Straw is by far the cheapest sorbent material to buy. It can also absorb up to five times its weight of oil. At $60/ton to buy, the cost for oil recovery is reduced to approximately $0.06/gal of oil recovered (Department of the Navy, 1970).

It is estimated that it takes 3.25 man hours to collect a ton of oil-soaked straw. Assuming the waste is 5 parts oil to 1 part straw, this converts to 3.9 man hours per ton of oil collected.

Suction

When large-scale contamination occurs involving very viscous or thick oils, large amounts of oil can be washed up on beaches and form thick layers or large pools. When this occurs, any locally available sludge or slurry pump with storage-tank system can be used to remove the oil. Septic tank or other vacuum trucks used in the petroleum industry have proven to be most effective.

These systems work by evacuating the storage tank of air and then sucking up the oil pools into the tank. Liquid pump systems, if protected and operated to avoid being clogged with oil-soaked debris, can be used.

Since their deployment is limited, vacuum systems often play a minor role in beach restoration. Oil-soaked debris must still be collected and disposed of. Oil-soaked sand must also be treated, handled, and/or disposed of.

It is estimated that it would require 0.0016 man hours per gallon of oil collected if the oil is in large pools and has easy access. The cost of recovery is approximately $0.03/gal. Transportation costs away from the site range from $0.10 to $0.15/cubic yard/mile (Department of the Navy, 1970).

Chemical Treatment

Many of the same chemicals used in dispersing oil in water can be equally effective in cleaning beach sand and debris and dispersing the oil. If excessive amounts of cleaning chemicals are used to remove the oil from the sand without subsequent washing of the oil/chemical mixture from the sand, the oil is dispersed both vertically and horizontally in the sand. This dispersion simply creates a larger volume of contaminated sand which must be handled. It also alters the vertical drainage characteristics of the beach, thus potentially leading to a severe erosion problem.

In locations where there is a good tidal flushing action, washing the dispersed oil/chemical mixture back into the sea can be effectively accomplished providing the chemicals are applied just prior to the incoming tide. This flushing generally occurs in the intertidal zones where much of the biological activity is taking place. Ecological damage can take place due to increased toxicity of dispersed oil in the intertidal zone.

Chemical treatment is the only available method for removing large quantities of oil from sand without physically moving the sand. In order to properly use these chemicals they must be mixed in the upper layers of contaminated sand and then flushed from the sand either by the tidal action or by water jets. Common farm equipment can effectively be used to provide for adequate mixing of the chemicals.

There are many dispersant agents which are capable of treating oil spills. They range in price from \$3.60 to \$10.00/gal. Application rates vary but average about 1 part dispersant to 5 parts oil (Department of the Navy, 1970). Therefore, the cost to treat oil ranges from \$0.75 to \$2.00/gal of oil treated. It requires about 0.003 man hours/gallon of oil spilled to apply the dispersants (Department of the Navy, 1970).

APPENDIX E

CAPSULE SUMMARY OF A DECADE OF OIL POLLUTION COMBUSTION DEVELOPMENT

APPENDIX E

CAPSULE SUMMARY OF A DECADE OF OIL POLLUTION COMBUSTION DEVELOPMENT

The following is taken from a detailed review of the Proceedings of the U.S. National Oil Spill Conference Seminar beginning in 1969 and held biannually by the American Petroleum Institute, the U.S. Environmental Protection Agency, and the U.S. Coast Guard until 1979.

The Proceedings of 1969 indicated that the National Oil Spill Conference planners were well aware of the activities which were ongoing pertaining to burning of oil. Under U.S. Navy contract, Battelle Northwest reported on a variety of methods of oil removal from harbors, including burning (page 20). The Airojet General Corporation reported on the feasibility of an incineration system for cleaning beaches which were oil contamined (page 21). A report on the United Kingdom oil spill cleanup by burning and tests which were run in three square foot tanks to establish burning rates were discussed (page 24). The Select Committee which prepared the report on the Torrey Canyon was discussed and is a particularly useful reference for documenting the facts at the time (page 26).

Mr. J. Wardley Smith provided a rather detailed report (page 26) on oil burning. He was primarily concerned with burning oil on the beach surface using a variety of oxidizers as promoters. The results of his experimentation were poor and he indicated that once ignition stopped, it was very difficult to restart and a sticky pitch-like residue was left. Using a solid combustible in addition to an oxidizer, provided no particular advantages and because air was thought to be limiting, use of wicks were considered. Mr. Smith concluded that heavy oil on beaches in the foreshore area burns only when heat is applied and then poorly. He felt that solid oxidents had to be added at the ratio of about 30% by weight, and then heat had to be added to raise the temperature of the oil and the oxidizers in the sand to an ignition temperature at probably excessive cost. He commented that the combustion additive helps but quite often it will burn before the high boiling point fractions of crude oil are combusted. His work with wicks did not overcome the limitations pertaining to the high heat sources required. He felt that an extreme negative was observed because heavy viscous oils, during the combustion process, will melt and move deeper into beach sand. His opinion was that burning oil on beaches is probably much more costly and less effective than mechanical or manual removal. Mr. Smith's paper goes on (page 37) and relates the results of work pertaining to combustion insitu tankers and some 50 tests which were carried out in 1 square meter cross-sectional area tanks. From these studies he noted that the crude oil could be ignited in 1 to 2 seconds at 0°C and would reach full burning in 10 to 15 seconds. It took from 5 to 10 seconds to ignite the crude oil at 15°C and full burning was reached at 30 seconds. He observed that coke formed and caused a layer which smothered the fire during these tests. Results from this work indicated that side and deck vents of equal size are optimum with the spacing of these vents of no real significance and that size should be about 25% of the cross sectional area of the oil. He observed burning rates increasing with wind velocity, e.g., 200 mm per hour burned at 11 meters per second wind velocity with 22% side vents and lid vents being essentially double the burning rate in still or calm air.

Steve Dorrler's paper (page 155) simply discounts the use of burning in harbors because of the damage potential.

Mr. Struzeki and Dewling's paper on chemical treatment of oil spills includes a topic on burning agents and sites 3 British references (page 221). Struzeki suggests that the British used bombing, incendiaries, and catalysts-oxidizing devices and says that floating oil less than 3mm thickness will not burn. It is reported that weathered oils present practically no fire hazard (Battelle Northwest sighted as stating this). Commercial combustion promoters were stated as being most useful for thick oil layers which are contained. Work at the Edison Research Laboratory in 24 square foot tanks employed several different combustion promoters from which it can be concluded that even light crude at 2.5 mm thickness needs combustion promoters plus an ignition source. The combustion promoters may be required at a dosage rate of 1 lb. per 12-15 sq. ft. of slick. The Edison Laboratory is sighted as having internal files and laboratory data to support this (Efforts during this study were made to obtain these data, but as of this writing the files were empty).

Paul Walkup and his colleagues reported (page 245) that work done under the Navy contract by Battelle Northwest was successful in evaluating a variety of oil cleanup systems including chemical burning agents and combustion promoters. And a ranking system suggested that they were 26 out of 27 systems when evaluated for effectiveness.

Two years of study and work transpired and several more papers were prepared pertaining to oil combustion. The 1971 Oil Spill Conference had several papers which dealt directly or indirectly with oil spill combustion as a mitigation tool.

Dan Charter, U.S. Coast Guard,reviewed the National Contingency Plan and demonstrated confidence in ruling out,in his specific comment no. 5, the use of burning in the open sea for heavier grades of oil because of the inability to maitain burning temperature (page 26). It was further noted that burning of chemicals is considered quite hazardous and the firing or bombing of vessels (combusting oil insitu tankers) would in his opinion probably aggravate the pollution further by releasing oil which was remaining on board the stricken vessel.

Oil spills in ice infested waters were reported by Barber, (page 133) and noted that burning was used to clean up a tank farm spill of diesel fuel and gasoline which went into the Hudson Strait (Deception Bay in June, 1970) The burn was deliberately initiated at low water at a time of maximum tidal range. At this point in time oil/water was pumped onto the sea ice which was 4 to 7 ft. thick and burned on its surface. It was suggested that by pumping the oil onto the surface of the ice, the evaporation which would take place would aid combustion and also by taking this action, the pending ice breakup would not be allowed to spread thereby contaminating near shore waters.

Matthews of the California State Division of Oil and Gas notes as many authors have (page 188) that burning may or may not be a a practical or acceptable tool but in any review of oil spill mitigation tools, he, as others, lists it as an alternative.

Freiberger and Byers produced a paper at this Conference on burning agents in which a quite comprehensive listing of factors and commercial products could be studied. Comments were made on the time of ignition relative to when a spill occurs as well as the point of volatile low flash point fractions being quickly lost and the thickness of a slick being reduced with time and breaking up. The question of heat loss to water for thin slicks was sighted as being impossible to overcome in reference to a 1970 Battelle study done for API. Early work by Nelson done in 1938 was sighted that oil less than 3mm thick will not burn on water. Winds and currents were noted as adding problems by assisting volatile fraction escape, dissipating heat, and breaking up the oil slick as well as promoting emulsification.

Freiberger, et al., listed advantages for oil burning (page 246) including large spill capacity, fast response, completes the job, economy, limited ecological harm, and little toxic threat. An attempt to define burning agents is made and materials are listed as igniters, ignition assisters, or combustion sustainers. Several commercial burning agents available in 1971 were listed as well as a few case histories. Results of the EPA lab tests at Edison were provided (page 248) where no. 6 fuel oil was used in the 24 sq. ft. shallow tanks which were outdoors and would not burn with oil 1/2-2/3" thick. The result of adding several combustion promoters was conservatively noted as nothing particularly outstanding. The ignition sources used by EPA were torches and flares. U.S. Navy field tests were reviewed and four burning agent application techniques and emission techniques gave rise to optimistic conclusions looking with favor at burning. Developments by the British Petroleum Company and Pittsburgh Corning Corporation were noted as developing systems to burn oil at sea.

Blacklaw, et al., (page 253) compiled information on oil spill treating agents and developed a series of test criteria such as level of and type of agitation, temperature, water composition, quality of oil type, contact time, the scaling dimensions, characteristics of solid materials in contact with the oil agent, and a few others.

The tests for the combustion promoters were selected from the "Burning Test-Joint Fire Research Station" of the United Kingdom. Further intest in combustion was expressed by Vanx and Walukas where they reported (page 303) that compost could be used to treat oil spills and then burn this mixture either at sea or on shore. Laboratory testing both indoors and outdoors indicated that crude oil could be sorbed at a 1500 mili-liter to 500 gram of compost ratio ignited after 10 minutes, burn with heavy smoke, develop a coke-like residue and sink.

Henager et al., reported on the methodology (page 405) where a numerical evaluation system could be explained which ended up placing chemical burning agents applied directly to spills 6th out of 21. The chemical burning agents with containment were 8th out of 21. The point is made (page 413) that burning of various oils in contained or uncontained form is difficult and burning is set out as not really being a practical universal system. The most effective (cost-wise) systems for open water are burning agents on Bunker C or Navy Special when it's quite thick, dispersants, and advanced skimmers.

Smith and MacIntyre reported (page 457) on the phenomena of oil weathering and noted that the volatile fractions of a boiling point of less than 270°C are lost with the rate being proportional to the rate of volatile present. It was observed that wind has increased effects and even water soluble fractions of low boiling alkile benzene are evaporated. Two hundered gallons of No. 2 fuel oil were discharged 15 miles off the Virginia coast; after 6 hours at sea, under 18 knot winds at 5°C, decane was 96.1% lost; hen decane 85.4% lost, dodecane 58.4% lost, tri decane 44.5% lost, tetra decane 7% lost, and penta decane 5.7% lost. Additional detailed references are made other workers findings indicating that even aromatic hydrocarbons are readily partitioned into the gas phase from an aqueous solution and other comments which were useful in appreciating the weathering phenomenon.

Two more years of study and research past such that the 1973 Oil Spill Conference produced a few more papers pertaining to the subject of oil burning. Of these, McMinn and Golden reported their view that oil burning on ice can remove as much as 80% of the oil by volume (page 272), but burning agents did little to help especially during Arctic summer tests. They indicated that if the oil was 1/4" thick or more, and less than 24 hours old, that ignition is feasible. The method of ignition they used was fuel soaked rags being placed on the upwind (0-14 knots) edge of the oil spill and that a heat pit forming such as occurs on snow is not too significant on ice. They used four agents (page 273) and test patches ten feet in diameter with oil 1/2" thick, ignition by a torch which produced 80% removal.

Oxenham et al., reported on the use of polyurethane foam for oil recovery and the application of burning being evaluated. They employed a natural gas fueled furnace and were quite conscious of the air emissions which were monitored (page 287). Although not directly used for burning, Jeffery reported (page 469) on the results of a large scale oil spreading test from which the derivation of a Blokker constant was derived for a 120 ton spill. Another paper which provides relevant information useful in burning evaluation was that by Sivadier et al., where work on evaporation rate measurements was noted indicating 5% weight was lost in approximately 10 hours and 10-15% was lost in 30 hours. It appeared that no real significant increase in loss occurred after 80 hrs. (p.475). Additional work on solubility and weathering was presented by Frankenfeld (page 485) using laboratory studies on several crude oils, however, there were no clear conclusions reported.

A successful burn on water was reported by Jerbo (page 559) in ice infested waters and using an onshore incinerator. The wicking agent absorbent known as SANERINGSULL was used in this work. About 400 tons of a 600 ton diesel oil spill were burned using this material which appears to be an oleophilic wicking agent.

Attention was paid by Begnon to attempt a petroleum classification scheme using wax content as the basis (page 619). In the context of this paper, burning was noted as a not too reliable alternative and it was noted that incendiary materials and burning aids appeared to be of little help. Burning of oil on ice conditions was regarded as feasible (page 626).

Another example of the successful use of burning was cited by Clark (page 795). This case involved the successful use of burning oil soaked debris which were washed ashore from the grounding of the General M.C. Meigs.

It may be observed that the trend in studies as measured by reports at the National Oil Spill Conference were shifting from the development of concepts for burning and the development of equipment and devices to understanding the principles of weathering and reserving burning applications for oil on ice and oil contaminated debris.

The 1975 Oil Spill Conference reflects a further reduction in the interest of burning. Snyder reported on the use of burning agents which were allowed in Annex X of the National Contingency Plan and made it clear that burning was to be evaluated on a case by case basis and that the local people must have the decision on whether or not burning would be accomplished (page 34).

Cormack et al., (page 71) recognized that burning should be included as part of the training element in oil spill cleanup courses offered in the United Kingdom . Steinman et al., indicated (page 180) the configuration of both existing and future ballast water tanks but there was no mention of the obvious implication of these designing modifications as they would pertain to insitu tanker burning. The data which Card et al. (page 208) presented on the amount of oil outflows between 1969 and 1973 indicated the number of vessels involved and the types of incidents and the amount of oil lossed, but did not provide any information and countermeasures such as oil burning.

Eiden et al., (page 220) reported on the successful use of incineration to dispose of oil soaked debris. This particular incinerator was a three-stage burner which operated at 3400°F and had a modified feed grate. Incinerator was located at Gray, Maine to handle the debris disposal of the Cascoe Bay incident. The system operated well and no more than $70,000.00 was spent to dispose of the debris. Another report on debris disposal was issued by Hancock et al., (page 223) indicating U.S. ports and the variety of work which must be done to handle debris. Oil coated debris was particularly noted as a problem which U.S. ports are dealing with. Experience was sighted that the desirable use of on-scene burning of oily debris is often stifled because of local air pollution ordinances and therefore a mobile forced air burner appears to be a valuable alternative to open burning for land fill disposal, and recommendations for development and demonstration were made.

Coetman, as many authors of this period, site the experience of others using burning to handle crude oil poured on snow, ice and Arctic water (page 260). He suggests that the oil may be burned leaving only a tar like residue. Logan (page 267) however, reports that oil spill countermeasures in the Beufort sea area include combustion as probably one of the main methods available to clean up crews for oil on ice. Work by Coupal and others is sited where peat moss is used to assist in the control combustion techniques. The effectiveness of the combustion technique is identified as it particularly relates to the oil in ice problems and the Government of Canada was favorably disposed to support this type of developmental work. The Canadian Government spokesman, Ross (page 329) reported on the Government's development program for spill control technology particularly as it relates to work on combustion.

James et al., (page 431) indicated that burning oil soaked straw on the beaches during the Santa Barbara incident in 1969 was effective but the smoke and odor and the heavy residue required termination of the response. He also noted that oil is often attempted to be burned off rocks using the flame thrower. Reference was made to the use of burning on the Arrow spill but he generally concludes that burning oil on a beach is seldom successful due to poor ignition and combustion.

Another report on oil debris removal was prepared by Ziegler (page 452) where he describes a remover boat and indicates that the debris so removed was incinerated upon delivery to shore.

A successful experience in the use of combustion for oil spill cleanup was reported by Keevil et al, (page 501) where a truck containing diesel oil fell through ice and as the ice slowly leaked to the surface it was successfully burned in place. This experience of treating oil spilled under floating ice was regarded as quite successful.

Again in 1975 essentially no techniques or technology development was demonstrated other than some beginning interest to demonstrate the effectiveness of oil combustion on ice and the application of incineration to collected oil contaminated debris.

The 1977 Oil Spill Conference included papers which pertained to burning primarily from Canada and of major interest in the Arctic oil spill problem. Melville (p.58) reported on the common practice of burning waste oils is approved commercial burners or even boilers to derive the energy benefit as well as reduce the waste problem.

Bohme et al., (page 94) issued a report urging that extreme caution be used in implementing an oil spill burning response. The burning of the oil spill to remove unrecoverable oil which is remaining on the surface of the spill site was suggested that it should be considered only when it is apparent that the spilled oil has destroyed essentially all vegetation in the area and that leaving the oil in place would seriously inhibit rehabitation. Other considerations which would allow the use of burning would be that the oil left in place would present a hazard to the public or to wildlife. It was recommended clearly that burned spill areas must be carefully cultivated following the burn to break up the crust formed and to ariate the soil to enable biological degradation of the remaining hydrocarbons. It was recommended that soil nutriants and pH controlled chemicals are essential.

A rather successful application of burning technology was reported by Wise et al., (page 277) where a rather large problem of disposal of oil contamined debris was solved. The Fleco Brush Burner was employed using 23,000 cubic feet per minute of the error and 15-30 gallons per hour of diesel fuel. This disposal technique took care of a tremendous quantity of black oil contaminated debris developed at the Chesapeake Bay spill in 1976.

A classification system was suggested by Westree (page 232) which indicated four types of oil, the oil industry class, the emergency response class, the substance penetration and toxicity class. This classification could be considered in evaluating a variety of priority responses such as burning. She reported in this biologically oriented paper that burning can be employed only in

Spartina marshes and only during the winter dieback period. She recommended against salt bush marshes and mangroves ever being subjected to oil burning.

The problems of underwater oil well blow outs were evaluated by Westergaard (page 294) and insitu combustion was offered as an alternative.

An evaluation of the technology was prepared by Schultz (page 311) where equipment to cleanup oil in cold climates was evaluated. He indicated that disposal was the most difficult problem in cold regions and considers incineration to be a viable alternative. He examined conventional incinerators, open flame burners, rotary kilns, and open combustion pit type incinerators. His recommendation is that rotary kilns are the best for the oil contaminated debris. Open flame burners are best for large amounts of oil and water mixtures that must be disposed and he sites several manufacturers.

Thorton (page 317) et al., reported on some of the initial work the Canadian Government was sponsoring as it pertains to insitu combustion of oil in ice as a probably countermeasure to an oil well blow out. Guidance was offered that combustion will work provided the oil does not thin out and is more efficient if escaping gas is present. If the water content is below 50% smokeless incineration can be done on mechanically removed oil which is pumped to a facility. Because of the rough terrain oil contaminated debris in shore areas cannot be feasibly transported. He states (page 318) that the most viable oil spill countermeasure for oil/ice is insitu combustion on the ice surface and the slick must be greater than a 1/2 centimeter thick and that 90% of the oil may be consumed. Indications were given that the Canadian government is evaluating the use of igniting agents, combustion promoters, the air deployment safety, space, weight, and reliability and their recommendations will be forthcoming.

Again the interest in using combustion as an oil spill countermeasure on ice received much attention during 1977. Little if any interest was expressed in combustion promoters or the applications of combustion other than for disposal of oil contaminated debris.

The 1979 Oil Spill Conference included the following papers pertinent to the subject of oil combustion.

The United States Coast Guard has maintained its interest in the burning alternative as represented by R. J. Imbrie (Page 257) who reported on the "SKIM" computer based inventory system. This system identifies the location and status of equipment available for pollution response covering some twenty-six general fields of data of which burning agents is number 23. G. Marsh (Page 357) reported on the use of the burning concept in Arctic conditions. He suggested that pooled oil could be burned by air drop incendiary devices or that the use of on-site flaring was very attractive in areas of the Arctic where there was no disposal immediately available. He suggested that high capacity flaring burners may have potential for use in sub-Arctic cleanup where disposal sites are also limited.

G. R. Buhite (Page 367) explained how burning was very successfully used on an Alyeska pipeline spill. Five hundred barrels of crude oil were ignited by two highway flares and approximately 1.9 acres of oil were engulfed in flame in about 5 min. This fire burned for more than two hours and then it continued in isolated pockets. This oil was exposed to 1°F temperatures in 18-in. snowpacks for more than sixty days during winter before burning was undertaken. The oil burned rather readily on shallow water (ranging from inches to 3-feet deep) and oil which was frozen in the tundra was released during the burning operation and floated to the surface and burned violently. Excessive steam was reported to cause some smothering but when cleared away, the vapors would reignite and burning would continue. The oil was quite readily burned off of ice with little melting being observed. The frozen tundra which thawed was disked and reburned. This area was fertilized and restored. Buhite suggests that flooding to refloat oil out of vegetation could be followed by burning.

C. J. Beckett (Page 373) reported that oil burning was used as a response to the Imperial St. Claire which was grounded in Lake Huron and lost some 67,000 gallons of diesel fuel. Armed with a bale of straw, diesel fuel, rags, and small sticks and flares, this diesel fuel was ignited in saturated snow. Advantage was taken of wind direction, the oil being spilled on ice, and the fact that the site was 14 miles from the nearest settlement. After overcoming difficulties in relocating the oil under the ice, other burns were successfully attempted covering some 1,000 ft^2, burning for two hours and consuming perhaps 4,000 gallons. These operations were continued as oil was identified. Holes were later blasted in the ice to collect oil but this was not successful in gathering sufficient oil to burn. As ice would melt with warm weather, other successful burns were initiated. This burning was conducted more than 90 days after the spill had occurred.

Burning was evaluated by J. L. Siva (Page 522) as one of the cleanup techniques that may cause ecological impact. Among the several techniques found objectionable for cleaning oil spills from marshes burning was included except in areas where fire is a normal occurrence and the marsh is well adapted (such as Louisiana). Sandy beaches were reported as likely candidates for burning but, ecologically, damage is suggested as being sufficient to prefer allowing the sandy beach to recover naturally.

E. Schrier (Page 423) reported on the use of fuel oil discharged into Buzzards Bay, January 1977. Within three days of the spill, Tullunox, a wicking agent, was employed to burn the oil. Several pools containing some 19 to 20,000 liters were located and 50 g of Tullunox combined with thermite grenades, jet fuel, and lube oil were deployed in 10 boxes. Ignition took place and 20 to 25 knot winds spread the flames and burned oil for about 0.4 to 0.8 km before rising. There were areas, however, where fires went out in 10 to 20 min leaving a residue of unburned wicking agent and other materials as well as oil. About twenty days later, oil rags were knotted into balls 15 to 20 cm in diameter, soaked with diesel fuel, ignited, and thrown into oil which had collected into surface pools. This burning lasted 40 to 50 min with flames rising 9 to 12 m high. A residue was left. It was speculated that as much as, perhaps, 15,000 liters (4,000 gal) could have been burned. Near shore pools were not burned due to safety and aesthetic concern.

APPENDIX F

INTERVENTION ON THE HIGH SEAS ACT

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INTERVENTION ON THE HIGH SEAS ACT

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For Legislative History of Act, see p. 2773

PUBLIC LAW 93-248; 88 STAT. 8

[S. 1070]

An Act to implement the International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties, 1969.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That:

This Act may be cited as the "Intervention on the High Seas Act".

Sec. 2. As used in this Act—

(1) "ship" means—

(A) any seagoing vessel of any type whatsoever, and

(B) any floating craft, except an installation or device engaged in the exploration and exploitation of the resources of the seabed and the ocean floor and the subsoil thereof;

(2) "oil" means crude oil, fuel oil, diesel oil, and lubricating oil;

(3) "convention" means the International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties, 1969;

(4) "Secretary" means the Secretary of the department in which the Coast Guard is operating; and

(5) "United States" means the States, the District of Columbia, the Commonwealth of Puerto Rico, the Canal Zone, Guam, American Samoa, the Virgin Islands, and the Trust Territory of the Pacific Islands.

Sec. 3. Whenever a ship collision, stranding, or other incident of navigation or other occurrence on board a ship or external to it resulting in material damage or imminent threat of material damage to the ship or her cargo creates, as determined by the Secretary, a grave and imminent danger to the coastline or related interests of the United States from pollution or threat of pollution of the sea by oil which may reasonably be expected to result in major harmful consequences, the Secretary may, except as provided for in section 10, without liability for any damage to the owners or operators of the ship, to her cargo or crew, or to underwriters or other parties interested therein, take measures on the high seas, in accordance with the provisions of the Convention and this Act, to prevent, mitigate, or eliminate that danger.

Sec. 4. In determining whether there is grave and imminent danger of major harmful consequences to the coastline or related interests of the United States, the Secretary shall consider the interests of the United States directly threatened or affected including but not limited to, fish, shellfish, and other living marine resources, wildlife, coastal zone and estuarine activities, and public and private shorelines and beaches.

Sec. 5. Upon a determination under section 3 of this Act of a grave and imminent danger to the coastline or related interests of the United States, the Secretary may—

(1) coordinate and direct all public and private efforts directed at the removal or elimination of the threatened pollution damage;

(2) directly or indirectly undertake the whole or any part of any salvage or other action he could require or direct under subsection (1) of this section; and

(3) remove, and, if necessary, destroy the ship and cargo which is the source of the danger.

Sec. 6. Before taking any measure under section 5 of this Act, the Secretary shall—

(1) consult, through the Secretary of State, with other countries affected by the marine casualty, and particularly with the flag country of any ship involved;

(2) notify without delay the Administrator of the Environmental Protection Agency and any other persons known to the Secretary, or of whom he later becomes aware, who have interests which can reasonably be expected to be affected by any proposed measures; and

(3) consider any views submitted in response to the consultation or notification required by subsections (1) and (2) of this section.

Sec. 7. In cases of extreme urgency requiring measures to be taken immediately, the Secretary may take those measures rendered necessary by the urgency of the situation without the prior consultation or notification as required by section 6 of this Act or without the continuation of consultations already begun.

Sec. 8. (a) Measures directed or conducted under this Act shall be proportionate to the damage, actual or threatened, to the coastline or related interests of the United States and may not go beyond what is reasonably necessary to prevent, mitigate, or eliminate that damage.

(b) In considering whether measures are proportionate to the damage the Secretary shall, among other things, consider—

(1) the extent and probability of imminent damage if those measures are not taken;

(2) the likelihood of effectiveness of those measures; and

(3) the extent of the damage which may be caused by those measures.

Sec. 9. In the direction and conduct of measures under this Act the Secretary shall use his best endeavors to—

(1) assure the avoidance of risk to human life;

(2) render all possible aid to distressed persons, including facilitating repatriation of ships' crews; and

(3) not unnecessarily interfere with rights and interests of others, including the flag state of any ship involved, other foreign states threatened by damage, and persons otherwise concerned.

Sec. 10. (a) The United States shall be obliged to pay compensation to the extent of the damage caused by measures which exceed those reasonably necessary to achieve the end mentioned in section 3.

(b) Actions against the United States seeking compensation for any excessive measures may be brought in the United States Court of Claims, in any district court of the United States, and in those courts enumerated in section 460 of title 28, United States Code. For purposes of this Act, American Samoa shall be included within the judicial district of the District Court of the United States for the District of Hawaii, and the Trust Territory of the Pacific Islands shall be included within the judicial districts of both the District Court of the United States for the District of Hawaii and the District Court of Guam.

Sec. 11. The Secretary of State shall notify without delay foreign states concerned, the Secretary-General of the Inter-Governmental Maritime Consultative Organization, and persons affected by measures taken under this Act.

Sec. 12. (a) Any person who—

(1) willfully violates a provision of this Act or a regulation issued thereunder; or

(2) willfully refuses or fails to comply with any lawful order or direction given pursuant to this Act; or

(3) willfully obstructs any person who is acting in compliance with an order or direction under this Act, shall be fined not more than $10,000 or imprisoned not more than one year, or both.

(b) In a criminal proceeding for an offense under paragraph (1) or (2) of subsection (a) of this section it shall be a defense for the accused to prove that he used all due diligence to comply with any order or direction or that he had reasonable cause to believe that compliance would have resulted in serious risk to human life.

Sec. 13. (a) The Secretary, in consultation with the Secretary of State and the Administrator of the Environmental Protection Agency, may nominate individuals to the list of experts provided for in article III of the convention.

(b) The Secretary of State, in consultation with the Secretary, shall designate or nominate, as appropriate and necessary, the negotiators, conciliators, or arbitrators provided for by the convention and the annexes thereto.

Sec. 14. No measures may be taken under authority of this Act against any warship or other ship owned or operated by a country and used, for the time being, only on Government noncommercial service.

Sec. 15. This Act shall be interpreted and administered in a manner consistent with the convention and other international law. Except as specifically provided, nothing in this Act may be interpreted to prejudice any otherwise applicable right, duty, privilege, or immunity or deprive any country or person of any remedy otherwise applicable.

Sec. 16. The Secretary may issue reasonable rules and regulations which he considers appropriate and necessary for the effective implementation of this Act.

Sec. 17. The revolving fund established under section 311(k) of the Federal Water Pollution Control Act shall be available to the Secretary for Federal actions and activities under section 5 of this Act.

Sec. 18. This Act shall be effective upon the date of enactment, or upon the date the convention becomes effective as to the United States, whichever is later.

Approved Feb. 5, 1974.

APPENDIX G

MECHANISM FOR IGNITION OF A FUEL TARGET BY A REACTIVE INCENDIARY MUNITION

APPENDIX G

MECHANISM FOR IGNITION OF A FUEL TARGET BY A REACTIVE INCENDIARY MUNITION

a. A fairly detailed sequence of events has been formulated to describe the reactive fragment/fuel container encounter. This sequence is based on an extensive collection of experimental results

b. The overall sequence of events is taken as follows:

(1) The munition detonates, projecting large primary fragments and numerous small burning reactive particles.

(2) If ignition is to occur, some of the primary fragments must have trajectories which intersect the fuel container.

(3) Any primary fragment having proper impact parameters penetrates the fuel container wall; if the penetration is below the liquid surface, the fragment causes a cavity of predictable size and period to form in the fuel.

(4) The cavity begins to collapse halfway through the period and spray of fuel issues through the orifice during the last half of the period.

(5) The fuel spray travels outward from the container as a cone of predictable included angle.

(6) When the cavity reaches the end of its period (maximum contraction), the spray stops and the cavity begins to expand again with degraded volume and duration. The cycle of expansion, contraction, and spray emission occurs several times, resulting in an interrupted, deconical spray.

(7) Meanwhile, the burning particles will be following the primary fragments because of the lower initial velocity and greater drag. If a burning particle encounters the fuel spray, and if the particle is moving slowly enough relative to the fuel spray (less than 200 feet/second for gasoline and less than 150 feet/second for diesel fuel) to provide ignition energy to the spray, the spray will ignite.

(8) For gasoline, if the spray is ignited, the fire propogates to the main fuel discharge through the perforation, and a sustaining fire results. If the area of the perforation exceeds a critical value, then an uncontrollable fire results.

(9) For diesel fuel, if the spray is ignited, the fire rarely propagates to the main stream or to fuel on the ground; even when it does, the fire will generally burn quietly for a period of about a minute before growing to uncontrolled levels.

(10) The phenomenon of superjetting can occur with containers holding diesel fuel or kerosene. If one or more fragments penetrate the container below the liquid level, an internal spray of fuel is generated in the ullage. If, at this time, a fragment enters the ullage and ignites the spray, the spray deflagrates and the resulting pressure surge on the liquid causes jets of fuel to be violently emitted though the subsurface penetrations to distances of up to 20 to 30 feet. The target area is to some degree sensitized to subsequent attack.

c. In summary, the preceding sequence of events is defined primarily as the result of an extensive collection of experimental results for the purpose of establishing the mechanism for ignition of a fuel target by a reactive incendiary munition.

APPENDIX H

SUMMARY REPORT OF BURNING EXPERIMENTS CONDUCTED IN CONJUNCTION WITH THE ARGO MERCHANT SPILL

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SUMMARY REPORT OF BURNING EXPERIMENTS CONDUCTED IN CONJUNCTION WITH THE ARGO MERCHANT SPILL

U. S. Coast Guard
Office of Research & Development
Operations & Environmental Technology Division
Environmental Technology Branch

1. PREVIOUS RESEARCH

Investigation into the use of burning/wicking agents to promote the sustained combustion of oil spilled at sea was recommended in 1967 by the Committee of Scientists on the Scientific and Technological Aspects of the Torrey Canyon Disaster. By 1970 eight commercially available burning agents had been identified and tested for effectiveness in both laboratory and field experiments by the U. S. Environmental Protection Agency (EPA). Additional field experiments were conducted by the U. S. Navy in May 1970 and by a Canadian Task Force in conjunction with the cleanup of the Bunker C spill from the ARROW in Chedabucto Bay, Nova Scotia, in February 1970. The results of the EPA and Navy experiments were reported in a joint paper presented at the 1971 Oil Spill Conference (Enclosure (1)). The results of the ARROW experiments were reported in "Report of the Task Force - Operation Oil (Clean-up of the Arrow Oil Spill in Chedabucto Bay)", July 1970, Canada, Ministry of Transport. Applicable excerpts from this report are attached as enclosure (2). A further review of the literature indicates that no significant research on the use of burning agents has been conducted since 1970. The findings of the EPA, Navy and Canadian experiments are summarized as follows: (1) fresh uncontained #6 fuel oil on water will not burn, (2) several commercially available wicking agents (Cab-O-Sil, SeaBeads, straw) can promote a sustained burn on properly treated (seeded) spills, (3) wind disperses burning agents making it possible to apply proper concentration to only a relatively small area, (4) ignition even of properly seeded areas, is extremely difficult and can be accomplished only with the liberal use of volatile primers (gasoline or kerosene), (5) even after successful ignition wind and waves disperse oil into separate pools preventing complete burning, and (6) attempts to burn weathered oil, i.e., with water in oil emulsions, were unsuccessful. The recommendations which resulted from these experiments included; (1) further development of burning agent application and ignition methods, (2) development of a containment method such as a fire proof barrier, and (3) development of methods to reduce or eliminate the thick black smoke which is produced by a burn at sea. The reasons why the Navy and EPA did not pursue these recommendations is not known. The Coast Guard did not undertake these development efforts because, even if successful, burning would be limited at best to 5 foot seas and 20 knot winds, the same environmental limits which apply to the Coast Guard's high seas oil containment and recovery systems.

2. ARGO MERCHANT BURN EXPERIMENTS

The ARGO MERCHANT spill has renewed interest in the use of burning agents. As a result of this interest both laboratory and field experiments on the effectiveness of the burning agent Tullanox 500 were conducted by the Coast Guard Research and Development Center. The results of these experiments are reported in enclosure (3). The findings of these experiments are in general agreement with the findings of previous researchers as described in paragraph 1 and are summarized as follows:

a. USCG Research and Development Center Laboratory Experiments

(1) Initial experiments utilized an ignition method considered to reasonably approximate what could be duplicated in full scale on an actual oil slick. The oil surface was primed with JP-4 jet fuel and a small primed cloth swatch was placed on the oil surface. Direct flame from a propane torch was then applied to the cloth swatch. With this ignition method the samples of #6 Fuel Oil, both treated with Tullanox 500 and untreated, did not achieve sustained combustion.

(2) Further experimentation showed that the #6 Fuel Oil samples could be made to sustain combustion under the following conditions:

(a) The oil slick thickness was greater than 1/2",

(b) The surface area of the pan containing oil was greater than or equal to 75% of the total surface area, and

(c) The torch was applied for more than 45 seconds over 40% of the oil slick.

(3) The addition of Tullanox 500 before attempting ignition on identical oil/water ratios had no noticeable effect.

b. USCG Research and Development Center Field Experiment

(1) Burning experiments were conducted on 31 December 1976 from the USCGC SPAR on a 90' x 120' slick of weathered #6 Fuel Oil from the ARGO MERCHANT. The slick was described as being of heavy tarry consistency and 6 to 10 inches thick. The slick was broken into several smaller patches as the SPAR maneuvered alongside.

(2) The actual dispersal of Tullanox 500 onto the now 30' x 60' slick was directed by Mr. Tully of Tulco Inc., manufacturer of Tullanox 500. Six eleven pound plastic bags were thrown onto the slick. Those that did not burst on impact were opened with birdshot from a shotgun. After the wind blew approximately 95% of the Tullanox 500 off of the slick an additional 66 pounds primed with JP-4 jet fuel was disbursed on the slick.

(3) Fifty-five gallons of JP-4 jet fuel was applied to the slick as a primer and three cotton sheets primed in JP-4 were distributed on the slick. One of the sheets was ignited with a 30 minute railroad flare, and burned for 4 minutes. The flame did not progress from the burning sheet to the primer around it. Attempts to ignite a larger area with flares were unsuccessful.

(4) A separate burn experiment was also conducted on 27 December 1976. Boxes of Tullanox 500 charged with JP-4 fuel were dropped on the slick from a helicopter and ignited with timed thermite grenades. The

isolated boxes burned, but due to lack of burning agent dispersal the flame spread was not sustained.

3. CONCLUSIONS

Burning agents, such as Tullanox 500, have been shown to permit, under the best of conditions, the sustained burning of #6 Fuel Oil spills at sea. However, the use of burning agents is not presently considered to be an effective or productive removal technique for the following reasons:

a. Burning is sustained only in those areas of the slick which have been treated with the proper concentration of burning agent. In practice, large areas cannot be properly seeded due to dispersion of the burning agent by wind. Hand broadcasting from a surface vessel is the only effective method available and is limited to a 4 to 8 foot width along the edge of a slick.

b. Even under the best conditions ignition of a treated slick is difficult. The relatively large quantities of volatile primer required present a significant safety hazard.

c. After a properly treated slick has been ignited it quickly disperses into smaller slicks and extinguishes itself making several reignitions necessary. Previous researchers have recommended that the slick be contained by some means such as fire proof barriers. High seas fire proof barriers are not commercially available.

d. The environmental conditions under which a fresh #6 Fuel Oil spill can be properly treated, ignited, and contained are at best equal to the 5 foot sea and 20 knot wind capability of present high seas containment and recovery equipment.

e. Burning, at best, is only 80 to 90% effective leaving a tarry residue which, for complete cleanup, must be removed by mechanical means.

f. Burning is effective only on fresh slicks. Under the action of wind and waves residual fuel oils and crude oils quickly mix with water to form water in oil emulsions. The TORREY CANYON spill produced emulsions containing 80% water. The ARROW spill of #6 Fuel Oil produced emulsions containing 30 to 50% water. Tests during the ARROW spill showed that emulsions with 30 and 40% water could not be burned.

4. RECOMMENDATIONS

The reports of previous researchers are in agreement in that they recommend development of 1) equipment and methods to properly disperse burning agents over a large area and retain it on the slick in the presence of wind and waves, 2) safe techniques for priming and igniting the treated slick, and 3) a method to contain the burning slick. However, before recommending that these research and development efforts be undertaken, it is first considered necessary to determine the overall applicability of spill removal by burning at sea. As discussed previously fresh #6 Fuel Oil can be burned after treatment with burning agents, but weathered #6 Fuel Oil cannot be burned. The length of time after a spill occurs that the oil changes from fresh and burnable to weathered and unburnable for a certain wind and wave condition is not known. It is therefore recommended that research be conducted to determine the range of conditions under which the commonly transported distillate fuels, residual fuels and crude oils are burnable at sea. If this research reveals that burning at sea has wide spread application then development of an in-situ burning system should be considered.

Encl: (1) FRIBEIGER, Arnold, BYERS, John M., Burning Agents for Oil Spill Clean-up,: 1971 Joint Oil-Spill Conference Proceedings; Washington, D. C.

(2) Excerpts from a Report of the Task Force - Operational Oil (Clean-up of the Arrow Oil Spill in Chedabucto Bay), July 1970, CANADA MINISTRY OF TRANSPORT

(3) Commanding Officer, CG Research & Development Center ltr 3913/8400-ARGO of 10 January 1977

APPENDIX I

MARINE SALVAGE SAFETY

APPENDIX I

MARINE SALVAGE SAFETY

The U.S. Navy has established safety criteria for salvage personnel based on many responses to a variety of salvage incidents. Common salvage hazards that can place a salvage crew in jeopardy include:

- Fire
- Gas Hazards
- Explosions
- Rigging and Mechanical Failure
- Weather and Casualty Conditions

Fire

The normal precaution in this respect is to guard against the outbreak of fire whereas the objective of this study is to determine the viability of establishing fire to dissipate a cargo of crude oil before it can escape and contaminate the environment. For this reason indepth considerations are warranted to remotely prepare and activate a burn action. Although crude oil appears difficult to burn in a pool fire, the vapors generated from the crude oil are highly flammable and explosive.

The safety criteria developed by the USN are considered the best available standards that could be applied to the present investigations they are therefore quoted verbatim from the U.S. Navy Salvors Handbook (NAVSEA 0994-LP-017-8010):

"5.2 FIRE

Shipboard fires are categorized as follows:

Class A - Fires in all ordinarily combustible materials extinguished by quenching, and cooling.

Class B - Fires in flammable liquids, greases, paints, and petrochemicals, extinguished by blanketing and smothering.

Class C - Fires in electrical systems extinguished by smothering with non-conducting agents.

5.2.1 FIRE PREVENTION

To guard against the outbreak of fire during salvage operations:

- Eliminate, restrict, or control any discharge of flammable substances especially leaks of vapors, gases, and liquids.
- Store flammable materials such as lubricants, oily rags, paints, and solvents properly.
- Eliminate all ignition sources including chemical, thermal, and pressure conditions conducive to autoignition. Do not allow hot work near untested spaces.
- Confine all possible sources of shocks, sparks, open flames, and static electricity to safe areas.
- Use spark proof equipment and clothing and wrap any deck tackle when working on a ship with fire or explosion potential.
- Prepare personnel and maintain firefighting equipment for any possible emergencies.

5.2.2 FIREFIGHTING PROCEDURES

- Secure the ship and ongoing operations.
- Close down ventilation systems.
- Shut down machinery.
- Isolate the area of the fire.
- Marshall firefighting forces and equipment according to the contingency plan.
- Safeguard all personnel.
- Keep all combustible cargoes cooled with a water stream over the deck.
- Request assistance when available.
- Do not abandon ship prematurely.

5.3 EXPLOSION

The threat of explosion arises from three primary sources: combustible petroleum cargoes, combustible gases, and explosives. Most explosions on board ships are the result of explosive vapors which accumulate in enclosed spaces and find an ignition source.

5.3.1 PETROLEUM CARGOES

In the proper concentration the vapors of all liquid petroleum products are explosive. When handling petroleum products during salvage operations, the following precautions should be observed:

- Do not spill petroleum products.
- Watch for leaks.
- Clean up spills and residual oil immediately.
- When temperature is high, ventilate tanks and cool decks with water to reduce vaporization.
- Inspect all tanks and spaces frequently for vapor concentrations. Conditions may change without warning.
- Insure adequate ventilation of all tanks, working, and berthing spaces.
- Isolate all ignition sources and potential combustible materials.
- Know the volatility of any petroleum product on board. The more volatile are more dangerous.

5.3.2 GAS & EXPLOSION

Gas in any enclosed space is potentially dangerous. If ignited, the heat causes rapid expansion which dramatically increases internal pressure. Without ventilation, the boundaries of the space give way in an explosion. An explosion in one space may generate enough heat to ignite gas in other spaces causing a series of explosions.

To reduce the chance of explosions:

- Never allow possible ignition sources, especially hot work, near any space that has not been declared gas free, including "empty" spaces. This particularly applies to the use of an explosive driven stud gun.

- Frequently check gas levels using an explosive meter.
- Ventilate all cargo and fuel tanks to allow expanding gases to escape instead of building pressure to dangerous levels.
- Keep volatile materials cool, reducing vaporization by running water over the deck above the space.
- In the event of fire, isolate all spaces containing volatile materials.
- Handle compressed gas containers with care. If dropped or allowed to bump against each other, leaks may develop or the container may rupture explosively.

5.3.3 EXPLOSIVES

Whether part of the stricken ship's outfit are brought aboard by the salvors, explosives must be treated with caution. Safety guidelines when encountering or using any explosives include:

- Check cargo manifests and weapons systems. Know what explosives materials are aboard.
- Always consider salvaged explosive materials to be sensitive.
- Do not expose explosives to water, excessive temperature, or changes in pressure because stability will be reduced.
- Isolate all ignition sources and combustile "filler" materials.
- Allow only authorized personnel to handle explosives.
- Dispose of explosives and ordnance only by prescribed methods.
- Always consider air and water shock wave potential in addition to physical and thermal consequences.
- Before attempting to detonate a charge, check the firing circuit with a galvanometer appropriate for the detonator in use.
- Never detonate explosives before checking the safety of personnel (especially divers), equipment, and adjacent structures.
- Never return to a blast area until all smoke and fumes have cleared away.

- Do not divide the responsibility for explosive work.
- Have a preplanned misfire contingency procedure in case of non-detonation or low order explosive results.

5.4. GAS

In addition to being explosive or flammable, gases may be poisonous or cause an oxygen deficiency. When it is necessary to work in an enclosed space, test for flammability and explosiveness, then for oxygen level and presence of toxic gases. Continue to check periodically because conditions change rapidly. No closed space, even if "empty" can be considered safe until tested.

5.4.1 OXYGEN DEFICIENCY

Oxygen deficiency is usually the result of combustion. In enclosed areas human respiration, fermentation, machinery operation, and the oxidation of metals deplete the oxygen supply.

The oxygen concentration in an air supply is diluted by the presence of other gases. Carbon monoxide (CO) and carbon dioxide (CO_2) and other by-products of combustion and firefighting dilute oxygen levels. Vapors from volatile cargoes, and gases leaked from ruptured tanks and pipelines also cause an oxygen deficiency.

5.4.2 TOXICITY

Many gases found around salvage jobs are poisonous in relatively small concentrations; they are often the results of combustion, organic decomposition and chemical reaction.

As a by-product of the combustion of gasoline and diesel fuel, carbon monoxide (CO) is always present in the vicinity of powered machinery. It is colorless, odorless, and generally undetectable by properties common to other gases, but it is lethal.

Hydrogen sulfide (H_2S) is the result of organic decomposition or the combustion of sulfur bearing fuels and other materials. While it has the odor of "rotten eggs" it also quickly paralyzes the sense of smell and may not be detected. Very deadly, it is soluble in water and heavier than air so it may be transported some distances and will accumulate near the deck.

The vapors of many petroleum liquids, particularly gasoline, are highly toxic in proportion to the concentrations. An increase in temperature will increase the vaporization of hydrocarbons consequently increasing their concentration in the atmosphere. Inhalation results in "drunken" behavior first and eventually loss of consciousness and death if not breathed out in fresh air.

Many dangerous gases are soluble in water. Increased pressure increases the amount of gas dissolved in water. A decrease in pressure releases gas to the atmosphere. When possible, dewater spaces completely before entering.

5.4.3 PRESSURE

A flooded space may contain gases under pressure. The ingress of water into an unventilated space compresses the gaseous content until it is pressurized enough to halt the flooding. If a space is opened under these circumstances the pressure will equalize violently. In addition to the explosive reaction, there is the danger that toxic or flammable gases will be permitted to spread uncontrolled.

If a pressure differential is suspected, no attempt should be made to enter the space until pressures are equalized. A preliminary test can be made via a compartmental pressure test fitting or "cracking" a vent.

Whenever venting or entering an untested space, all personnel must wear protective gear and test for all gas hazards in the prescribed sequence.

5.4.4 GAS FREEING*

Simple ventilation may not remove all gas hazards from a space.

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* This section has considerable importance during a tanker spill response action. As of 1979 all tankers over 70,000 DWT will have an inert gas (scrubbed stack gas) pumped into the void between the cargo level and the ship deckhead.

The source of the danger must be identified and eliminated. Steaming removes petroleum residues but carries an electrostatic charge and is dangerous in the presence of combustible vapors. Care should be exercised to properly and safely introduce steam to a space.

Fans are more efficient as extractors than blowers. With an extension tube to the bottom of the space, heavier than air gases can be extracted like a liquid and the entire atmosphere is replaced by air entering through high openings.

Any ventilated vapors must be dissipated into the surrounding atmosphere or collected in appropriate containers in cases of extreme danger. Caution should always be taken to insure that the vented gases do not accumulate on deck or in other compartments, or come in contact with any ignition sources.

In general, when necessary in gas freeing any space, be sure to:

- Pump all liquid from the space since many dangerous gases are soluble.
- Clean all surfaces by safe means.
- Replace or replenish the atmosphere entirely.
- Provide for the control or dispersion of all displaced gases.
- Continue to monitor the space.

5.4.5 GAS SAFETY

In areas where any gas hazards may be suspected, precautions are necessary.

- Test initially, extensively, and continually in accordance with prescribed damage control procedure to determine the type and extent of the hazard.
- Use breathing apparatuses and tended lifelines when entering an enclosed area for testing.
- Provide sufficient ventilation to continually replace the air supply in a space where people are working. This will dilute and remove toxic gases and flammable vapors, and insure an adequate oxygen supply.

- Do not allow ignition sources near an area suspected of containing flammable or explosive substances.
- Look for dead spaces and gas stratification when inspecting any space.
- Keep doors and ports closed when not required for ventilation to avoid movement of gases to other spaces.

5.4..6 GAS HAZARDS

Many substances release toxic gases in reaction to contact with water or heat. The salvor should ascertain the stability and other characteristics of any raw, chemical, or organic materials aboard a stricken ship. All materials should be handled with respect for their worst potential. If necessary, seek the advice of an expert and proceed only after thorough examination and consultation.

5.5 MONITORING EQUIPMENT

Only approved test equipment should be used to evaluate the danger arising from any of the above situations. It is essential that personnel be trained in their use and that the equipment be maintained in good working order.

- Explosive Meter - measures the level of combustible gas present.
- Burrell Indicator - determines the level of explosive or combustible gases.
- Hydrocarbon Indicator - detects presence of hydrocarbons in petroleum tanks.
- Flame Safety Lamp - for monitoring oxygen.
- Oxygen Indicator - measures oxygen level without generating an explosion hazard.
- Universal Tester - colormatic break-tip or chemically treated paper used to test for specific toxic or anoxemic gases.
- Galvanometer - for testing cicuitry.

5.5.1 TESTING SEQUENCE

Never gas test a space without wearing an air breathing apparatus.

The testing sequence is as follows:

First: Check for and equalize any pressure diffentials before opening an enclosed space.

Second: Test for explosive or combustible gases using an explosive meter, Burrell Indicator, or Hydrocarbon Indicator. If none of this equipment is available, postpone the investigation until one of them can be obtained.

Third: Test for oxygen sufficiency. Use an Oxygen Indicator or a Flame Safety Lamp only if the space has been checked for explosion or combustible gases and found safe.

Fourth: Test for toxic or anoxemic gases especially hydrogen sulfide and carbon monoxide using Universal Testers. The "smell" test cannot be relied on and is often fatal.

5.6. WEATHER AND CASUALTY CONDITIONS

There are often complications and hazards related to the location of the casualty. A stranded or sunken ship can be the victim of heavy weather or dangerous waterway conditions. The salvor has to contend with these same forces including shoalwater, reefs, strong currents, vast tidal ranges, fog, hurricane or gale force winds, heavy sea and surf, exposed location or any combination of these.

It is necessary to calculate the casualty's stability aground and afloat, seaworthiness, watertight integrity, and any other factors that may influence the safety of anyone aboard the refloated ship and the success of the operation. The salvor must be alert for any changing conditions aboard and around the casualty and expect the unexpected.

General safety precautions in ship salvage include:

- Follow prescribed damage control procedures to insure personal safety and stabilize the situation.
- Secure all cargo, deck machinery, and heavy objects.
- Use tethered lifelines and tenders and life jackets inheavy weather.

- Keep advised of weather forecasts and unusual local conditions.
- Operate small boats only in favorable conditions.
- Do not expose personnel to hazardous situations needlessly.
- Be prepared to control the ship when it is returned to the seaway.

5.7 RIGGING AND MECHANICAL FAILURE

The salvor must use good seamanship, rigging practice, and cargo and small boat handling. Salvage is accomplished only through the sequential application of the talents of many persons. Unseamanlike work by anyone involved can mean the failure of the entire task and result in injury.

There are many precautions which are inseparable from good salvage practice.

- Know safety load and safety tolerance factors for every phase of operations and stay within the prescribed limits.
- Inspect all essential gear frequently. Investigate any unusual incidents and noises. Never use any component in doubtful condition.
- Never leave any operating equipment unattended.
- Stand clear of any gear under strain, or suspended loads.
- Only authorized personnel, directly involved, should be on deck during an evolution.
- Secure all hatches, doors and other accesses when not in use.
- Protective clothing should be worn as necessary. Protection includes hard hats, gloves, safety shoes, goggles, life jackets, and the proper clothing. Loose clothing should never be worn around deck machinery and moving rigging.
- Ensure communication between all stations during all phases of any operation.
- Cease operations if any doubt or unexpected situation arises.

5.8. FOAM-IN-SALVAGE

Whenever cast-in-place polyurethane foam is used, a qualified foam technician should be present. During batching, blending, and dispatching, a most important consideration is adequate ventilation. Blending foam components gives off highly toxic vapors. Foam produces a strong irritant to the eyes and skin.

When casting foam in a dry compartment or void, it is imperative that personnel wear respirators and protective clothing. Avoid contact with any of the chemicals involved or produced in the foam process. Whether foaming on the surface or underwater, make sure that the person casting the foam leaves an exit from the space and does not become trapped.

5.9 SALVAGE SAFETY EQUIPMENT

Proper safety gear is essential as any pump or rigging tool, and its use is the rule on any salvage job. The salvor should be prepared to cease operations until personnel are supplied with the appropriate protective equipment.

5.9.1 CLOTHING

Standard safety clothing should be worn in the salvage operations area.

- Protective clothing for the body, covering arms and legs should be ventilated but not loose.
- Wet suits may be worn to protect the skin surface as necessary.
- Special fire fighting clothing should be available.
- Safety shoes with steel toes or non-spark rubber soled shoes decrease the danger of fire or explosion.
- Hard hats should be worn to protect the head when necessary.
- Safety goggles should be worn to protect the eyes when necessary.
- Gloves should be worn especially when working with rigging.

5.9.2 BREATHING APPARATUS

If toxic, foul, or anoxemic atmospheres are suspected or known, the following breathing applicances are recommended:

- Hose supplied air breathing masks.
- Oxygen Breathing Apparatus (OBA)
- Self-Contained Breathing Apparatus (SCBA) or if available, Self-Contained Underwater Breathing Apparatus (SCUBA)"

These safety recommendations should apply to all federal and commercial salvors. There is however an exception related to the boarding of a stricken vessel. It would normally be assumed that a time will eventually be reached when it would appear to be inadvisable for persons to board a stricken vessel when there is every indication of a complete foundering, or sinking. When a commercial salvor decides to board a vessel at a time of obvious extreme danger he is actually financially encouraged to do so under existing insurance underwriting practices. The commercial salvor is <u>paid more</u> for a successful salvage job based on the personal risks he undertakes to complete the project.

APPENDIX J

COMBUSTION PROMOTERS

APPENDIX J

COMBUSTION PROMOTERS[a]

GROUP A

TRADE NAME

Cansorb A

Composition

Sphagnum Peat Moss, heat treated

Manufacturer

Annapolis Valley Peat Moss Company, Ltd.
Berwick, Nova Scotia
Canada BOP 1Eo

Experience or Tests

No test data or oil spill experience reported.

TRADE NAME

Peat Moss

Composition

Natural organic fiber

Manufacturer

Local nurseries and garden centers

Experience or Tests

- Materials absorbs 8 times its weight in oil (Robertson, 1976).
- Used as a combustion promoter during cleanup of the "Raphael" incident near Emusulo, Finland.
- Combustion efficiencies of 85% on Ceuta crudė and Bunker C oils have been reported (Coupal, 1972).

(a) Also refer to: Energetex Engineering. 1978. Combustion Promoters. Prepared for the R&D Division, Environmental Emergency Branch, Environmental Protection Service, Canadian Department of Fisheries and Environments.

TRADE NAME

Sawdust

Composition

Natural organic fiber

Manufacturer

Local Sawmills

Experience or Tests

Application rate, 1 part for every 3 to 4 parts oil by weight -- no oil spill cleanup experience reported.

TRADE NAME

Slickwick

Composition

Ground corn cobs

Manufacturer

Ashwell Feeds, Ltd.
139 Millwide Drive
Toronto, Ontario
Canada

Experience or Tests

One part material for every 3 to 4 parts oil by weight (Robertson, 1976; Schatzburg, 1971) -- no oil spill cleanup experience reported.

TRADE NAME

Sorb-Oil

Composition

Recycled fiber board

Manufacturer

McArthur Chemical Company, Ltd.
62 Arrow Road
Weston, Ontario
Canada

Experience or Tests

One part material for every 10 to 20 parts oil (Schatzburg, 1971) -- no oil spill cleanup experience reported.

TRADE NAME

Straw

Composition

Natural organic fiber

Manufacturer

Local agricultural outlets

Experience or Tests

- Absorbs 2 to 6 times its weight in oil (Schatzburg, 1971)
- Tested by EPA on combustion promoter, 80% effective on No. 6 fuel oil (Byers, 1971)

GROUP B

TRADE NAME

Capillardiamin

Composition

Urea formaldehyde foam

Manufacturer

U. F. Chemical Corporation
Woodside, New York
(no longer commercially produced)

Experience or Tests

- Material absorbs between 30 and 50 times it weight in oil (Robertson, 1976; Battelle, 1972).
- Pilot operation in Santa Barbara (Battelle, 1972).

TRADE NAME

Imbiber Beads

Composition

Alkylstyrene polymer

Manufacturer

Dow Chemical Company of Canada
P.O. Box 1012
Sarnia, Ontario
Canada

Experience or Tests

- Absorbs up to 27 times their volume in solvents (data by manufacturer).
- No oil spill cleanup experience reported.

TRADE NAME

Seabeads

Composition

Cellated glass beads

Manufacturer

Pittsburgh-Corning Corporation
One Gateway Center
Pittsburgh, Pennsylvania

Experience or Tests

- Used for cleanup of Bunker C following the "Arrow" incident off Nova Scotia (Byers, 1971; Battelle, 1972).
- Manufacturer claims near 100% effectiveness in 10 ft diameter tank tests (Battelle, 1972).

TRADE NAME

Sol-Speedi-Dr.

Composition

Attapulgite (hydrated magnesium aluminum silicate)

Manufacturer

Engelhard Minerals and Chemicals Corporation
Menlo Park
Edison, New Jersey

Experience or Tests

- Used as a sorbent to cleanup small oil spills (Battelle, 1972).
- No test data reported.

TRADE NAME

Sorbent Type C

Composition

Expanded Peclite (aluminum silicate) and fibrous wood material (cellulose)

Manufacturer

Clean Water, Inc.
P.O. Box 1002
Toms River, New Jersey

Experience or Tests

- Used as a sorbent for cleanup of pipeline spills and a spill at Port Reading, New Jersey (Battelle, 1972)
- Absorbs 9 to 10 times its weight in oil (Robertson, 1976; Schatzburg, 1971).

TRADE NAME

Wonderperl 1640

Composition

Perlite (aluminum silicate)

Manufacturer

Perlite Popped Products
12655 East Imperial Highway
Santa Fe Springs, California

Experience or Tests

Used as a sorbent on the Santa Barbara spill and on the "Arrow" incident near Nova Scotia. Absorbs between 3 and 4 times its weight in oil (Schatzburg, 1971).

TRADE NAME

Seawick

Composition

Bonded silica discs or plates 1/2 in. - 3/4 in. thick by 1 in. - 3 in. diameter

Manufacturer

None, patent pendings.

Experience or Tests

- Inventor states seawick worked well with aged crude oil.

GROUP C

TRADE NAME

Absorbent 1012

Composition

Expanded pumic (treated)

Manufacturer

Colloid Spilldam, Inc.

P.O. Box 861

Brockton, Massachusetts

Experience or Tests

- Absorbs 4.5 times its weight in oil (Robertson, 1976).
- No oil spill cleanup experience reported.

TRADE NAME

Aerosil R-972

Composition

Silicon dioxide, surface treated with silane

Manufacturer

Degussa, Inc.

Hollister Road

Teterboro, New Jersey

Experience or Tests

None reported

TRADE NAME

Bio Sorb

Composition

Vermiculite (treated)

Manufacturer

John Dunn and Company, Ltd.

1847 West Georgia Street

Vancouver, British Columbia

Experience or Tests

- One part material to 3.5 parts oil by weight (Robertson, 1976).
- No oil spill cleanup experience reported.

TRADE NAME

Cab-O-sil ST-2-0 (now Tullanox)

Composition

Fumed silica treated with silane

Manufacturer

Tulco, Inc.

Faulkner Street

North Billerica, Massachusetts

Experience or Tests

- Sea trials at Wayland, Massachusetts, where 4000 gallons of No. 5, and 6 oil were burned (Battelle, 1972).
- A test near Boston Harbor, Massachusetts burned off 200 gallons of No. 2 and Bunker C oil (Battelle, 1972).
- Used for oil spill cleanup near Tralhauet Bay, Sweden (Byers, 1971)
- Absorbs 10 times its weight.

TRADE NAME

Calidria Asbestos

Composition

Chrysotile asbestos, surface treated

Manufacturer

Union Carbid Corporation

270 Park Avenue

New York, New York

Experience or Tests

- Tested as combustion promoter on the Buffalo River (Energetex, 1978).
- Absorbs up to 21 times its weight in Bunker C (Schatzburg, 1971).
- Absorbs 3 times its weight in light curde and No. 2 fuel oil (Schatzburg, 1971).

TRADE NAME

Ekoperl

Composition

Aluminum silicte treated to be water repellent

Manufacturer

Grefo, Inc.
3450 Wilshire Boulevard
Los Angeles, California

Experience or Tests

- Used as a sorbent on the "Torrey Canyon" spill (Battelle, 1972).
- Used as a sorbent for cleanup of the Ocean Eagle spill off Puerto Rico (Battelle, 1972).
- Used for oil spill cleanup at W. Falmouth, Massachusetts and Camden, New Jersey as a sorbent (Battelle, 1972).
- Absorbs between 3 and 5 times its weight in crude oil.

TRADE NAME

Mistron ZSC

Composition

Talc (magnesium silicate) powder, coated with zinc stearate

Manufacturer

Cyprus Mines Corporation
P.O. Box 1201
Trenton, New Jersey

Experience or Tests

- Used as a sorbent for oil slick cleanup after the "Ocean Eagle" spill near Puerto Rico (Battelle, 1972).
- No test data reported.

TRADE NAME

Perlite King SRD-32

Composition

Aluminum silicate (perlite) treated with silicone

Manufacturer

Filter Media Company

P.O. Box 19156

Houston, Texas

Experience or Tests

No test data reported.

TRADE NAME

Saneringsull

Composition

Rockwool, impregnated with phenol formaldehyde resin

Manufacturer

No current manufacturer reported

Experience or Tests

Used for oil spill cleanup on the Ume River (Energetex, 1978)

TRADE NAME

Petroabs

Composition

Waste rubber

Manufacturer

Experimental product developed by the Marine Research Institute in Constantsa, Romania.

Experience or Tests

- Reportedly removed an "important quantity" of oil in a local harbor.
- After absorbing the oil, the material can be used as a low rate fuel (World Environmental Report, 1978).

TRADE NAME

Susquehanna Oil Sorbent (SOS)

Composition

High melt temperature mineral fiber treated to be hydrophobic and oleophillic

Manufacturer

Susquehanna Corporation
3600 S. Yosemite St., Suite 700
Denver, Colorado 80237

Experience or Tests

Limited lab work indicates oil 8 to 10 times the material weight may be sorbed and the material floats on water, able to burn oils which were not otherwise ignitable.

TRADE NAME

Dow Imbiber Beads

Composition

Lightly cross linked polymer chains available as loose beads, matrix in pads, blankets, and packets.

Manufacturer

Dow Chemical Company
MidLand, Michigan

Experience

- Used to sorb and reclaim light oils and solvents and cleanup spills.
- Sorbent property used to act as media for volatile fuels applications as igniters.

TRADE NAME

Norsorex

Composition

Organic synthetic expanded powder, hydrophobic and oleophilic

Manufacturer

American Cyanamid

CDF Chimie

Paris, France

Experience

- Used on small spills to collect and form a gel/rubber
- Employed on the Amoco Cadiz
- No burning suggested, but collection of material and avoiding spreading could be of interest.

GROUP D

TRADE NAME

Pyraxon

Composition

Unknown. Reported to contain an oil cracking catalyst plus small amounts of oxidizing agent. Pyraxon liquid is employed as a starting fluid.

Manufacturer

Guardian Chemical Corporation
41-45 Crescent Street
Long Island City, New York

Experience or Tests

- No oil spill cleanup experience reported.
- No test results reported (Energetex, 1978)

GROUP E

TRADE NAME

Oilex Fire

Composition

Combination of a sorbent and a hydro igniting agent.

Manufacturer

Keltron, Inc.
Switzerland

Experience or Tests

Manufacturer reports product has been used on small spills on Swiss lakes and the Adriatic Sea

TRADE NAME

Kontax

Composition

Paste containing a hydro ignitable chemical

Manufacturer

Edward Michels GmbH
Essen, West Germany

Experience or Tests

85 kg of Kontax successfully burned 10 tons of heavy Arabian crude in the North Sea (Energetex, 1978).

TRADE NAME

Aluminum Alkyls

Composition

Aluminum Alkyls are a group of liquid chemicals that ignite spontaneously on contact with air and on water.

Manufacturer

Ethyl Chemicals Corporation
Ethyl Tower
Baton Rouge, Louisiana

Texas Alkyls, Inc.
2060 North Loop West
Houston, Texas

Stauffer Chemicals Company
Westport, Connecticut

Experience or Tests

Texas Alkyls has done a minimum amount of testing aluminum alkyls as an igniting agent.

TRADE NAME

Sodium

Composition

Pure sodium metal

Manufacturer

A number of companies manufacture sodium metal

Experience or Tests

Sodium reacts violently with water to produce heat and hydrogen gas.

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16. Abstract

The need for this study was based upon: a) the lack of definitive information available to responsible program managers to decide on the use of combustion as an option and b) the question - what, if any, research should be conducted to optimize the use of this tool for spill mitigation. The scope was designed to evaluate the use of combustion for: in situ in a stricken vessel; oil released upon water; and oil-contaminated debris disposal.

The report consists of Part I, which is a practical guide oriented toward the needs of potential users, while Part II is the research or resource document from which the practical guidance was drawn. The study included theoretical evaluations of combustion of petroleum pool fires under the effects of weathering and an oil classification system related to combustion potential. The theoretical analysis of combustion is balanced by practical experience of oil burning and case history information. Decision elements are provided which can be used as a guide for technical evaluations of a particular oil spill situation. The rationale for assessing technical feasibility is given in the context of other alternatives available for response to an oil spill. A series of research and technology development concepts are included for future research. The ethics of using oil burning are discussed as issues, concerns, and tradeoffs. A detailed annotated bibliography is appended along with a capsule review of a decade of oil burning studies and other support information.

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