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SPILL TECHNOLOGY NEWSLETTER

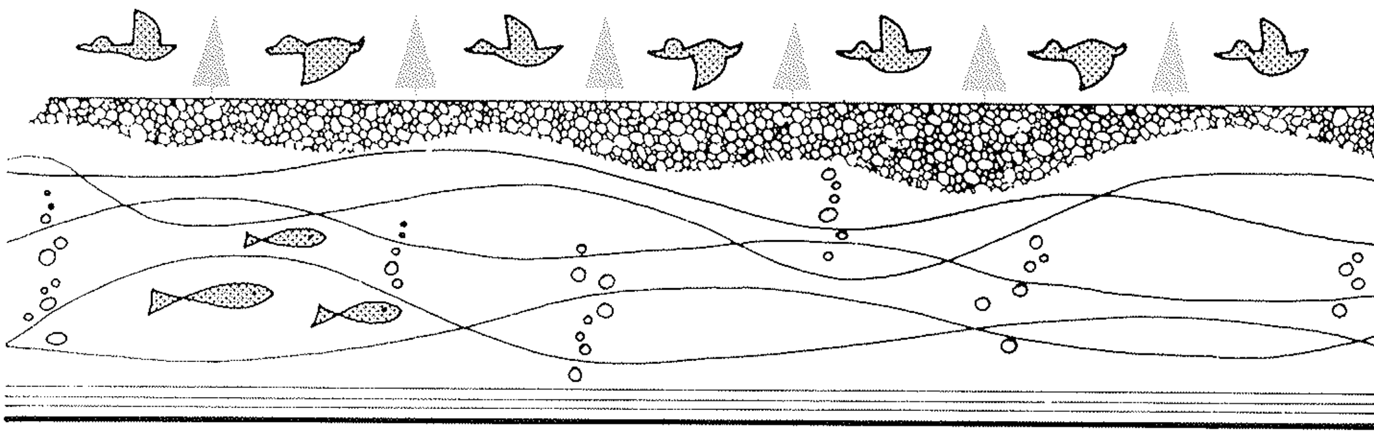

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TABLE OF CONTENTS

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The Spill Technology Newsletter was started with modest intentions in 1976 to provide a forum for the exchange of information on spill countermeasures and other relted matters. We now have over 2000 subscribers in over 40 countries.

To broaden the scope of this newsletter, and to provide more information on industry and foreign activities in the field of spill control and prevention, readers are encouraged to submit articles on their work and views in this area.

INTRODUCTION

The first article of this issue is by S. Murray and Ed Owens who describe oceanic fronts and relate their importance to oil spills. Oceanic fronts are the contact zones between two different masses of water; oil will often collect at the interface of the two water masses. In cases where oceanic fronts and oil spills coexist, the fronts become the dominant force in transporting the oil.

The second article, by Ken Meikle, summarizes the main areas of work under the Arctic and Marine Oilspill Program (AMOP) since it began in 1977.

Good reading!

REPORTS AND PUBLICATIONS

CONCAWE, "The Oil Companies' European Organization for Environmental and Health Protection", has released the report: "A Field Guide to The Application of Dispersants to Oil Spills", report number 2/88. To obtain a copy contact: CONCAWE, Kronigin, Julianaplein 30-9a, NL-2595 AA Den Haag, Netherlands.

OCEANIC FRONTS AND CURRENTS: OIL SPILL DISPERSION AND RESPONSE PLANNING IN THE COASTAL ZONE

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Introduction

Over the past decade, coastal and marine oil spill response plans have become more sophisticated with the inclusion of data on many aspects of the physical process environment. For example, inlet booming strategies are being designed to allow for variations in the direction and velocity of tidal currents at different locations and at different stages of the tides (Foget et al., 1979; Owens et al., 1985; Paskewich et al., 1981).

The role of winds and surface currents in the movement and dispersion of surface slicks has been defined and modeled (e.g., N.A.S., 1985; Spaulding, 1988). One physical element that, to date, has been missing from trajectory modeling and response plans is the role of oceanic and nearshore fronts. The role of fronts was described by Murray (1982), and the major part of this discussion considers some applications of this knowledge to coastal response planning.

Forces That Affect The Movement of Oil on the Sea Surface

The primary forces that control transport and dispersion of oil on the water surface are the movement of air above (wind), and water below (currents), the oil. The relationship between these two variable factors is described in many studies.

Winds are generated by a range of driving forces that may include planetary circulation, regional weather systems, pressure gradients or local sea breezes (Figure 1). Currents are generated by many factors that include oceanic circulation, tidal forces, winds, density gradients and sea surface slopes. Interaction between these factors is often complex, but the net result is that oil is transported and dispersed. In some cases, predictive models can accurately forecast the movement of a spill but, where the data base is inadequate or incomplete, models may be of little value.

Other factors that must be considered include local conditions, such as wave reflection from headlands, river discharge, and the possibility of the slick sinking and being moved subsurface. In addition, it is also necessary to add physical oceanographic elements that may affect surface, or subsurface, movement and spreading. These elements are associated with density, temperature, or salinity gradients or fronts that exist where two or more water bodies meet.

The Character and Role of Fronts

The zone of contact between two water masses of sharply different densities, salinities or temperatures is referred to as a "front". The physical processes controlling fronts in ocean and coastal waters are similar to those involved in cold and warm atmospheric fronts.

Fronts are particularly common in coastal waters where they are associated with the outflow of rivers and estuaries, with topographically-induced upwelling at capes and headlands, and with larger scale wind-induced upwelling that is common off the west coasts of continents at all latitudes. Another type, "shallow sea fronts" is common in shallow seas and bays where bathymetric variability and strong tidal mixing coexist.

The complex velocity field associated with fronts makes them critically important in oil spill dispersion. Current velocities on both sides of the front converge toward the frontal axis, carrying flotsam, and especially, spilled oil. In the immediate vicinity of the front horizontal currents are very strong and turn to move parallel to the front. At the same time, both water masses move vertically downward, with the denser water mass diving under the lighter. Buoyant oil, influenced by the frontal zone, will first move toward the front and then, unable to cross the front or to sink at the convergence zone, will collect and string out parallel to the front. Frontal zones, which are ubiquitous in coastal waters, therefore, become large and very efficient traps or natural booms for spilled oil. Data on the presence, location, spatial variability and temporal variability of fronts are important as these fronts can vary with seasons, wind regimes, daily and fortnightly tidal cycles, and river stages.

Whatever its cause, the density front acts as a natural barrier that can prevent the oil from moving as it would under normal driving forces such as near-surface winds.

Examples of Dominant Forces

<u>TORREY CANYON - Winds</u>. The movement of the 1967 Torrey Canyon spill is an example of the effects of wind on long-term drift of a slick. The track of the slicks can be directly related to wind shifts, despite strong reversing tidal currents that exceeded 1.0 m/s in this area.

For the first six days oil moved south, away from the English coast under the influence of winds from the north. Then, a wind shift to the southeast stranded newly released oil, and moved the existing slick into the English Channel. This was followed immediately by another shift and consistent westerly winds for two weeks, until winds out of the northeast pushed oil southwards onto the Brittany coast.

<u>ARGO MERCHANT - Winds and Tides</u>. Oil from the ARGO MERCHANT spill in December 1976, did not contact the shoreline and dispersed into the Atlantic because of "prevailing offshore winds for most of the spill period" (NAS, 1985). Actual movement of the slick was

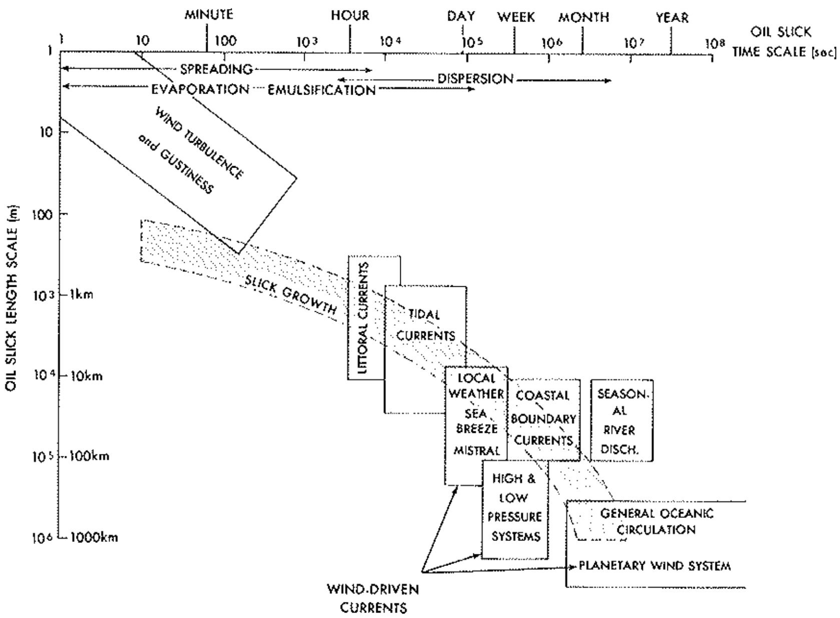


FIGURE 1 TIME AND LENGTH DEPENDENCE OF OIL SLICK GROWTH ON PHYSICAL PROCESSES (Murray, 1982)

more complex than a simple offshore motion, and is an example of the combined effects of wind and tidal currents.

The oil initially moved shoreward under the influence of ENE winds and maximum tidal currents, greater than 1.0 m/s. Following a wind shift, the slick turned to the southwest, but then reversed into the wind-generated northeasterly current as the tide turned (Murray, 1982). Wind became the dominant force as three strong low-pressure systems passed through the region when the ship broke up and oil releases were at a maximum. These systems resulted in winds of 20 m/s and generated currents of 80 m/s to move the oil to the east.

AMOCO CADIZ - Winds, Tides, Currents, etc. The spill from the AMOCO CADIZ, near the coast, was characterized by persistent onshore winds. During this incident, nearshore and inner shelf processes played a dominant role in trapping oil against the shore.

Initially, tidal currents, often over 1 m/s, running parallel to the shore, carried oil along the coast. The oil was released inside the coastal boundary layer (a wedge of highly stratified water only a few tens of kilometres wide) and the onshore winds resulted in a water-level setup that generated a 50 cm/s current downwind along the coast.

Local physical conditions resulted in a wide range of forces that controlled the movement of the oil. These included zones of flow separation that left some waters oil free, headland fronts, and unusually high tides due to shelf (Kelvin) waves in the English Channel. These varied forces prevented the use of standard trajectory and forecasting models (Galt, 1978).

CHEVRON MP-41C - Weather systems and density fronts. The explosion on this offshore production platform, located off the east flank of the Mississippi delta (Gulf of Mexico) in February 1970, discharged more than 1000 bbl/d (1590 m^3/d) of oil over a 20-day period. At the time, several different water bodies were present in the area. During a period of high discharge turbid, cool, river water contrasted with clear, warm, saline Gulf water so that sharp density fronts formed near the major river outlets. The location of these semi-permanent fronts varied under the influence of tidal currents and wind stress.

Oil slicks were driven primarily by wind-generated currents but, upon meeting a density front, were deflected along or trapped against the fronts. Examples of slick movements are given in Figure 2, illustrating how density fronts played a role in altering drift patterns. In example C, the slick was initially pushed away from Pass A Loutre and Southeast Pass, and later deflected to the southeast along the density front associated with discharge from South Pass. Example E, a slick mapped the following day, again shows deflection caused by density change when the oil reached the Pass A

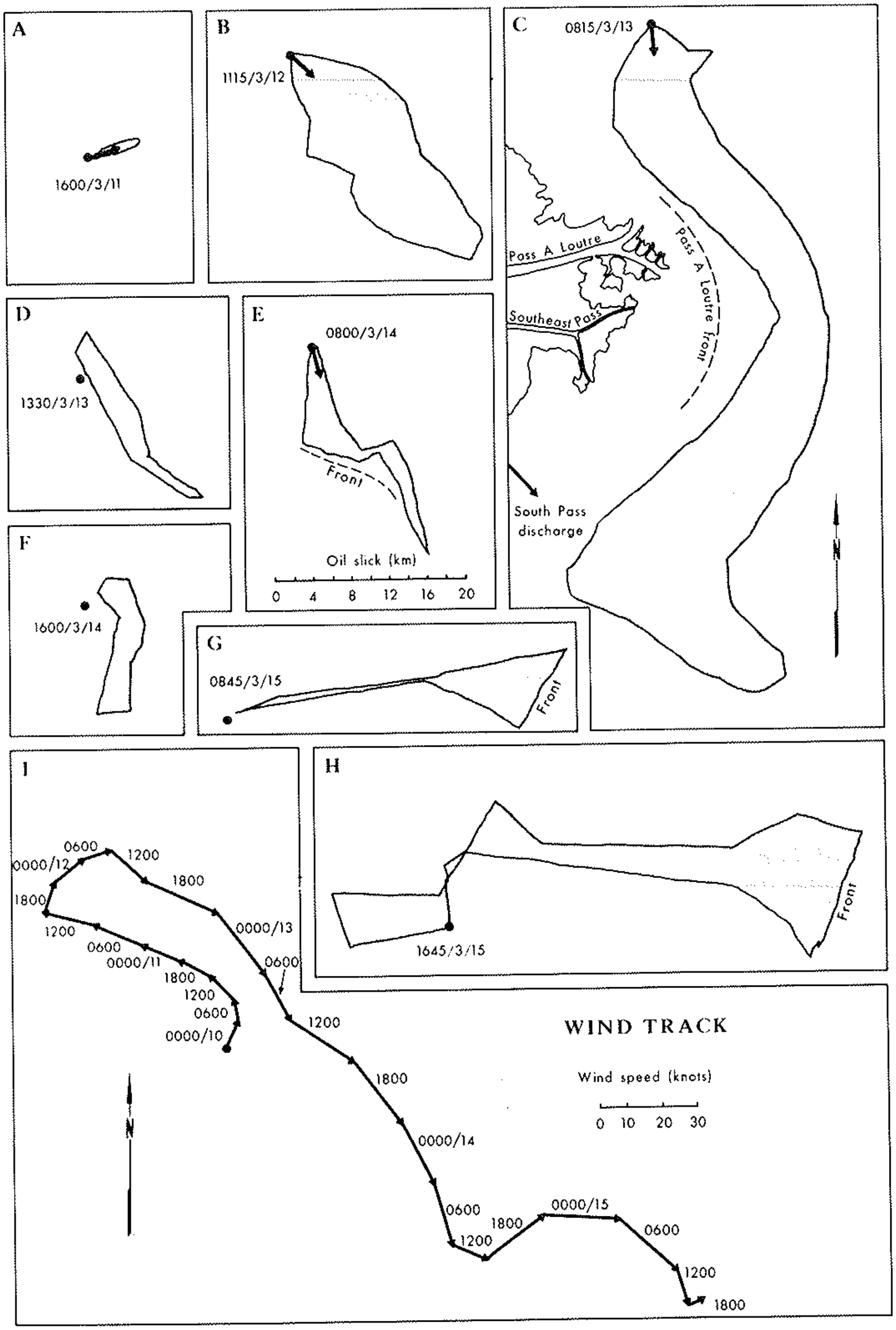


FIGURE 2 MAPS (A through H) OF OIL SLICK TRAJECTORIES FROM THE DAMAGED CHEVRON PLATFORM MP-41C, MARCH 11 TO 15, 1970 COMPARED TO WIND VELOCITIES (I) RECORDED AT A NEARBY (10 KM) LIGHTSHIP (Murray, 1975)

Loutre front. Examples G and H show the effects of a drop in wind velocities that resulted in a westerly rebound current that halted the progress of the slick.

Figure 3 is a thermal scan image of the slick taken the following day that shows movement of the oil away from the platform (curved arrow) to the north (right). The movement of the oil is cut off by an extensive front and oil is concentrated along the frontal line (arrow). Although winds associated with migrating pressure systems controlled the overall movement of the slicks, also important in this area was the role of density fronts blocking and realigning slicks in different directions from local winds.

against the coast, preventing seaward movement and dispersion of a slick.

local scale, the discharge from large (eg., Mackenzie, Yukon, Fraser) and small deltas would protect the coastal zone near river outlets. Usually considered sensitive and vulnerable, these environments could be considered in more detail to define sections where some natural self-protection exists so that response activities could be focused in other, less protected, sections. Similarly, within estuarine environments, oil could be trapped or deflected to one shore rather than another, depending upon tidal and river current circulation patterns.

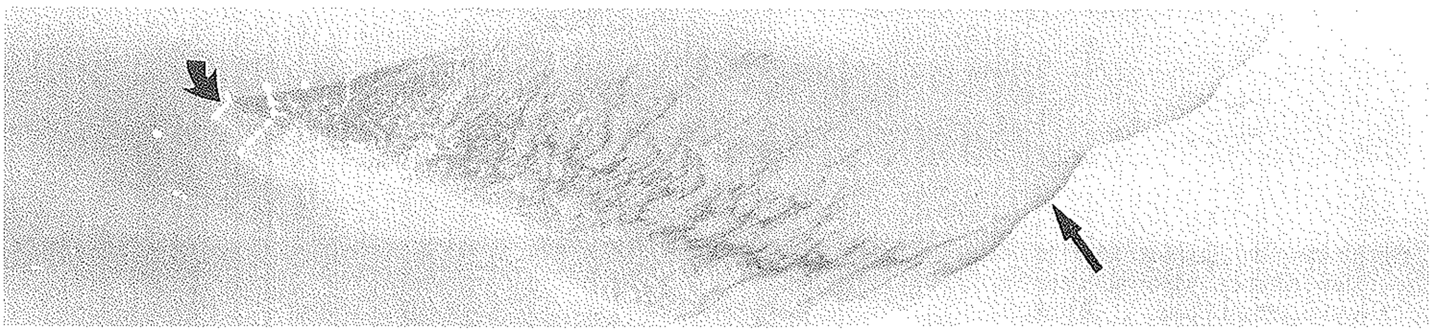


FIGURE 3 NASA THERMAL SCANNER IMAGERY OF THE SLICK FROM THE CHEVRON PLATFORM ON MARCH 6, ILLUSTRATING THE SLICK BEING CUT OFF BY A DENSITY FRONT (ARROW). The seven white rectangles adjacent to the platform (curved arrow) are barges used to deploy booms across the path of the slick, obviously with little success.

Fronts - Importance and Applications

Fronts are only one factor influencing the movement and spread of oil on the water surface. However, where present they may be the dominant factor. Geographically, the role of density currents is most likely to be critical near a river outlet (estuary or delta). In this environment, the meeting of two sharply different water masses (river and oceanic) creates strong fronts that a slick may not be able to cross.

A regional study was conducted (Murray, 1988) on the Guyana Current, off the north coast of South America, to characterize conditions under which a spill would be affected by this major current and by a wide (tens of On a kilometres) brackish, coastal boundary current flowing northwest from the mouth of the Amazon River.

It is unlikely a major offshore spill from an ocean-going very large cargo carrier would reach the adjacent coast, despite consistent onshore winds due to the strong (>0.5 m/s or 50 km/d) alongshore current. If the spill were to reach the inshore shelf area it would be on the ocean side of the density front and probably be deflected alongshore, eventually joining and mixing with the waters of the Atlantic. In this region, coastal density fronts act as a natural barrier to protect the coast from spills on the middle and outer shelf, but would trap an inshore spill

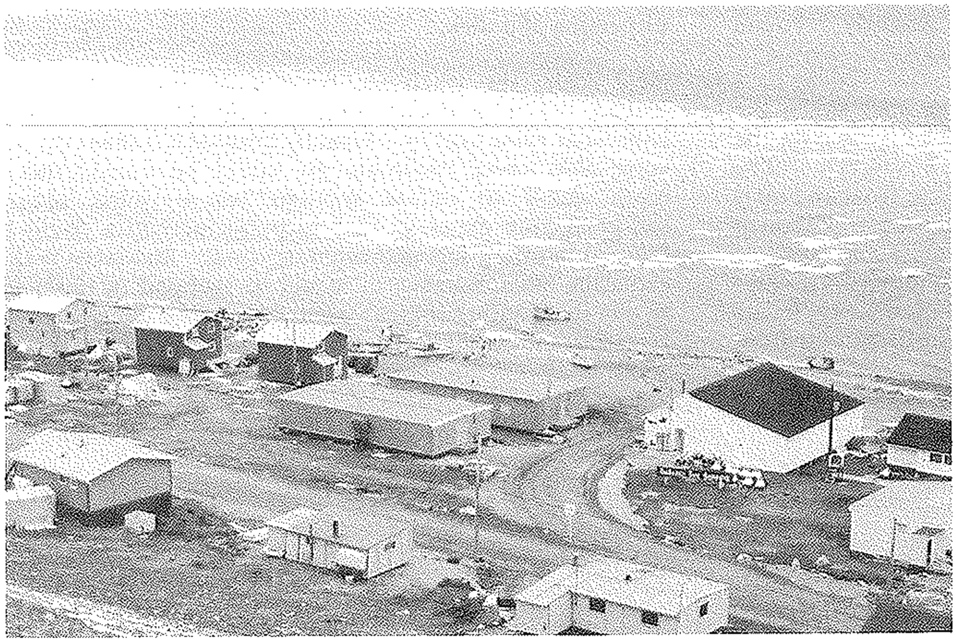
An Arctic Example of the Role of Fronts From Eclipse Sound, Baffin Island, N.W.T.

Eclipse Sound is a large, deep, drowned glacial valley separating Bylot Island from Baffin Island. On the evening of August 13, 1987, a plume of water moved rapidly to the east, along the shoreline adjacent to the settlement of Pond Inlet (72°44'N, 78°00'W), on the south shore of the Sound (Figure 4). The plume was about 100 m wide, and was visibly different from the main water body in the Sound:

1) the water colour was lighter (Figure 4b),
2) the surface was calmer (i.e., fewer waves and ripples) (Figure 4a), and
3) ice floes were travelling west to east (whereas ice in the Sound was travelling NE to SW).

At the time, the wind was from the northeast, at an estimated velocity of 15 to 20 km/h. The wind generated waves approximately 20 to 30 cm high, and drove ice floes from northeast to southwest.

The front was first observed at the west end of the settlement and was visually tracked as it moved alongshore at a rate of between 1.0 and 1.5 km/h. The plume evidently originated from Salmon River, 2.0 km west of the settlement. Within the area of the plume, although the



(a) shows the coastal plume with ice trapped against the front, and refracted waves out of the northeast at the shoreline. The difference in colour between the two water masses is due to reflectance as the waters of the Sound have a rougher (rippled) surface.

(b) shows the leading edge of the plume, with rougher wave conditions. Bylot Island is in the background. In this case, the difference in colour of the two water masses was real, with the plume waters being a lighter shade of blue.

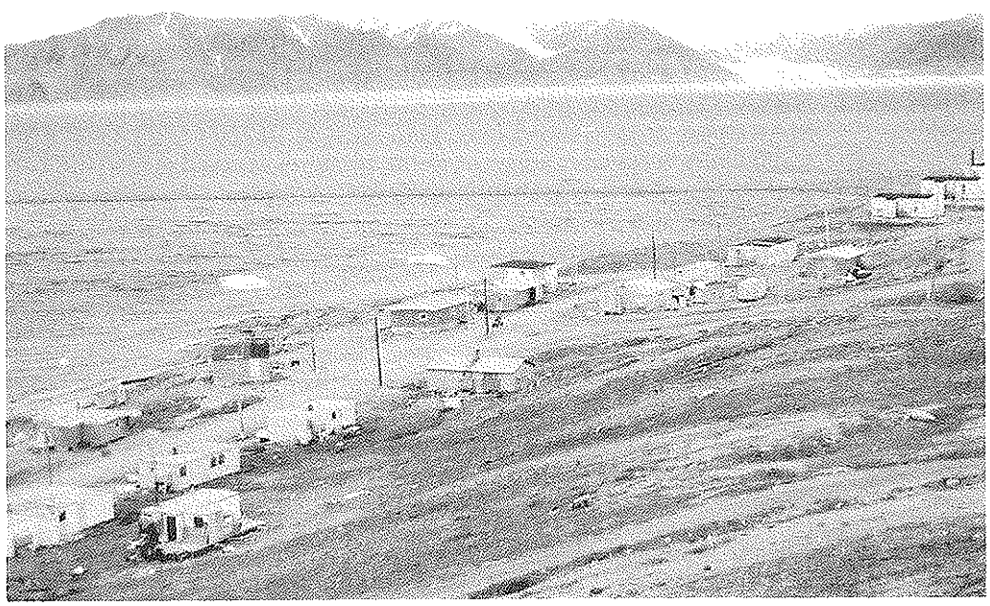


FIGURE 4 VIEWS TO THE NORTHWEST[(a)] AND NORTHEAST[(b)] AT 21:00 ON 13 AUGUST 1987 AT POND INLET, BAFFIN ISLAND, N.W.T.

surface was calmer with fewer ripples and small amplitude waves, 10 to 20 cm "swell" waves generated in the Sound by the northeast winds refracted and broke at the shoreline (Figure 4a). It appeared that waves were dampened because the water surface was rougher near the leading edge of the plume and became progressively calmer downwind.

Within the plume, ice floes were travelling from west to east at a faster rate than the progression of the plume alongshore. The floes did not cross the outer (seaward) boundary of the plume. As they caught up with and approached the leading edge of the plume they were deflected south, towards the shoreline, and collected against the beach (Figure 4b). Similarly, ice floes that approached from the east and northeast did not cross the front of the plume, and were deflected alongshore to the west, never moving closer than 20 m to the front.

Movement of ice floes can be taken to approximate the general movement of surface oil. In this example of coastal oceanography, the two contrasting water masses would have had a dominant effect on the movement and dispersion of oil, had it been present.

The floes in the plume were driven at a rate of about 3 to 5 km/h into a headwind of more than 15 km/h. They neither entered nor escaped the plume.

The analogy for an oil spill in this situation, therefore, is that the fronts which defined the plume would have acted as a natural barrier to either;

1) contain the oil within the near-coastal waters and transport it, against the wind, alongshore to contaminate the beach in front of the settlement; or
2) protect the shoreline from any oil carried towards the settlement from a spill in the Sound.

A Tropical Example of the Role of Currents and Fronts on the Trans-Guyana Coast of South America

The northeast coast of South America is dominated by easterly trade winds that drive a major Atlantic Ocean current (the Guyana western boundary current) which runs northwest along the coast within 30 km of the shoreline. The current's core is near the shelf break, between 100 and 200 km offshore. Current velocities decrease from 1.0 m/s off the Amazon Delta to 0.5 m/s off Suriname, and increase again off the Orinoco coast to 0.7 m/s.

Fresh water input from the Amazon is brackish and lighter than the ocean waters but the influence of the River diminishes past French Guyana. In this down-drift region of high rainfall (greater than 9398 mm/yr) the discharge of local rivers is important on the adjacent coast.

In this region there are, therefore, two major physical oceanographic factors that must be taken into account: the meteorological-oceanographic forces that transport oil on the surface of the shelf waters; and the density fronts that separate the blue shelf waters from the brackish, sediment laden, inshore waters associated with river discharges.

Murray (1988) evaluated the effects of surface winds and currents on oil spilled adjacent to the coast. The information provided by the study is valuable for regional spill response plans since this coastline is adjacent to a major oil tanker shipping route, and the mangrove and mud coasts are extremely sensitive environments in terms of the potential effects of marine pollution. In particular, this is a major shrimp fisheries area. At the larval stages, shrimp spend their life in the coastal swamps and mangroves.

Major conclusions from this analysis are:

- Oil from a spill at or near the shelf break would be unable to traverse the entire shelf to affect the coast.
- Mid-shelf spills could threaten Guyana's coast, but not French Guyana's or Suriname's which are protected by density fronts associated with the nearshore brackish water. A spill could be gradually pushed onshore toward the Guyana coast but would be deflected alongshore, unless river discharge were low. In this case, the oil could be stranded on the shore zone. Oil spilled within the Guyana current could be transported towards Trinidad and Tobago. This area would be most vulnerable during June-September when the winds are from the southeast.
- A spill within 20 km of the coast would have a high probability of affecting the shore zone at all times because prevailing winds blow towards the shore. A spill near the coast would be trapped by the density fronts, and likely not escape onto the shelf.

The results of Murray's study (1988), which focus on the combined effects of ocean currents and trade winds, the primary forces of movement on the water surface, have been integrated with the role of fresh water input from rivers, which can act as a natural barrier to oil spill movement, and with a study (Owens, 1988) on the sensitivity of the trans-Guyana coast to provide information on the effects of spilled oil within this system.

These combined studies are an important example of a regional application of physical oceanography to contingency planning. At this scale, it is possible to predict the probable movement and associated effect of oil spills on different coastal and shelf environments.

In this region, a trajectory analysis based on wind data alone would show that a spill would likely move onshore, but the inclusion of data on currents gives a very different result. Although onshore tradewinds persist throughout the year, an oil spill on the outer shelf, or near the shelf break, would be unable to reach the coast before being carried into the Atlantic by the Guyana current. Thus, knowledge of physical oceanography is crucial to the development of trajectory models, or of spill effects, in this environment and at this regional scale.

Conclusions

Regional and local spill response plans should include data about fronts and currents, where available, to take advantage of natural oceanographic processes in the coastal zone. Spill trajectory analysis should include similar information so that projected slicks do not cross density fronts that in reality would act as a barrier.

A local study of frontogenesis, frontal movement and frontal dissipation should be conducted for high-risk areas. Coastal bays, estuaries and deltas are often environments where fronts develop, and are often highly sensitive and vulnerable to spilled oil. Similarly, shelf and inshore current data, combined with wind data, will give a more accurate trajectory analysis of spilled oil than if wind data alone is used.

Acknowledgements

The two South American studies were funded under the International Maritime Organization/Swedish International Development Agency (IMO/SIDA) Program for the Protection of the Maritime Environment. The Baffin Island observations were made during a stop-over on a study of the oiled BIOS beaches at Cape Hatt, funded by the Technology Development and Technical Services Branch of Environment Canada.

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THE ARCTIC AND MARINE OILSPILL PROGRAM - AMOP

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Introduction

This paper summarizes the work of the Arctic and Marine Oilspill Program (AMOP). The program began in April 1977, and initially focused on the southern Beaufort Sea. Studies triggered by an oil industry proposal to undertake offshore exploratory drilling concluded that few proven countermeasures were available to deal with a blowout or any large oil spill in arctic waters (1,2,3). AMOP is still active, and its primary objective is to improve technology for combating the effects of arctic oil spills.

Many papers have been published in the proceedings of the annual AMOP technical seminar and elsewhere. A total of 148 reports have been produced covering the more than 70 separate studies that AMOP has completed. The Environmental Emergencies Technology Division (EETD) of Environment Canada is responsible for the AMOPs overall management and direction, but joint projects are managed and directed by representatives of the funding agencies involved.

This paper describes some of AMOP's achievements, listed under the following headings: Detection and Tracking, Properties, Behaviour and Modelling, Remedial Measures and Disposal. It will also identify some of the things that must still be done before a recommendation would be made to terminate the program.

Detection and Tracking

Since many of Canada's coastal areas are far from population centres and potential operating bases, and ice and darkness complicate detection and tracking, effort has been made to evaluate and develop equipment to locate, identify, and track oil spilled at sea.

Tracking Buoys

One of the first devices developed was the slick-tracking buoy by Orion Electronics Ltd. of Nova Scotia. Sea trials of this floating battery-powered radio transponder have shown that its drift closely approximates that of oil (5,6,7).

Remote Sensing

The more than $400,000 spent on remote sensing has given us a good understanding of the strengths and weaknesses of various techniques available, including satellite imagery (8). Each technique has its limitations, but a recommended outfit consists of a side-looking radar; an infrared-ultraviolet, dual-channel linescanner; a laser fluorosensor; a low-light level television; an annotated colour camera; and onboard real time display equipment. The last item did not exist when AMOP began, but was developed as a joint undertaking between AMOP and the Canada Centre for Remote Sensing.

Another major joint undertaking was a six-year project with Esso Resources Canada Ltd. which investigated the use of acoustic and radio-frequency technology to detect oil encapsulated in ice. The radio-frequency work ended after a series of theoretical studies showed little or no potential for success (9,10,11). The acoustic studies, however, have produced prototype hardware that has performed quite well in field tests (12).

Problems experienced using a commercially-available towed fluorometer, led EETD to build its own prototype system that has performed well. Details have not been reported, but are available on request.

A recently completed remote sensing project evaluated sensors to detect chronic oil losses from offshore platforms. Funding was provided by the Northern Oil and Gas Action Program (NOGAP) of Indian Affairs and Northern Development Canada. None of the several instruments tested satisfied the requirement, save one; the Wright and Wright Infrared Oil Film Monitor showed potential to perform adequately if more development could make it operational (13).

A long overdue comparison between existing remote sensing imagery and available surface observations has been initiated to find a way to discriminate between continuous and discontinuous slicks.

Properties, Behaviour, and Modelling

A prerequisite for the development of effective countermeasures for arctic oil spills is knowledge of the conditions under which they must work and the effect those conditions have on the properties and behaviour of the oil. Acquiring that knowledge has been a major and ongoing task that has, so far, consumed about $9 million, almost half of the total amount spent on AMOP.

The Baffin Island Oil Spill (BIOS) Experiment

The $7 million BIOS experiment was the largest component of properties and behaviour work. This four-year international government and industry undertaking provided previously unavailable data on short-and long-term fate and effects of crude oil stranded on the arctic shoreline compared to those of the same oil when chemically dispersed in the nearshore arctic environment. Data on the effectiveness of selected shoreline cleanup techniques have also been collected, in addition to more information about physical, chemical, and biological processes found in common arctic marine ecosystems.

Results show no major ecological reasons prohibiting the use of dispersants on oil slicks in nearshore areas similar to the experimental site. They also show no major ecological reasons for the cleanup of oil stranded on arctic shorelines, except where wildlife is present, their critical habitat is threatened, or the oil is in an area used by humans (14).

Another four years of folow-up work has extended our knowledge of the long-term fate of stranded oil in arctic environments compared to that of a temperate situation (15,16,17).

Subsea Blowouts

Canadian Marine Drilling Ltd. feasibility studies of subsea containment concepts (18), followed by an attempt to capture escaping oil with the "Sombrero" subsea collection device during the 1979 Ixtoc blowout in the Gulf of Mexico, were the basis of a series of AMOP studies (19,20,21,22,23). AMOP also contributed to a quarter scale plume and collector experiment performed by Professor J. Milgrim of the Massachusetts Institute of Technology for the U.S. Minerals Management Service (MMS) and the Office of Naval Research at Bugg Spring, Florida in April 1982. Since then a strong cooperative program has developed between MMS and Environment Canada.

AMOP studies have shown that if conditions are favourable, it is technically possible to capture escaping oil near the seabed. However, because the probability that such conditions will exist is so low, and the cost of having an available system so high, EETD does not consider subsea containment as a practical countermeasure.

Work currently in progress at the University of Calgary is not in pursuit of subsea containment. Its objective is to remove uncertainty regarding the amenability of oil to countermeasures once it arrives at the sea surface. It may be that the size of the seabed opening controls oil droplet size to the extent that it may be the determining factor for the formation of a coherent slick instead of discrete globules.

Ice Influence

Various AMOP studies that have examined the influence of ice on the physical fate and behaviour of oil and gas range from the compilation of available information on ice type and extent into an arctic atlas (24), theoretical analysis (25), the determination of ice dynamics from satellite imagery (26,27), and experiments in laboratories and test tanks (28,29), to field experiments involving the release of oil in ice-covered waters (30).

One important discovery was that oil beneath stationary multi-year ice can migrate to the surface, and disperse so widely by natural processes that it is undetectable after five melt periods.

It was also discovered that lead closure rates are rarely high enough to force oil onto the ice surface where it might be removed. Normally, lead freezes, in which case any oil will be trapped within the ice, or the closure rate is so slow the oil is forced under the ice.

Photo-oxidation

Apart from a small study that examined ways to enhance oil degradation by ultraviolet light, the effect of photo-oxidation on spilled oil behaviour has not had sufficient priority, until recently (31).

While seeking better understanding of factors governing oil dispersion, it became apparent that one key might be the change in natural surfactant content resulting from photo-oxidation. That aspect is currently being explored in EETD's laboratory. Important preliminary observations include:

- considerable variation in the susceptibility of oils to photo-oxidation;
- heavy oils that do photo-oxidize form a skin that flakes. The flakes sink in synthetic seawater; and
- an increase in the water-soluble component of oils that photo-oxidize.

Oil Catalogue

As part of the work on the physical fate and behaviour of oil under AMOP, a catalogue of properties of oils that could be spilled in Canada or adjacent waters is being compiled (32). The Canadian oil industry supports the project by providing data and representative samples of frontier oils, common pipeline blends, imported cargos and various products.

The catalogue combines industry data with experimental data obtained in EETD's laboratory. Dispersion and emulsion-forming characteristics of the oil are two elements of the data. An expanded version of the catalogue will soon be available. As with most EETD publications, it is free, but we have the right to limit quantities available.

Remedial Measures

Environment Canada has been working to improve spill countermeasures for 15 years. One of the first decisions was to focus attention on problems peculiar to cold climate operations and to make maximum use of technology developed for spills elsewhere. Another of those initial decisions was to tackle ice-free and complete ice-cover situations first and to defer the problem of removing oil under intermediate conditions.

Arctic Oil Skimmers

Before AMOP began, most of the effort devoted to remedial measures was spent on performance evaluations, either in enclosures adjacent to wharves or in open water. Although three Canadian manufactured skimmers were potentially effective under near-freezing conditions, all required modification to correct problems.

Initially, AMOP's objective was to develop and prove necessary modifications to each skimmer and to derive an arctic oil recovery vehicle. However, after looking at platform options, including hovercraft, it was concluded that special-purpose skimming vessels, able to operate safely in the Arctic at reasonable distances from few widespread support bases, were possible but too costly.

Work to that end was abandoned in favour of devices that could be deployed from offshore support ships or other vessels, such as barges.

The most successful skimmer was developed in cooperation with Morris Industries Ltd. of Vancouver. Following cold-room tests at the National Research Council in Vancouver and a series of tank tests, including some at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) in New Jersey, improvements made to Morris oleophilic-disk models transformed their products into industry leaders worldwide.

Prototypes of arctic variants of the Bennett/Versatile oleophilic belt skimmer and Oil Mop Pollution Control's rope mop were built and tested. The belt skimmer was tested in the OHMSETT and then given a sea trial with oil off Newfoundland with help from the Canadian Coast Guard (CCG) (33). Shortly thereafter, it was loaned to Dome Petroleum Ltd. for a side-by-side comparison with the Lockheed skimmer, originally mounted on their oil recovery barge in the Beaufort Sea (34). The AMOP product was clearly superior and was purchased and installed in place of the Lockheed model. Smaller derivatives were subsequently built and sold but, so far, there has been no market for the full-sized arctic model.

After simple stability trials alongside a Canadian Coast Guard (CCG) base, the Oil Mop prototype was tested with oil in a refinery settling pond. Here, it was confirmed that the modified rope-drive mechanism cured the slippage problem experienced with other models. The CCG, however, decided not to add it to their inventory because it was too cumbersome to deploy safely from their ships. There were no responses when it was declared surplus and offered for sale. Eventually, the device was scrapped, but it did perform one very useful function. Due to its similarity to the larger ARCAT II, developed in the United States for use off the Alaska coast, the AMOP prototype was loaned to the U.S. Coast Guard and tested with blocks of ice to investigate the extent to which drifting ice might degrade performance (35). With 50% or less ice cover, performance compared to that of ice-free conditions. At higher concentrations, as indicated by smaller-scale tank tests in Canada, ice blocked the inlet to the skimmer.

Conventional Booms

Nothing was done to further the development of conventional booms for several years because of the focus on open-water situations. Also, Norway and other countries, were developing booms for offshore use. Until the CCG specifically asked for an upscaled version of the river model of the Bennett self-inflating "Zoom-Boom", to evaluate as an open-ocean replacement for their Vikoma SeaPacks, AMOP hadn't ventured into this area of countermeasures development.

The result was a 366 m 12-section boom combining similar designs from two manufacturers. Packaged in a specially configured hull, it could be transported by helicopter, from which it could be remotely deployed while towed by either a helicopter or work-boat.

A test section performed well in the OHMSETT, but when the full length was deployed at sea in conjunction with the Bennett/Versatile arctic skimmer trials, it did not perform as well as expected. The CCG decided that it was not a suitable replacement for their Vikomas (33).

Fireproof Booms

The Beaufort Sea Studies at Balaena Bay showed that confined floating oil could be burned-off in-situ (2). Therefore, one of AMOP's first projects was to determine the feasibility of constructing a fireproof boom to confine oil in the absence of sufficient ice or other natural features.

A variety of materials and approaches were considered. Small-scale tests indicated that fire-resistant booms were indeed feasible, but floating nets were ineffective (36). Efforts to create a fireproof oil confinement device were discontinued when Dome Petroleum Ltd. started to develop a fireproof boom for offshore use in the Beaufort Sea.

Largely because of CCG interest, AMOP resumed a parallel effort to develop a lighter and cheaper product a few years later.

In OHMSETT tests the Gem Eng boom, with its ceramic protected, foam-glass flotation, revealed that its ability to hold oil matched that of conventional booms (37). It also withstood repeated and prolonged exposure to burning crude oil with only minimal and readily repairable damage. However, in both the tank test and subsequent deployments where it was subjected to moderate wave action, it sustained unacceptable structural damage despite several design changes (38). Work was discontinued for lack of sufficient market interest.

Water Jet Barrier

A novel approach to controlling oil on water was proposed by Mr. D. Christie of Vancouver. His concept used a horizontal array of high pressure water jets to induce an artificial wind over the water surface to oppose movement of the oil. The airflow induced by the waterjets in the proposed arrangement does effectively move oil on water. It is interesting that waves, which made conventional booms ineffective, had no measurable effect on the ability of the jet-induced wind to move oil (39).

A basic prototype, consisting of two opposing arrays mounted on improvised floats, was built and tested on the Mackenzie River at Norman Wells, NWT. The system's performance as a deflection barrier clearly surpassed that of conventional booms (40). Its ability to hold oil in the containment mode in a current was comparable to that of conventional booms. Although time did not permit making necessary changes, the boom probably could have been made substantially better in the containment mode too. The fact that it could be held in position without anchors or tow vessels and manoeuvred by pressure adjustments was a major advantage.

The prototype has since been outfitted with custom-designed floats to minimize drag and make more power available for resisting current or increasing the span of the array. Optimum flowrate, pressure, spacing, height and other key design parameters have been determined through further experimental work in test tanks in Canada and Japan (41,42).

Brief trials conducted in the Quebec City harbour during spring breakup indicated that the barrier does not effectively separate oil from drifting ice. Its usefulness in shallow waters, such as tidal mud-flats, has yet to be investigated.

Preliminary assessment of the water jet barrier as a fireproof boom was made in an Ottawa-area test tank. Although the contractor's report is still being prepared, it was evident that induced wind and/or influence of sprayed water significantly reduces the amount of smoke characteristic of oil-pool burns.

Boom Test Protocol

The largest experimental oil spill released in Canadian waters was off the coast of Newfoundland in the late summer of 1987. The experiment realistically assessed the capability of CCG's booms and skimmers to function in offshore sea conditions. The containment and recovery effort was one of the most successful on record (43).

A secondary objective was to deploy booms with oil in a pre-planned situation and validate an OHMSETT Interagency Technical Committee (OITC) protocol for assessing the capability of offshore booms to contain oil without having to spill it. Such a protocol is necessary to prevent environmental stress by spilling oil at sea. It is also impractical to adequately assess offshore booms in the confines of a test tank.

Oil Slick Igniters

As a result of the Balaena Bay experiment, and the discovery that oil trapped in or under sea ice will surface on melt pools in burnable quantities, a project to ignite oil from the air was developed.

Ice movement studies indicated that oil from a continuous subsea blowout in the Beaufort Sea could be distributed over a 16 000 km area, with burnable quantities of oil in perhaps 50 000 or more separate melt pools.

Safety considerations aside, it is unrealistic to expect people working on the ice surface to ignite all of the pools in the approximately three weeks typically available before breakup, and escape the burning oil. Therefore, an igniter, which could be dropped from a helicopter or fixed-wing aircraft, was developed with the cooperation and assistance of Canada's Defence Research Establishment at Valcartier, Quebec. Tests showed that existing devices used to fight forest fires did not produce enough heat to ignite oil subjected to the amount of weathering that could be expected (44).

Laser Oil Slick Igniter

Although air-dropped incendiary devices have proven capable of igniting pooled oil, they are still not entirely satisfactory. Igniters have a five-year shelf life, there are only a few places in North America equipped and approved to make them, and production capacity is limited, even in an emergency situation. Transportation restrictions further complicate the task of getting a sufficient number to the right place on time.

However, an AMOP contract was awarded to Physical Sciences Inc. of Andover, Maryland to establish design criteria for a laser igniter. A small trial, conducted under typical late winter conditions, proved the system successful. An engineering study has shown that an operational system could be installed in a helicopter using existing technology (45). Work is continuing under a joint project with Minerals Management Service (MMS) to build and test a system. A laser focusing telescope has been built and tested, and an aiming and tracking system is being assembled (46). Concurrently, in view of the success achieved by the University of Tasmania (47), and as a prelude to possible co-sponsorship of the project, the Canadian Forestry Service is determining laser power requirements to ignite typical Canadian bush.

Disposal

Two methods of disposal of recovered oil and oiled materials have been addressed by AMOP.

Burial. Despite difficulty operating land vehicles in the Arctic and long-term terrain damage that can result from burial, it may at times, be the only practical alternative along the shores of the southern Beaufort Sea. Site selection criteria were established, and possible sites identified from aerial photographs (48).

Incineration. Under AMOP over $400 000 has been spent to develop an oil incinerator in the Arctic and other remote areas where it would be too expensive to transport oil, and oil-contaminated materials, elsewhere. Simple wicking devices to collect and burn floating oil have proven impractical (49).

A prototype device, making use of ultrasonic energy to herd, lift and atomize floating oil, has burned-off emulsified crude oil under calm conditions with virtually no smoke. Subsequent laboratory work has established engineering tolerances and power requirements. A contract was recently awarded to test the modified prototype in a tank under calm and controlled wave conditions. Also, an air-transportable pit incinerator has been developed to dispose of oiled combustibles, and a rotary kiln, assembled from materials such as used oil drums and car wheels, has been tested in cooperation with the Petroleum Association for the Conservation of the Canadian Environment (PACE) (50).

Future Needs

In addition to unresolved dispersal and treatment agent problems mentioned by Fingas (4), a number of other important questions are still unanswered. The following are being addressed under joint project agreements with MMS, or are expected to become the subject of future agreements.

Photo-oxidation/Heavy Oil Behaviour

Discovery of the reason for the variable susceptibility of oils to photo-oxidation could lead to development of either an inhibitor or promoter that would lessen the impact of spilled oil on the environment.

Laser Ignition of Oil Slicks

Until the capability of the laser ignition system has been proven, with the successful remote ignition of floating oil under typical arctic springtime conditions, there will be skepticism about its effectiveness. The University of Tasmania may make their laser available so that tests can be carried out.

West Coast Experimental Oil Spill

Recent public hearings on the proposed resumption of exploratory drilling off the coast of British Columbia, whose geography and characteristics such as the heavy driftwood accumulations are peculiar to much of the west coast of Canada and the United States, have raised doubts regarding the effectiveness of oil spill cleanup techniques applied elsewhere. As a first step in what would, of necessity, be a multi-year undertaking, a study has been initiated to identify those uncertainties that can only be resolved by spilling oil in one or more controlled experiments and to define the essential characteristics of the test site or sites. Follow-on phases would be the identification of sites with those characteristics, site selection in consultation with all potentially affected parties, arranging for the funding, establishing baseline pre-spill ecological conditions, depositing the oil, applying selected countermeasures and monitoring the short- and long-term effects.

In-situ Burning of Oil in Leads and Drifting Ice

Laboratory experiments and numerous burns in simulated ice conditions in the OHMSETT and other tanks indicate that in-situ burning is an effective way to remove floating oil confined by leads or drifting ice. So far, however, this technique has been applied only once, in-situ burning was used to successfully remove oil spilled off Canada's east coast and to determine its physical fate and behaviour in pack ice (51). It is unknown whether the small-scale results are a true indication of the effectiveness of in-situ burning in other, typical ice-forms. A study is being initiated to define experimental needs to identify possible locations and make appropriate site selections.

Waterjet Barrier

The marked reduction in smoke generated by in-situ burning of oil enclosed by a waterjet barrier as observed during the recent simulated situation dictates a full-scale trial to confirm that finding.

Identification of Substitute Facilities for the OHMSETT

EPA's decision to deactivate the OHMSETT and return it to the U.S. Navy has eliminated the capability to assess the performance of new or improved oil skimmers and techniques under controlled conditions.

New, and allegedly improved, equipment and techniques continue to appear on the market, but cannot be evaluated by direct comparison to the performance of skimmers previously tested in the OHMSETT. A MMS/AMOP study has been initiated to determine if OHMSETT capability can be matched in Canada.

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