Oil Dispersants New Ecological Approaches

L. Michael Flaherty, editor (AST) STP 1018 **STP 1018**

Oil Dispersants: New Ecological Approaches

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The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM.

Foreword

ASTM Committee F-20 on Hazardous Substances and Oil Spill Response sponsored a state-of-the-art review of "Dispersants: New Ecological Approach through the 90's" at its symposium held in Williamsburg, VA, 12–14 Oct. 1987. Over 145 people from 7 countries attended to learn of the latest technological advances in spill countermeasures. L. Michael Flaherty, formerly with the Environmental Protection Agency and now an independent consultant, was chairman of the symposium and served as editor of this book. William B. Katz, Illinois Chemical Corp., and Stephan Kaufmann, Sunshine Technology Corp., served as cochairmen of the symposium.

A Note of Appreciation to Reviewers

Many new and exciting things have been happening in the field of environmental response activities, and these formed the cornerstone of our Williamsburg symposium. The successful transfer of information, however, is dependent not only on those who contributed documentation but also on those who reviewed this documentation for clarity, comprehensiveness, and completeness. Without them, we could not adequately get our message to the public and, without them, we could not be assured that our publication would meet the highest professional standards. Our appreciation is heartfelt.

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Overview

The Symposium on Dispersants: New Ecological Approach Through the 90's held in Williamsburg, Virginia, in October 1987, summarized research and development on dispersants and other chemical countermeasures and their use during the past 5 years. It was one of the best attended symposia of Committee F-20 on Hazardous Substances and Oil Spill Response in many years with over 145 total participants representing 7 countries.

In the January 1987 call for papers, the chairman requested that papers be submitted stressing the positive developments and uses of innovative countermeasures. There was sound reasoning behind this request. Since the Torrey Canyon grounding in 1967, little "good" or "positive" has been said or written about dispersants. In the United States, the two major agencies controlling the use of dispersants have had what many refer to as an *unwritten* prohibition on their use. This may have been somewhat warranted because of the toxicity of the early first generation dispersants produced from the late 1960s through the early 1970s. However, in the case of the Torrey Canyon spill, the oil itself was highly toxic, the dispersants were almost totally improperly applied, and explosives and napalm were also heavily used. Just the latter two on their own were responsible for tremendous fish kills.

The time has come to add to the technical literature positive papers that address many new and advanced areas, such as guidelines for dispersant use in freshwater and the effects of elastomers on the efficiency of oil dispersants. Several papers in this book discussed modern computer usages to assist response application while another paper described using a computer for both training and contingency planning. Other papers also related the crisis in response training, while another makes an indepth analysis of the behavior of dispersed and nondispersed fuels in sewer systems. The papers assembled in this book break new ground in many innovative areas of chemical countermeasures.

Let it be said from the beginning that the preferred countermeasure will always be to recover the oil as completely as possible and recycle it. Up until recently, recovery of oil was confined to small-scale operations in calm waters and, because it was a labor intensive endeavor, it was generally not very cost-effective. Now, new products and techniques discussed in this book make recovery both a broader and more economical reality.

In the past five years, noted marine biologists, oceanographers, and environmental scientists have spoken out on the positive aspects and overall usefulness of dispersants. Again, it is important to qualify the application of dispersants by repeating what must always be understood . . . When a properly selected dispersant is applied with correct techniques at an approved rate and in a timely manner to an oil that is fresh and known to be dispersible, in water of 10 m or more with some current or flushing action, then one should expect to obtain good results. While this may connote an idealistic scenario, emergency response personnel can today use dispersant chemicals correctly with only minimal training and good contingency planning.

We are definitely in the third generation of dispersants (many will say the fourth). While these newer dispersants are slightly more specialized in their applicability, they are considerably more effective and less toxic than the earlier generations of products. Generally, when we spoke of dispersants in the past, we simply meant a chemical formulation of surfactants, solvents, and additives which, when applied and agitated, formed an oil-inwater emulsion. Today, there are products listed as dispersants that are designed and formulated for land use only while others may be formulated primarily to emulsify oil or gasoline on street or highway spills. Some products are designed for use in holding ponds and small streams; yet others are designated to be used to clean offshore rigs or bilge tanks. Furthermore, there are probably another half dozen cleaners or emulsifiers for specialized applications that are also called "dispersants." It is, therefore, a case of caveat emptor. One must scrutinize carefully what one buys in order to stock for the appropriate application.

For those of you who may read this book with the intention of formulating or designing a new dispersant or other type of chemical countermeasure, let us in a few words address what might be considered an ideal product. It should be reasonably priced, effective on all types of oil (both fresh and weathered), and easy to apply from shipboard, aircraft, or fire hose. It should be nontoxic to fish and other aquatic life, good for both fresh and saltwater, be self-mixing or require minimal agitation, should help break down the "mousse," and perhaps even be effective on land as well as on the sea. It is obvious that no product could possibly satisfy all these criteria, but low toxicity and high effectiveness are the key elements, and the ability to work on a wide variety of oils (weathered and otherwise) is also crucial.

One can see from the above list of effectiveness standards that there are many qualifications involved in formulating and marketing a new product. A true dispersant should principally be designed for water application rather than as a cleaning agent. Furthermore, a really good dispersant will serve naturally as a deterrent to fires and subsequent explosions.

It is also important that we consider the cost-effectiveness of dispersant used in cleaning up spills to navigable waters. When an effective dispersant is used on an oil known to be dispersible, in water which has adequate current or wave action and is of sufficient depth, there is now little doubt that dispersants are probably the most cost-effective method of cleanup short of total removal by vacuum truck or skimmers followed by recycling. Use of dispersants at sea is certainly 10 to 30 times safer and more economical and effective than any attempts to remove an oil slick on shore.

There is a soon-to-be-released (if not already published) National Academy of Sciences, National Research Council, Marine Board two-and-one-half year study on dispersants which, in essence, states that third and fourth generation dispersants are both effective and of minimum toxicity. It was hoped that this book would contain an executive summary of these findings; however, the printing deadline did not allow the release of the data in time.

Over the past five or six years (and perhaps longer), a new breed of oil spill countermeasure products has come to the attention of the Environmental Protection Agency. The first of these were called gelling agents. They originated in Japan and have been in use there for quite some time. These products work well in still waters but are labor intensive and require disposal after utilization. Another group of products is known as emulsifiers. Emulsifiers differ from dispersants in the manner in which they suspend the oil. On the other hand, dispersants disperse it in very small droplets in the upper 3 or 4 m of water. Finally, there is a relatively new line of products known as elasticizers or viscoelastic enhancing agents. One of these is a two-step chemical procedure that forms the oil into a carpet, which can be rolled up and retrieved from the aqueous environment; another process, accomplished in one step, temporarily congeals oil into an elastic bond which can be vacuumed or collected by a skimmer with little or no water separation required. Initially, it was believed that this latter product could only be used in the relatively calm waters of bays or tributaries; however, recent trials 25 miles (40 km) off the coast of Saint Johns, Newfoundland, indicate that it can achieve outstanding results in open, heavy seas and particularly in holding oil within boomed areas. Films of the test spill of 18 000 gal (68 000 L) of oil indicated great increases in oil recovery using this new agent.

In addition to dispersants, other innovative countermeasure products were demonstrated during the "show-and-tell" session and indicated great increases in oil recovery using this new agent. Products that show tremendous potential are the new sorbents, which for the first time can truly be called ABsorbents in that they collect and retain oil. These absorbents and this viscoelastic enhancing agent indicate great hope for future oil spill cleanups. Some were demonstrated at a special show-and-tell period during the last days of the Williamsburg symposium. The session included about ten booths and was greeted enthusiastically by participants. It is hoped that organizers of future symposia will consider this as an educational and profitable element of the overall program.

Appreciation of help in the review and critique of papers should be recognized. A special expression of gratitude is extended to Bill Katz and Stephen Kaufmann, who, as assistant chairmen gave greatly of their time and valuable knowledge that contributed to the success of the symposium and the completion of this book.

L. Michael Flaherty

U.S. Environmental Protection Agency (retired), 10332 Democracy Lane, Potomac, MD; symposium chairman and editor John R. Clayton, Jr.,¹ Garry H. Farmer,¹ James R. Payne,¹ G. Dan McNabb, Jr.,¹ Paul C. Harkins,¹ John S. Evans,¹ Nicholas P. Rottunda,¹ Charles R. Phillips,¹ and Mark L. Evans²

Effects of Chemical Dispersant Agents on the Behavior and Retention of Spilled Crude Oil in a Simulated Streambed Channel

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ABSTRACT: Field experiments were performed to obtain first-step estimates of the effects of selected chemical dispersant agents (OFC D-609 and Corexit 9550) on the behavior and retention of spilled crude oil in a shallow freshwater streambed environment in southcentral Alaska. Comparisons between experiments with and without prespill additions of dispersants to the oil included measurements of oil in sediment and water samples. Sediment and water contamination by oil was quantified by flame ionization detector capillary gas chromatography (FID-GC) as well as visual observations in the simulated streambed channel following the spill events. Inclusion of dispersants in the oil produced the intended result of enhancing dispersion of oil into the aqueous phase. However, distributions of oil in aqueous and sediment samples were controlled by interactions between a variety of factors including rheological properties of the oil (for example, oil/water interfacial surface tension values), particle size distributions of sediment matrices, exposure of sediment surfaces to oil, and in situ water flow characteristics at specific streambed channel sites. The results imply that use of chemical dispersants to mitigate effects of oil spills in freshwater streambed environments must include an understanding of the interplay between variables related to both the type of oil released and the specific streambed environment.

KEY WORDS: chemical dispersants, crude oil, freshwater streambed, sediments, water, oil dispersion, surface oil slick, rheological properties, interfacial surface tension, sediment particle size distribution, water flow properties

Oil exploration, development, production, and transportation operations in nearshore and inland areas of Alaska and Canada may result in the release of oil into cold, low salinity waters. In addition to habitats for indigenous biological communities, the coastal freshwater rivers and streams in this region serve as sites of (or routes to) spawning areas for migratory species such as pink, coho, chinook, chum, and sockeye salmon. The estuarine zones at the mouths of rivers and streams also serve as crucial nursery regions for juvenile forms of other vertebrate and invertebrate species. Consequently, methods need to be

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developed and evaluated for the mitigation and removal of potential oil spills in the cold, freshwater streambed environments in these arctic and subarctic regions.

One approach for minimizing problems associated with potential oil spills would involve the application of chemical dispersant agents to an impacted area. Application of a dispersant to an oil slick on water is intended to lower oil/water interfacial surface tension values and facilitate dispersion of small oil droplets into the water phase. This in turn can lead to the transport and dilution of the oil droplets by subsurface water currents.

In laboratory tests of several commercially available chemical dispersant formulations [1], Corexit 9550 (Exxon Chemical Co.) and OFC D-609 (ChemLink Petroleum, Inc.) were found to be effective dispersants under conditions of varying salinity (0 to 33 parts per thousand) and temperature (1 to 10° C). However, it has been noted in other studies [2,3] that the effectiveness of a dispersant agent will depend on numerous factors including; (1) the composition of the dispersant formulation, (2) characteristics of the oil (that is, its viscosity, density, and chemical composition), (3) the dispersant to oil ratio (D:O), (4) methods of application of the dispersant to the oil, (5) methods of mixing of the dispersant with the oil, (6) ambient water and air temperature, and (7) the salinity of the water. Therefore, extrapolating results from laboratory tests to "real world" situations must be done with a considerable degree of caution. Furthermore, existing information on the behavior of dispersed oil in shallow freshwater streambed environments is still incomplete for supporting predictions of relative environmental impacts of chemically dispersed versus nondispersed oil. This paper presents results from a series of experiments that were conducted to determine effects of dispersant additions on the behavior and fate of oil released into a confined bench scale test model of a streambed. Effects of dispersants on retention of oil by the streambed (for example, in sediment matrices) were of particular interest. The model contained flow regimes and sediment mediums and topography that were patterned after those observed in natural streambed environments in southcentral Alaska.

Materials and Methods

Experimental Streambed Construction and Maintenance

The bench scale test model for the streambed channel was constructed at the National Oceanic and Atmospheric Administration (NOAA) field laboratory at Kasitsna Bay, Alaska. For maximum use of available space and to increase access to sampling sites, the channel bed (Fig. 1) consisted of three sets of adjacent, parallel "runs" connected in series by two short runs. Each long run was 0.42 m wide and 4.66 m long. A false bottom was installed in the channel bed to create an even slope with a 0.91-m drop over the total 29.3-m length of the empty channel bed.

Freshwater from a natural stream adjacent to the lab was introduced at the start of Run 1 at a flow rate of 30 L/min. Water left the streambed at the end of Run 6. The water exiting the channel was either diverted into a 360-L reservoir or discharged onto the beach adjacent to the lab. For the streambed experiment, the reservoir was used to collect the freshwater and major portion of an oil slick immediately after a spill event. Oil sorbent pads were placed at the discharge point on the beach to aid in the cleanup and collection of oil that was not captured in the 360-L collection reservoir.

Before experiments were undertaken, careful observations were made of the natural flow path of water through the empty channel bed. This flow regime served to direct the placement of fill materials in the bed to simulate more closely natural stream conditions. Typical characteristics of natural streams and creeks in the southcentral Alaska area were also surveyed and duplicated in the test channel as closely as possible. Fill for the empty channel was collected from natural stream and beach environments adjacent to the lab. This



scale I ft = 0.305 m.)

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fill consisted primarily of mud, sand, gravel, rocks, sod, dirt, sticks, logs, and tree branches. These materials were placed in the channel in configurations to augment not only predisposed flow patterns in the empty channel, but also approximate characteristics observed in the natural streambed environments. Following the addition of fill to the channel and before any experiment was started, the channel was maintained with running water for 24 to 72 h. This "acclimation" period was adopted to allow for natural flow mediated redistribution and sorting of sedimentary materials throughout the channel. The 24- to 72-h period proved sufficient to yield reasonably stable sedimentary profiles in the channel. During experiments water temperatures in the channel ranged from 8 to 11°C depending on ambient sun and weather conditions.

Prominent features of the bench scale test model are shown schematically in Fig. 1. It should be emphasized that empty portions of channel bed shown in the figure indicate only submerged substrate surfaces rather than an absence of sedimentary material. The entire channel was filled with sedimentary material. The general appearance and composition of the completed channel bed can be better observed in the photographs of selected runs in Figs. 2 and 3. Because three experiments were performed with this test configuration (that is, one experiment with oil only and two with oil plus a chemical dispersant agent), portions of the channel fill had to be replaced between experiments. Particular care was taken to insure that channel configurations were the same in the three experiments. A much more detailed schematic drawing of Fig. 1 as well as photographs of previous channel configurations were used for direction in each subsequent channel reconstruction effort. Furthermore, only those portions of a previously used channel bed that retained oil were replaced with new fill material.



FIG. 2-Experimental channel: (left) Runs 1 and 2 and (right) Runs 3 and 4.



FIG. 3—Experimental channel and sediment sampling procedure: (left) Runs 5 and 6 (sampling at Site 8, Run 6) and (right) sampling at Site 2, Run 1.

Eleven sites were selected for sediment sampling to monitor oil levels in the channel bed following a spill event. Site selections were made with the intention of providing information on oil loadings in a variety of sediment types (that is, varying particle size distributions) under a variety of water flow regimes. The sites are shown in Fig. 1. Samples were collected from Sites 1 through 9 at the following times relative to a spill event: time zero or background (0.5 to 1 h before the spill event), 0.5, 2, 4, 8, 24, 48, 72, 120, 168, and 190 to 220 h. Because of the multiple sampling events over time at each of these nine sites, careful efforts were made to sample randomly each site and leave representative site material for subsequent sampling events. Samples at Sites 10 and 11 were only collected at the final sampling time in each experiment. More frequent sampling at these latter two sites was not feasible because of the nature of their substrates (that is, large gravel and sand) that necessitated large volume collections to obtain representative samples.

Detailed descriptions follow for the sediment sampling sites and the general composition and sediment types in the channel runs in Fig. 1.

Run 1—Inflowing water to the test channel entered through an initial catch basin. The submerged portion of the upper half of Run 1 was composed mostly of gravel. Two major beach areas occurred approximately mid-run. The first of these was protected by an upstream sod embankment, and included a point bar comprised of sand and a protected backwater area on the downstream side. This point bar formed sampling Site 1. The second half of Run 1 was primarily an expanse of submerged sand overlying pebbles. The flow of water over this area resulted in a slow migration and sorting of sand grains in the down-

stream direction to expose periodically underlying pebble substrate. This submerged sandy area formed sampling Site 2.

Run 2—The entire submerged portion of Run 2 was composed of gravel, small rocks, and sand. Side bars occurred in the middle and lower half of the run. The first of these bars (comprised of gravel, intermittent sand, and some fine silt and clay) occurred on the upstream side of a sod embankment and formed sampling Site 9. Further downstream, the second side bar (also composed of gravel, sand, and some fine silt and clay) occurred on the upstream side of a rock/sod embankment and formed sampling Site 3.

Run 3—Water flowed through a complex arrangement of rocks, sod, and tree branches at the start of Run 3 before passing over a more open gravel bottom. Large rocks and clumps of sod combined to support moderate sized beaches in the middle part of the run. The lower half of the run contained the upper portion of a deeper pool created by the cinder block dam in Run 4. Correspondingly, the depth of the water column increased and the longitudinal flow rate of water decreased in the second half of Run 3. A layer of fine silt, clay, and detrital organic material covered a gravel substrate in the bottom of this pool. A large sod embankment with an accompanying side bar of sand and gravel occurred at the end of Run 3. This bar around the sod embankment formed sampling Site 4.

Run 4—The upper three quarters of this run was dominated by a relatively deep pool of water (12 to 15 cm in depth) forming upstream of a waterfall (10- to 12-cm drop) constructed by a cinder block dam. An embankment with an accompanying sand and gravel side bar occurred midway through the pool. Sampling Site 5 occurred in the pool downstream of the sand/gravel embankment. Sediment in the bottom of the pool at Site 5 consisted of a nonuniform thin layer of fine organic detritus, silt, and clay overlying a sandy substrate. Sediment immediately below the waterfall formed sampling Site 10 and was comprised almost exclusively of large gravel as a result of the force of the falling water. A backwater area comprised of fine silt and mud overlying sand and gravel was formed in an eddy behind a large rock at the end of Run 4. This area served as sampling Site 6. The subsequent short runway between Runs 4 and 5 was composed of sand and large gravel and formed sampling Site 11.

Run 5—The majority of the submerged streambed in Run 5 was comprised of gravel. A small longitudinal bar consisting of sand and gravel occurred in the middle of the channel approximately one third of the way down the run. This mid-channel bar formed sampling Site 7. A subsequent configuration of rocks, sod, logs, and sticks combined to produce an area of restricted water flow with an accompanying upstream clockwise eddy pattern.

Run 6—The upper half of Run 6 consisted of a narrow, sinuous channel with a greater elevation drop than that occurring in other parts of the test channel. Steep gravel and sod embankments with accompanying point bars of sand formed the sides of this channel. Water flow through this portion of the channel bed was relatively faster and more turbulent than that in other areas. The sandy point bar at the midpoint through this sinuous channel served as sampling Site 8. The second half of Run 6 consisted of a submerged gravel substrate with accompanying sod and rock embankments.

Spill Scenario

Three experiments were performed in the test channel with the following spill solutions (dates are shown in parentheses): (1) fresh Prudhoe Bay crude oil with no dispersant addition (6–14 June 1985), (2) fresh Prudhoe Bay crude oil and OFC D-609 (30 June-8 July 1985), and (3) fresh Prudhoe Bay crude oil and Corexit 9550 (15–24 July 1985). The choice of dispersant agents was based on results from previous laboratory studies that indicated that OFC D-609 and Corexit 9550 were effective chemical dispersant agents in freshwater

systems [1]. A total of 5.0 L of crude oil was used for each experiment. In experiments with OFC D-609 or Corexit 9550, 500 mL of the dispersant agent were mechanically mixed into the oil (that is, a D:O ratio of 1:10 v:v) immediately before the spill. The spill solution was then gently poured over a 3-min period onto the surface of the water at the head of Run 1. When the leading edge of the oil slick reached the end of Run 6 (approximately 5 min after the spill), the channel effluent was diverted into the 360-L collection reservoir. After the reservoir was filled, the effluent water was diverted onto the oil sorbent pads on the adjacent beach.

Sediment Sampling-Hydrocarbon Methodology and Extraction Procedures

As described previously, sediment samples were collected over time from the sites shown in Fig. 1. The samples were collected with stainless steel or Teflon® coated spatulas or scoops, placed in glass containers with aluminum foil or Teflon cap liners, and kept at 2 to 4°C until the times of analyses. Figure 3 illustrates the sediment sampling procedure (as well as photographic detail of certain locations in the channel bed). Although sediment samples were collected up to 190 to 220 h following a spill event, hydrocarbon analyses were performed on samples from Sites 1 through 9 only up to the point when the analytical measurements of hydrocarbon concentrations returned to time zero background levels. Triplicate samples for hydrocarbon analysis were periodically collected from randomly selected sites during each experiment to allow for estimates of sample variability through the complete collection and analytical procedures (see below).

For hydrocarbon analyses, a known wet weight of sediment (usually 30 to 60 g) was transferred to a 200-mL glass container and mixed with methanol. The methanol was then decanted into a 1000-mL separatory funnel. The methanol dried sediment was then sonicated three times with (1) 100 mL of methylene chloride:methanol (65:35 v:v), (2) 100 mL of methylene chloride, and (3) 100 mL of methylene chloride. Each sonication lasted 3 min and was performed with a Heat Systems-Ultrasonics, Inc. sonicator (Model W-375; pulsed mode; output control setting 7; 50% duty cycle). The solvent extracted sediment was dried in an oven (100°C) to determine the dry weight of sample extracted. The combined methanol-methylene chloride extracts were backextracted with a 3% sodium chloride (NaCl) solution (precleaned with methylene chloride) to remove the methanol, and the NaClmethanol solution was then backextracted two more times with 25-mL volumes of methylene chloride. The combined methylene chloride fractions were dried with anhydrous sodium sulfate (Na_2SO_4) and reduced to appropriate volumes for analysis. Gas chromatography with flame ionization detection (FID-GC) was used to quantify hydrocarbons in the final sample extracts. A Hewlett-Packard Model 5840A gas chromatograph (splitless injection mode, 1.0-µL automatic injection volume) containing a fused silica capillary column (DB5 stationary phase, J & W Scientific, Inc.) was used for all GC analyses. Hydrocarbon quantities were determined by comparing sample chromatograms with those from a combined *n*-alkane standard (n-C₁₂ through n-C₃₂, plus pristane and phytane).

Representative hydrocarbon chromatograms of not only the fresh Prudhoe Bay crude oil but also prespill and postspill sediment samples are shown in Fig. 4. Because prespill sediments (Fig. 4 [middle]) contained naturally occurring (biogenic) hydrocarbons such as plant wax *n*-alkanes with odd carbon numbers (for example, *n*-C₂₅, *n*-C₂₇, *n*-C₂₉, and *n*-C₃₁) and mono- and poly-olefinic compounds in the range of C₁₉ to C₂₁ [4], the sum of *n*-alkanes with an even number of carbon atoms between *n*-C₈ and *n*-C₃₂ was selected as the indicator for the occurrence of oil in samples. In replicate sediment samples from the channel bed, mean coefficients of variation (CVs) for "oil" (that is, the sum of even *n*-alkane) concentrations were 13% when concentrations were >1.00-µg/g dry weight. CVs increased to approximately 64% when "oil" concentrations were less than 1.00-µg/g dry weight.



FIG. 4—FID-gas chromatograms of (top) fresh Prudhoe Bay crude oil, (middle) prespill sediment hydrocarbons (Site 4, Experiment 2), and (bottom) sediment hydrocarbons after a spill event (Site 4, Experiment 2, 2 h postspill). Positions of selected n-alkanes are noted in chromatograms. The spill mixture for Experiment 2 was fresh Prudhoe Bay crude oil plus OFC D-609.

Method blanks without sediment were periodically processed through the entire analysis procedure to correct for any background contamination. Methanol and methylene chloride used for extractions were distilled-in-glass, pesticide quality (Burdick and Jackson). Na₂SO₄ was placed in an oven at 500°C for at least 12 h before use.

Water Sampling-Hydrocarbon Methodology and Extraction Procedures

Known volumes of effluent water (approximately 1600 mL) were collected from the channel bed. These samples were partitioned against three sequential 100-mL volumes of methylene chloride. The combined methylene chloride fractions were concentrated and

analyzed by FID-GC in the manner described for sediment samples. Triplicate water samples were periodically collected to estimate sample variability for hydrocarbon concentrations. Mean coefficients of variation for these estimates were always <40%.

Oil Samples—Hydrocarbon Methodology

Oil samples for FID-GC analyses were prepared by adding 10 to 25 mg of oil to a tared GC vial and diluting to an appropriate volume with methylene chloride. Samples prepared in this manner included fresh Prudhoe Bay crude oil, the dispersants OFC D-609 and Corexit 9550, prespill mixtures of the oil and dispersants, and surface oil from the collection reservoir downstream of the channel bed discharge pipe. FID-GC analyses were performed as described above.

Rheological Properties of Oil—Methodology

Oil/water and oil/air interfacial surface tension values for oil samples were determined with a Surface Tensiomat, Model 21 (Fisher Scientific Co.). Kinematic viscosity measurements of oil samples were performed at 38°C (100°F) with a Fisher Scientific Viscometer, No. A97.

Sediment Characterization—Particle Size Analysis

Particle size analyses of sediment samples were performed with a combination of sieving and pipet methods [5]. The procedure produced fractional weight estimates for the following particle size ranges: (1) >2000 μ m (μ m = 10⁻⁶ m), (2) 500 to 2000 μ m, (3) 250 to 500 μ m, (4) 125 to 250 μ m, (5) 53 to 125 μ m, (6) 5 to 53 μ m, (7) 2 to 5 μ m, and (8) <2 μ m. Values in these ranges were combined to yield information for the following categories: gravel (>2000 μ m), sand (53 to 2000 μ m), silt (2 to 53 μ m), and clay (<2 μ m).

Results

Particle Size Analysis of Sediments from Primary Sampling Sites

Results of analyses of weight percent distribution for particle size classes in sediments from Sites 1 through 9 are summarized in Table 1. In general, the composition at the nine sites was primarily sand and gravel. At Sites 1 through 5 and 7 through 9 the combined clay and silt fractions were less than 4% of the total sediment dry weight. However, in the backwater eddy area of Site 6, the clay/silt fraction comprised approximately 15% of the total dry weight. In fact, the surface sediment at this site (that is, that collected for hydro-carbon analyses) consisted almost exclusively of clay/silt sized particles. Although size analyses were not performed on samples from Sites 10 and 11, sediments at these sites were comprised almost exclusively of large sand and gravel.

Rheological Properties of Experimental Oil Samples

Surface tension and kinematic viscosity measurements for oil samples from the three channel bed experiments are summarized in Table 2. With no dispersant addition, the oil/ water surface tension measurement for oil from the collection reservoir downstream of Run 6 was essentially identical to that of the initial crude oil. However, in the experiments receiving prespill additions of either OFC D-609 or Corexit 9550, the oil/water surface tension values were dramatically reduced in both the initial spill mixtures and the surface

	Particl	e Size Range	(% of Total Dry	Weight)	
Site	Clay	Silt	Sand	Gravel	
 1	2.17	1.76	57.96	40.23	
2	1.02	0.97	50.24	44.52	
3	1.01	1.64	42.18	57.56	
4	0.05	0.39	43.33	52.61	
5	0.16	0.78	72.00	27.80	
6	5.32	9.94	49.71	48.89	
7	0.10	0.55	63.79	36.09	
8	0.11	1.07	45.89	59.05	
9	1.12	1.55	38.44	61.69	

TABLE 1-Particle size analyses for sediment samples.

oil from the collection reservoir (Table 2*a*). In contrast, oil/air surface tension values were not affected by the dispersant additions (Table 2*a*). As for kinematic viscosity, oil samples from the downstream collection reservoir in the experiments involving prespill additions of OFC D-609 or Corexit 9550 exhibited slightly higher values than those measured in the initial crude oil (Table 2*b*).

Direct Observations of Oil During Experimental Studies

Very close visual inspections of oil behavior in the test channel were made during each of the three experiments as a result of the easy physical access to all locations along the

(a) surface tension measurements					
	Surface Tension, dynes/cm				
Oil Sample Type/Experiment ID	Oil/Water	Oil/Air			
Prudhoe Bay crude oil	26.1	31.9			
Experiment 1 (no dispersant addition)					
collection reservoir surface oil	24.6	31.8			
Experiment 2 (crude oil $+$ OFC D-609)					
initial oil/OFC D-609 mixture (10:1 v:v)	0.4	30.0			
collection reservoir surface oil	0.4	32.2			
Experiment 3 (crude oil + Corexit 9550)					
initial oil/Corexit 9550 mixture (10:1 v:v)	1.2	33.5			
collection reservoir surface oil	0.3	30.7			
(b) KINEMATIC VISCOSITY	MEASUREMENTS				
Oil Sample Type/Experiment ID	Viscosity, centistokes				
Prudhoe Bay crude oil	14-19				
Experiment 2 (crude oil + OFC D-609) collection reservoir surface oil	31.7				
Experiment 3 (crude oil + Corexit 9550) collection reservoir surface oil	26.5				

TABLE 2-Rheological properties of oil samples.

channel bed (for example, see Figs. 1, 2, and 3). This allowed for valuable visual information and insight to be obtained pertaining to not only the general behavior and fate of oil in the channel bed, but also surface based estimates of oil droplet sizes and distributions in the water column. In the experiment with no dispersant addition, oil remained primarily on the surface of the water as a continuous slick that passed through the channel. Oiling of sediment substrates occurred when the slick either came into direct contact with sediment at the air/water interface along a channel bank or was stranded in quiescent backwater areas (for example, Site 6). The oil was noticeably dispersed into discrete droplets only in areas of high turbulence (for example, the splash zone under the waterfall in Run 4). The tendency of the oil phase to remain separate from the water phase in the absence of dispersants was also evident from water samples obtained from the collection reservoir downstream of Run 6. The reservoir contained the bulk of the spilled oil as a surface slick, and yet water samples drawn from a bottom sampling port 2 to 2.5 h after the spill event were completely clear with no visible evidence of oil droplets (see discussion below of gas chromatographic hydrocarbon measurements in water samples for more information).

In the experiments with prespill additions of OFC D-609 or Corexit 9550, the oil still moved through the channel as surface slicks. However, in contrast to the continuous, uniform, shiny surface texture of the slick in the experiment with no dispersant addition, the presence of both dispersants resulted in a discontinuous, mottled appearance in slick texture. Close visual inspection of the chemically dispersed oil at the water's surface revealed that much of the oil existed as small, discrete droplets with estimated diameters of <1 mm. These droplets were observed to penetrate readily into sand and gravel matrices at sites that had sufficient exposure to the droplets and appropriate water velocities and flow directions to promote penetration into the sediments. The increased dispersion of oil into the aqueous phase with the dispersant agents was also apparent from water samples drawn from the collection reservoir at the end of Run 6. Close visual inspection of these samples in their clear glass containers immediately after collection revealed that the water was completely opaque with a yellow-brown color, although no oil droplets were visibly present at this point in time. However, oil slicks did recoalesce to the surface of these samples after they had remained stationary for several hours.

The close visual inspections of oil in the channel bed during experiments demonstrated that small, discrete oil droplets were common to both experiments with dispersant additions. However, these inspections revealed that the oil droplets tended to remain more concentrated at the air/water interface in the experiment with OFC D-609. When Corexit 9550 was premixed with the oil, the oil droplets had a greater tendency to be advected down into the water column. This implied that Corexit 9550 was more effective for dispersing oil into the freshwater aqueous phase in these experiments (see following section for accompanying hydrocarbon analyses).

Hydrocarbon Measurements—Water Samples

FID-GC analyses revealed that more water soluble aromatic hydrocarbons were present in water samples from all three experiments. These compounds largely disappeared from subsequent water samples after the main oil slick exited from the channel bed as a result of both declining levels of residual oil in the channel bed and continued evaporation and dissolution losses of aromatics from any residual oil.

In contrast to the aromatics, the presence of less water soluble aliphatic components of oil in water samples was indicative of small oil droplets or micelles of bulk oil in the samples. These aliphatic compounds were much more abundant in water samples from the experiments involving prespill additions of the chemical dispersant agents to the oil. For



FIG. 5—Total even n-alkane concentrations over time in effluent water from the three channel bed experiments.

example, concentrations of even *n*-alkanes in effluent water samples are presented in Fig. 5. A logarithmic time scale is used to illustrate better the trends at the early sampling times. In all three experiments the concentrations of even *n*-alkanes were highest in samples shortly after the spill event (that is, 0.25 h postspill). However, concentration maxima at 0.25 h postspill for the three experiments followed a trend of Corexit 9550 > OFC D-609 > "no dispersant." Therefore, GC analyses indicated that both dispersant agents increased dispersion of oil into the aqueous phase, with Corexit 9550 being the more effective of the two agents. Results of these GC analyses corroborate the previously discussed visual observation that the dispersant agents increased aqueous phase levels of oil.

Hydrocarbon Measurements—Sediment Samples

Concentrations of even *n*-alkanes in sediments over time are presented in Fig. 6. Maximum concentrations of the summed even *n*-alkanes always occurred at 0.5 to 2.0 h postspill. This approximates the time of maximum even *n*-alkane concentrations in water samples (Fig. 5), reflecting a temporal coupling between the passage of oil through the channel bed and a coincident "oiling" of exposed sediments. Concentrations of even *n*-alkanes in sediment samples from Sites 1 through 9 at 2.0 h postspill are shown in Fig. 7 to illustrate relative oil levels at a common time at these sites. For sites that were only sampled at the final time point in each experiment (that is, Sites 10 and 11), concentrations of summed even *n*-alkanes are presented in Table 3.

Trends are apparent from the FID-GC data of Figs. 6 and 7 and Table 3. Premixing of oil with either OFC D-609 or Corexit 9550 resulted in higher oil loadings in sediments at nine of eleven sampling sites (that is, Sites 1 through 5, 7 through 9, and 11). In the experiment with no dispersant addition, higher oil concentrations were observed only at Sites 6 and 10. Furthermore, Corexit 9550 produced the highest concentrations at eight of nine sites where dispersant additions resulted in higher oil loadings (Site 4 being the only exception).

Factors contributing to these trends in the sediment oil concentrations appear to be related to properties of both the spilled oil and the sediment matrices and water flow characteristics at specific sampling sites. Details of water flow characteristics and particle size distributions at sites have been presented previously. It has also been noted that premixing



FIG. 6—Total even n-alkane concentrations over time in sediments from the three channel bed experiments.

of oil with OFC D-609 or Corexit 9550 decreased oil/water surface tension values (Table 2a). The latter phenomenon would help explain the increased dispersion of oil into aqueous phases that was noted in not only visual observations of water samples but also the FID-GC analyses of these water samples. As for concentrations in sediment samples, oil from prespill mixtures with Corexit 9550 or OFC D-609 appeared to be less likely to adhere (or "stick") to sediments that had relatively nonporous matrices. For example, lower concentrations of oil were observed in sediments from Site 6 in the experiments with OFC D-609 and especially Corexit 9550 (Fig. 6f). These lower concentrations in sediment in the presence of dispersants presumably reflect not only a minimal penetration of oil into the relatively nonporous mud substrate at this site, but also a decreased tendency of the chemically dispersed oil to "stick" to the exposed mud surface.

Although premixing of oil with the chemical dispersant agents lowered the tendency of oil to adhere to surface sediments, the results at other sediment sampling sites in Fig. 6 indicate that small oil droplets produced by the dispersant agents had a greater ability to



penetrate into more porous sediment matrices (for example, with particle sizes generally larger than mud or silt). For example, sites comprised primarily of sand and gravel and with sufficiently turbulent water flow characteristics generally exhibited higher levels of oil in sediments in the presence of both OFC D-609 and Corexit 9550. These higher oil levels would also indicate that once the oil had penetrated into the sediment matrix, it appeared to become relatively trapped if there was not sufficient water flow through the matrix to "flush out" the oil. This mechanism can be used to explain the elevated sediment oil concentrations at Sites 1 through 5, 7 through 9, and 11 in the experiments with prespill additions of the dispersant agents. The high water flow through the sediment matrix at Site 10 as a result of the presence of the small waterfall was apparently sufficient to "flush out" the chemically dispersed oil from this very porous matrix (for example, see results for dispersed versus nondispersed oil samples in Table 3).

In conjunction with the preceding mechanism involving penetration of dispersed oil droplets into relatively porous sediment matrices, the in situ water flow characteristics at specific sites can also be used to explain certain relative differences in the measured oil concentrations in Fig. 7. For example, concentrations of chemically dispersed oil (that is,



both OFC D-609 and Corexit 9550) in sediments with similar particle size distributions (for example, primarily sand) exhibited the following trend: Site 8 > Sites 1, 3, and 7 > Site 2 (see Fig. 7). Sites 1, 3, and 7 included sandy bar areas that directly intersected the air/water interface and were, therefore, directly exposed to the surface oil slick and dispersed oil droplets on the water's surface. In contrast, the sand substrate at Site 2 was submerged and did not receive comparable exposure to oil on the water's surface, thus resulting in lower sediment oil concentrations. Site 8 consisted of a sandy bar area (like Sites 1, 3, and 7), but occurred in a narrow, sinuous portion of the channel bed with a more turbulent flow regime. The combination of water turbulence and a sand/gravel matrix at the air/water interface resulted in an "enhanced" penetration of small dispersed oil droplets into the matrix at Site 8, which produced the highest relative concentrations of oil in sampled sediments (Fig. 7).



FIG. 6-Continued.



FIG. 7—Total even n-alkane concentrations in sediments at 2 h postspill in the three channel bed experiments.

Comparison Between Oil Behavior with OFC D-609 and Corexit 9550

Several points indicate that Corexit 9550 was the more effective oil dispersant agent in these freshwater channel bed experiments. It has already been noted that the highest concentrations of oil in water were observed with Corexit 9550 (Fig. 5). Of the nine sediment sampling sites that had higher oil concentrations with prespill additions of dispersants (that is, Sites 1 through 5, 7 through 9, and 11), eight had the highest concentrations with Corexit 9550 (Site 4 exhibiting the only variant behavior). Exceptions to these general trends with dispersants (that is, at sediment Sites 4, 6, and 10) can be explained with a mechanism involving a combination of the behavior of the two chemically dispersed oil mixtures and the water flow characteristics at the specific sites. The low sediment oil concentrations with Corexit 9550 at Sites 6 and 10 (Fig. 6f and Table 3, respectively) would appear to reflect the fact that more efficiently dispersed oil (that is, oil premixed with Corexit 9550) not only had a lower tendency to "stick" to surfaces (for example, Site 6), but also was more easily "flushed out" of porous sediment matrices having sufficient flow-through water characteristics. As for Site 4 (Fig. 6d), the water column at this site was deeper than that at other sites with comparable sand/gravel particle size distributions. Note that the dispersed oil droplets with OFC D-609 tended to remain at the air/water interface, while those with Corexit 9550 had a greater tendency to be advected down into the water column. Therefore, the sandy bar sediments at the air/water interface at Site 4 would have been exposed to more dilute concentrations of oil at the water's surface (that is, both the oil slick and

	Even n-	Alkanes, µg/g Dry	Weight
		Experiment ID	
Site	No Dispersant	OFC D-609	Corexit 9550
10	7.84	5.25	0.41
11	0.21	1.31	2.02

TABLE 3—Hydrocarbon concentrations in sediment samples from Sites 10 and 11.^a

^a Samples collected 190 to 220 h after a spill event.

droplets) with Corexit 9550, thus explaining the higher sediment oil loads at this site with OFC D-609.

Discussion

Both OFC D-609 and Corexit 9550 induced increased dispersion of small droplets of Prudhoe Bay crude oil into the water in the experimental channel bed. This elevation of chemically dispersed oil levels in water samples is similar to that reported by other investigators [6]. Of the two dispersant agents, Corexit 9550 was more effective in the low salinity waters of the channel. Similar results have been reported in controlled laboratory tank tests where Corexit 9550 was more effective than OFC D-609 at a water salinity of 0 parts per thousand (ppt) and temperatures of 1 and $10^{\circ}C$ [1]. However, the importance of salinity in influencing dispersant effectiveness should not be overlooked. OFC D-609 has been found to be more effective than Corexit 9550 at 18-ppt salinity, while the two dispersant agents produced comparable dispersion results at 33-ppt salinity [1].

Based on the results from the channel bed experiments in this study, it would appear that the behavior and fate of oil spilled in natural freshwater streams will depend on interactions between factors related to both the oil and a specific streambed environment. Such factors include the following.

1. Rheological properties of oil—Lower oil/water surface tension values will accompany a greater tendency for oil to form small dispersed droplets that can be mixed into the water column if sufficient turbulence is present. Furthermore, lower oil/water surface tension values appear to be correlated with reduced tendencies for oil to adhere (or "stick") to wetted sediment surfaces [7,8]. Such factors will affect not only the retention of oil by exposed sediment surfaces, but also the rates at which aquatic microbial systems can degrade the oil [9, 10].

2. The degree of exposure of sediment surfaces to oil—Sediment surfaces at the air/water interface will have a higher probability of being contacted by oil slicks and droplets concentrated at the water's surface. However, submerged sediments can be impacted if oil is injected into the water column through processes such as chemical dispersion or high levels of turbulence.

3. Sediment substrate characteristics—The size distribution of particles comprising a sediment bed can influence oil retention by determining the degree to which oil penetrates into the bed matrix. Data from the experiments in this study indicate that chemical dispersion of the oil enhanced its ability to penetrate into sand/gravel matrices. Similar results have been reported by other investigators for sandy beach areas [8, 11]. In contrast, oil retention by sediments was reduced with dispersants in relatively nonporous matrices (for example, mud) as a result of the enhanced aqueous "mobility" and reduced "stickiness" of the dispersed oil. Similar trends can be expected for other nonporous matrices such as solid rock surfaces.

4. Water flow characteristics—Factors such as the flow rate and turbulence level of water at locations in a streambed can affect oil retention by sediments. These factors will influence not only the distribution of oil in the water (for example, surface slicks versus dispersion of droplets into the water column), but also the tendency of oil to be physically washed off of sediment surfaces or "flushed out" of porous sediment matrices.

Inclusion of chemical dispersant agents into oil resulted in changes in the behavior of the oil in the experimental system in this study. An understanding and appreciation of the factors listed above appear to be helpful for explaining the results of the oil distributions in the bench scale test model used here. Although it is recognized that the confined channel bed system in this study is not entirely representative of natural streambeds, efforts were made to include substrate types, topographies, and water flow regimes that were representative of many characteristics in natural systems. Therefore, the results that were generated should be viewed as a first-step effort toward estimating effects of chemical dispersant agents on the behavior and fate of spilled oil in natural systems. The combination of shallow water depths, relatively porous substrate matrices, and moderate water turbulence levels contributed to higher oil loadings with dispersants in sediments at numerous sites in the experimental channel. Further studies with an experimental streambed more closely approximating all aspects of a real world stream are warranted from the results of this study.

Ideally, oil spill countermeasures should minimize exposure of sensitive biological communities to spilled oil. For areas characterized by either relatively low sediment porosities (for example, Site 6 in this study) or high water turbulence levels (Site 10), dispersant application would appear to be useful because oil concentrations in sediment areas with these characteristics in this study were actually reduced with prespill additions of dispersants to the oil. However, application of dispersants in areas with sand or gravel matrices and only moderate turbulence levels must be approached with caution because such areas in this study were typically characterized by higher oil loadings with dispersants. The necessity either to dilute dispersed oil rapidly or promote its removal by advective transport processes from such areas is important for minimizing potential biological impacts. Studies have shown that chemically dispersed oil can have a greater biological impact in both relatively closed systems (that is, minimal dilution) as well as situations where oil and dispersants are directly applied to biological communities [12-15]. Therefore, the chemical dispersion of oil must be accompanied by either dilution or physical removal by advective processes to minimize biological impacts. This "dilution" phenomenon can also explain the observation that effects of oil on aquatic communities have been found to be more pronounced with dispersants in the short term as a result of elevated water column concentrations of dispersed oil, whereas long-term effects have been found to be greater in the absence of dispersants as a result of the continued presence of residual, nondispersed oil [16].

Conclusion

To summarize, it appears that the positive use of chemical dispersant agents should be done in conjunction with a knowledge of not only the characteristics of a spilled oil and a specific streambed environment, but also the location(s) of sensitive biological communities. If specific conditions are not favorable for a net positive result with dispersant agents, it may be prudent to consider alternatives such as either no cleanup action or approaches including application of film forming chemical agents, surface collecting agents, or oil gelling agents [17]. It is also conceivable that alternating use of chemical dispersant agents with one or more of the other cleanup strategies might produce the most positive results for a selective transport of oil not only past sensitive biological communities but also to streambed regions that would be more amenable to the collection and physical removal of oil.

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Dispersant Use Guidelines for Freshwater and Other Inland Environments

REFERENCE: Flaherty, L. Michael, Katz, W. B., and Kaufmann, S., "Dispersant Use Guidelines for Freshwater and Other Inland Environments," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 25–30.*

ABSTRACT: Work is in progress by ASTM Subcommittee F20.13 on Treatment on a series of guidelines covering the use of dispersants in nonsaline environments. These environments include freshwater ponds, lakes, and streams, as well as land. The guidelines are to be patterned after those produced by an earlier task group of the same committee covering saline environments. This paper describes what has been accomplished thus far. Participation by those interested, whether an ASTM member or not, is welcomed.

KEY WORDS: dispersants, dispersant use guidelines, management of oil spills, oil spills, oil and hazardous material spill response, freshwater spill research, use of dispersants on inland waters and land

ASTM Committee F-20 on Oil and Hazardous Material Spill Response has produced a series of guidelines for the use of dispersants in saline waters. The process of producing guidelines and their intended use was described at the 1987 Oil Spill Conference [1]. The Guides for Ecological Considerations for the Use of Chemical Dispersants in Oil Spill Response: Marine Mammals (F929), Rocky Shores (F930), Seagrasses (F931), Coral Reefs (F932), Mangroves (F971), Nearshore Subtidal (F972), Tidal Flats (F973), Sandy Beaches (F990), Gravel or Cobble Beaches (F999), Salt Marshes (F1008), Offshore (F1009), Bird Habitats (F1010), and the Arctic (F1012) cover a series of ocean and shore environments where dispersants are one tool to be considered in the management of oil spills.

Data collected by the U.S. Coast Guard [2] between the years 1977 and 1984 indicate that the number of "inland" spills varied between approximately 20 and 40% of the total recorded. (The other categories are Atlantic, Pacific, Gulf, and Great Lakes.) While most such spills are small in size, some are very large, and the cumulative impact on the environment is substantial. Figures 1 through 6 show typical inland spill situations where dispersant use should be considered along with other remedial actions.

Table 1 shows the breakdown of the "inland" data for the years 1977 through 1984. The severity of the problem is evident, and these data do not include spills on land.

These reports issued by the Coast Guard contain much data of interest. Spills of oil, and of hazardous and other materials, are tabulated by kind of material spilled, month of year, states, and spill size. These overall categories are not broken down within each general

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FIG. 1—Spill into a ditch—no water present.



FIG. 2-Sheen along the shore of a small pond.



FIG. 3-Contained oil in marshy area of inland lake.



FIG. 4—Leak on pipeline right-of-way crossed by slow creek.



FIG. 5—Nonfunctioning straw dam on rapidly moving creek.



FIG. 6—Dock in industrial area along major inland river.

Year	Number of Spills	Total Gallons ^a	River Channels, gal	Beaches, Nonnavigable Water, gal	Ports and Harbors, gal	Open Internal Waters, gal
1977	2408	3 313 902	1 154 919	1 874 682	230 963	53 338
1978	2661	3 388 855	1 238 886	2 017 489	118 123	14 357
1979	1972	36 685 825	1 399 564	1 816 303	427 612	25 046
1980	3050	6 286 278	3 009 408	2 166 202	558 010	552 658
1981	3435	16 291 282	14 083 902	1 582 991	79 945	554 414
1982	3202	6 057 484	3 584 582	2 960 942	95 692	150 329
1983	3639	5 969 921	2 167 400	2 291 108	278 137	1 233 276
1984	2300	3 692 725	2 637 095		932 854	122 776

TABLE 1—"Inland" oil spills.

^a 1 gal = 3.7854 L.

^b Category eliminated in 1984 report.

area, so such detail for inland spills does not appear in the reports. The raw data may be available from the Coast Guard if anyone is interested.

Table 2 shows data relating to the source and cause of leaks selected from the data in the reports. What is amazing about these figures is their year-to-year consistency.

Environment Canada has issued an undated bibliography [3] on freshwater oil spills. It is unedited, has limited distribution, and is intended to transfer results to those working in related research. The 232-page report has few references to the use of dispersants in freshwater environments.

The Philadelphia Academy of Natural Sciences issued a draft report to the American Petroleum Institute in 1984 which covers petroleum in the freshwater environment.⁴ Of some 275 pages in the report, only 3 discuss dispersants. This report has not been published and is not generally available to readers of this paper.

Esso Resources Canada, Ltd. has an ongoing freshwater spill research program. A field trial under this program resulted in the first reported study on the effects of a dispersant-treated oil spill on a natural freshwater environment. The report was issued in December 1986 [4].

It seems apparent that oil spills into freshwater environments occur frequently and that the use of dispersants as a tool for managing such spills has had little attention.

The guidelines for saline environments (ASTM Guides) were written with the goal of minimizing environmental impacts of oil spills (ignoring aesthetic and socioeconomic factors, which are admittedly important). The use of dispersants is given equal consideration with other spill countermeasure methods and is not considered as a "last resort" after all other methods have failed.

It was recognized by members of the dispersant use task group of ASTM F-20.13 that there were many spill situations in nonsaline environments in which the use of dispersants should be considered. For the last year another task group under F-20.13 has been attempting to prepare a set of guidelines for dispersant use in freshwater and other related environments.

⁴ "Petroleum in the Freshwater Environment: A Literature Review," Draft Report 83-4DD, Division of Environmental Research, Academy of Natural Sciences of Philadelphia, 25 June 1984 (unpublished).

	1977	1978	1979	1980	1981	1982	1983	1984
		BY	SOURCE					
Vessels	31.4	34.6	33.0	34.7	32.5	26.7	25.3	26.0
Land vehicles	4.2	4.4	4.1	2.9	3.5	4.9	4.5	6.4
Nontransportation facilities	20.6	17.9	18.1	18.5	20.0	20.7	23.3	20.3
Marine facilities	5.9	5.7	5.6	6.6	6.5	7.2	5.9	3.0
Land facilities	1.5	1.9	1.8	1.4	1.6	1.6	1.3	0.8
Pipelines	4.3	3.7	5.4	6.1	6.1	7.7	6.3	0.6
- · F ·		BY	CAUSE					
Hull/tank rupture	7.6	8.5	7.6	8.3	7.3	7.2	6.1	8.3
Pipeline leak	4.6	2.4	1.1	1.6	1.0	0.8	3.1	3.6
Tank overflow	8.9	10.0	9.5	10.7	12.0	9.9	9.3	8.1
RR/hwv/air	2.2	2.4	2.1	1.6	1.5	2.2	2.2	6.4
Unknown	35.0	36.4	35.9	33.9	34.5	34.3	38.6	51.2

TABLE 2—Percent distribution of oil spills reported (partial data only).

Discussion over a long period of time developed the outline shown in Table 3 of those environments where the use of dispersants might be considered. It was apparent almost immediately that any experimental work actually done or being considered was confined to arctic and near-arctic areas. Use of dispersants on inland water or land, or in tropical areas, has had almost no consideration at all. The environments listed may be augmented in the future if discussion and thought indicate such to be desirable.

Dispersants for use in nonsaline environments may have a quite different composition than those for use in the ocean. And what is meant by dispersant effectiveness may require redefinition. Consider the following situation.

As a result of an accident involving a tank truck delivering home heating fuel oil during a severe rainstorm, fuel oil enters a creek flooded because of the rain. The high water in the creek eventually recedes, leaving a mile or two of vegetation on the creek bank contaminated with fuel oil. The vegetation is sprayed with a dispersant especially formulated NOT to form permanent dispersions upon dilution. An underflow dam is constructed across the creek below the spill area. The banks are washed down with water from the creek, using a small floating pump which is pulled along the creek as washdown proceeds. The fuel oil is washed off the bank into the creek, whereupon the dilution allows the dispersion to "break" and the oil to float on the surface of the water. It is caught at the underflow dam and recovered using skimmers and sorbents.

TABLE 3-Nonsaline environments for dispersant use guidelines.

I.	No surface water
	a. over permafrost
	b. over porous ground
	c. over nonporous ground
II.	Permanent surface water
	a. moving water
	1. rivers, creeks
	2. large lakes
	b. nonmoving water
	1. swamps (sloughs, muskegs)
	2. small lakes and ponds
III.	Nonpermanent surface waters

Such a cleanup actually occurred some years ago. The "dispersant" used obviously had different properties than those of dispersants formulated for use in the ocean.

A second situation in which dispersants might be used inland is after a large gasoline spill from a barge at a dock in a busy metropolitan area. Water velocity is reasonably rapid, and the barge is surrounded by a containment boom. Equipment is available and used to apply foam over the spill, reducing the possibility of fire and explosion, but complicating removal of the spilled gasoline from the scene, either by recovery or safe evaporation into the atmosphere.

In such a situation a "weak" dispersant might be used, applied by induction into a fire hose, to disperse the gasoline slowly into the river water. The flow of the river would provide dilution to the dispersed gasoline. If the dispersion was "weak" or "inefficient" as judged from the standpoint of an ocean spill, the gasoline would rise to the surface and evaporate well below the lower explosive limit, reducing the chance of fire or explosion. The bacteriological oxygen demand (BOD) load on the river would also be greatly reduced, as would the chance of contaminated water entering any intake using the river as a water supply source.

There are many other possible uses for dispersants "inland." Pipelines have spills on land, occasionally in areas where there is considerable population density. Spills occur in inhabited desert areas where flash floods create problems because sun-baked soil becomes almost impervious to water. There are also spills in non-inhabited areas ranging from the tropics to the arctic. Some of these spills are on land, some on water. Consideration of damage to subsurface water, surface flora and fauna, and the atmosphere requires evaluation of the same sort of trade-offs that must be considered in any spill situation. Dispersants for nonsaline use are a tool that must be considered along with other available methods for handling such spills.

ASTM Committee F-20.13 is attempting to review the kinds of spill situations and environments in which the use of dispersants should be considered. Participation by anyone interested is welcome, whether a member of ASTM or not.

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Dispersants in the Freshwater Environment

REFERENCE: Brown, H. M. and Goodman, R. H., "Dispersants in the Freshwater Environment," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018*, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 31–40.

ABSTRACT: During the past four years, a research program to investigate the effect of oil and dispersant chemicals on a freshwater ecosystem has been carried out. Laboratory experiments were used to select a suitable dispersant for a field trial and to develop monitoring techniques which would be capable of detecting chronic and sublethal effects in selected species of the freshwater ecosystem. The field trial demonstrated that a spill of light oil covering 5 to 10% of the surface of a small shallow freshwater lake had no long-term measurable effects and that the application of a dispersant ameliorated some short-term effects even in this low energy system.

KEY WORDS: freshwater ecosystem, dispersants, oil spills, field trial

Dispersant chemicals have been used as a mitigation tool in many accidental oil spills at sea and evaluated during various oil spill tests. The fate and biological effects of oil and oil spill chemicals have been studied in increasing detail for at least 15 years [1]. However, these studies have been concerned almost exclusively with saltwater environments, a not surprising result of the perception that most potentially large and environmentally devastating spills would occur from tanker traffic or an offshore well blowout. The cleanup difficulties in such an environment may be very onerous and this too has led to much research concerning oil and the ocean.

A less appreciated fact is that large quantities of crude oil and refined products are produced and transported over land and near freshwater systems by pipeline, rail, and truck [2]. The literature on the fate of petroleum in this environment is much less extensive than is the case of the ocean [3]. Although a spill from these sources is likely to be smaller and more easily controlled than an ocean spill, the environmental impact may be no less severe, given the high use accorded many freshwater systems for potable water, agriculture, industry, and wildlife. The use of freshwater systems for potable water particularly differentiates the pollution concerns from those in the ocean.

Approximately 15% of the world's freshwater resources are contained in Canada's many rivers and lakes. Concern over the environmental impact of oil spills on these, and the most appropriate way to respond to them, led to the formation in 1982 of a multidisciplinary group of industry, government, and university personnel. The goal of this group was to study the use of dispersants in freshwater environments, and a research program called the Freshwater Oil Spill Research Program (FOSRP) was established. Four objectives were identified: to determine which commercially available dispersants were suitable for low energy, freshwater systems; to determine the short- and long-term environmental effects of dispersants and oil in low energy freshwater systems; to demonstrate the potential

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use of a dispersant in a field situation; and to identify other concerns of water usage once oil spill chemicals had been used in a freshwater system. During 1983 and 1984, a series of laboratory studies was completed to establish the parameters for a full-scale field test. That test was conducted during the summer of 1985. This paper presents an overview of the Freshwater Oil Spill Research Program and the conclusions from that study which will assist in the development of dispersant use guidelines for freshwater systems.

Laboratory Studies

The FOSRP Committee recognized that the effects of a dispersed oil spill could not be adequately monitored unless some preliminary laboratory studies were conducted. Questions to be resolved included:

1. Could a limited number of species be chosen for observation whose response to oil and dispersants would be representative of the general well-being of the freshwater ecosystem?

2. Could a commercially available dispersant be found which was effective in dispersing oil but whose toxicity to the representative species was acceptable?

3. Would analytical procedures be available and sufficiently sensitive to monitor sublethal and long-term effects of oil/dispersant mixtures on the freshwater ecosystem?

Preliminary laboratory studies to investigate these questions were carried out from 1983 to 1985, the results of which are summarized below.

Dispersant Effectiveness

Nine commercial dispersants were evaluated by the Environmental Protection Service of Environment Canada for effectiveness on Norman Wells crude oil using the McKay-Nadeau-Steelman (MNS) apparatus. The mixing energies and temperatures were chosen to simulate a typical cold freshwater environment. Norman Wells oil was used because it is currently transported by pipeline through northern freshwater systems and was readily available. These tests identified commercial products which dispersed as much as 90% of the oil.

Toxicity Studies

The toxicity of several possible dispersants, both alone and with oil, was tested on a number of plant and animal species thought to be representative of the aquatic and shoreline communities of northern fresh waters. Microorganisms were tested to determine if oil biodegradation was affected by the addition of various dispersant chemicals.

For example, a study of the acute toxicity of six dispersants on trout (Salmo gairdneri), dafnia (Dafnia magna), and algae (Selenastrum capricornutum) found that dispersants with oil (at 1:10 v/v) always gave significantly lower LC_{s0} ppm values (that is, higher toxicity) than dispersants used alone. No dispersant was clearly less toxic than the others.

In a very detailed study of dispersant and oil toxicity to dafnia (funded separately by the Petroleum Association for the Conservation of the Canadian Environment [P.A.C.E.]), Bobra and MacKay [4] devised a bioassay in which there were no evaporative losses of chemically or physically dispersed oil from the water column. They found that chemically dispersed oil was more toxic than physically dispersed oil and that some dispersants (the nonsoluble ones) were more toxic alone than in typical oil/dispersant mixtures. Usually

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	Effectiveness ^a		Acut	te Toxicity	
			Species and Conditions	s	
Dispersants	 MacKay, Nadeau Steelman Test 5 and 10°C Norman Wells Crude Wave Energy as Shown 	Juvenile Trout ^b	Juvenile Trout ^e 1:10 Dispersant: Oil Ratio, 5°C	Algae ^c	Daphnia ^c 1:10 Dispersant: Oil Ratio, 10°C
Corexit 9550 (Exxon)	> 75% low energy		$96-h LC_{50} = 41 ppm;$	EG ₅₀ range 1-10 ppm	$48-h LC_{50} = 150$
Corexit 9527 (Exxon)	> 90% moderate energy	<50 ppm	$w/0 \ 2/5 \ ppm$ 96-h LC ₅₀ = 28 ppm	EG ₅₀ range	$\begin{array}{c} \text{ppm} \\ 96\text{-h LC}_{50} = 11 \text{ ppm} \\ 100 \text{ ppm} \end{array}$
Corexit 7664 (Exxon)	not effective	<pre></pre>	W/0.02 ppm 96-h LC ₅₀ = 41 ppm	EG ₅₀ range	$48-h LC_{50} = 25 ppm$ $96-h LC_{50} = 14 ppm$
Corexit 9600 (Exxon)	>60% low energy	with oil	w/o 9/2 ppm 96-h LC ₃₀ w/o 22 ppm	100-10 000 ppm	48-h LC ₅₀ = 25 ppm 96-h LC ₅₀ = 10 ppm
Corexit 8667 (Exxon)	> ou% mouerate energy ineffective at low energy	<1500 ppm w/o oil		EG ₅₀ range 100-500 ppm	
MP 900 (Lawton Specialty)	>60% moderate energy ineffective at low energy	<75 ppm		4	
W-1911 (Tretolite)	> 80% moderate energy > 80% moderate energy ineffective at low				
Dispersol SD (C.I.L.)	energy	= 100 ppm			
BP1100X (British Petroleum)		<100 ppm			
Value 100 (Value 100 Industries Alberta) Dish Drops (Amway)		with oil <200 ppm with oil <10 000 ppm w/o oil			

		TABLE 2—Sublethal e	ffects of dispersant i	and oil on freshwater sp	ecies.	
	Microbiology	Botan	×	Behaviora	l Toxicity	Sublethal Effects
			Species an	d Conditions		
Dispersants	 Lab Cultures Normal Wells Oil [7] 	Lichen; Moss; Sedge; Willow Dispersant: Oil Ratio 1:10 [6]	<i>Lemna minor</i> Normal Wells Crude [5]	Daphnia magna Dispersant: Oil Ratio 1:20 at 20 and 5°C 48-h LC50 A. Fresh Oil B. 20% Weathered C. 42% Weathered	Gammarus lacustrus 15 and 5°C [5]	Larval Rainbow Trout 10°C [5]
Corexit 9550	Noninhibitory to microbial oil degradation Need to add N, P to promote growth		Addition of dispersant ameliorated effects of oil	A. 2.0 ppm (20°C) 15 ppm (5°C) B. 2.8 ppm (20°C) 11.5 ppm (20°C) 4.0 ppm (20°C)		
Corexit 9527				C. 1.5 ppm (20°C) A. 1.5 ppm (20°C) 1.4 ppm (5°C) B. 2.3 ppm (5°C) 1.5 ppm (5°C) C. 5.2 ppm (5°C) 1.7 nnm (5°C)		
Corexit 7664	Noninhibitory to microbial oil degradation Possibly stimulatory Need to add N, P	Defoliation of willow	Addition of 7664 ameliorated effects of oil	A. 3.6 ppm (20°C) 6.4 ppm (5°C) B. 3.5 ppm (5°C) 10 ppm (20°C) C. 3.0 ppm (20°C) 14.3 ppm (20°C)	Animals avoided aged oil/ dispersant mixtures less than fresh ones	At 1:100 disp:oil ratio, fish continued to develop edema even after being placed in clean water for ten days. Fish kill was 22% mortality after clearance

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600 10 10 10 10 10 10 10 10 10 10 10 10 1	Possibly stimulatory to oil degradation process. Need to add N, P Slightly inhibitory to degradation process Noninhibitory to microbial oil degradation Need to add N, P Noninhibitory to microbial oil degradation May be slightly stimulatory to oil degradation Very toxic to bacteria	New growth noted on sedge Defoliation of willow Moss appeared dead	Addition of dispersant ameliorated effects of oil effects of oil cracerbated oil effects. Use questionable.	A. 1.1 ppm (20°C) B. 2.2 ppm (5°C) 14 ppm (5°C) C. 3.6 ppm (5°C) 16.4 ppm (5°C) A. 1.8 ppm (20°C) B. 2.6 ppm (5°C) 6.0 ppm (5°C) 7.0 ppm (5°C) 7.0 ppm (5°C)	No differences noted between the two dispersants or two temperatures	9600 has 2.5 times less edemous fish than 7664
			Exacerbated oil effects. Use questionable.			

BROWN AND GOODMAN ON DISPERSANTS IN THE FRESHWATER ENVIRONMENT

the dispersants were less toxic alone than with oil. Two dispersants were significantly more toxic than the group and were rejected as field trial candidates on this basis.

Larval rainbow trout were used in toxicity testing of two dispersants with Norman Wells crude by Lockhart et al. [5]. A flow-through apparatus was used in which oil concentrations of the system water were measured directly. Fish mortality was found to be higher with dispersant and oil than with oil alone, and one dispersant was clearly more toxic than the others.

The acute toxicity of oil and dispersant chemicals to plants was also studied. Blunden et al. [6] determined the toxicity of two dispersants and oil to five representative species of northern freshwater shoreline communities, including examples of a sedge, moss, sandbar willow, lichen, and spruce. Treatment was either by soil inundation or by atomized spray of the foliage, either of which would present the worst possible exposure cases. In general, oil alone caused more damage to the plants. Moss and black spruce were the most sensitive to either oil or oil followed by dispersant, while sedge and lichen were the most tolerant. One of the dispersants was clearly more toxic to the plants than the others.

Microbial activities remove spilled oil from the environment, so it is important to know the effect of dispersants on biodegradation processes. Screening experiments with oil degrading bacterial cultures of known activity indicated that four of the twelve dispersants tested did not significantly inhibit bacterial growth [7]. A suitable field trial dispersant was chosen from among these four noninhibiting dispersants.

Most of the acute toxicity tests are summarized in Table 1 and the various dispersants are identified. Some of these tests are reported with sublethal experiments and are listed in Table 2.

Chronic and Sublethal Tests

The dispersant effectiveness tests and tests of acute toxicity described above were used to screen out dispersant chemicals that were clearly inappropriate for a cold low energy freshwater system. However, additional experiments were required to identify processes and develop analytical procedures that could be used to monitor longer term changes in an ecosystem.

Behavioral reactions in animals may be one such sensitive indicator of potential longterm detrimental effects. Lockhart et al. [5] reported on preference-avoidance behavior of the freshwater amphipod *Gammarus lacustris* when subjected to low levels of dispersants and Norman Wells oil. For oil/dispersant concentrations of >0.2 ppm, the animal's behavior was measurably altered. Similarly, growth may be affected by low levels of chemicals. These authors report that larval trout (*Salmo gairdneri*) exposed to oil/dispersant mixtures of 30 ppm developed an edematous condition (an excess of fluid in tissue) and experienced deterioration of caudal fins. Weight gain was much slower than in control fish. Under certain conditions, the addition of dispersant ameliorated some of the detrimental effects of the oil.

Plant species as well as animals may be affected by nonlethal doses of contaminants. When common duckweed (*Lemna minor*, an aquatic plant) was exposed to oil in water at concentrations as low as 5 ppm, fewer fronds were produced than in control plants [5]. However, the addition of some dispersants ameliorated the effects of oil alone. In fact, some dispersants by themselves acted as fertilizers and were slightly beneficial to plant growth.

Blunden et al. [6] and Goudey et al. [8,9] studied the longer term effects of oil and dispersants on five representative northern freshwater shoreline plant species with a view to

developing standardized laboratory bioassays to assess the impact of oil spills and treatment with dispersant chemicals. Seven weeks after the plants had been treated with oil or dispersants or both, they were subjected to a simulated seasonal growth cycle including a period of induced dormancy. After the dormant period, recovery of the plants was measured. In the lichens, ¹⁴CO₂ uptake was measured to determine the photosynthetic rate. This indicated that activity was decreased to 30% of that in control plants in those treated with dispersants and to 10% in those treated with both oil and dispersants. In sedges, recovery was much better than for lichens in both oil or dispersant treated plants or both. Vegetative and flowering regrowth measurements showed only minor retardation of growth after one growing season. Similar results were found for dispersant treated willows. Obviously, photosynthesis in lichens is a sensitive indicator of contaminant damage.

Microbially mediated environmental processes may be used as a monitor of long-term effects of oil and dispersants. Several such processes were identified and tested in natural lake samples [7]. It was found that assays of phosphatase, nitrogen fixation, and methane production could be related to the addition of oil or dispersants or both to natural lake water. These assays were developed as laboratory tests so that they could be used to monitor the long-term effects of a field test oil spill.

The laboratory studies of chronic and sublethal effects of dispersant and oil are summarized in Table 2.

The result of all the laboratory studies has been to identify a few dispersant chemicals that are effective in freshwater environments and have toxicities to representative northern freshwater species that are acceptable. A number of analytical procedures and biological assays have been identified that can be used to monitor the longer term effects of oil and dispersants in a freshwater system. Such studies were the prerequisites to a full-scale experimental oil spill at a field location.

Field Trial Oil Spill

The preliminary laboratory studies identified Corexit 9550 as a suitable dispersant for freshwater oil spills. Techniques for monitoring the effects of oil and oil + dispersant on a number of representative freshwater plant and animal species had been developed. The results of these studies were used during 1985 to monitor the impact of a test oil spill treated with a dispersant on a small fen lake.

Spill Site and Measurements

Three shallow fen lakes of approximately 15 hectares each, located in the Athabasca region of north-central Alberta, were chosen for the trial (Fig. 1). Three cubic metres of Norman Wells Crude oil were slowly pumped onto floating spill plates on each of two of the lakes (labelled WEST and SOUTH); one of these was subsequently sprayed with the dispersant (WEST). The third fen lake (EAST) was used as a control. The oil was spilled about 75 m from the nearest shoreline and initially drifted away from the shore. On both fen lakes some oil contacted the shore within about 6 h of release. Based on an average depth of 1 m, the West fen lake with an area of 20 hectares contains 2×10^5 m³ of water while the South fen lake with an area of 14 hectares contains 1.4×10^5 m³. If the spilled oil mixed uniformly into the water column, the West fen water would contain 15 ppm of oil and the South fen 20 ppm of oil.

For 18 months, at regular intervals before, during, and after the spill, components of the fen lake ecosystem were monitored. Monitoring included physical and chemical measure-



FIG. 1—Map of Athabasca region of north-central Alberta showing the three shallow fen lakes chosen for the trial.

ments of the fen water, and measurements on representative species of the botanical, microbial, and planktonic life. During the period of the field trial, the following parameters were measured at one or more times:

- meteorological data;
- slick aerial extent by aircraft remote sensing;
- water column oil concentration and droplet size;
- botanical assays: extent and composition of plant communities, evaluation of community changes, photosynthetic rate of lichens, and light attenuation in fen water;
- microbiological studies: microbial populations in the water and sediments, microbial oil degradation in situ, and phosphatase, nitrogen fixation, and methane production;
- plankton assessment; plankton species and type and plankton biomass and metabolic rate; and
- physical and chemical measurements: water temperature, pH, conductivity, and O₂; total organic and inorganic phosphorus; anionic surfactants and phenols; total organic carbons, oils, and greases; and Kjeldahl nitrogen and nitrogen as NH⁴₄, NO⁻₃, and NO⁻₂.

The analytical and assay procedures used are described in the references cited in the section above on laboratory studies.

Field Study Results and Conclusions

A detailed analysis of the results of this freshwater oil spill test are contained in a report distributed by the Prairie Region Oil Spill Containment and Recovery Activities Committee (PROSCARAC) of the Canadian Petroleum Association [10]. A summary paper emphasizing the observations and conclusions of the field study is in preparation.

A general conclusion of the contributors to this project was that the oil spills had only a temporary effect on either of the two fen lakes. No oil was observed on the surface of the dispersant treated lake after a few days, although it persisted for more than a month on the lake in which only oil was added. Damage to shoreline and floating aquatic plants occurred in both lakes but was more severe in the oil only lake. New growth was observed one month after the spill in both lakes. Submerged aquatic plants appeared unaffected in either lake.

Measurements of total organic carbon, nitrogen, phenols, and surfactants did not reveal any significant differences among the three lakes during the field tests. Neither Microtox nor 96-h trout assays detected any toxicity of the fen waters. Indigenous bacterial populations and activities showed little change on either of the oiled lakes, although some enrichment of hydrocarbon degraders was observed. Plankton density, biomass, and productivity was unaffected. One year after the spills, no apparent difference could be detected between the two oil treated lakes, or between these lakes and the control lake. Seasonal regrowth appeared to be normal in all three.

A preliminary conclusion that can be drawn from this trial is that a light oil, even when it initially covers between 5 and 10% of the shallow freshwater lake surface, will have only a temporary effect on the plant and animal communities. After one growing season the system has apparently recovered. The application of a dispersant was successful in removing the oil from the water surface even in this low energy environment, and apparently decreased immediate damage to the shoreline and floating plants. Appropriate selection of a dispersant chemical for use in a low energy freshwater lake may ameliorate some of the harmful effects of an oil spill.

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Economic Evaluation of Dispersants to Combat Oil Spills

REFERENCE: Lasday, A. H., "Economic Evaluation of Dispersants to Combat Oil Spills," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018*, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 41–48.

ABSTRACT: Chemical dispersants for combatting oil spills increasingly are being recognized as a most valuable addition to the available means for damage prevention and cleanup. A study of oil spill cleanup costs enables one to apply a most useful perspective to the issue of costs. Based on public information sources where costs were reported for cleanup of oil that impacted a shoreline, mechanical methods ranged in cost from a minimum of \$65 per barrel of oil to a maximum of \$5000 per barrel. In contrast, costs for intercepting the oil at sea by spraying dispersant from four-engine fixed wing aircraft ranged between a minimum of \$15 per barrel of oil treated up to a maximum of \$60 per barrel of oil treated. The study spill sizes were 10 000 to 100 000 barrels of oil.

KEY WORDS: dispersants, petroleum, crude oil, oil spills, environmental protection

Recognition of dispersants as a legitimate tool along with the more conventional mechanical devices for combatting oil spills has been slow in coming to the United States. The setback to dispersant acceptability was a consequence of the wreck of the super tanker Torrey Canyon off the West Coast of England in 1967. First generation dispersant materials of that time were rather toxic to marine biota and that problem was seriously compounded by incorrect and excessive application. The result was large scale destruction of marine life. Since then the U.S. Environmental Protection Agency (EPA) as well as other regulatory agencies, both federal and state, have been quite reluctant to authorize dispersant usage for combatting oil spills in U.S. waters, as provided for in the National Contingency Plan.

In the interim since Torrey Canyon there has been impressive development in the state of the art of formulating dispersants. Present-day ones are far more effective and are almost nontoxic, compared to those used at the Torrey Canyon spill. Thus, the attitudes of the regulators toward dispersants have changed materially. The EPA first authorized dispersant use in 1978 at Rockaway Point, Long Island, New York. Since then there have been other instances of official approval for dispersing oil slicks. Today, some of the U.S. Coast Guard (USCG) districts have established plans for the authorization of dispersant usage by the Coast Guard On-Scene Commander, in conformity with the provisions of the National Contingency Plan.

Thus, an awareness of the factors that determine when it is appropriate to use dispersants becomes important for oil industry personnel involved in oil spill response. Of course, the spill response team also needs to be well versed in all of the technical details that pertain to successful dispersant application. Today, the oil industry evaluates disper-

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sants as one of the many tools that are available for oil spill management. In some situations, such as in rough seas and inclement weather, only dispersants will work; it is not possible, let alone safe, to try to operate mechanical equipment such as booms and skimmers in such conditions. In the case of a massive, overwhelming oil spill event, such as the Ixtoc-1 well blowout at Campeche Bay in 1979, only dispersants sprayed from fourengine aircraft can be expected to have a significant impact. For smaller spills, and especially close to shore or in harbors, booms and skimmers assume the dominant role.

Where use of both dispersants and mechanical cleanup equipment is feasible, the choice of an oil spill control method or methods should be based, first, on an analysis of what actions can be expected to prevent or to minimize damage to natural habitats and to other resources, as well as to promote the most rapid recovery of oil impacted ecosystems. In this context, please note that the evaluation of the ecological suitability of all oil spill control and cleanup methods is the topic of the American Petroleum Institute (API) publication, "Oil Spill Response: Options for Minimizing Adverse Ecological Impacts" [1]. The next consideration in deciding between mechanical and chemical methods is that of relative costs, and economic evaluation of dispersants versus shoreline cleanup is the topic of this paper.

An Exxon Corporation study of the relative costs of shoreline cleanup as compared to dispersant spraying from four-engine aircraft is the basis of and has been used extensively in preparing this manuscript,² as well as other published materials [2,3].

Oil Spill Cleanup Costs on Shorelines

Various public information sources have been used to obtain data about shoreline cleanup costs: the *Oil Spill Intelligence Report*, Proceedings of the various API-EPA-USCG Oil Spill Conferences, the *Canadian Environmental Protection Services Newsletter*, the *Marine Pollution Bulletin*, and publications of the International Tanker Owners Pollution Federation, Ltd., and of the Organization for Economic Cooperation and Development.

Reports of oil spills have been used only where the spill was accompanied by significant shoreline impacts. Although most of the sources do not distinguish containment and recovery costs from shoreline cleanup costs, many of the references implied that shoreline cleanup costs were much greater than the other costs. No damage claims or liability costs are included; they could, in some instances, exceed all cleanup costs. The reported costs have been recalculated in 1985 dollars.

It can be anticipated that shoreline cleanup costs in the United States will increase in the future, and at a rate exceeding that of inflation. The major reason is that oil spill debris may be classified as a hazardous waste. This entails high hauling and disposal costs.

The essential data are summarized in Figs. 1 and 2. The first figure depicts the log normal distribution of cleanup costs both as dollars per barrel³ of spilled oil and as dollars per square metre of shoreline impacted. Figure 2 plots the length of oil spill impacted shorelines as a function of the quantity of oil impacting the shorelines. The data are plotted as a straight line on a log-log graph; the slope of the line shows that, as the volume of oil impacting a shoreline increases, the length of shoreline impacted increases roughly as the square root of that volume.

Summarizing the cost data of Fig. 1, we obtain the information in Table 1 about costs for cleaning up oil spill impacted shorelines.

² G. Lindblom, Exxon Chemical Co., private communication of analyses by R. R. Goodrich.

 $^{^{3}}$ As the barrel (42 gal) is the unit of measurement used worldwide for crude oil, it is used in this paper instead of the litre.



FIG. 1—Distribution of reported oil spill cleanup costs. Costs in 1985 /bbl oil and /m² shoreline.



FIG. 2-Length of shoreline impacted versus amount of oil cleaned up.

	\$/bbl	\$/m ²	
 Range	65-5000	0.2-120	
Mean	1130	24	
Median	620	4. 1	

TABLE 1-Data on costs for cleaning up oil spill impacted shorelines.

Chemical Dispersant Treatment Costs for Oil Spills

Turning now to the parallel subject of calculating the costs of applying chemical dispersant to oil spills, simple and logical considerations lead to an equation that allows rapid calculation of dispersant application costs. This equation involves certain assumptions, as detailed below. The scenario which is the basis of computing dispersant costs is given by Fig. 3. D_{B_1} , D_{T_1} , and D_S are the travel distances between the four locations as shown in the figure. These are: D_{B_2} the flying distance for the dispersant spraying aircraft to travel from its home base to the spill operations base; D_{T_1} the distance to transport drums of dispersant from the manufacturing or from the supply base, as the case may be, to the spill operations base; and D_{S_2} the flying distance between the spill operations base and the spill location.

To arrive at an overall dispersant treatment cost equation, the following simplifying assumptions are made:

1. The oil slick is sprayed with an average dispersant dosage, D.

2. A unit flying cost, C_{F} is assumed that includes all personnel (that is, flight crew and ground support) as well as all other related aircraft costs (for example, fuel, maintenance, and even a spotter aircraft to direct spraying operations from above).

3. The cost of mobilizing the dispersant spray plane can be treated either as a flat callout fee or a cost per mile fee, or a combination of both.

4. Only one dispersant spraying plane is used (although the equation can be modified easily if more aircraft are used).

5. The flying distance required by the spray plane at the spill location to spray its entire cargo of dispersant onto the slick is multiplied by a factor of four. This accounts for the extra flying distance required for turning the spray plane between spraying passes over the oil slick, and for repositioning so as always to be spraying while flying on a heading into the wind. (Spraying crosswind results in erratic coverage; flying both upwind and downwind while spraying would require adjusting the rate of spraying for each pass to achieve a constant coverage of the slick in gallons of dispersant per acre.)

Constructing the equation to give the unit treatment cost is done simply by linearly assembling all of the cost elements.

- 1. Unit cost (\$/bbl) = treatment cost/volume oil treated.
- 2. Treatment cost = dispersant cost + aircraft mobilization cost + aircraft spraying cost.
- 2a. Dispersant cost = spill area treated \times dosage

×	unit dispersant + cost	unit dispersant transport cost	×	transport distance	
= A	$\overline{D}(C_D + C_T D_T)$)		_	

where

- A = area of the slick, in square kilometres,
- D = average dispersant dosage in litres per square kilometre,
- C_D = unit dispersant cost in dollars per litre,
- C_T = unit dispersant transport cost in dollars per litre per kilometre, and
- D_T = the transport distance between supply plant and the spill operations base in kilometres.



FIG. 3—Scenario that is the basis of computing dispersant costs.

2b. Aircraft mobilization cost = call-out or positioning or both. Flat fee + cost per distance =

$$C_C + 2D_B C_F$$

where

 C_c = the call out/flat fee in dollars,

- D_B = the distance between the aircraft home base and the spill operations base (which distance is flown twice) in kilometres, and
- C_F = the flying unit costs in dollars per kilometre.

2c. Aircraft spraying cost =

Flying unit cost
$$\times$$

Flying distance \times of trips $+$ flying distance $+$ at spill $=$

$$C_{\rm F}[2D_{\rm S}(DA/P) + (4A/S)]$$

where

- $D_{\rm s}$ = the distance between the spill operations base and the oil slick in kilometres,
 - P = the spraying aircraft payload in litres, and
 - S = the spray swath width in kilometres.

Combining 2a, 2b, and 2c into 2 we arrive at:

2. Treatment cost = $AD(C_D + C_T D_T) + (C_C + 2D_B C_F) + C_F [2D_S(DA/P) + (4A/S)]$

If one assumes the values given below for C_D , C_T , C_F , and P, and substitutes these factors in 2, we obtain:

3. Treatment cost (multiengine) =

 $AD(3 + 0.000\ 25\ D_T) + (80\ 000 + 14\ D_B) + (0.001\ 4\ D_SDA + 370\ A)$

where

 C_D = dispersant cost - 3/L(11.3/gal)

- C_T = dispersant transport = 0.00025 \$/L/km(Boeing 747 aircraft),
- C_F = unit flying cost = \$7/km(DC-4, DC-6, C-130 spray planes)
- $P = \text{spray plane payload} = 10\ 000\ \text{L}\ (2\ 650\ \text{gal})$
- S = swath width = 0.075 km (250 ft), and
- C_c = spray plane call-out fee = \$80 000.

Note that these calculation methods have been validated and found to be accurate by means of field data from the Ixtoc-1 oil well blowout of 1979 (see Ref 2).

Several oil spill scenarios have been worked out by means of the above treatment cost formula. These are: an easily dispersed light oil spill along the U.S. Gulf Coast, in a moderately thick slick; a similar location but a not easily dispersed heavy oil in a thin slick; and a not easily dispersed heavy oil in a thin slick and in a Middle East location. See Table 2 for a comparison of dispersant application costs in dollars per barrel.

Total costs range between a low of \$13.30 per barrel of oil that is dispersed in the case of the easily dispersed light oil in the Gulf of Mexico for a 100 000-bbl spill up to a maximum of \$147 per barrel for a 10 000-bbl spill of a not easily dispersed heavy oil in a Middle East location. Note that, for the Middle East case, dispersant cost at \$112 per barrel of oil spilled is much the largest cost component of the \$147 per barrel total. This reflects the high cost of air transport of dispersant to the spill operations base. Obviously, if dispersant had been transported by ship and stockpiled at strategic locations in the Middle East, the total dispersing cost would have been much closer to the U.S. Gulf Coast case.

			Cost, \$/bb	ol	
	Oil Spill Scenarios	Dispersant	Mobilization	Spraying	Total
1.	Easily dispersed light oil, moderately thick slick, favorable logistics (U.S. Gulf Coast), D/O ratio = 1/40 (250 L/ ha) ^a , slick thickness = 1 mm, D_M = 1000 km, D_T = 200 km, D_S = 50 km A. 10 000-bbl spill	12.1	9.4	0.3	21.8
2.	B. 100 000-bbl spill Not easily dispersed heavy oil, moderately thin slick, favorable logistics (U.S. Gulf Coast), $D/O = 1/$ 10 (100 L/ha), slick thickness = 0.1 mm	12.1	0.9	0.3	13.3
3.	A. 10 000-bbl spill B. 100 000-bbl spill Not easily dispersed heavy oil, moderately thin slick, unfavorable logistics (Middle East location), D/O ratio = 1/10 (100 L/ha) slick thickness = 0.1 mm, D_B = 16 000 km, D_T = 16 000 km, D_5 200 km	48.6 48.6	9.4 0.9	1.7 1.7	59.7 51.2
	A. 10 000-bbl spill B. 100 000-bbl spill	112 112	30 3	5 5	147 120

TABLE 2—Examples of dispersant treatment costs.

 $a \ 1 \ ha = 10\ 000\ m^2$.

		Oil Spill	Response Costs
	Spill Scenario (10 000-bbl Slick 0.1 mm Thick)	Dispersant, \$ (\$/bbl) .	Shoreline Cleanup, \$ (\$/bbl)
1.	No dispersant treatment—shoreline impact		
	A. 50% of oil impacting shoreline		5 650 000 (1130)
	B. 30% of oil impacting shoreline		3 390 000 (1130)
	C. 10% of oil impacting shoreline		1 130 000 (1130)
2.	Disperse entire slick—no shoreline impact		- (,
	A. dispersant/oil ratio 1/10 (11 gal/acre) ^a	600 000 (60)	
	B. dispersant/oil ratio 1/20 (6 gal/acre)	350 000 (35)	
	C. dispersant/oil ratio 1/40 (3 gal/acre)	230 000 (23)	
3.	Both dispersant treatment and shoreline impact		
	50% of spill dispersed, $D/O = 1/20$	$175\ 000\ (35)\ +\ 1$	130 000 (1 130)
		1 30	5 000 Total
	prevents 20% of spill impacting shore, that is, 10% of spill still impacts shore		

 TABLE 3—Comparison of costs—dispersant treatment versus shoreline cleanup.

 $a \mid gal = 3.7854 \text{ L} \text{ and } 1 \text{ acre} = 4046.873 \text{ m}^2$.

Comparison of Dispersant Treatment Versus Shoreline Cleanup

Now that we have examined both shoreline cleanup costs based on analysis of a number of actual spill incidents, as well as computed costs of spraying dispersant from aircraft, it is pertinent to make comparisons and to draw conclusions therefrom. We assume a 10 000 barrel of not easily dispersed heavy oil spill spread out over 16 km² whose average thickness is 0.1 mm. The slick is located about 30 km from shore in the Gulf of Mexico.

For the case of shoreline cleanup (Fig. 1), we had previously obtained a mean shoreline cleanup cost of \$1130 per barrel of oil impacting the shore. Also, from Table 2, we find for this situation that the total dispersant spraying cost was \$59.70 (say \$60) per barrel of oil dispersed. We now apply these basic costs to three scenarios, as given in Table 3.

The marked contrast of the costs of dispersant application versus shoreline cleanup is quite evident. Even for the worst dispersant case, a dispersant-to-oil ratio (D/O) of only 1/10, the costs of \$600 000 are only about one half of the \$1130 000 required for the most favorable shore cleanup case, where only 10% of the oil impacts the shoreline. Comparing a more reasonable 1/20 D/O ratio with 30% of the oil going ashore, shoreline cleanup is about 10 times more costly than is dispersant application (\$350 000 versus \$3 390 000). If we compare Case 3, both dispersant treatment and shoreline impact, with Case 1b, no dispersant use and 30% of the oil going ashore, it is evident that the latter costs over \$2 000 000 more than the former.

The conclusion is obvious; on the basis of costs of cleanup, the larger the spill the greater the cost advantage of using dispersants compared to waiting until the oil strands along shore and then cleaning up the oil. And this cost comparison does not include other potential penalties of waiting to clean up oil along the shore, such as ecosystem damage and natural resource damage assessment penalties.

References

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- [3] "Chemicals for Oil Spill Control," Exxon Corp., Houston, TX, April, 1980.

The Use of Chemical Dispersants to Control Oil Spills in Shallow Nearshore Waters

REFERENCE: McAuliffe, C. D., "The Use of Chemical Dispersants to Control Oil Spills in Shallow Nearshore Waters," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 49–72.*

ABSTRACT: Oil slicks should be dispersed in shallow nearshore waters to prevent oil from stranding. Field and laboratory studies show that chemically dispersed oil causes fewer adverse biological effects, and those are transitory. Spilled oil attains an average thickness of 0.1 mm or less in an hour or two on the water surface. Thus maximum concentrations in water are 100 ppm at 1 m and 10 ppm at 10 m. Most volatile/soluble hydrocarbons that cause toxicity evaporate from the slick in a few hours. Soluble hydrocarbons under field slicks and in chemically dispersed oil plumes are generally a factor of 150 to 1 million lower than those found to cause mortality of a wide range of organisms in laboratory studies. Chemical dispersants appear to protect some organisms, apparently by reducing oil droplet "stickiness." A relatively few mechanically dispersed crude oil droplets, compared to many chemically dispersed droplets, caused (1) increased larval abnormalities in herring egg exposures and (2) increased petroleum content in adult coho salmon tissue. Chemical dispersion of crude oil prevented (1) mortality of mature mangrove trees in Panama and (2) adverse effects on intertidal organisms in Maine and immediate subtidal organisms in the Arctic. An oil spill is large or small relative to the receiving water. Scenarios of large and small spills show that there are no environmental reasons for not using chemical dispersants. A review of control capabilities shows that spills exceeding 160 m³ (1000 bbl)/day can only be accomplished by multiengine aircraft spraying dispersant, with mechanical methods assisting in critical areas. This assumes that the oil is dispersible. If not, most oil from spills over 160 m³/day may strand on shores. To be most effective, dispersant spraying must be initiated early, meaning that preapproval is necessary. Reduced adverse environmental effects along with greater control capabilities indicate that chemical dispersants should be used even in shallow nearshore waters.

KEY WORDS: chemical dispersants, field studies, mangrove, salmon, soluble hydrocarbons, volatile hydrocarbons, crude oil, herring, bioassay, spill control

There has been a general reluctance in the United States to use chemical dispersants to control oil spills. This has been particularly true when their use has been proposed in shallow waters and on slicks nearshore. This reluctance has resulted from lack of information on the fates and biological effects of chemically dispersed oil as compared with those of untreated oil, or in some instances, to being overly conservative.

There are now a relatively large number of studies that have been conducted in the field and laboratory that allow an evaluation of the use of chemical dispersants for oil spill control, and comparisons with no treatment or other control methods such as skimmers. Open ocean field research studies have been particularly helpful in determining the fate of spilled oil by following spreading and the concentrations of oil in underlying water from

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untreated and chemically dispersed crude oils [1-11]. Studies of some accidental oil spills have also measured the concentrations of oil under untreated slicks and some that were chemically dispersed [12-15].

Open ocean studies have been followed by intertidal and immediate subtidal investigations to compare the effects of untreated and chemically dispersed oil on various habitats. These have ranged from the Arctic waters at Baffin Island, NWT, Canada [16-21], through the cool temperate waters of Searsport, Me [22-27], to the tropical waters of Panama [28,29].

There have been hundreds of laboratory bioassays or behavioral studies made with crude oils. A number of studies have measured the hydrocarbons (dissolved and total) in the exposure waters [30-48].

McAuliffe [49,50] compared soluble hydrocarbons and total oil exposures found in field studies with those measured in laboratory bioassays and behavioral studies. The field exposures were much lower than those required in laboratory studies to cause adverse biological effects on a large number of marine organisms.

This paper:

- briefly reviews some of the above material;
- presents two scenarios for dispersant use: spill small relative to receiving water and spill large relative to receiving water;
- discusses chemical versus mechanical oil spill control; and
- discusses oil spill control decision making.

Providing an overview of the many aspects that affect the use of chemical dispersants places their use in perspective and allows an evaluation of their advantages and disadvantages.

Fate of Spilled Oil

A comparison of the biological effects of untreated oil and chemically dispersed oil requires a knowledge of the oil concentrations and time of organism exposure. Chemical dispersion of a slick on the water restricts biological effects to water column and benthic organisms, whereas untreated oil generally has a lesser effect on open water and often severe effects when it accumulates on a shore or enters a sensitive area such as a mangrove forest.

A number of factors determine the amount of total oil and dissolved hydrocarbons that enter the water from an oil slick. These include type of oil, spreading, drifting, evaporation, dissolution, biodegradation, photolysis, and formation of oil-in-water and water-in-oil emulsions. Mixing energy from wind and waves are also important. Of these factors, oil slick thickness affects both total oil mixed into the water column and the amount of hydrocarbons that dissolves in water. Evaporation greatly reduces the amount of hydrocarbons that dissolves. Slick thickness will be discussed first, followed by measurements of total oils under open water spills. Then, evaporation and dissolution will be discussed along with field measurements of soluble hydrocarbons.

Oil Slick Thickness

The spreading of oil on water has been the subject of several studies and correlations, but it is generally recognized that the hydrodynamic situation is more complex than is

Oil Spill	Volume of Spill, m ³ (bbl)	Mean Thickness, mm
API research studies	1.6 or 3.2 (10 or 20)	0.1 to 0.2
North Sea research spill	~750 (~4700)	0.013 to 0.06
Gulf of Mexico, Main Pass Block	240 to 950/day	0.02 to 0.09
41C Platform blowout	(1500 to 6000/day)	
North Sea, Ekofisk Bravo Platform blowout	2800 (17 600)	0.01
Gulf of Mexico, Ixtoc I	4800 (30 000)	0.07

 TABLE 1—Average measured or estimated oil slick thickness for research and accidental crude oil spills (Adapted from Ref 49).

commonly represented in models. The status of many of these calculation capabilities has been reviewed by Huang [51] and in the National Academy of Sciences (NAS) review [52].

Spreading is influenced by the various interfacial tensions which are known to change as a result of oil type, evaporation, dissolution, and photolysis, which causes the formation of surface active species. The net result is that crude oils tend to spread to a mean thickness of approximately 0.1 mm in a few hours, but this includes heterogeneous areas of sheen and thicker oil patches. The entire slick is subject to break up and spreading by horizontal water currents and eddies of various scales. With time, residual oil with higher viscosity may align as windrows or accumulate along tidal riffs with debris. Some oils resist spreading to form stable pancakes or rafts later which gradually increase in density and viscosity, eventually becoming tar lumps.

Table 1 summarizes the mean slick thickness of the area of the slick that contained the majority of the spilled oil (often 80 to 90%) for relatively small research spills and for large accidental spills [50,53]. It does not include the very much larger areas over which the slick has passed and left a surface sheen visible from the air. These data show that as long as the slick remains on open water and has not encountered a barrier, such as a shoreline, the amount of oil that can be introduced into the underlying water from a 0.1-mm-thick slick (if completely dispersed and uniformly mixed) cannot exceed 100 mg/L (ppm) in the top metre of water. For most of the spills shown in Table 1, the amount would be lower. If the oil was uniformly mixed in 10 m of water, the concentration would not exceed 10 ppm.

Table 1 also shows that oil slicks generally attain the same average thickness whether they are 1.6 to 3.2 m³ released over 3 to 7 min (750 m³/day) from small research oil spills, to 3800 m³/day as from the Ixtoc 1 blowout. Thus, it appears that small spills can produce oil concentrations in the water column that are as high as those from large spills.

Oil Concentrations Under Research and Accidental Slicks

However, untreated oil slicks generally break up slowly with the highest oil concentrations observed in the top 1 to 2 m of water. The highest concentrations have been 1 to 2 mg/L (ppm) at 1 m for La Rosa, Murban, and Prudhoe Bay crude oils [7,10,11]. Concentrations were much lower at greater depths. The highest measured oil concentration in water under a 100-metric ton (~750-bbl) release of a light Statfjord crude oil in the North Sea was about 90 μ g/L (ppb). The mean values were 10 to 15 ppb in the top 10 m of water [1].

The oil concentrations from large accidental oil spills have been similar to those found under research spills [49]. Oil concentrations under the light Ekofisk crude oil slick in the North Sea ranged from 0.4 to 88 ppb as measured by Law [14]. Grahl-Nielson [13] found oil concentrations ranged from 100 to 300 ppb. During the Ixtoc 1 blowout, Boehm et al. [19] measured total oil concentration of several parts per million (mg/L). These investigators suggested that the shear and turbulence of the gas and oil moving to the surface caused mechanical dispersion of some oil into fine droplets, much like that produced by chemical dispersion. They concluded that the surface slick contributed little of the oil to the underlying water.

Chemical dispersion of slicks has produced the highest observed total oil concentrations in the upper water column. Chemically dispersed La Rosa crude oil slicks [10] had oil concentrations of 2 to 3 ppm at 1- and 3-m depths in samples collected 10 to 15 min after aerial spraying, 0.5 ppm at 6 m. Concentrations of 1 to 1.5 ppm persisted at 1 and 3 m through 100 min. Oil concentrations under the Murban crude oil slick were 18 ppm at 1 m and 10 ppm at 3 m, 23 min after spraying. After 50 to 57 min, the concentrations were 3 to 4 ppm at 1 m, 3 ppm at 3 m, and 1 ppm at 6 and 9 m.

For the best dispersed Prudhoe Bay crude oil slicks in research studies off southern California [11], the measured total oil concentrations 15 min after aircraft spraying were 30 to 50 ppm at 1 m and 20 ppm at 3 m; 54 min after spraying, the concentrations were 12 to 14 ppm at 1, 3, and 6 m, and 2 ppm at 9 m. After 3 h 40 min, the concentrations at 1, 3, 6, and 9 m were 1, 2.3, 1, and 0.5 ppm, respectively.

Cormack and Nichols [4] and Lichtenthaler and Daling [8] found similar concentrations of Ekofisk and Statfjord crude oils chemically dispersed into underlying waters. Other field dispersant tests have measured lower concentrations [2,3,5,6]. Nichols and Parker [54] summarized measured oil concentrations in water for dispersant field trials through 1984.

Evaporation and Dissolution

Evaporation is a fairly well characterized process—primarily a function of the wind speed and the oil vapor pressure. As evaporation (dissolution) occurs, the vapor pressure decreases. Typically 30% of a crude oil spill may evaporate in a day or two.

The loss of volatile hydrocarbons to the atmosphere appears to be a major factor in preventing a buildup of dissolved hydrocarbons in underlying water. The rates of loss by evaporation and solution (controlled by diffusion from the oil slick) are greatest for the smallest molecules. Thus, rate of loss decreases with increase in molecular weight. Mackay et al. [55], using an evaporative model, showed rapid losses from various specific gravity crude oils that spread on the water surface. As shown in Fig. 1 [56], about 50 to 70% of the amount that will ultimately be lost by evaporation occurs by 10 to 12 h.

Equilibrium values for concentrations of dissolved hydrocarbons (from an excess of crude oils and with evaporation prevented), as used to prepare water soluble fraction (WSF) in laboratory studies discussed later, do not occur at the time of spills. The principal reasons are: (1) a thin slick does not have sufficient hydrocarbons present to approach values obtained with an excess of oil, (2) evaporation dominates solution, and (3) nonequilibrium conditions exist. If the slick has an average thickness of 0.1 mm, the oil-to-water ratio is 1 to 100 000 for the top 10 m. If the average slick thickness is 0.01 mm, there would only be 1 volume of oil to 1 million volumes of water. These factors predict low concentrations of dissolved hydrocarbons under oil slicks.

Volatile/Soluble Hydrocarbons Measured in Slick Oils

Collected samples of oil from open ocean research slicks showed the loss of benzene and toluene (and corresponding carbon number saturate hydrocarbons) from a 0.91 specific



FIG. 1—Relationship between time after spillage and percentage of oil evaporated for different crude oils (after van Oudenhoven et al. [56]).

gravity (24° API gravity) La Rosa crude oil in less than 1 h [7,9]. The xylenes (C₈) were lost in 4 h, and the trimethylbenzenes (C₉) in less than 8 h. Smith and MacIntyre [57] measured the complete loss of $n - C_{10}$ and 50% loss of $n - C_{12}$ in 7 h from a No. 2 fuel oil slick at sea.

Also in open water tests, Harrison et al. [58] found cumene (a trimethylbenzene, C_9) was completely lost in from 40 to 80 min (as related to wind and wave conditions) from five spills of a South Louisiana crude oil.

Boehm and Fiest [12] and Boehm et al. [59] collected samples of the slick at increasing distances from the Ixtoc 1 well blowout (largest offshore spill). Oil near the well had lost C_8 and lower normal alkanes; after 12 h, C_{11} and lower were gone; and after three days, C_{14} and lower were lost. Low concentrations of volatile hydrocarbons in surface slicks would predict still lower concentrations in the underlying water.

Volatile/Soluble Hydrocarbons Measured under Field Slicks

Harrison et al. [58] in a mathematical model predicted that aromatic hydrocarbons would evaporate 100 times faster than they would go into solution, alkanes, 10 000 times faster.

The American Petroleum Institute sponsored five separate series of offshore research oil spills that included untreated and chemically dispersed crude oil slicks. The dominance of evaporation over solution was demonstrated during these spills.

Sixty-eight water samples were collected at 1.5 and 3.0 m over 7 h from under untreated La Rosa and Murban oil slicks. Only five samples collected within 20 min after oil release had measurable concentrations (60, 16, 6, 3, and 2 ppb $[\mu g/L]$).

More recent studies with untreated La Rosa, Murban, and Prudhoe Bay crude oil spills have shown total dissolved hydrocarbons (C_1 to C_{10}) to range from 1 to 3.5 ppb in the top 3 m of water only in samples collected 15 to 30 min after oil discharge [10,11].

Even under chemically dispersed Prudhoe Bay crude oil slicks with total oil concentrations ranging from 10 to 40 ppm, the total dissolved hydrocarbons (C_1 to C_{10}) averaged 46 ppb during the period 10 to 30 min after spraying and 16 ppb from 30 min to 1 h. The higher concentrations were in less than 6 m of water. After 3 to 4 h, the concentrations were <2 ppb and after 6 to 7 h, <1 ppb.

During the Gulf of Mexico MP-41C platform spill, surface dip samples collected in the dispersed oil plume near the platform (275 to 1250 m) contained from 22 to 200 ppb of these hydrocarbons [60]. Samples collected at 6-m depth contained from 2 to 20 ppb.

Biological Effects of Chemically Dispersed and Untreated Crude Oils

This section will evaluate crude oil (total and dissolved fractions) in the water column measured in field studies, and compare organism exposures with those measured in laboratory studies that cause mortality or behavioral changes [49,50].

The exposure comparisons have been made using the product of concentration multiplied by time, and expressing it as parts per million-hours (ppm-h). This allows a comparison to be made between different exposures used by different investigators, and to allow an exposure to be calculated when concentrations are changing as occurs in the field. This concept probably holds over time periods from an hour to a day or two. The use of ppm-h assumes that organisms will respond in the same manner to a toxicant if exposed, for example, to 20 ppm for 1 h or to 1 ppm for 20 h. There are obvious limits to this concept. If the time is short and the concentration high, the organism may be killed immediately. If the time is long and the concentration correspondingly lower, many organisms can tolerate or metabolize hydrocarbons and live without apparent adverse effects.

This section also briefly reviews (1) the immediate subtidal Baffin Island Oil Spill (BIOS) project, (2) the intertidal study in Long Cove, Maine, and (3) the shallow tropical habitats in Panama. These studies were designed to compare the biological effects from chemically dispersed crude oils with untreated oil.

Shoreline Studies

Arctic Nearshore Subtidal Research—At the Baffin Island Oil Spill project (BIOS), 15 m³ (94 bbl) of slightly weathered Lago Medio crude oil was released over 6 h on 200 m of shore, of which 44 bbl was retained on the beach. After one year, 31 bbl of oil remained on the beach, and eroded oil continued to enter the subtidal sediments.

The untreated oil release had no immediate effects on the subtidal benthic organisms, but intertidal amphipods and some larval fish were affected by physical coating [16,61]. Oil was found in concentrations between 0.01 and 2.8 ppm, only in the top metre of water. As the sediment oil content increased, oil increased in the subtidal organisms and was having an adverse effect on these organisms [21,62].

Another 15 m³ (94 bbl) of oil was mixed with 1.5 m^3 (9.4 bbl) of a dispersant in a tank and then continuously fed into a seawater line (one part oil + dispersant to five parts of water). The mixture was discharged subtidally on the seafloor through a diffuser pipe extending 100 m from shore in waters up to 10 m deep over a 6-h period. The highest oil concentrations were 55 to 167 ppm, and organism exposure was 300 to 400 ppm-h.

At the dispersed oil site, macrobenthic organisms were markedly affected. The dispersed oil (probably the dissolved hydrocarbons) appeared to have caused narcosis. Benthic sediment dwellers like clams and polychaetes surfaced. Although the crude oil was partially weathered, total dissolved hydrocarbons were as high as 9 ppm in some bottom water samples. Within one to two weeks, the majority of the stressed animals appeared to have regained normal functions. The "surfaced" polychaetes and bivalves reburied and the numbers of urchins were near prespill levels [63]. After one year, there were no statistically significant differences from controls in benthic community composition [16].

Intertidal Research in Maine—In August 1981, a field study in Long Cove, Searsport, Maine, was conducted comparing the fates and effects of two 6-bbl spills of Murban crude oil, one dispersed and one untreated [24]. The study was designed to simulate frequent small spills that occur in nearshore Maine waters. It was not designed to simulate large oil spills where shoreline oil concentrations would be higher, or where chemically dispersed oil could persist in a given area.

The spill of untreated oil was observed to coat and adhere to the tidal flat as the tide receded (3.5 m, [11 ft]). The next day, after two tidal cycles, oil was cleaned from the beach using conventional methods, as if it were an actual spill.

The spill of crude oil mixed with dispersant was released over the intertidal zone at high tide, in a separate section of the cove. Concentrations of 15 to 20 ppm of dispersed oil were measured 10 cm from the bottom. The exposure to dispersed oil totalled 20 to 30 ppm-h (concentration \times time) at the bottom sampling locations [25-27].

Following discharge, no Murban crude oil could be found in sediments exposed to the cloud of dispersed oil. However, significant amounts were found in the test plot exposed to untreated oil, mostly in the upper intertidal zone [22,23].

Petroleum hydrocarbons from the crude oil were found in clams and mussels collected from the untreated oil site one week after the spill, but were absent or near the level of detection in these species from the dispersed oil site [23,25,26].

Effects on infaunal communities mirrored the chemical results. There was no evidence of adverse effects on infaunal community structure from exposure to dispersed oil, but there was clear evidence that exposure to untreated oil did adversely affect community structure. Some species were reduced in number or eliminated, and there were blooms of opportunistic polychaetes. The changes in community structure as a result of the untreated oil are consistent with results observed at accidental oil spill sites [22-24].

In clams and mussels from the untreated oil site, two enzyme systems were markedly elevated after the spill: glucose-6-phosphate dehydrogenase (sugar metabolism) and aspartate amino transferase (protein metabolism). The activities of those enzymes at the dispersed oil site were similar to those at the control site [23,24].

The much more severe and long-lasting effects from the untreated oil in the Long Cove study were due to the much greater persistence of oil in intertidal sediments, as compared to the transitory effects of dispersed oil in the water column.

Shallow Tropical Habitat Research in Panama—The Panama studies [28] also measured the biological effects of untreated and chemically dispersed crude oil (Prudhoe Bay) on mangrove, seagrass, and coral habitats. The BIOS and Maine studies discharged equal volumes of untreated and chemically dispersed oil. Different volumes were used in Panama. The Panama studies were intended to simulate a worst case for dispersed oil: a spill that was large (relative to the receiving water) in a shallow semienclosed bay with relatively slow flushing. As presented earlier, most oil slicks attain an average thickness of 0.1 mm or less in an hour or two. If completely dispersed and uniformly mixed, the oil concentration in the top metre of water would be 100 ppm, 10 ppm in 10 m of water. Concentrations approaching these have been found at some of the best chemically dispersed research oil slicks [8,11]. With further dilution by intervening water, it was estimated that the average concentration of dispersed oil that could reach a shore and persist for three to four days is 10 to 15 ppm. With available time and manpower, it was not feasible to release oil continuously at this concentration for such a long period. Thus a concentration of 50 ppm for 24 h was selected. The untreated oil volume selected was about 1 L/m^2 . This estimated coverage at field spill sites has been observed to cause defoliation and death of mangrove trees [64]. It requires only a small spill to produce this coverage on a 30-m-wide band on a shoreline, depending on slick orientation. Idealized, if the slick is ten times as long as wide, a 0.9-m³ (5.7-bbl) slick driven ashore by wind (perpendicular to the shoreline) would cover 30 m of shore with a 30-m band averaging 1 L/m^2 , or a correspondingly thicker layer on a narrower band. If the slick were oriented parallel to the shore (that is, by long shore currents without wind), and then driven ashore by wind, it would require a 90-m³ (570-bbl) slick (spill) to cover a 30-m band with 1 L/m^2 , but 3 km of shore would be covered. Table 2 shows the thickness of oil that would theoretically accumulate as an even layer over a 10-m (33-ft) band of shoreline. If the orientation was perpendicular to the shore, the thickness on shore would be in theory ten times greater.

Stranded oil does not generally attain such thickness because sediments and vegetation can only retain a given amount of oil. Nonretained oil is free to move elsewhere or return later.

The Panama studies, therefore, were designed to test a worst case situation for chemically dispersed oil, as compared to moderate amounts of untreated oil.

Fresh crude oil was used in the Panama studies. Normally, an offshore spill of crude oil (dispersed or untreated) arriving at a shore after an hour or two will have lost a large proportion of the volatile/soluble hydrocarbons (as discussed above) that are known to cause immediate biological toxicity. In accidental oil spills, an hour or two will normally have passed before dispersant is applied. Thus, it would have been desirable to have used partially weathered oil, but in this remote location in Panama, there was no feasible method of doing so.

The dispersed oil concentrations in the water over the mangrove and seagrass habitats exceeded 80 ppm during most of the 24-h release, and was 20 to 30 ppm over the corals. Total oil in the water over the three habitats during the untreated oil release was 1 to 2 ppm.

In the Panama study, the principal objective was to determine the effects of untreated and chemically dispersed oil on mangrove trees, seagrasses, and various species of coral. Adverse effects on associated organisms were of interest, but of secondary importance relative to making a decision as to whether an oil slick approaching a tropical shore should be chemically dispersed or allowed to strand. If the trees, grasses, and corals were not harmed,

Sr Vol	bill ume	Slick Area (0.1 mm	Assumed Slick	Leng Shor Cov	th of eline ered	Oil Thickness on Shore in 10-m (33-ft) Band	
m ³	bbl	km^2	km	km	mi	mm	in.
10	63	0.1	0.1×1	1	0.6	1	0.04
100	630	1	0.32×3.2	3.2	2	3.2	0.13
1 000	6 300	10	1×10	10	6.2	10	0.39
10 000	63 000	100	3.2×32	32	20	32	1.3
100 000	630 000	1000	10×100	100	62	100	3.9

TABLE 2—Stranding of	of oil	from	various	volume	oil	slicks.ª
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^a Modified from Ref 53.

the associated organisms that might have been killed would repopulate the habitat relatively quickly from outside the affected area. This would not occur, for example, if the mangrove trees were killed. It would take an estimated 20 years to have introduced seedlings grow to mature trees. During this time, associated organisms such as tree snails, crabs, and oysters would be much reduced in numbers.

The principal adverse effect was the killing of adult red mangrove trees by the untreated oil. There was no effect of the chemically dispersed crude oil on the mangrove trees, even though some of the oil was not dispersed and a surface slick entered the mangrove forest. It appears that chemical dispersion of the crude oil reduced the toxicity of oil to mangrove trees.

Another observation is that the toxicity of untreated crude oil was not due to the dissolved hydrocarbons, including benzene, toluene, and xylenes. The total dissolved hydrocarbon exposures at the untreated oil site ranged from 0.7 to 1.1 ppm-h, and from 7 to 16.4 ppm-h at the dispersed oil site. Because the dispersed oil persisted at the site longer than 24 h, the dissolved hydrocarbons exceeded 7 to 16.4 ppm-h by an estimated 25 to 50%. These high concentrations at the dispersed oil site had no significant effect on mangroves. Thus, the much lower concentrations of dissolved hydrocarbons at the untreated oil site would not have appreciably contributed to the observed defoliation and tree mortality. It appears that untreated oil (probably weathered or unweathered) caused the severe adverse effects by physically coating tree roots (possibly including coverage or penetration of oil into the sediments in the intertidal area of the mangrove forest).

Oil treatments did not have an adverse effect on seagrasses, except that the growth rate at the untreated oil site decreased slightly during the 20 months postspill, and did not follow the consistent increase in growth that occurred during this time at the dispersed oil and reference sites.

Oil treatments appeared to have little or no effect on corals except on growth. There was clear evidence of reduced growth of one of four coral species at the dispersed oil site. A general decline in coral coverage occurred at all three sites, apparently related to weather changes.

There were adverse effects of the oil treatments on organisms associated with the three habitats. The effect shown most clearly was the elimination (by mortality or moving out) of black-and-white sea urchins from the seagrass area of the dispersed oil treated site. The dissolved hydrocarbons were apparently sufficiently high to cause some mortalities (discussed later).

Because the dissolved hydrocarbons at the untreated oil site were so much lower, it is unlikely that urchin mortality occurred. During dispersed oil release, small territorial fish were narcotized and became prey for two small barracuda that entered the site.

Some mortality of sponges at the dispersed oil site was observed, but correlation analyses of other animals (zooanthids, sponges, and anemones) showed no significant difference compared to the reference site. Sea anemones attached within the mangrove forest at the dispersed oil site were coated with oil and fully extended, but they responded to touch. After six days, the anemones had returned to normal, apparently unaffected by either the oil coating or the dissolved hydrocarbons. Mangrove oysters had high survival rates at both oil treated sites despite the relatively high levels of petroleum hydrocarbons in their tissues.

Table 3 shows total oil and dissolved hydrocarbon exposures (ppm-h) for the above described field studies. The total oil in the dispersed oil plumes was about the same off southern California and at Long Cove, Maine. It was ten times higher at the Baffin Island study, and still higher in Panama, particularly in water surrounding the seagrass blades and the mangrove roots. Total oil under the untreated oil slicks was much lower than in

	Tota	al Oil	Soluble Hy	/drocarbons
Study	Dispersed Oil	Untreated Oil	Dispersed Oil	Untreated Oil
Southern California offshore [11]	20-50	2-5	0.060	0.002
Long Cove, Maine [25] Baffin Island, NWT, Canada [18]	20-30	1–17		
Panama—mangroves [28]	1715	120		
seagrasses corals	2080 615	55 } 45 ∫	/-10	0.7-1.1

 TABLE 3—Total oil and dissolved hydrocarbon exposures (as ppm-h) in the water column measured during several research studies.

the dispersed oil plumes as expected. The differences between sites is related to different oils, sea states, different release times, and water depths. The offshore tests measured oil in the top 3 m of water, whereas the water depths in Panama ranged from as little as 0.1 m (distance from bottom to water sample inlet that was exposed at low tide) in the mangroves to an average of 0.5 to 0.6 m over the seagrasses and corals.

The soluble hydrocarbons (C_1 to C_{10}) that cause immediate biological effects were very low in the dispersed oil plumes and in water under the untreated oil slicks in the offshore California studies, compared with the high concentrations found in Panama. This difference appears to be due to the rapid loss of these volatile hydrocarbons from the surface oil slick during the 30 to 60 min the slicks were on the water before and during aerial dispersant spraying. At Maine and Panama, fresh crude oils were released and immediately mixed into the underlying water. More evidence will be given in a later section that discusses salmon "tainting."

The soluble hydrocarbon exposures at the dispersed oil site in Panama are sufficiently high so that mortality of more sensitive organisms might be expected to occur and did occur (urchins, sponges, small fish that were narcotized and became prey). At BIOS, narcosis of macrobenthic organisms occurred, but apparently without mortality. The soluble hydrocarbon fraction in bottom waters at BIOS was probably lower than that in the Panama investigations.

The organism exposure to the soluble hydrocarbons from chemically dispersed oil in Panama was an extreme situation, that is, rarely if ever likely to occur. As will be discussed later, it might be possible under unusual conditions to have total oil concentrations that were used, but not the dissolved hydrocarbon concentrations contributed by the fresh oil. Under almost all conditions, spilled oil will be on the water surface for an hour or two before it is chemically dispersed. During this time, many of the hydrocarbons causing narcosis or mortality of organisms will have evaporated. The BIOS scenario was to simulate dispersion of an offshore oil slick. It is unlikely (as discussed later) that oil concentrations can attain values from 50 to 150 ppm in shoreline waters (7 to 10 m deep), because of dilution by intervening water.

Laboratory Studies

This section compares measured concentrations of volatile/soluble hydrocarbons (thought to cause immediate biological effects) found in waters under field crude oil spills (reported above) with the concentrations of soluble hydrocarbons which must be used in laboratory studies to cause mortality or behavioral changes [49,50].

There have been numerous bioassays (mortality studies) of various organisms with the water soluble fraction (WSF) of crude oils obtained by equilibrating an excess of crude or refined oils with water. In only a few of these investigations are there reports of measured or known dissolved hydrocarbon concentrations of aromatic hydrocarbons that are the principal water soluble components of crude oils.

Brannon et al. [33], Nakatani et al. [38,39], and Nevissi and McAuliffe² measured the effects of untreated and chemically dispersed Prudhoe Bay crude oil on the homing of (1) adult chinook salmon in fresh water and (2) adult coho salmon in seawater and the amounts of these oils to cause 50% mortality (LC_{50}) of (1) adult coho salmon and (2) chum salmon fry.

Pearson et al. [40] studied the effect of Prudhoe Bay crude oil and chemically dispersed oil on Pacific herring egg fertilization, hatching, and larval abnormalities. The acute toxicity of the WSF and chemically dispersed Prudhoe Bay crude oil to coonstripe shrimp, Pacific herring, and the sand lance fish were studied by Anderson et al. [65].

Extensive studies have been conducted with the WSF of Cook Inlet crude oil on 39 marine species [44]. Bioassays were conducted with the larvae of 5 marine species to total aromatic hydrocarbons in the ballast water treatment effluent at Port Valdez, Alaska [45]. Morrow et al. [37] tested a number of individual hydrocarbons of the WSF on young coho salmon. Caldwell et al. [34] measured the effect of the WSF of Cook Inlet crude oil on larval stages of the Dungeness crab.

Carr and Reish [35] conducted bioassays of six polychaete species to the WSF of South Louisiana crude oil and No. 2 fuel oil, while Strusaker et al. [46] tested benzene with eggs and larvae of Pacific herring and Northern Anchovy.

These laboratory studies can be summarized as follows. Exposure necessary to induce mortality for over 50 species ranged from 9 ppm-h of dissolved hydrocarbons (chum salmon fry exposed to chemically dispersed Prudhoe Bay crude oil) to >1900 ppm-h (3 species of polychaetes exposed to the WSF of a South Louisiana crude oil).

Larval stages of organisms were no more than twice as sensitive to the WSF of crude oil compared with adults. The kelp shrimp larvae was the most sensitive at 14 ppm-h.

Limited studies indicate that chemically dispersed crude oil is about twice as toxic as the WSF of crude oils based upon the total C_1 to C_{10} hydrocarbon exposures using chum salmon fry.

Chinook salmon homed successfully and without apparent effect in fresh water and coho salmon in seawater after exposure to 0.9 to 1.5 ppm-h of total C_1 to C_{10} hydrocarbons from chemically dispersed Prudhoe Bay crude oil.

Exposure to >19 ppm-h of WSF of Prudhoe Bay crude oil before or during fertilization had no effect on Pacific herring percent egg fertilization. Exposure to >227 ppm-h had no effect on the percentage of eggs that hatched, the time to hatch, or on larval abnormalities.

The measured field exposures to C_1 to C_{10} dissolved hydrocarbons from untreated and chemically dispersed crude oils are thus much lower than those observed to kill a wide range of organisms in laboratory bioassays (by a factor of 150 to 1 million) [50]. Thus, dissolved hydrocarbons from oil spills and chemical dispersion of crude oil slicks are unlikely to have an adverse effect on larval, juvenile, or adult marine organisms in the water column of open waters or in well flushed bays or estuaries. This general conclusion is in accord with the findings of Abernethy et al. [31] that dissolved hydrocarbons toxicities are narcotic in nature (and thus often reversible), and that concentrations of at least 5% of the water solubilities are necessary to induce narcosis after prolonged exposure, that is, 48

² A. E. Nevissi, and C. D. McAuliffe, manuscript in preparation, 1987.

h. It thus appears that dilution to less than 1 ppm renders the dissolved hydrocarbons nontoxic.

It can be argued that the spill response implications are that in many cases the oil slick should be chemically dispersed in the water column to protect biologically sensitive shoreline habitats (bulk accumulation of oil), and to prevent oil from entering water areas occupied by sensitive organisms such as birds and sea otters. There may be situations in which dispersing the slick may cause increased concentrations of oil in filter feeding organisms such as mussels. However, the exposure is generally transitory from dispersed oil, whereas stranded untreated oil causes prolonged exposure and greater oil accumulation or biological effects as was demonstrated at BIOS and the Maine studies. The Panama study showed that unusually high concentrations of chemically dispersed oil had no adverse effects on mangrove trees, whereas a moderate stranding of untreated crude oil caused extensive tree mortalities.

Chemical Dispersants Appear to Protect Organisms

In the field studies reported above, chemically dispersed oil caused less environmental damage, even in shoreline releases, compared with the adverse effects that were caused by the stranding of untreated oil. This may be related to the adhesion of untreated oil to other surfaces.

Pacific Herring Larval Abnormalities—Pearson et al. [40] have shown that chemically dispersed Prudhoe Bay crude oil droplets adhered less to Pacific herring eggs than did mechanically dispersed oil droplets that remained in the aqueous phase in the preparation of a WSF. These droplets were sticky and adhered to the eggs as the WSF flowed through the exposure chambers. They caused increased larval abnormalities over those that occurred naturally in controls. Oil on eggs appears to provide a direct route for entry of toxic components into eggs. Filtering the WSF in studies the next year removed the oil droplets and no increase in abnormalities was observed. Many times more total oil as droplets of chemically dispersed oil flowed through the exposure chambers, but the droplets did not adhere to the eggs and did not cause an increase in abnormal larvae over that observed in controls.

If these findings are generally applicable, dispersed oil should adhere less to surface floating fish eggs, and to those deposited in intertidal or proximal subtidal zones, thereby reducing adverse effects. And there should be less entrapment in oil slicks of zooplankton that inhabit near-surface waters.

Reduced adhesion should also lessen the adverse effects of oil on seabirds and marine mammals, because dispersing the oil slick (1) can prevent or reduce the amount of oil entering their habitats and (2) can prevent or reduce contamination because dispersed oil is less likely to adhere to the birds.

Hydrocarbon Uptake and Loss by Adult Salmon—In a salmon tainting study [66], adult chinook (king) and Coho (silver) salmon were exposed for 24 h to untreated and chemically dispersed Prudhoe Bay crude oil using oil concentrations measured during field research studies [11,50]. In some experiments, fish were taken at intervals during the 24-h exposure to determine hydrocarbon uptake. In others, fish were exposed for 24 h and then held in net pens at a marina on Hood Canal. Fish were taken at intervals over two weeks to measure petroleum hydrocarbon depuration (loss).

The exposure waters were analyzed for soluble hydrocarbons (C_1 to C_{10}) and for total oil. Fish muscle was analyzed for soluble hydrocarbons, one- to five-ring aromatics, and total alkane hydrocarbons. Fish behavior demonstrated that chinook and coho salmon would avoid oil if they had the opportunity. Salmon exposure waters showed relatively high concentrations of dissolved hydrocarbons and total oil in the tanks that received chemically dispersed crude oil. Dissolved hydrocarbons and total oil under the untreated oil slicks were low in comparison, less than 5%. It was expected that hydrocarbons in salmon flesh would reflect the concentrations in the exposure waters. This was true for the dissolved C_1 to C_{10} hydrocarbons. Soluble hydrocarbons in tissue attained their highest concentrations 2 to 6 h after exposure and thereafter declined. Apparently hydrocarbons in solution can readily enter salmon, although these are some of the first tissue analyses for this fraction.

A different picture was found for the C_{12} + hydrocarbons. Salmon took up lower amounts of aromatic hydrocarbons from the chemically dispersed crude oil than from the untreated oil. Similar effects were shown for the C_{12} + alkane hydrocarbons (same tissue extract). Decreased uptake occurred despite the fact that the fish were exposed to much higher concentrations of dispersed oil compared with untreated oil.

It appears that the dispersant prevented oil uptake by salmon as occurred with Pacific herring eggs discussed above. The untreated oil droplets appeared to adhere to the gill tissue and thereby allowed short path transfer of hydrocarbons into the fish. Most of the dispersed oil droplets, present in very high numbers, appeared to flow through the gills without sticking.

The direct transfer of petroleum hydrocarbons to the lipids of salmon is likely because the relative composition of C_{12} + hydrocarbons (over all molecular weights) in the tissue was very similar to the hydrocarbon composition in Prudhoe Bay crude oil. The water solubilities of C_{12} + hydrocarbons are very low, and entrance into fish by transfer through a water phase is improbable.

In these experiments, it appears that the chemical surfactant molecules oriented at the oil droplet-water interface kept most of the oil droplets from adhering to the surface of fish gills.

The Use of Dispersants in Nearshore Shallow Waters

The information and discussions presented above about the fates and biological effects of untreated and chemically dispersed oil have provided background for presentation of two oil spill scenarios for dispersant use in nearshore shallow waters. Although there has been general opposition in the United States to the use of chemical dispersants for oil spill control, their use in offshore waters has been authorized. However, there has been great reluctance to their use in shallow nearshore waters. Several state plans for dispersant use have been developed, but they commonly restrict dispersant spraying to waters that are 20 m (66 ft) deep, and 3 miles (5 km) from shore. These restrictions remove areas for which the greatest benefit of dispersant use generally exists.

Oil spills vary widely in size and occur in a variety of locations. The selected scenarios are for the conditions (1) where the oil spill is small compared with the receiving water and (2) where the oil spill is large relative to the receiving water. It is also assumed that the oil will be completely dispersed, using an average oil slick thickness of 0.1 mm.

Scenario 1—Oil Spill Small Relative to Receiving Water

This scenario could represent a 1-m³ (6.3-bbl) spill in Long Cove, Maine, or a 1000-m³ (6300-bbl) spill off the U.S. Gulf Coast. In each case, the spill is assumed to be sufficiently far from shore to allow time (principally related to onshore wind speed) to spray dispersant before the oil stranded.

Long Cove is a semienclosed bay with an opening 0.7 km wide at the mouth [22]. It is

2.2 km long and averages about 0.8 km in width at high tide. At low tide (tidal range is 3 to 3.5 m), it is about the same width, but only 1.4 km long. The average depth at high tide is 13 m, and 10 m at low. The surface area and volume at high tide are 1.76 km^2 and $22.9 \times 10^6 \text{ m}^3$. At low tide the area and volume are 1.12 km^2 and $11.2 \times 10^6 \text{ m}^3$. Thus 1 m³ of oil chemically dispersed and uniformly mixed (hypothetical) would produce oil concentrations of 0.04 ppm at high tide, 0.08 ppm at low. In reality, 1 m³ of oil would produce a 0.01-km^2 slick (0.1 mm thick), less than 1% of the water surface area. When dispersed it would mix downward and further dilute on the flood or ebb tides. Biological effects would be little or none as was demonstrated by the research spill conducted in Long Cove [22-27].

A 1000-m³ (6300-bbl) spill would cover 10 km². If the slick were 2 by 5 km (long dimension parallel to coastline) in the relatively shallow nearshore waters (assume 3 m [10 ft]) for the Gulf Coast, complete dispersion and uniform mixing would produce 33 ppm (less if evaporation from slick before spraying is considered) total oil in the water. If the longshore current is 0.5 kn (0.9 km/h), it would take 5.6 h for the dispersion plume to clear the bottom over which dispersion initially occurred. The benthic organisms exposure would be 185 ppm-h (33 ppm \times 5.6 h). This is less than that measured during dispersed oil release at the BIOS project. Thus, adverse effects to the benthic organisms would not be expected. In practice, exposure would be less because of the time it takes even a large aircraft to spray the spill. If spray application was 5% of the volume of oil spilled, 50 m³ of dispersant would be applied. The largest dispersant system (20-m³ [5500-gal] tank) is the Airborne Dispersant Delivery System (ADDS) package flown in a C-130 (Hercules) aircraft. It would require three sorties of this aircraft to spray this quantity of dispersant. The actual spray time might be 2 h plus the time to return to make round trips to the airfield from which it operated. Therefore, the untreated slick would have moved, and the oil concentrations in the water would be diluted. Before and during spraying, the volatile/soluble hydrocarbons that can cause biological toxicity would have evaporated from the slick.

If slick dispersion was successful, oil reaching the shore or sensitive habitat would be much diluted with the intervening water. Dispersed oil might not reach the shore, because only a small volume (the intertidal volume) of seawater would be involved. There may be wind driven currents that in some areas might bring water containing dispersed oil ashore, but the volume would be small. Water entering larger bays or estuaries could funnel in some of the dispersed oil, but further dilution would occur, and significant adverse biological effects are not expected. They would certainly be less than those caused by wind concentrating untreated oil on shore (including subsequent attachment to sediment and deposition in the immediate subtidal sediments) or sensitive habitats such as an intertidal mud flat or mangrove forest as shown at the BIOS, Maine, and Panama studies.

Scenario 2—Oil Spill Large Relative to Receiving Water

A large spill would be one that filled the confining area with a 0.1-mm-thick slick. Long Cove in Maine can again serve as an example. A 176-m³ (1109-bbl) spill at high tide or 112 m³ (706 bbl) at low tide in theory would cover the cove with a 0.1-mm slick. Under these assumed conditions, if the slick was instantaneously dispersed and uniformly mixed at high tide, the oil concentration would be 7.7 ppm. The volume of water at low tide is 0.5 that at high. Thus, one tidal cycle would reduce the concentration by half assuming uniform mixing, and each succeeding tide would act in like manner. After six tidal cycles (three days), the oil concentrations would be near background and the total benthic organism exposure would be about 130 ppm-h, lower than the 300 to 400 ppm-h during the 6h oil release at BIOS and much lower than in the Panama study (Table 3). In practice, some of the oil would probably strand, unless spraying response was very rapid. The dispersed oil would probably not mix uniformly throughout the water column; parts of the cove have waters greater than 30 m. With the greater mixing by wind and waves in the offshore field trials, dispersed oil concentrations exceeding 10 ppm were not found below 6 m. The lesser mixing in Long Cove would result in higher oil concentrations at shallower depths. Dispersed oil would also leave the cove more rapidly than the assumption of uniform mixing during each tidal cycle. As a result of the Coriolis effect, water enters the cove more rapidly than uniform filling and mixing. Piston displacement would completely change the water in two tidal cycles.

A 100 000-m³ (630 000-bbl) spill in the Gulf Coast would be large. It is one fifth the amount of oil released by Ixtoc 1. A spill of this size would cover 1000 km² (384 mi²), a slick 20 by 50 km and 0.1 mm thick.

Such a release would be unlikely to occur quickly. A well blowout might last for weeks or months. The release would normally be less than the 4 800 m³ (30 000 bbl)/day that occurred at Ixtoc 1. Even a tanker release would normally be over a few days. If a 20- by 50-km slick was instantaneously dispersed, the oil concentrations in the water column would be the same as for the smaller 1000-m³ spill discussed above. Therefore, the concentrations of oil contacting the shore or entering bays and estuaries would be little changed from that of the smaller spill. However, a greater length of shoreline would be affected. This is not true for untreated oil that is driven ashore by winds. The amount of oil that strands on a unit length of shore from a large slick is much greater than from a small slick (Table 2).

In practice, it would not be possible to disperse chemically a 20- by 50-km slick instantaneously. It would require 250 sorties of a C-130 with ADDS systems to spray 5% dispersant relative to the amount of oil spilled. If 1 aircraft could fly 8 sorties per day, it would take 31 days, or 4 ADDS systems a little over a week. If a blowout from a platform was 2 400 m³ (15 000 bbl)/day, it could probably be controlled by 1 ADDS system (6 sorties/ day under ideal flying conditions).

Because there are practical limitations as to the amount of dispersant that can be sprayed, the concentrations in the water column will probably be less than the theoretical. Horizontal currents and tidal currents in nearshore waters will continue to mix and dilute the dispersed oil. Thus, the concentrations used in the Panama investigation are unlikely to be attained. The fact remains that it is very difficult to obtain high concentrations of dispersed oil in the water column.

As mentioned previously, delay in slick spraying allows the volatile/soluble hydrocarbons that cause biological toxicity (as occurred with some organisms in Panama with fresh oil) to be largely evaporated from most oils that can be effectively dispersed (those that spread on the water surface). It seems preferable to disperse oil slicks chemically even in shallow nearshore water rather than allow oil to strand with the resulting known adverse effects.

The ecological impacts of oil spill cleanup [67] considered all methods of protection of all the various coastal habitats, and their subsequent cleanup if the oil stranded. The American Society for Testing and Materials (ASTM) has published ASTM Guidelines for Ecological Considerations for the Use of Chemical Dispersants in Oil Spill Response: Marine Mammals (F 929), Rocky Shores (F 930), Seagrasses (F 931), Coral Reefs (F 932), Mangroves (F 971), Nearshore Subtidal (F 972), Tidal Flats (F 973), Sandy Beaches (F 990), Gravel or Cobblestone Beaches (F 999), Salt Marshes (F 1008), Offshore (F 1009), Bird Habitats (F 1010), and the Arctic (F 1012). Almost without exception, dispersant use was recommended on oil slicks before they reached a coastal habitat or sensitive offshore habitats containing birds or sea otters. The ASTM guidelines also recommended the use of dispersants as a cleanup method in several habitats after the oil had entered them [68]. J. H. Vandermeulen³ has stated that he thought it would have been better to have used chemical dispersants (assuming they would be effective) to remove the oil from some of the estuaries in France that received oil from the AMOCO CADIZ tanker stranding, rather than having used bulldozers to clean up the oil. This technique removed much of the native vegetation and sediments. It has been predicted that it may take 100 years for the grasses and sediment contours to recover to precleanup conditions.

Biological effects are very important when considering how to control oil spills. There are also practical aspects as to what can be done, some of which have been discussed above. The following section gives additional details of various control methods.

Spill Control Capabilities

Making logical decisions concerning oil spill control requires evaluation of the capabilities of the available methods [53]. For purposes of this discussion, an average slick thickness of 0.1 mm will be used in the calculations.

Method capabilities are limited also by operating conditions, which implies that operations should be carefully monitored during a spill. Monitoring, control, and evaluation can usually best be done from the air by spotter aircraft. Thus, operations, whether by skimmers, spray boats, or spray aircraft are limited to daylight and adequate flying conditions. Night operations are seldom possible, except for spray barges (and boats) and skimmers operating at the source of a continuous spill.

Skimmers

With 100% efficiency, skimmers encountering a 0.1-mm-thick slick at 1 kn (1.8 km/h) with sweep widths of 10 and 100 m (33 and 330 ft) would collect, respectively, 18 and 184 m³ (116 and 1160 bbl) of oil in a 10-h day (Table 4). Thus, it would take all day for a skimmer with a 10-m sweep width to collect about 16 m³ (100 bbl) of oil. A large ocean-going skimmer system with a 100-m encounter width (heavy seaboom, three ships, and collection barge) might handle a 160-m³ (1000-bbl) spill in a day under ideal conditions.

	Sweep Width		Amount Collected ^a	
System	m	ft	m ³	bbl
Individual system with	5	17	9	58
Individual system with	10	33	18	116
Open ocean (three ships and barge, heavy seaboom)	100	330	184	1160

TABLE 4—Amount of oil skimmer systems can collect in a 10-h day.

^a Calculations assume an average 0.1-mm-thick slick, 1-kn (1.85-km/h) sweep speed, and 100% efficiency.

³ J. H. Vandermeulen, Bedford Institute of Oceanography, personal communication, 1980.

System	Spray Width		Amount Dispersed ^a	
	m	ft	m ³	bbl
One boat with	5	16	56	350
One boat with	10	33	111	700
One boat with	30	100	333	2100

TABLE 5—Amount of oil spray boats could disperse in a 10-h day.

^a Calculation based on boat traveling at 6 kn (11.1 km/h), an average slick thickness of 0.1 mm, and 100% efficiency.

Spray Boats

Under good conditions and 100% dispersant efficiency a spray boat moving through a slick at 6 kn (10.8 km/h) with spray widths of 5 to 10 m (16 to 33 ft) might disperse, respectively, 55 to 110 m³ (350 to 700 bbl) of oil in a 10-h day (Table 5). Although a spray boat can operate in sea states where skimming systems are ineffective, larger waves reduce its efficiency. The boat may have to decrease speed and the outboard nozzles may dip into the water. Larger boats roll less and can carry large amounts of dispersant.

Generally, boats spray a dilute dispersant solution. This permits more liquid to be sprayed in a pattern resistant to misting in high winds. Because the bow wave will move the oil aside, the spray boom should be mounted as far forward as possible.

Spray Planes

A large plane flying 140 kn (260 km/h) with a spray swath width of 100 m could cover 28.5 km² in 1 h. Thus, the capacity of the spray tanks—not area—is the controlling factor. The 20-m³ (130-bbl) tank of the ADDS (Airborne Dispersant Delivery System) package in a C-130 (Hercules) has been discussed before. Other fixed wing aircraft and helicopters have lesser capabilities (Table 6). Helicopters and small agriculture spray planes can carry from 0.5 to 2 m³ (3 to 13 bbl), while DC-4 and DC-6 aircraft can carry from 6 to 11 m³ (38 to 70 bbl).

The above analysis has assumed 100% dispersion of the slick. That is not generally the case except for low viscosity oils. Higher dispersant application rates might be required,

	Tank Volume		
Aircraft	m ³	bbl	
Various helicopters	0.4-2.3	2.4-14	
Agriculture spray planes (Piper Pawnee, Cessna Agtruck,			
Ayres Thrush)	0.4-1.1	2.4-7	
(Turbo Thrush)	1.5-2.6	10-17	
DC-3, Fokker F-27, Canadair CL-215	3.0-4.5	19-29	
Four-engine aircraft (DC-4, DC-6)	5.7-11.4	36-71	
Hercules C-130	20.8	130	

TABLE 6—Dispersant spray capabilities of various aircraft.^a

^a Modified from Ref 53.

and correspondingly larger spray capabilities for oils that are not so readily dispersible. Water-in-oil emulsion formation hinders or prevents effective chemical dispersion. Thus, to be effective, oil slicks should be sprayed before the oil incorporates water. Canevari [69] lists a number of crude oils and their relative water emulsifying tendencies.

In practice, if control of the entire slick is not possible, spraying should be directed to the slick closest to shore or nearest to a sensitive resource.

Oil Spill Control Decision Making

The previous sections have discussed the fate and biological effects of untreated and chemically dispersed oil, demonstrated that chemical dispersion is often the method of choice to minimize or eliminate adverse biological effects from stranded oil, and considered limitations of the various methods used to control oil spills. Figure 2 is an oil spill control discussion diagram that outlines the realistic available options and suggests an oil spill control strategy. If oil is spilled on offshore waters, its movement should be predicted based upon historical meteorological and oceanographic conditions for the season of year in which the spill has occurred.

If the oil slick is expected to move offshore and is not too close to shore, no action may be acceptable. Such a decision must be carefully made, however, because unexpected wind changes could cause the oil to strand or enter a sensitive shoreline area, and as time passes, both mechanical and chemical response methods are less effective on more weathered oil.



- [a] Small spills normally should be completely controlled, particularly if both mechanical and chemical methods are used. However under some conditions some oil may need to be removed from the shore. Is large spills, perturbatively 1500 to 4.800 m3 (10.000 to 50.000 bbh) per day, will be difficult to control.
- memory are used. Novever under some containors some the initial may need to be removed into in the same [b] Large splits, particularly 1,500 to 4,800 m3 (10,000 to 3),000 bbi) per day, will be difficult to control. Only large allorant spray systems are suitable, and some oil may still strand. [c] Appropriate methode should be used to clean shorelines and sensitive habitats. See, for example,
- [C] Appropriate methods should be used to clean shorelines and sensitive habitals. Se [67-70].

FIG. 2-Oil spill control decision diagram, modified from Ref 53.
Even if oil is spilled miles from shore, and calculated spill trajectories show no chance of significant amounts of oil stranding, the presence of a large population of seabirds may require spill control measures.

If an oil slick is moving toward shore with sensitive biological habitats, it is necessary to obtain information on the prevailing winds and sea states, the type of oil spilled, and an estimate of the amount of oil spilled. If the estimated spill volume is less than 160 m³ (1000 bbl), a choice can be made between mechanical recovery and dispersant spraying (if mechanical equipment is available and winds, waves, currents, and response time are suitable, and if spray planes are available and the oil dispersible) (lower left part of Fig. 2). If neither is available, the shoreline or sensitive habitats or both can be cleaned using appropriate methods such as suggested by API [67], ASTM guidelines, or the oil can be left to weather naturally.

Spills much over 160 m³ (1000 bbl), and certainly those of 4 760 m³ (30 000 bbl) or more, have little possibility of being controlled by mechanical means unless conditions are ideal (waves less than 1 m and surface currents less than 1 kn [1.8 km/h]) and a large amount of equipment is available. Dispersant application by large aircraft spraying systems would appear to be the only serious control possibility for large oil spills (lower right part of Fig. 2). Because it is unlikely that there will be sufficient mechanical equipment available to control larger oil spills, equipment that is available should be used to collect or divert spilled oil as it approaches critical locations.

Mechanical equipment can most effectively be used on spills of oil that are above their pour point, highly viscous, do not spread, or have formed a viscous mousse. If the oils have not spread, mechanical recovery devices have less area to cover.

Chemical dispersants, as discussed previously, are most effective when applied near the spill source before the oil weathers or incorporates water. However, if the oil remains dispersible after being on the water for several days or if the spill is close to shore, the oil slick should be sprayed before the oil reaches a shoreline or enters habitats known to be harmed by surface oil, even if it means spraying in shallow nearshore waters, bays, or estuaries. The studies presented earlier showed that less biological damage occurred from chemically dispersed oil than from untreated oil in these shoreline environments. If oil has entered a sensitive habitat, then the most appropriate cleanup techniques should be used [67] (ASTM guidelines); in some cases, dispersant application may be advisable.

Health hazards must be considered. Mechanical cleanup and spray boat personnel must be protected from volatile hydrocarbons when operating in an oil slick downwind near, for example, a well blowout. Special precautions must be taken if the oil and associated gas contain hydrogen sulfide (H_2S). Operations also must be outside the zone in which gas and air form an explosive mixture.

Planning for Dispersant Use

Many of the response decisions required during a spill can be made in advance. These will likely vary depending upon, among others, the probability of spills occurring, the kind of oil that may spill, water temperatures, meteorological and oceanographic conditions, and the resources to be protected.

Questions about the availability of dispersants and their effectiveness (based on laboratory tests) are fairly easy to answer. The principal oils produced or refined and transported in an area, and thus most likely to be spilled, can be tested for dispersant effectiveness in laboratory studies, using a range of water temperatures and salinities. These tests can identify the most effective dispersant(s). For example, an oil like Prudhoe Bay from Alaska can be tested at 0, 10, 20, and 30°C. It does not need to be tested for each water temperature for each region through which it is transported by tanker (that is, from Alaska to U.S. West Coast refineries, to Panama, and then on to U.S. Gulf and East Coast ports).

The dispersant use component of a spill response plan for local situations can also be developed in advance, just as for other response methods. Most areas or regions can or have now identified biologically sensitive areas, along with other economically important areas such as recreational beaches. Thus, the areas most in need of protection have been identified and response measures can be planned well in advance of any spill incident.

Chemical dispersion of oil spills can be a significant protective measure, and in some instances, the only effective method for controlling an oil spill. The use of chemical dispersants is routine in the United Kingdom. To be most effective, dispersant spraying must be initiated early, meaning that preapproval or quick concurrence for dispersant application by concerned governmental regulatory agencies is necessary.

Response to an oil spill should minimize environmental damage. The overall evaluation presented here shows that chemical dispersion reduces adverse effects compared with those that result from untreated oil when the oil strands. Concerns that dispersed oil would prove to be unacceptably toxic to marine biota have been generally shown to be exaggerated.

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Arnold Paddock¹

Field Experience with Dispersants for Oil Spills on Land

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ABSTRACT: When oil spills onto coastal water of the United States or leaks reach the inland waters, an elaborate set of U.S. federal and state regulations comes into effect under the National Contingency Plan (NCP). Ironically, when an oil discharge is confined to land alone, very few regulations exist. Although spills on land are quite frequent, they do not arouse the news media nor even local regulators, and the oil is often left in place. Dispersants, up to now not widely used, offer an economical and environmentally preferred option compared to other actions that might be taken.

Although the use of dispersants for oil spills on land has never been regulated under the NCP, spillers have been reluctant to use them on land as a result of the possible rainfall runoff into controlled waters. Under the NCP (Subpart H) revised as of 20 Nov. 1985, however, the attributes of a dispersant on land can now be considered along with the existing techniques of burning, plowing under, or hauling away.

Dispersants specifically formulated for use on contaminated soil have been on the market for over ten years. The first criterion for such a dispersant is that it must be compatible and effective with freshwater. Many of the most common dispersants on the market are for use on saltwater only. Other dispersant characteristics to be considered are emulsion stability and rapid biodegradability. Results of actual field experience on a wide variety of soil types, land uses, and topographies indicate that dispersant use on land can be effective.

KEY WORDS: dispersants, oil dispersants, oil spills, biodegradation

Discussion

Whereas the spreading pressure of the oilwater interface will cause an oil slick on water to be very thin and large in surface area, oil without water is just a viscous liquid that is repelled by the soil surface. The result is a confined area of damage with a thickness often as high as 0.5 m. This confinement significantly reduces the environmental impact of any specific leak, however, there may be hundreds of these events of 0.15 m³ or more occurring in the United States every day. The causes can be tank truck turnovers, valve leaks, storage tank overflows, pipeline leaks, or even vandalism. High volume pipelines are cathodically protected from corrosion and generally well maintained so their leaks, although grave and well publicized, are infrequent. Most of the pipeline length in the United States, however, is in gathering systems in the oil fields and they are old, not corrosion protected, and not as well maintained.

The emergency response to a land spill is to: (1) contain, (2) recover, and (3) clean up. Economically, there is an incentive to contain and recover a land spill even if there was no environmental responsibility since the value of "dirty" oil is still significant. Contain-

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ment can be done with simple earthen dams, and recovery is done with common oil field vacuum trucks and hoses. Small skimmers are often helpful but not necessary. Once the oil pool thickness gets below 2 to 5 cm, recovery is difficult, and the project moves into the cleanup phase.

There are several options for the cleanup phase. An extreme one is to "forget about it." Most of the land in the United States is privately owned, and it is customary for the spiller to pay a small penalty to the landowner and assume no other responsibility. The landowner generally will do nothing either since oil spills on land will go back to nature if one is patient enough. Spills on some federally controlled land are also settled by a penalty or fine, and as in the private case, no further action is taken. In the meanwhile, the spill will kill the flora it covers and will also be hazardous to animals which pass through it, or which eat the oiled vegetation.

The most expensive option, on the other extreme, is to scrape and replace the affected soil. Earth-moving equipment is expensive to operate and may cause environmental damage in accessing the site. In addition, there is the increasingly difficult problem of where to dispose of the oil-contaminated soil. The long-used tradition of just spreading it on unimproved roads has all but stopped. A refinery land farm, if nearby, is the best option for disposal, but if this is not available, the soil may have to be drummed and put into a hazardous waste disposal site. As a result of these expenses, this process is seldom accomplished.

A surprisingly common option is to burn the spill. In many oil-producing states permits to burn are requested and commonly granted. Even without a permit, some oil field hands say that lightning can strike from out of a clear sky. Lightning does not need a permit. Burning is, in practice, surprisingly incomplete in converting hydrocarbons to carbon dioxide and water and leaves a messy carbon residue. Often butane burners are used to sustain the fire. Although flagrantly unsafe, gasoline is often used for this purpose too.

Water hoses are often used to push the oil to lower recovery ponds. It is here that the oil/water immiscibility interferes, and the oil splatters without moving along.

Commercial sorbent materials or even straw are used to sorb up the oil. The spiller then accumulates the sorbent material for burning or disposal. This technique is effective with shallow pools of liquid, but an oil coating still exists on the ground or on the local vegetation. There is no protection for the cattle who will eat oil-soaked grass.

Another option is to till the oil spill into the soil. The oil will biodegrade by the action of anaerobic microbes in the soil with oxygen provided from dissolved oxygen in the rainfall. Nitrogen sources in the form of common fertilizers are often used too. Depending on the soil type and rainfall amount, biodegradation times given by the following reaction are generally measured in seasons or years:

$$C_xH_y + O_2 + NH_3 \rightarrow CO_2 + H_2O + cells$$

However, in spite of this treatment, black oil sometimes percolates to the surface leaving a visual scar as well as preventing the infiltration of oxygen-bearing rainfall, which further slows down the process of going back to nature.

Now, having evaluated several cleanup options, we can look at dispersants. Dispersants have been regulated in the past because they are toxic to fish. Even the least toxic dispersant will have some effect since the dispersed oil begins to biodegrade using dissolved oxygen in the water. It is the same dissolved oxygen that the fish normally breath, so they can suffocate if they cannot swim away from the affected area. Understandably, this entire toxicity question is moot on land. The authority of the NCP is under the Clean Water Act: therefore, the use of a dispersant on land is not specifically regulated in the United States. If the dispersant and oil are carried off by rainfall to a controlled inland waterway, it is regulated and prior approval should have been sought. As a result, the decision to use a dispersant has generally been relegated to only those spill sites suitably remote from controlled waters.

As of 20 Nov. 1985 the NCP has been modified whereby the use of dispersants on water can be approved by the On-Scene Coordinator (OSC) provided that the affected state and the Environmental Protection Agency (EPA) concurs with the use through their Regional Response Teams (RRTs). Now, where the states and EPA can jointly concur, the OSC has much of the information needed to make a judgement on a case-by-case basis. Therefore, not only is it more likely that dispersants will find more favor on land near waterways, but also their use for bank and shore cleaning can also be considered.

Another caution on the use of dispersants inland is that care must be taken to avoid interaction with shallow aquifers. Solvent-type products like gasoline should not be dispersed if usable water is near the surface since gasoline will penetrate the soil and lay on top of the aquifer water. As such, there are techniques to recover the gasoline from the aquifer. Crude oil, on the other hand, does not normally penetrate soil. If the oil is emulsified and dispersed, the resulting liquid does penetrate the soil, but our experience indicates that although the water penetrates as far as a metre or more, the filter action of the soil particles holds the emulsified oil within the top few centimetres from the surface. If an aquifer is within 2 or 3 m from the surface, the cleanup option of dispersing should be evaluated with respect to water quality and aquifer use. Since dispersants are only one of several options, it need not be expected that they are applicable on all inland oil discharges.

The advantages of dispersants to be considered are environmental soundness and economy. Rather than ending up as air pollution from burning or a pile of oil-soaked dirt to be responsible for, the spilled oil can be distributed into the top-most layers of soil for rapid biodegradation by the same techniques used for years in refinery land farms. The sight and smell of the spill is gone from the surface, as well as the hazards to flora and fauna. As for economy, after the "contain-and-recover" phase is completed, relatively little oil is left to be cleaned up, but it may spread over a wide area. Only a small amount of dispersant needs to be used, which explains why few companies produce materials for this limited market. Access to the area to be treated is done by laying hoses and using the additional distance of the hose spray; therefore, there is a minimum of intrusion to the area by the cleanup effort. The only equipment needed is a water truck with a side pump and hoses. The truck can stand off by a distance of several hundred metres, and as few as three men can clean up a 4000-m² area in less than 30 min.

Application of dispersants to oil spills on land differs from the more familial marine applications in that for a marine spill the dispersant is brought to the oil and water. For a spill on land, the dispersant and water are mixed first and then applied to the oil. In the field experience reported on here, the dispersant is diluted in freshwater to a concentration of between 2 and 4%. The water will not only be available to form the emulsion, but also by spraying out of the pressure hose in large volume, the mixing energy needed to form the emulsion is also provided. This is the equivalent to the wave action needed to form the dispersion on a marine spill.

In the example of field use given here the dispersant is the formulation called Petro-Green ADP-7 water-based dispersant concentrate. Although ADP-7 has been specifically formulated to work on oil spills on land, other freshwater-compatible dispersants could be used. The most commonly used marine dispersants, however, are not suited for terrestrial use as they are labeled "for saltwater use only."

There are two main tasks that dispersants can perform for an oil spill on land. In both cases the oil is emulsified so that it is water wet, thereby acting somewhat like water flowing

over or into soil. The first task is to move the oil along the surface if there is a chance to enhance recovery. The example of a normally dry creek is representative. If a water hose with just freshwater is used to flush the oil down the creek there will be much splattering, resulting in partial recovery and a messy looking creek because the oil will stick to any nonwet surface. By first emulsifying the oil, the creek bed can be cleaned, and the resulting emulsion can be accumulated in a temporary containment pond. A demulsifier can be added to float the reclaimable black oil to the surface.

At some point of a spill event the oil is well distributed over the land and on the vegetation and is neither economically nor easily recoverable. This is the opportunity for the second task of a dispersant which is to remove the environmental impact of the spilled oil without removing the oil. In the recovery example the emulsion was hosed so that it would flow downstream. In this application the emulsion is left in place or even pushed uphill by the force of the hose. In either case, oil adhering to bushes or grasses can be washed off. Highly volatile fractions in crude oil can damage plants or grasses by adsorption, however, if the crude oil is washed off quickly the plants can usually survive. This is important to protect the plants in the path of an oil spill since their survival is necessary to hold the soil and prevent later erosion.

Returning to the situation where the emulsion of oil and water is soaking into the soil, the dispersant needs to provide several characteristics that may not be present in a marine dispersant. Those characteristics are:

1. The dispersant must contain strong emulsifiers to break up a wide variety of crude oils. In situations where a spill has weathered, or if the crude was paraffinetic or asphaltic, it may be necessary to apply the dispersant mixed with water that is heated to about 70°C. In the oil field this may be accomplished by using a hot-oiler truck.

2. The dispersant must be biodegradable itself and also be compatible with freshwater, or saltwater. Although the dispersant is always diluted in freshwater for application, sometimes the oil discharge is accompanied by a discharge of salty produced water.

3. The dispersant must contain persistent fending surfactants to keep oil droplets from each other so that the oil does not reaglomerate and reappear on the surface as black oil. In an open water dispersion the oil droplets distribute throughout the water column and are not in close proximity. When dispersing oil into soil the discrete droplets never move very far away from each other.

4. The dispersant should contain some readily biodegradable surfactants that will attach to the oil droplets. Natural soil microbes are not readily attracted to crude oil. However, if a more natural food source is attached to the oil droplet it will attract soil microbes so that a digesting culture flourishes at the surface of the droplet. This technique speeds up the biodegradation time of the oil droplet itself.

5. Finally, the dispersant should contain persistant wetting agents so that rainfall will absorb into the soil providing the necessary dissolved oxygen for anaerobic biodegradation.

Until now we have only discussed the application of a dispersant onto oil on land. The revised NCP rules only help the OSC to make a judgement where there is a possibility that the dispersed oil may reach controlled waters. The revised rules, however, open up new possibilities to use the dispersant on the banks or shores of the water, or even to disperse rainbows on the water by direct dispersant application. A long length of river bank or lake shore that is fouled with oil may have an environmental impact that is great compared to the amount of oil present, since land animals must cross through the polluted zone to get to freshwater. Although the original restrictions against dispersant use were primarily to

protect aquatic life, the OSC must now weigh the impact on all the flora and fauna at a spill site.

No field experience of spraying dispersant onto a shore or bank from a boat is presented. Hopefully with the reasoned judgement towards responsible use, this technique will be used where needed.

Conclusions

Oil dispersants specifically formulated for use on oil discharges on land have been on the market for several years. They differ from other classes of oil dispersants because of the specific characteristics of the relationship between oil, water, and soil. Although not specifically regulated on land, the use of oil dispersants on land has been limited as a result of possible runoff into controlled waters. Recent changes in the NCP allow for local evaluations of the benefits and impacts of using a dispersant. Field experience using dispersants on oil spills on land has shown this technique to be an economic and environmentally sound approach to inland oil pollution.

The Effect of Elastomers on the Efficiency of Oil Spill Dispersants

REFERENCE: Waters, P. F., Hadermann, A. F., Lambrecht, L., "**The Effect of Elastomers** on the Efficiency of Oil Spill Dispersants," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018*, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 78–83.

ABSTRACT: The concept that an oil spill might be immobilized on the surface of a body of water and subsequently dispersed has been advanced. The exploratory studies reported here demonstrate that an ultrahigh molecular weight elastomer, known to retard oil spreading, can be used in conjunction with an oil soluble surfactant to disperse the oil in water. The elastomer retards the dispersibility of the oil to some extent, but at concentrations of the elastomer sufficient to prevent oil spreading there is still significant dispersion.

KEY WORDS: oil spills, polyisobutylene, molecular weight, dispersants, turbidity

This work was done as a result of an observation by Michael Flaherty, who suggested that it might be possible to contain an oil spill by the addition of a polymer to the oil and subsequently, to disperse the immobilized spill with one or more dispersants. The study was not designed to be an exhaustive investigation of dispersants, per se. The one and only objective of the work was to demonstrate that, within the time frame of the experiments, one elastomer and one surfactant were not incompatible in a limited set of circumstances, and thus the Flaherty concept had sufficient validity to warrant further study. The decision to use SPAN 80 was based on the suggestion of Merv Fingus that the probability of success would be improved if an oil soluble dispersant were used. Within the constrained objective of such an exploratory study the concentration of SPAN 80 was kept constant in the four hydrocarbon liquids selected, while a relatively low and a relatively high molecular weight elastomer, polyisobutylene (PIB), were used; the latter at two concentration levels. The effect of saline solution on the compatibility of the elastomer and the dispersant was studied in one oil.

Low concentrations of high molecular weight elastomers limit the spread of oil on the high seas, even in storm-driven waves of 2 to 3 m.⁴ By contrast, dispersants break up oil films and distribute the oil in the subsurface water. If the spreading of a newly spilled oil slick can be curtailed, it could, provided there were no antisynergism, be dispersed with less dispersant than might otherwise be required, because the elastomer-treated slick would cover less area. In the tests in footnote 4, the area of an untreated spill soon increased to that of six times the elastomer-treated spill of the same initial volume.

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⁴ Results of tests carried out in September 1987 with oil spills on the Atlantic Ocean communicated by Edward Tenneson.

Procedure

Equipment

A Yankee Variable Speed Rotator provided oscillatory motion at 112 cpm to mix the samples at ambient temperature in stoppered HACH cuvettes. The gentle oscillatory motion is likely to be much less energetic than the mixing energy available at sea, for example, but the difference is of no consequence here since the PIB used dissolves sufficiently in the oils, wet or dry, in less than 1 min. A HACH Model 2100 A turbidimeter, calibrated using a standard at 100 nephelometric turbidity units (NTU), was used to measure the turbidity of all samples.

Specimen Preparation

Stock solutions were prepared by adding the oil soluble surfactant SPAN 80 to each of the oils tested to provide 1% by weight solutions. To each oil sample (including the neat oils) sufficient PIB was added to yield solutions containing 500 and 1500 ppm of polymer. Elastomers with viscosity average molecular weights of 2.8 and 8.0 megadaltons were studied in commercial K1 kerosene, No. 2 fuel oil (U.S. EPA-API Reference Oil, WP 681), Arabian light crude oil (U.S. EPA-API Reference Oil, WP 681). The samples to be mixed were prepared as follows: To 0.024 kg of distilled water in a HACH cuvette 0.005 kg of test oil (containing SPAN 80 and PIB) was added. The stoppered cuvette was placed on the mixing table horizontally in such a manner that a 10^{-5} -m³ bubble of air shuttled from one end of the cuvette to the other during oscillation to promote mixing. After 300 s the cuvette was transferred immediately to the calibrated turbidimeter and turbidity readings (NTU) were recorded at 60-s intervals during 600 s.

Experimental Work

The turbidity measurements, recorded as a function of time, for the four oils, the dispersant dissolved in the oils, the elastomer dissolved in the oils, and both the dispersant and the elastomer dissolved in the oils and shaken with distilled water at ambient temperature are presented in Figs. 1 through 5. The results obtained upon mixing a treated oil with 3.5% saline solution are given in Fig. 6. Only those data are recorded which reveal the effects of the variables: dispersant, elastomer, elastomer molecular weight, elastomer concentration, and salt in the water on selected oils.

Results

Figure 1 shows that kerosene and No. 2 fuel oil disperse more readily in water than either Arabian or Prudhoe Bay crude oil, and Fig. 2 further shows that SPAN 80 disperses all oils to an extent greater than an order of magnitude beyond that which occurs without the dispersant.

Figure 3 reveals that kerosene can be dispersed in the presence of 1500 ppm of PIB. The 8-megadalton molecular weight elastomer has a slightly retarding effect on the dispersability while the 2.8-megadalton molecular weight PIB has a slightly enhancing effect.

Figures 4 and 5 illustrate the effects of 500- and 1500-ppm concentrations of 8-megadalton molecular weight PIB on the dispersability of the four oils tested. For No. 2 fuel oil and kerosene (Fig. 4) the dispersability was higher for the lower than for the higher concentration.



FIG. 2-Turbidity levels for four oil samples containing 1% dispersant.



FIG. 3—Turbidity levels for K1 kerosene containing 1% dispersant with 1500 ppm of 2.8 and 8.0-megadalton PIB.



FIG. 4—Turbidity levels for No. 2 fuel oil and K1 kerosene containing 1% dispersant and 500 and 1500-ppm of 8.0 megadalton PIB.



FIG. 5—Turbidity levels for Arabian light crude oil and Prudhoe Bay crude oil containing 1% dispersant and 500- and 1500-ppm of 8.0 megadalton PIB.



FIG. 6—Turbidity of No. 2 fuel oil containing 1% dispersant and 0-, 500-, and 1500-ppm of 8.0-megadalton PIB in 3.5% aqueous sodium chloride.

For the Arabian crude oil, whereas Fig. 2 shows that it disperses readily when there is no elastomer present, Fig. 5 reveals that the PIB greatly retards its dispersability.

The Prudhoe Bay crude oil is poorly dispersed, even with SPAN 80 present as seen in Fig. 2, and the PIB does affect its dispersability as shown in Fig. 5.

The dispersability of No. 2 fuel oil in 3.5% saline solution (Fig. 6) is greatly diminished from that measured in distilled water for solutions with and without PIB added. The higher concentration of the 8-megadalton molecular weight PIB has a greater retarding effect than the lower concentration.

Discussion

Ultrahigh molecular weight PIB has been shown to exhibit remarkable viscoelasticity in hydrocarbon liquids [1-4]. This property significantly impedes the spreading of oil on water surfaces. It was anticipated that this property of the polymer might forstall the ability of dispersants to disseminate oil spilled on the high seas if both were used simultaneously.

The results obtained here demonstrate that whereas the PIB does indeed retard the dispersability of the oils to some extent, at concentrations of polymer sufficient to impede the spread of oil, treatment with an oil soluble dispersant still promoted dispersion.

Conclusion

Further studies are required to delineate the concentrations of elastomers and dispersants that will be optimum for dispersing any spilled oil. The ultimate objective is to disperse the oil with minimal effort and materials and this, in turn, requires that there be a trade-off between the quantity of polymer used and the quantity of dispersant applied.

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Use of a Computerized Spill Response Tool for Emergency Response, Personnel Training, and Contingency Planning

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ABSTRACT: Under the aegis of the U.S. Environmental Protection Agency (EPA), a computerized decision tree (CDT) was developed in 1984 to assist On-Scene Coordinators (OSCs) during an oil spill incident in the decision-making process. Since that time the CDT has been expanded and refined for use not only in real-time spill response, but for personnel training and contingency planning.

The CDT has been distributed to EPA Regions, U.S. Coast Guard Districts, and other spill response officials in the United States and overseas. Its widespread acceptance, however, has been somewhat hampered by a lack of understanding of its maximum use beyond immediate spill response activities.

This paper describes enhancements that have been made to the CDT during the past three years, and its potential for applications in personnel training in both emergency situations and for contingency planning. In it possible extension of the CDT to hazardous materials incidents is also explored and other future plans for the CDT as a powerful tool in combatting environmental damages are discussed.

KEY WORDS: computerized decision tree, emergency response, decision making, personnel training, contingency planning, dispersants

Parallel technological advances in the late 1970s and early 1980s led to the development of innovative and effective countermeasures to combat the actual or potential threat of oil spills. The first major advancement was the new generation of chemical countermeasures with low toxicities and high levels of effectiveness. The value of these countermeasures was first recognized following the Ixtoc 1 Well blowout, which dumped 524 700 m³ (3.3 million barrels) of oil into the Gulf of Mexico between June 1979 and March 1980. Fixedwing aircraft applied dispersants to the spill and less than 1% of the oil reached the Texas coast. Dispersants were somewhat restored to respectability after having been consigned to an environmental limbo following their disastrous use in the wake of the 1967 Torrey Canyon wreck [1]. The past few years have seen improvements not only to dispersants themselves but to the delivery systems through which they are applied to spilled oil. Guesswork has been replaced by sophisticated spray systems and controlled metering to permit accurate distribution of the dispersant on the spill surface. Furthermore, a greater under-

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standing of application vehicles has been developed, and helicopters, fixed-wing aircraft, or boats are now used according to the specific situation at hand. The past few years have also witnessed the emergence of a new breed of chemical countermeasures that can be used alone or in combination with each other to mitigate, control, and clean up oil spills more efficiently than was ever thought possible 20 years ago [2].

Concurrently with the efforts of the international chemical industry to put on the market low toxicity, functional products to deal with oil spill pollution, other researchers were working on ideas on how use of these products could be optimized. The products presented a viable alternative to the mechanical methods traditionally employed, which were always limited by sea states. Researchers realized that as these products grew in numbers and diversity of composition, it would not be possible for every On-Scene Coordinator (OSC) to memorize the exact characteristics of each and, thus, know exactly what product should be applied to what kind of spill in any given scenario.

Researchers from governments, the oil industry, and private organizations, therefore, put forth various proposals for introducing orderly decision-making processes to spill response. Although nomenclatures and formats differed, the "decision trees" all had the same general purpose of guiding an OSC through a series of steps in combating an oil pollution incident [3]. Some "decision trees" were extremely simplistic, while others were extraordinarily complicated. Some dealt strictly with dispersant use [4-10], while others included mechanical methods and other alternatives [11-15]. By 1984, the U.S. Environmental Protection Agency (EPA) had recognized the need for a database of spill countermeasure technology that could be constantly updated and refined to reflect new products and processes and could provide OSCs with all the complete, accurate information necessary for speedy, effective spill response.

The Computerized Decision Tree (CDT)

The Computerized Decision Tree (CDT) was developed by L. Michael Flaherty, the then Chief of EPA's Chemical Countermeasures Section and A. G. Hansen of Analysis Group, Incorporated (AGI). Originally intended as a tool for determining the timely and optimal use of chemical countermeasures during and, in concept, even at the scene of an oil spill, the scope of the CDT expanded over time to include unique capabilities for contingency planning and personnel training.

The CDT was first presented at the Los Angeles Oil Spill Conference in 1985. It was refined following suggestions from government and private specialists in spill response, and the revised version was presented to EPA field operations and U.S. Coast Guard (USCG) officials in 1986. Other test demonstrations were given at EPA Regional Response Team (RRT) meetings in Kona, Hawaii and St. Thomas, Virgin Islands. The CDT was again expanded and modified during 1986 with input from EPA Headquarters, RRTs, the National Response Team (NRT), USCG, the National Oceanic and Atmospheric Administration (NOAA), the American Petroleum Institute (API), and other government and industry representatives. The improved version of the CDT was then presented at the 1987 Oil Spill Conference, held in Baltimore, Maryland [16].

A generalized flowchart of the CDT is given in Fig. 1. Software for the CDT is written in the BASIC programming language, and the program has been converted for use on the C3 microcomputer, which is standard equipment throughout the USCG. The system is menu driven, so the operator does not have to memorize any commands. Because of its modular form, it can be easily updated or revised.

When the program begins, the user is presented with several paragraphs of text that describe the CDT purpose and use. The user is then presented with a series of questions



FIG. 1—Flowchart of the decision tree.

related to the oil spill and the environment. As each question is answered, the program branches to the appropriate follow-on question, omitting questions that are irrelevant because of answers previously given. The CDT has several unique features, including: (1) the ability to print out the entire decision process or any portion thereof while the user is inputting information; (2) the capability to review a decision and to change the response to questions as necessary; (3) the ability to insert comments into the printed output (for justifications, caveats, or other items); (4) the complete National Contingency Plan (NCP) Product Schedule, which provides technical and scientific data on all dispersants and other chemical countermeasures listed by EPA; (5) the capability to highlight the path taken and superimpose this on the entire process flowchart; (6) on-line help files to explain in greater detail the meaning of each question being asked and to provide additional background information; and (7) a checklist for gathering data during an oil spill response. The CDT, however, is not just step-by-step decision making but has many special features that provide invaluable information and documentation. These include, for example, a colorometric description of the sheen, which explains the nature of the oil spilled, and calculations for analyzing the color and thickness of the sheen which can thereby estimate the number of cubic metres or gallons spilled.

The principal attraction of the CDT, in the context of U.S. Government regulations, at least, remains the speed with which the spill response mechanism can become operational. The procedures involved in convening an RRT previously required one to one and a half days to complete. Now, through use of matching software and telephone hookups, the entire process can be completed in an hour or two.

Use of the CDT in Contingency Planning

Contingency planning is the cornerstone of any successful environmental protection program. The CDT can play a major role in contingency planning by providing information and guidelines for quick, beneficial action. Further, the versatility of the system means that it can be modified and adapted to suit the particular environmental scenarios encountered in a given body of water, state, or region. For example, for inland states, detailed data on high sea states, and water salinity levels may be extraneous. Response officials in these areas might wish to see the CDT include data on the treatment of oil spills in freshwater along the lines of research conducted by the Canadian Freshwater Oilspill Research Program (FOSRP) [17].

Contingency planning for coastal states would require other priorities, however, given the fact that dispersal of oil on the sea is of paramount importance to protect the shoreline. The U.S. National Contingency Plan, for example, requires that dispersants, biological additives, and surface collection agents may only be applied after the consent of EPA, USCG, and the state whose waters are affected is obtained. Florida led the way in signing consent agreements with EPA and USCG to give the first responder the opportunity to use dispersants in designated areas before notifying the state, although permission to continue use is still mandatory. Other coastal states have followed suit. Thus, the quality and scope of data contained in the CDT permit the state to relax notification requirements in the interests of speeding spill response even further. Also note that the NCP does not require consent or consensus of the RRT for the first responder to use the new "miscellaneous" countermeasures (gels, elastomers, colloidal suspension agents), which thus grants him/her greater latitude in handling speedy emergency response. The merits of both the new products and the state-Federal pre-event agreements will be determined through experience, and there is a possibility that other states may enter into agreements permitting OSCs greater freedom in first response decision making.

For contingency planning purposes, the CDT is updated every six months to show data on new products, application techniques, and safety methods. One of the new efforts currently underway is to gather laboratory test information on the dispersibility of approximately 40 different crude oils transported through U.S. waters.

Electronic mail could also be used to provide a network for decision tree users to correspond with each other to discuss the CDT, problems encountered with it, and even to use the program simultaneously at different locations. A program could also be initiated through implementing the CDT on a multiuser computer system, where the OSC has program control, and other RRT members are able to view the decision process on individual screens while discussing response alternatives through telephone conferencing.

Personnel Training Using the CDT

The CDT is now in all EPA Regional offices and in all USCG District offices. The entire National Response Team (composed of 13 U.S. Federal Government agencies) has copies of it, and NOAA has sent it to all its Regional offices. To date there has not been general distribution to the states, although some have requested and received copies, minus the product information.

An enthusiastic response to the CDT presentation at the Baltimore Oil Spill Conference in 1987 included requests for training in the autumn of 1987 from the Governments of France and Bermuda which have subsequently been completed. Bahrain and the Bahamas have also expressed serious interest in training. Generalized training for EPA and USCG personnel began in the summer of 1988.

Comprehensive, ongoing training is an absolute necessity if the CDT is going to achieve the widespread results of which it is capable. This is especially true for the USCG, where regular transfers lead to rapid personnel turnovers. Furthermore, lack of knowledge about the CDT means that some response personnel may be reluctant to use it, preferring to rely on older manual methods. Initial training, therefore, should stress the speed with which the CDT can activate the response mechanism. Quarterly followups in which response personnel practice on the CDT using a variety of scenarios are recommended to maintain user familiarity with the system.

As has been mentioned previously, the CDT has support data to assist an OSC in the decision-making process. Again, the visual acumen and response experience of the OSC can be assisted by the CDT's ability to perform rapid calculations. The CDT, after all, is a guideline and not a rule book (although certain help modes do contain important regulations, reporting requirements, and other significant references).

Of special significance is the CDT's ability to keep pace with new products. There are now, for example, 28 dispersants, 4 surface collecting agents, 9 biological additives, and 6 miscellaneous chemical products on the NCP Product Schedule. To memorize the composition and performance of each product would be a formidable task. Yet, based on detailed data available from the CDT, a decision on each product can be made with confidence in a very short period of time.

Training has another important aspect; namely, that the CDT cannot be developed to a stage of maximum effectiveness without input from the people who use its services. For example, the CDT is composed of two floppy discs. Disk 1 contains the entire decision tree process plus it lists all dispersants and other chemical countermeasures cross-indexed by type, brand name, and manufacturer's name. Disk 2 of the CDT has only product formulas and detailed findings on effectiveness and toxicity, which are for *official use only*. The expansion of the CDT to include freshwater spill data, application techniques, precautions for use, or other factors will depend to a great degree on feedback received from the trainees and users of the CDT.

Discussion

Increased awareness of environmental pollution has led governments, industry, and private organizations to seek new technology in preventing, mitigating, and controlling oil pollution incidents. Among the tools that have been developed is a Computerized Decision Tree (CDT) for use in decision making for oil spill emergency response. Originally envisioned as a step-by-step guide for On-Scene Coordinators (OSCs) at the site of an oil spill, the CDT's use has now been recognized as an effective mechanism for utilizing new spill countermeasures, such as dispersants, biological additives, surface collection agents, and a new group of miscellaneous products, such as gelling agents, colloidal suspension agents, and viscoelastic enhancing agents. These products, currently listed in the NCP Product Schedule's Miscellaneous category, appear to be a completely new breed of oil spill countermeasures. They have been found to be almost totally nontoxic and highly biodegradable. While, like all other products, their effectiveness is somewhat limited by sea states and application techniques, they have the potential for use in many situations involving oil spill response and clean up.

While the theory of the CDT has received international acceptance, it is important that its capabilities in training and contingency planning be explored further. Spill response personnel should be trained in its maximum use and, most importantly, trained to overcome any lack of general computer knowledge on the part of some and lack of specific CDT awareness on the part of others. It must be emphasized that the CDT is a guide, not a set of instructions; that it provides information that previously was based only on educated guesses; that it permits assembly of Regional Response Teams within a fraction of the time previously required; and that it maintains updated data on new products and procedures that have generally proven effective in combating oil pollution of navigable waters. The CDT also makes available instantaneously OSC's data on new products and processes. The CDT can also provide thorough documentation of specific decisions that were made throughout the response action.

Note that the CDT was developed in conjunction with the most knowledgeable individuals in oil spill response from such agencies as the EPA, U.S. Coast Guard, the National Oceanic and Atmospheric Administration, the Fish and Wildlife Service, and Environment Canada, to mention a few.

In conclusion, all presentations of the Computerized Decision Tree have met with positive, enthusiastic responses both nationally and internationally. The age of computerization is here, and acceptance of new uses, improved procedures, and advanced techniques can only enhance our capabilities to prevent pollution of the environment in which we live.

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The Crisis in Response Training

REFERENCE: Kaufmann, S., "The Crisis in Response Training," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018,* L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 91–97.

ABSTRACT: The need for training of first responders, contractors, government agencies, and insurance companies to use chemical dispersants effectively is demonstrated by the loss of opportunities both to reduce cleanup costs and to gain helpful data in evaluating the advantages of using dispersants. The interest shown in a new method of training in the use of chemical countermeasures emphasizes the need to be prepared to use them on actual spills as they occur.

KEY WORDS: response training, chemical dispersants, oil spills

With the publication of Subpart H of the National Contingency Plan by the U.S. Environmental Protection Agency (EPA), it was expected that the use of dispersants would be regularly authorized for use on oil discharges and it would become feasible to consider realistically chemical dispersants and other chemical countermeasures for oil spill control. However, because there are very few people in this country, among both enforcers and responders, who have adequate experience in the application of dispersants, just as there was a need to train workers to deploy booms and skimmers in the early 1970s.

To fill this need, training in the *practical* use of oil spill dispersants should be, and—in some cases—is now being undertaken by cooperatives, contractors, and government agencies. The excellent EPA "Oil Spill Countermeasure Decision Tree" computer program is widely known and available from the EPA and their regional offices as well as the U.S. Coast Guard districts. The demand for training becomes more urgent when opportunities for chemical countermeasure use on "spills of opportunity" have been missed as a result of a lack of knowledge and experience by the early responders, spillers, and their insurance carriers.

Virgin Islands Oil Spill

One example of the need for adequate training occurred during a major spill of black fuel oil in the Virgin Islands in 1986, under weather conditions that made use of the containment booms, which were on hand, less than optimum, in a strong southwest wind and a harbor wide open in this direction. The operator of the barge *St. Thomas*, a respected international terminal operator, had on hand a large quantity of spill response equipment, including booms, skimmers, sorbents, and a considerable quantity of EPA-listed dispersant. Environmental conditions resulted in ineffective booming which therefore precluded

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effective skimming. As a result, the cleanup cost of 24 000 gal (90 000 L) of oil exceeded \$1 000 000, more than \$41.66 per gallon, or \$1750 per barrel!

The opportunity to use dispersants and evaluate the result under multiagency supervision was lost because none of the representatives on-scene were familiar with current EPA policy and had no training or experience in dispersant use. Local citizens proceeded to use dispersants to restore the ambiance of their facilities until they ran out of drums and were stopped by the On-Scene Coordinator (OSC) staff. Although no government agency with jurisdiction in this U.S. paradise failed to send representatives, none had the training or experience to consider realistically the use of dispersant chemicals, which were on hand, for this "spill of opportunity."

The loss of the opportunity to observe the use of dispersant on this and numerous other spills shows that there is a critical need for training. The early responders already know that booms are not completely effective, and other response methods are needed to prevent the "caveman" tactics of allowing the oil to strand on the shore and picking it up with shovels and sorbents. Not only is there a need for training, but there is also a critical need for real-life data which will result from the use of dispersants on such spills.

Training Session

The training session which is the subject of this paper was initiated by the Virgin Islands Department of Conservation and Cultural Affairs (DCCA) when they realized, following the major oil spill debacle, that there had to be a better way to protect their "American Paradise." Although local handlers of petroleum products possessed an adequate quantity of protective gear, there had been a lack of communication and coordination between the various government agencies. To remedy this problem and prevent future accidental spills from turning into disasters, DCCA contacted the EPA and a contractor to conduct handson training and work on implementing government/industry cooperation.

The planning for this training was done by DCCA. It included the Public Safety Departments of Police and Fire, Civil Defense, Water and Power (which included the desalinization plant on which the island depends for drinking water), and the governments of nearby islands, including the British Virgin Islands and the Netherlands Antilles; the federal government was represented by the EPA and Coast Guard.

Initially the training was planned for 50 attendees, but when the word got around that new technology, especially the use of dispersants, would be included, the demand for space increased dramatically. The last reservation count was 100, but 120 persons showed up (Fig. 1). There is never a problem to get "stateside" government agencies to attend meetings in the Virgin Islands, but these were all *locals* (plus 2 interested observers from Puerto Rico). It illustrates the pent-up demand for training in this new field of chemical countermeasures!

Following the introductory session, the question was raised: why had chemical dispersants not been used for the recent major spill? Chief Enforcement Officer Joseph Sutton answered that the method was never considered because the On-Scene Commander and his scientific adviser gave the impression that it was undesirable and illegal; the Virgin Islander did not know that he had local authority over any such decision. He had somehow expected the "feds" to fly in with expertise and money and magically clean up the spill. Instead, there was delay and aggravation, as the spill increased by at least 100 barrels because of the failure of a "patch" solution. The need for local knowledge and input was clearly evident.

The first day of training included much theory on the use of many types of spill response equipment and its relation to successful cleanup and restoration of areas impacted by accidental oil spillage. Demonstrations were used to show applications, and slides and video-



FIG. 1-Virgin Islands DCCA training group at Sunshine Technology site.

tapes illustrated training methods and case histories of other spills. One of the most useful aids is the EPA's "Oil Spill Countermeasure Decision Tree" computer program, which leads the operator through a variety of options to decide, on the basis of government and public policy, what the method of cleanup should be. Unlike so many other "decision trees," this program is firmly directed toward the use of chemical countermeasures when they are appropriate. The decision tree considers size of the spill, sea state, and other environmental factors. It is a great help to those who are inexperienced in the use of dispersants.

Hands-On Training

Even more important than learning the legal basis for dispersant use is the hands-on training which requires every attendee to assist in

- (1) layout of the training area
 - a. realistic location
 - b. visible to all trainees and general public, for media coverage
 - c. double-boomed for environmental protection
- (2) creation of a training "spill"
 - a. classroom demo on overhead projector
 - b. use of actual oil to be dispersed
 - c. obtaining permission
- (3) detection and measurement of spills
 - a. taking legal samples for identification of "mystery" spills (Fig. 2)
 - b. measuring surface film thickness
 - c. finding oil spills during hours of darkness
 - d. using the Field Dispersant Effectiveness Test to determine suitability of dispersant



FIG. 2-Sampling of oil slick for identification and possible legal action.

- (4) demonstration of physical equipment
 - a. booms (Fig. 3)
 - b. skimmers
 - c. sorbents
- (5) types of dispersant application equipment
 - a. small fuel spill sprayer
 - b. educators



FIG. 3—Deployment of Sea Broom containment directed by EPA official.



FIG. 4—Treatment of simulated harbor oil spill with chemical dispersant.

- c. Warren Springs gear
- d. Hovercraft
- e. helicopters and fixed wing aircraft
- (6) types of chemical countermeasures (Figs. 4 and 5)
 - a. dispersants: differences between commercial products
 - b. surface collecting agents
 - c. viscoelasticity enhancing agents



FIG. 5—Application of elastolizing agent to oil spill for increased recovery efficiency.



FIG. 6-Recovery and final polishing of training spill site.

- (7) hands-on involvement of trainees
 - a. dispersing boomed slick with eductor
 - b. spraying slick in training tank with fuel spill sprayer
 - c. learning appearance of dispersed oil
- (8) polishing of the spill area (Fig. 6) following the drill, using
 - a. dispersant
 - b. sorbent
 - c. boom cleanup and recovery

Among the considerations covered are:

- (1) the cooperation of the various regulatory agencies,
- (2) the education of the clean-up contractor, and

(3) the willingness of the spiller and his representatives (including insurance "loss con-

trol" engineers) to be at the leading edge of spill control technology.

Benefits of Training Program

One of the major benefits of the training program is the presence, among the 120 attendees in this instance, of regulators, enforcement officers, petroleum facility employees, contractors and the media. The interaction of this group is of great value, because they have the opportunity to meet and talk without the pressure of a spill situation and its spirit of confrontation. The meeting of persons with a common interest in a locality fosters cooperation which is of immense value in the future.

The training emphasizes the importance of timely decision making. Round-robin conferences can be very costly, on the order of \$1000 per minute, when they are held while the oil slick is spreading. Delays can quickly take such decision making out of the hands of the authorities and the responders once a spill has spread over a large area, impacted the environment, including bird and wildlife, and stranded on miles of shoreline. All instructors and trainees have the common goal of minimizing the environmental impact of oil spills. Dispersant use is a spill control method that should not be considered as a "last resort" after other methods have failed. Instead, it should be considered as a major spill control method to reduce the impact of spilled oil on sensitive environments. Dispersed oil is in the water column only a relatively short period of time, but stranded oil has a more severe, long-term effect on the shoreline. Birds, marine mammals, mangroves, marshes, sea grasses, coral reefs, rocky shores, and other habitats, along with amenity beaches and commercial harbors, can be protected from the impact of floating oil slicks by the use of dispersants.

Follow-Up

The importance of this realistic on-site training is brought out by a follow-up to the Virgin Island report. One year after the training program, the Regional Response Team (RRT) held an On-Scene Coordinator/RRT Simulation in St. Thomas. The majority of the participants flew in from their offices in the continental states, and their responses during the "simulation" were virtually the same as during the real spill. The chaotic realm of human decisions overtook the OSC; he again was enmeshed by advisers and let them run the show resulting in the treatment of humankind as an intrusion upon nature rather than as a special part of it. The result of this "simulation," for the Virgin Islanders, was the same as the real thing: another disaster!

The benefits of the training were quite evident. People who have participated in these efforts are prone to reflect after a time on what has been accomplished. The local authorities expressed the hope that there would not be another "spill of opportunity," but now they are prepared to make a proper local response to this crisis. In this respect, all the activity has clearly achieved an important success: They will continue to train, and they will protect their own environment.

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A Computer-Assisted Planning System for Oil Spill Response Chemical Applications

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ABSTRACT: The microcomputer is a very useful oilspill response tool: It can help the spill contingency planner organize and present a wide variety of information; it can help the spill response trainer create realistic scenarios and models of spill events; and it can help the spill response operations manager optimize operational decisions and expedite a variety of communications. This paper suggests some specific ways microcomputers can help plan for and respond to oil spills, and it focuses on a computer program written to help expedite operational decisions and optimize operations for the chemical dispersion of spilled oil in Alaskan waters.

KEY WORDS: dispersants, oil spills, computers, models, Alaska

Computer Applications in Contingency Planning and Oil Spill Response

Below are some examples that illustrate the variety of potential applications for microcomputers in combating oil spills.

Trajectory Modeling

Many application programs have been written for modeling the movement and chemical fate of spilled oil. Such programs can be designed to perform either or both of two distinct functions. First, trajectory models can be used with hypothetical spill events to help planners predict possible outcomes and impacts and their relative probabilities. Such modeling can help planners and managers decide what equipment should be in their inventories and where it should be located. The same models can be used to construct scenarios for training exercises. The second function for trajectory models is to provide estimates of the location of an oil slick at any given time after an actual spill event and to predict the time, location, and severity of shoreline impacts.

Trajectory model programs have evolved over the years with increasing sophistication. They now may include such features as files of historic weather and sea state data and the capability to include factors such as surface and subsurface current predictions, probable sea ice distribution and its effects on oil movement, Coriolis effect, and oil weathering. For use in training scenarios or for an actual spill event, programs can be used interactively permitting the operator to input actual weather, current, and sea state information and to consider oil removed from the environment through response actions.

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Inventories

Inventories of spill response equipment and materials are maintained by a variety of government and private organizations. Generally the owners of these spill response assets have procedures whereby they can be made available to others if needed.

Access to various spill response assets can be expedited if data on these assets are maintained in a computer database with such information as quantities, locations, ownership, and procedures for obtaining. For efficiency, such data might be maintained on a regional basis in a database that can be remotely read by anyone with a computer and a modem. To facilitate collecting information for this database from the various owners, use by all parties of a standardized inventory data format should be considered. The system should be arranged so that anyone phoning in can download (read) the data, but contents of the database can only be changed by a control operator or the owners of the affected equipment and materials.

A microcomputer can also help in the periodic checking of inventory lists of equipment, supplies, and repair parts. For example, after inventory listings are entered into a database, the database can be used to print out inventory labels for each item bearing computer readable bar codes. Attachment of these labels would be part of the next periodic inventory, and subsequent inventories would be conducted by scanning the labels with a bar code reader attached to a portable microcomputer.

Spill Reporting

In a given spill situation several agencies may require spill reports. Various federal, state, and local agencies each have a need to know particulars of spills within their respective jurisdictions, and each may have different specified reporting format requirements. A microcomputer program can facilitate rapid compliance with varied spill reporting requirements. The program would request input from the operator on such things as quantity and type of material spilled, location, and so forth, and based on stored information on regulatory and procedural requirements, print out reports for each concerned agency in the proper format. While doing this, the program could also build a database of spill statistics for subsequent review and analysis. Consideration might be given to improved standardization of spill reporting requirements and use of computer communication nets such as "E-Mail" for filing initial and follow-up spill reports.

Response Decision Making

Artificial intelligence systems could provide spill response managers with a rapid review of available equipment, manpower, and response techniques. The system could help in analysis of the various response options and selection of the course of action for optimum use of resources.

Records and Communications

Oil spill operations managers have a variety of communications needs. For example, response team members (who may be widely scattered geographically) can be kept current with events surrounding a spill through use of a phone-in computer data system [1]. Contingency plans frequently call for a daily "morning report" to senior management and staff that summarizes activities for the previous 24 h and provides a channel for reporting problems and logistics needs. Such reports provide a valuable history of operations for subse-

quent analysis. Software is available for encrypting such reports if secure communication is needed.

CADA: A Program for Computer-Assisted Dispersant Application

This section describes a computer program prepared to help spill response operations managers quickly make decisions about application of dispersants once government approval for dispersant use has been received. This program is an example of the software that can be developed to help solve spill response problems.

Fresh oil is generally much more responsive to the action of chemical dispersing agents than is weathered oil. With few exceptions, any significant delay in application of dispersing agents can be expected to reduce their effectiveness, and at some point if delays continue the shoreline and wildlife protection afforded by dispersants will be lost altogether. Concern over the loss of valuable time during the approval process is producing efforts to expedite that process, including at least one computer program to guide decision makers through the necessary steps involved [2]. Once applicable agencies have approved dispersant use, the spill response operator must be prepared to act quickly and decisively.

Decisions regarding dispersant use facing the response operator are not trivial. What dispersant chemical should be used? What aerial or surface vessel application system is



FIG. 1—CADA logic diagram (somewhat simplified).

most appropriate for the spill? What locations are available for equipment to operate from, and which locations offer most in speed and efficiency? Pumping rates must be chosen, and strategies must be selected to optimize application efforts.

Recognizing the complexity of these questions and the need for quick operational decisions, Alaska Clean Seas (a spill response organization cooperatively funded by a number of petroleum companies) has produced a manual that covers in detail the information required for such decisions for spills in Alaskan waters [3]. To expedite further the decision process, Alaska Clean Seas has undertaken to prepare microcomputer software, based largely on material in the manual, to guide and assist response operations managers with optimization of dispersant application decisions. The software is discussed here to illustrate one approach. Each region has its own set of problems and requirements, but this example, developed for Alaska, may help suggest parallel approaches to problems in other environments.

The software described here is called "CADA," an acronym for Computer-Assisted Dispersant Application. It is written in the Pascal programming language.

Figure 1 is a somewhat simplified logic diagram showing the steps taken by the computer under direction of the program found in the CADA.COM file on the distribution diskette. (The distribution diskette for CADA includes several files that perform various functions. These files are listed and discussed in Table 1.) The various steps in the program as shown on the logic diagram are discussed below.

1. Select next nearest base. A number of Alaskan locations have been selected which could be used for logistics support for spill response operations. Data on these potential

The distribution diskette for CADA contains several files that are listed and discussed below.	
CADA.COM	A core program that (a) displays the software's main menu, (b) provides access to the various supporting programs and files on the diskette, (c) calculates parameters of interest, and (d) outputs guidance to the operator.
OPBASES.DAT	A database file that contains data associated with various potential bases of operation. Included are geographic position (latitude and longitude), delivery vehicles and dispersants on hand, and time required to deploy delivery vehicles and dispersants to the base if local stocks are nonexistent or insufficient for an entire operation.
VEHICLES.DAT	A database file that contains information on characteristics of various dispersant delivery vehicles and associated spray systems. Data include speeds during application and while transiting between the spill site and the base of operations, payloads, the range of pumping rates that can be achieved, and the effective swath width from recommended application altitudes.
CHEMICAL.DAT	A database file that contains information on characteristics of various chemical dispersants. Included are data on recommended dispersant- to-oil ratios for use with different oils.
OPBASES.COM	A program file that can create the file OPBASES.DAT or modify its contents.
VEHICLES.COM	A program file that can create the file VEHICLES.DAT or modify its contents.
CHEMICAL.COM	A program file that can create the file CHEMICAL.DAT or modify its contents.
COMMENTS.TXT READ.ME	Text file that contains various aids and advisories. Text file that contains directions for use of the CADA program.

TABLE 1—Files on CADA distribution diskette.

support bases are included in the database file, OPBASES.DAT, on the distribution diskette. The latitude and longitude of each potential base, together with operator input data on the latitude and longitude of the spill, are used for calculation of the distances between the spill site and each potential support base. Data on each base are then indexed in accordance with distances from the spill site, and the program takes each base in order, from the nearest to the farthest, as it works through the logic scheme.

2. Select next dispersant delivery vehicle set and determine time to deploy it to the base. The OPBASES.DAT file contains a list of all vehicle sets (that is, groups of one or more identical surface or aerial delivery systems) that might potentially operate from each listed base. Included are data on how many of each kind of dispersant application system are ordinarily immediately available and how much time would be required for deployment to the base if equipment would have to be brought in. These data are extracted and organized in temporary buffers for each vehicle set in turn.

3. Select next suitable dispersant and determine dispersant-to-oil ratio (DOR) dose rate. The file OPBASES.DAT also contains a list of all chemical dispersants that might potentially be used at each listed base. Included are data on how much of each kind of dispersant is ordinarily immediately available and how much time would be required for transportation if chemicals would have to be brought in. These data are extracted and organized in temporary buffers for each dispersant in turn.

4. Check dispersant suitability with oil and determine DOR dose rate. The file, CHEM-ICAL.DAT, contains data on the suitability of using each of the listed dispersant chemicals to disperse several different types of spilled oil. Recommended DORs are provided for each dispersant-oil combination considered suitable. The operator inputs information on the type of oil and the average thickness of the slick. From this information suitability is established and a dosage rate is determined where applicable.

5. Dosage rate (dr) < 20 gal/acre? (about 20 μ m). Experience has shown it to be impractical to apply oil to thick slicks where the recommended DOR would require application rates in excess of about 20 gal/acre (approximately 20 μ m). If this situation is encountered, the program advises the operator to consider waiting until natural spreading thins the slick.

6. Calculate real application rate, number of passes required to achieve the required rate with the selected equipment, and the total time for the mission. The file VEHICLES.DAT has information on such factors as dispersant payload, the range of dispersant pumping rates achievable, average speeds of the vehicle during dispersant application and while transiting between the spill site and the base of operations, fuel capacities, fuel consumption rates, turnaround times required for refueling and for refilling dispersant tanks (these two refill problems are worked together), effective swath width, and so forth. The program seeks to adjust variable parameters such as speed and pump rate within allowable limits so that the recommended application rate can be achieved in just one pass. Where this cannot be done, factors are adjusted so that the number of passes (N_i) is the smallest feasible integer.

7. Print. Various pertinent data, including total time (T_t) required for the operation, are calculated and are output to a line printer for each run.

8. Save data on best run. Compare the total mission time (T_i) with the best previous T_i , and data relating to the best (shortest total time to complete the operation) are temporarily saved in a buffer.

9. Last dispersant? In this step the computer determines whether the dispersant just examined was the last in the CHEMICAL.DAT database. If so, the program goes on to Step 10. If not, the program returns to Step 3.

10. Last vehicle? After the dispersant list is exhausted then the next vehicle in turn (if any) is selected and all applicable dispersants are again examined by the program.
11. Last base? When all combinations of vehicles and dispersants have been examined for a given base, the next base on the list is selected and the process repeated until all bases have been examined.

12. *Print advisory notes.* For example, if none of the iterations found a suitable application rate an advisory note is outputted to the screen or printer or both describing the situation and making recommendations.

13. Print data on solution with best time. The data on the run with the best time (if any) are extracted from the buffer, organized, and outputted to the screen or line printer or both.

Future Development

As dispersant tests refine recommended dosage rates, or as changes occur in assets available for particular bases of operation, pertinent files can be revised. Various model refinements might also be made. For example, routines could be added to estimate operational costs as well as time required for each mission, procedures could be added to account for weathering of the spilled oil over time, and the model might be combined with a trajectory model which would predict the locations and chemical fate of dispersed oil within the water column as well as any undispersed floating oil.

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Approaches to Planning for Dispersant Use in Oil Spill Response

REFERENCE: Lindstedt-Siva, J., "Approaches to Planning for Dispersant Use in Oil Spill Response," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 104–113.*

ABSTRACT: Using dispersants to control oil spills has been highly controversial since the 1967 Torrey Canyon spill. Since that time many spill responders have viewed dispersants only as a "last resort" option. Dispersant use is most effective in the early stages of an oil spill, yet most response plans call for dispersant use decisions to be made only after a spill occurs. These decisions require, at a minimum, hours, and may require days. Recently, there have been efforts to shorten this decision-making process. Two of these are discussed in detail. A multidisciplinary, multiagency task force under the auspices of ASTM (American Society for Testing and Materials) developed ecologically based guidelines for dispersant use in marine environments. The guidelines for 13 different marine and coastal habitat types consider dispersant use both to protect and to clean the habitat. They also identify those habitats that are the highest priority to receive protection in the event of a spill. The other project was developed by an American Petroleum Institute (API) task force and contractor with input from federal and state government agencies. It is a site-specific method for planning in advance where to use or not use dispersants in marine environments. It involves dividing an offshore region into "dispersant use zones" based on ecological considerations. This method was applied to selected areas offshore southern California as a test.

KEY WORDS: dispersants, oil spills, spill response planning, spill clean up, ASTM, API

Oil spill response planning emerged as a discipline in the early 1970s, after the 1967 Torrey Canyon spill in Europe and the 1969 Santa Barbara spill in the United States. At that time, oil cleanup cooperatives were established by industry to purchase equipment and implement major response action. Individual companies also developed plans for their facilities and oil-handling activities. Government developed the multiagency Regional Response Teams (RRTs).

Early spill response plans identified response personnel, available equipment, and lines of communication. Since the late 1970s, response planning has also included identification of sensitive resources [1-10]. Much work has also been done identifying the ecological implications of various cleanup methods and making recommendations for or against their use [11-19]. This work has enabled spill response planners to design response to "fit" ecologically the environments for which they have responsibility. Until recently, the exception has been advance planning for the use of chemical dispersants.

Using dispersants to control oil spills has been highly controversial since the 1967 Torrey Canyon spill where toxic chemicals were applied directly to shorelines, causing greater damage than the oil itself. Since that time, U.S. regulatory agencies and some other spill

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responders have tended to view dispersant use as something to be considered only when mechanical recovery is not feasible or successful [20]. The primary reason is that dispersants do not remove the spilled oil from the environment, rather, oil is removed from the surface, diluted, and dispersed into the water column. Because dispersants have not been generally considered a first-response option, decisions regarding their use have been made only after a spill occurs. To date, they have been used on very few spills in U.S. waters. They are more commonly used in other parts of the world.

Some Regional Response Teams have streamlined the dispersant use decision-making process so that it is likely to take only a few hours. It could take days in other regions where this planning has not been done. Dispersant use is most effective in the early stages of an oil spill both because the chemicals themselves work best on fresh oil and because it is then that their potential influence on the extent and severity of the spill's impact is greatest. Therefore, it makes sense not only to streamline decision making but also to make as many decisions about where and when to use or not to use dispersants as possible, before a spill occurs.

The decision of whether or not to use dispersants in a given spill situation always involves trade-offs. Dispersing a slick at one site introduces more oil into the water column at that site than would be there if a surface slick floated over it. Therefore, impacts on water column organisms may be increased at the site so that impacts may be decreased or eliminated elsewhere.

What are some possible advantages of dispersant use? Aerially applied dispersants have a greater chance than most other methods to influence the outcome of the spill event because large slicks may be treated in a relatively short time compared with other methods. Since some environments are more vulnerable to the longer lasting impacts of spilled oil than others, an acceptable trade-off may be to protect those environments by dispersing an oil slick in a less sensitive/less productive environment. In general, the trade-off that must be evaluated is between the impact of the relatively long residence time of spilled oil which strands on shorelines versus the short-term impact of dispersed oil in the water column.

Flaherty et al. [21] have developed a computerized decision tree for dispersant use decision making. It can be used after a spill occurs to streamline decision making. More importantly, it can be used as a response planning tool, enabling RRTs and other spill responders to gather information about oils, dispersants, and resources at risk in their areas and run through scenarios *before* a spill occurs. This could shorten decision-making time even further. Trudel and Ross [22] developed a workbook designed to aid dispersant use decision making. Originally designed as a teaching tool for workshops, it allows for comparison of the fate and effects of an oil slick which is dispersed or left untreated. This approach can also be used as a basis for advance planning.

Two additional, complementary programs designed to enhance the dispersant use decision-making process are described in more detail. They were both developed with input from industry, government agency, and university representatives. I chaired both work groups.

The ASTM Guidelines

Under the auspices of ASTM (American Society for Testing and Materials), a large task force (approximately 90 on the task force and mailing list) with representatives from federal and state government agencies, industry, universities, and environmental groups met over 4 years to develop ecologically based guidelines for dispersant use in marine environments.

Assumptions

Certain goals and assumptions were agreed upon when the process began. The task force agreed that the primary goal of the guidelines would be to minimize the ecological impacts of an oil spill. Aesthetic and socioeconomic factors would not be considered, even though it was recognized that these can be important aspects of spill response decision making. The task force further decided that dispersants would not be considered a "last resort" to be considered only after other response options had failed or been eliminated from consideration. To maximize effectiveness dispersants should be considered equally with other response options. The most effective response strategy will often include a combination of methods. Further, the guidelines do not consider individual dispersants, their effectiveness, or application methods. Dispersants are assumed to be effective, applied correctly, and within the toxicity range of modern, low-toxicity products on the National Contingency Plan Product Schedule.

The ASTM Standards Development Process

The ASTM standards development process requires consensus of the task force proposing the standards and then balloting at subcommittee, committee, and society levels. At each level there is opportunity for dissent. Every negative vote must be considered and resolved in some manner, either by acceptance of the suggested change by the task force, modification of the text to satisfy the concerns of the negative voter, or a task force vote that the criticism is "nonpersuasive." The draft guidelines were each written by a task force member, then reviewed, revised, and balloted by the full task force and finally submitted through the ASTM Subcommittee and Committee balloting process. The resulting guidelines represent the consensus of those involved in this lengthy process.

The Guidelines

The ASTM guidelines are published individually by ASTM as standards in a series called "Guide for Ecological Considerations for the Use of Chemical Dispersants in Oil Spill Response." Guidelines were developed for 13 habitat types and consider dispersant use both to protect the habitat and to clean it if oiled during a spill. They also identify those habitats that, based on ecological considerations, should be given high priority for protection in the event of a spill. Recommendations may be quite different when considering dispersant use for protection versus cleanup.

The 13 standards are (1) Bird habitats (F 1010), (2) Marine mammals (F 929), (3) Rocky shores (F 930), (4) Sandy beaches (F 990), (5) Gravel or cobble beaches (F 999), (6) Coral reefs (F 932), (7) Seagrasses (F 931), (8) Mangroves (F 971), (9) Tidal flats (F 973), (10) Nearshore subtidal (F 972), (11) Offshore (F 1009), (12) Salt marshes (F 1008), and (13) the Arctic (F 1012). Table 1 contains a summary of the major recommendations of the guidelines.

Each guideline has an *introduction* that describes the habitat and its ecological significance. A *background* section discusses the effects of oil spills and of dispersant use (if known) in the habitat. This section also identifies those habitats that are most sensitive to the longer lasting effects of oiling and recommends that they be given high priority for protection (using dispersants or other methods) should a spill occur. The *recommendations* section makes specific recommendations about whether and how to use dispersants to protect the habitat as well as on dispersant use during cleanup. For example, the bird habitat guideline recommends dispersant use, remote from bird habitats, to prevent or reduce the

Habitat	Protection Priority	Recommendations Protection	Cleanup
Birds	high	Recommended remote from habitat.	Not recommended. No cleanup of any kind recommended near habitat where it may cause disturbance.
Mammals	high	Recommended remote from habitat.	Not recommended. No cleanup of any kind recommended near habitat where it may cause disturbance.
Rocky shores	med-high	Recommended remote from habitat.	Possible for some situations.
Sand beaches	med-low	Recommended remote from habitat.	Possible for some situations.
Gravel/cobble	low	Acceptable.	Possible for some situations
Coral reefs	high	Recommended remote from habitat.	Not recommended.
Seagrass	high	Recommended remote from habitat.	Not recommended.
Mangroves	high	Recommended remote from habitat.	Possible for some situations.
Saltmarsh	high	Recommended remote from habitat.	Possible for some situations.
Tidal flats	high	Recommended remote from	Not recommended.
Near shore	low-high	Recommended remote from sensitive areas	Recommended to minimize
Offshore	low-high	Recommended remote from sensitive areas	Recommended to minimize
Arctic	low-high	Recommended remote from sensitive areas.	Possible for some situations.

TABLE 1—Summary of ASTM guidelines.

amount of oil entering them. Dispersant use is not recommended in bird habitats as an oil removal method. See Table 1 for a summary of the recommendations in the guidelines. The last section contains *references*.

The guidelines were developed to serve as reference documents for Regional Response Teams and other spill response planners as they develop site-specific dispersant use plans for their areas of responsibility. There is now an ASTM task force developing similar dispersant use guidelines for fresh water and inland habitats.

The American Petroleum Institute (API) Site-Specific Planning Project

A task force composed of oil industry, Environmental Protection Agency (EPA), and U.S. Coast Guard (USCG) representatives, with input from several other federal and state government agencies, along with a contractor (RPI International, Inc.), developed a method for site-specific, advance planning for dispersant use [23].

The EPA has recognized the value of advance planning and its revisions to subpart H of the National Contingency Plan authorize the federal On-Scene Coordinator (OSC) to approve dispersant use with the concurrence of EPA and the affected state. The OSC can approve dispersant use without first obtaining concurrence if a plan for dispersant use has been agreed upon in advance.

Assumptions

Critical considerations in planning for dispersant use are the dispersibility of the spilled oil and the logistical and technical aspects of dispersant application. For planning purposes it was assumed that the oil is dispersible and dispersant is available, effective, and applied correctly.

As in the ASTM project, the basis for making the recommendations was ecological. Aesthetic and socioeconomic factors were secondary considerations.

The Planning Method

The method requires dividing a coastal and offshore area into "dispersant use zones." These include: Zone 1—dispersant use recommended, Zone 2—dispersant use acceptable, and Zone 3—dispersant use conditional.

Zone 1—Dispersant Use Recommended—Zone 1 is characterized by (a) sufficient water depth or mixing energy or both to allow dispersed oil to be rapidly diluted to low concentrations, (b) ample distance from sensitive resources (for example, marine mammal rookery, bird nesting area) that dispersant application operations will not cause disturbance, and (c) significant likelihood that oil spilled in this zone will eventually impact sensitive resources. Therefore, action is warranted and dispersant use is recommended to prevent or reduce these impacts.

Zone 2—Dispersant Use Acceptable—Zone 2 has the same ecological characteristics as Zone 1: (a) sufficient water depth or mixing energy or both to allow dispersed oil to be rapidly diluted to low concentrations and (b) ample distance from sensitive resources that dispersant application operations will not cause disturbance. The difference is that (c) oil in this zone is not likely to impact sensitive resources eventually. Therefore, immediate action is less critical. There are no ecological reasons not to use dispersants in this zone, only that cleanup or control action of any type is less critical based on the likely trajectory of the spill (for example, the Argo Merchant).

Zone 3—Dispersant Use Conditional—Zone 3 includes (a) shallow or low energy habitats where dilution of dispersed oil may be restricted, (b) proximity to sensitive resources such that dispersant or other operations could cause disturbance, and (c) oil in this zone is likely to impact sensitive resources. In Zone 3 the ecological trade-offs between dispersing the slick, other control or cleanup methods, and no action must be considered. Dispersant use may emerge as the preferred method after evaluation of other options, but these decisions may have to be made after the spill occurs. If dispersants are used, operations could cause disturbance and higher concentrations of dispersed oil in the water column will be available to near-shore organisms. The effect of this must be weighed against the effects of whole oil on the water surface and stranded on shorelines. This method allows Zone 3 areas to be identified and discussion of various "what if" scenarios that can make decision making faster when a spill happens.

The task force debated at length about whether to recommend a specific depth to separate the "recommended" from "not recommended" areas. We finally decided against a specific depth because environmental conditions are so variable. Dispersants may be a viable control method in shallow water, provided mixing energy and exchange are sufficient to promote rapid dilution. In fact, it might be critical to use dispersants in just such an environment if the alternative is to allow oil to strand in a sensitive habitat (for example, mangroves, marsh). On the other hand, there may be cases where important spawning activity is occurring offshore and the potential site of onshore stranding is a low-productivity habitat. Here, mechanical cleanup of the oiled beach may be the most ecologically sound option. These are matters that RRTs will have to consider as they determine the boundaries for their dispersant zones and confront the trade-offs encountered when oil is in Zone 3.

Application of the Method

Several steps are necessary to apply the dispersant use zone criteria described above. The data to accomplish these steps are now readily available for most areas. They include:

1. Define the geographic area for which dispersant use is to be planned and obtain National Oceanic and Atmospheric Administration (NOAA) navigational charts for coastal and offshore areas.

2. Determine the distribution and seasonality of oil-sensitive wildlife in the area. U.S. Fish and Wildlife Service "Ecological Inventories" and state fish and game data are excellent sources of this information.

3. Identify habitats sensitive to the longer lasting impacts of spilled oil, including those that are sensitive to cleanup or reclamation methods. NOAA environmental surveys, state data, and surveys done for oil cleanup cooperatives in the area should be consulted.

4. Identify socioeconomic resources at risk.

5. Analyze available meteorological and oceanographic data to determine "likelihood of impacts to sensitive resources" for spilled oil. These data are available from the Coast Guard and NOAA.

6. Plot the oil-sensitive wildlife data, sensitive habitats, and socioeconomic resources information obtained in Steps 2, 3, and 4 above on navigation charts.

7. On navigation charts, identify those areas where dispersant application operations and other cleanup or control methods could cause disturbance to sensitive wildlife (for example, nesting seabirds, marine mammal aggregations).

8. Using the data obtained in Step 5, determine the offshore and coastal areas where spilled oil would be likely to impact sensitive resources and, conversely, unlikely to impact sensitive resources.

9. In accordance with dispersant use zones described, identify areas as Zones 1, 2, and 3. It is possible that seasonal variations could change the locations of zone boundaries. This can be depicted on the chart, or separate charts can be made for each season.

Test Application of the Methods—Southern California

A portion of the southern California coast and offshore between Los Angeles and San Diego was selected as the study area (NOAA Charts 18746 and 18774). Resources and shoreline types were plotted on the maps using the Research Planning Institute (RPI) Environmental Sensitivity Index methods [24,25]. The nature of the resources as well as seasonality are shown (Figs. 1 and 2). Colors may be used to identify shoreline types and to distinguish between the zones. This produces a very readable, easy-to-use map. However, if color is used, it becomes expensive. Black-and-white versions are possible using number codes or various shading patterns. Though not as easy to read at first, they cost less and are easy to duplicate.

Based on wind and current data, oil spilled anywhere offshore in this study area, under normal conditions, may eventually reach sensitive resources. Therefore, all offshore areas have been designated as Zone 1 (Dispersant Use Recommended). Several coastal and some offshore regions have been designated Zone 3 (Dispersant Use Conditional) because of limited water exchange and proximity to sensitive resources. Areas further offshore (that



FIG. 1—Key to symbols for shoreline types, oil-sensitive wildlife, and socioeconomic features (from Research Planning Institute, 1985).

is, off the chart) would be classified Zone 2 (Dispersant Use Acceptable) since oil in this zone is unlikely to contact sensitive resources.

Each chart is accompanied by approximately six pages of text. Physical characteristics of the habitats are described, including sediment type, wave energy, winds, and currents. Biological characteristics are listed, including dominant wildlife species; endangered, threatened, or protected species; migrating and overwintering birds; spawning and nursery areas; and wildlife refuges. Socioeconomic features are also listed, including commercial fishing areas and public use areas.

Discussion

Dispersants were used during the 1984 T/V Puerto Rican spill off northern California [20]. Although actual use of dispersants in U.S. waters has been rare, more and more RRTs are seriously considering them. Several have appointed Dispersant Work Groups to study the issues and develop plans for dispersant use in their areas of responsibility or to develop a streamlined decision-making process. Several RRTs have held workshops or drills during





which spill scenarios are presented and dispersant use considered. The ASTM guidelines, the API advance planning project, and other planning efforts such as the EPA computerized decision tree [21] and the Canadian workshop approach [22] should aid all of these efforts.

There seems to be a building consensus among those who study dispersants that this response method should be considered early in the spill response process and equally with other response methods. The most effective response strategy may be to use dispersants and mechanical recovery. Dispersants do rate another look. Since the Torrey Canyon spill in 1967, second and third generation dispersants have been developed that are both less toxic and more effective than early products. The most compelling reason to reevaluate them and make them an integral part of response planning, however, is that, more than other methods, they have the potential to influence the outcome of a spill event. When applied from the air from a large aircraft they can treat a large slick in a short time compared with other methods. This could mean the difference between massive amounts of oil stranding on shorelines or in sensitive habitats and protecting those areas at the expense of a short-term exposure to water column organisms. Generally (though not necessarily always), the ecological trade-off favors protection of the habitat subject to longer lasting impacts. Approaches to dispersant use planning like those described can aid local RRTs and other spill response planners with responsibility for one offshore area. In the 1970s and early 1980s there was a major effort on the part of government agencies and industry to identify sensitive resources and to develop plans to protect them in the event of an oil spill. It is now time for a similar commitment, based on that information, to develop sitespecific plans for dispersant use.

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Planning for Dispersant Use

REFERENCE: Fraser, J. P., "**Planning for Dispersant Use**," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L.* Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 114–134.

ABSTRACT: Although the National Contingency Plan states that the Federal On-Scene Coordinator (OSC) may authorize the use of dispersants on an oil spill, such authorization is not automatic. In practice, the applicant for permission to use dispersants must submit a plan which then will be considered by the OSC and others involved in the approval process. This plan generally must indicate not only that dispersant use is desirable as a means of mitigating the spill but also must show why use would result in lower environmental impact than if dispersants were not used.

Some parts of a dispersant use plan are time-consuming to prepare and require acquisition of large amounts of information. Fortunately, the most time-consuming parts can be prepared well in advance of any spill. If these parts are prepared in advance, decisions regarding dispersant use can be made in a timely fashion at the time of a spill.

The components of a dispersant use plan should include the following:

1. Spill specific information such as how much of what oil was spilled, when did it occur, wind and sea conditions, and expected oil spill trajectories.

2. Information on resources available for dispersant application such as dispersant stockpiles that may be used, properties of these dispersants, application equipment, and information on application and monitoring methods. This information can best be gathered well in advance of any spill event.

3. Information on environmental impacts, including the comparative impacts of dispersed oil versus untreated oil. This information should be prepared and available in a form that will enable ready assessment, at the time of a spill, of the trade-offs which must be considered. It should be possible to identify well in advance of a spill those areas in which dispersant use should be considered and those in which use might not be favored.

4. A guide or system for decision making; this guide will show how the above information is used in developing the on-scene decision for or against dispersant use. The decision making system should be agreed upon well in advance of any spill.

5. Recommendations regarding dispersant use on the specific spill incident and justification for the recommendations.

Use of this planning method will expedite decision making at the time of a spill, will lead to more rational and logical dispersant use decisions, and will enable the decision maker to document his decision.

KEY WORDS: dispersants, planning, decision diagrams, decision trees, monitoring, guidelines, trade-offs

Response Options

If an oil spill occurs, several response options are usually possible. These options include mechanical recovery, use of dispersants, allowing for natural removal of oil from the environment, and cleanup of the shoreline or other area which may be impacted by the spill.

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None of the available methods of response provides a panacea for combatting spills; but the intelligent use of each of these methods, where appropriate, including dispersants, will result in minimizing (or reducing) environmental damage. In practice, more than one option may be used simultaneously, in different parts of the spill.

The problem is to choose which countermeasure(s) to use for each situation. This is especially a problem when considering the possible use of dispersants owing to the many regulatory concerns as well as the substantial technical questions.

Dispersant use has been a realistic tool to consider for use in oil spill mitigation for about 20 years. But for at least two thirds of this period (that is, from the time of the Torrey Canyon until the early 1980s), the U.S. National Contingency Plan made dispersant use impractical; primary emphasis was placed on use of mechanical means to contain and remove the spilled oil [1]. The resistance to use dispersants was based on reports of serious environmental damage which resulted from the dispersants used in 1967 at the time of the Torrey Canyon spill [2].

In more recent times, the National Contingency Plan (NCP) has been modified so as to make dispersant use more realistically available as a tool for oil spill mitigation. Subpart H of the NCP now clearly states that the federal On-Scene Coordinator (OSC) may authorize use of dispersants with concurrence from the Environmental Protection Agency (EPA) and the affected state(s) [3]. However, this change in the NCP has not resulted a major increase in dispersant use. One reason for this situation seems to be that a major period of time is still needed for the OSC, the EPA, the affected state(s), and other government agencies to reach a decision after a request has been made to allow dispersant use. The time involved in making a decision may take many hours or even days, during which time the opportunity for effective dispersant use has been lost. In some cases, there may not be a system established for making a dispersant use decision. In other cases, the procedures for making a decision may require a detailed assessment of species that are at risk and the comparative effects on all critical species of dispersant use versus the effects of no treatment. Gathering the data needed for this type of assessment could take days.

Experience shows that dispersants will be most effective if used promptly. Indeed, the International Tanker Owners Pollution Federation [4] has stated that it is usually not worthwhile to use dispersants if more than one or two days have elapsed since the oil was spilled.

Thus, authorization for dispersant use is not automatic, despite the recent changes in the NCP. The reasons for this include:

(1) remaining concerns by regulatory officials about dispersant toxicity, despite the publicized changes in formulations and reportedly reduced toxicity of the newer dispersants;

(2) continued concern that use of a dispersant necessarily means that the applicator is adding a contaminant which otherwise would not be present;

(3) recognition that use of a dispersant will change the fate and effects of the spilled oil; a need is felt to understand more fully the implications of these changes;

(4) perception by the resource agencies that whatever actions are taken should reduce the overall impact of the oil spill, not increase it; and

(5) a residual concern by the regulatory agencies that the spill responder should be addressing cleanup of the spill, not simply removing the spilled oil from sight.

Planning for Dispersant Use

The purpose of this paper is to describe procedures which are currently in use for making dispersant use decisions.

	Time in Hours for Oil	to Reach 2000 cSt ^b at
Wind Speed, Knots ^b	Water Temp. = 10°C	Water Temp. = 27°C
5	21–56	29-56
10	12-27	14-27
15	8-16	9-16
20	6-13	7–12

TABLE 1—Range of times available for spill response by use of dispersants.^a

^a See also data in Table 2. Oils included in this study ranged in properties from 17.4 to 40.4 API gravity.

 b 1 knot = 0.5144 m/s and 1 cSt = 1 Mm²/s.

An acceptable plan for dispersant use must demonstrate (1) that the requestor is prepared to manage the spill response properly, including use of means other than dispersants where appropriate; (2) that use of dispersants will be controlled and deliberate; and (3) that use of dispersants will likely lessen the overall environmental impact of the spilled oil.

In addition to addressing the concerns of the regulatory community, a plan for dispersant use must be practical from the standpoint of operations. It must identify those resources for dispersant application that are realistically available. And it must recognize the constraints of time; if dispersants are to be effective, they must be applied quickly. Thus, a dispersant use plan must allow a decision to be rendered in a short period of time.

As an indication of the restrictions of time, a computer program [5] was used to estimate the time available before spilled oils will become too viscous to disperse effectively, simply from weathering. The results of the calculations are shown in Tables 1 and 2. Based on these calculations, the time available for most effective use of dispersants (defined for purposes of this illustration as being the time before the oil viscosity exceeds 2000 cSt [2000

		Pour	Visc.	Water Temp. °C =		1	0			2	7	
Name of Oil	API Gravity	Point, °C	at 38°C	Wind Speed, knot =	5	10	15	20	5	10	15	20
Eugene Island												
Block 128	40.4	-1	9		52	24	16	11	47	22	15	10
Arabian light	33.4	-34	6		55	25	16	11	52	25	16	11
Arabian												
medium	30.8	-15	10		54	25	16	11	56	27	17	12
Main Pass												
Block 69	29.4	-9	36		21	12	8	6	43	21	14	10
Main Pass												
Block 35	28.4	-15	32		56	27	18	13	52	26	16	11
Alaska North												
Slope	26.5	-18	15		41	20	14	10	53	25	16	12
Isthmus/Maya												
blend	26.0	-26	40		42	21	14	10	48	24	15	11
Shengli	24.2	22 ^a	200		а	а	а	а	34	16	11	8
Merey	17.4	-23	260		\mathbf{X}^{b}	Х	Х	Х	29	14	9	7

 TABLE 2—Calculated number of hours available for effective use of dispersants (viscosity = 2000 cSt) for oils transported through and produced in the Gulf of Mexico.

^a The high pour point of this oil makes is nondispersible at 10°C.

^b X—This oil is not dispersible at the temperature indicated owing to the viscosity as spilled.

 Mm^2/s]) is only slightly affected by the type of oil which is spilled and by the water temperature. The one factor that has a major influence on the time available is the wind speed; and even wind speed can be viewed as being relatively unimportant, because the average wind speed is likely to be fairly constant over any extended period of time. In general, the data indicate that less than one day is typically available for effective use of dispersants, and the time may be significantly shorter than this.

Advance Planning

A large amount of information is usually desired or required when making a decision regarding dispersant use. Although some of the information needed for decision making will only be available at the time of the spill, much can be obtained well in advance and can be incorporated into an advance plan for dispersant use. Information useful for an advance plan includes:

• Identification of the crude oils and products that may be spilled; what oils are produced in or transported through the area of interest, what volumes are involved, and what are the routes traveled (tankers and pipelines) and platform sites (oil production).

• What are the environmentally sensitive resources that might be impacted by spilled oil, whether dispersed or not; what are their relative sensitivities; what are the local priorities for protection; and what are the relative importances of these resources, that is, to the agencies which are entrusted with management of the resources.

• What dispersants are available and where are they stored; what data are available on the dispersant properties and on performance of the dispersants with the oils of concern; and what rates of application will be appropriate to use on the oils which are likely to be spilled.

• What equipment is available for dispersant application; has it been properly calibrated using the dispersants which will be applied; where is it located; and have operators been adequately trained in use of the equipment.

• What means will be used to monitor dispersant application and to determine its effectiveness; what other measurements or observations will be appropriate at the time of the spill; and are any instruments needed and available and have operators been properly trained to use them.

Additional data needed for a dispersant use decision will be specific to a given spill, such as the spill location, volume and type of oil spilled, and local meteorological and hydrographic data.

One other component is needed to prepare for dispersant use: a well conceived system for making the dispersant use decision and acceptance of this system by the regulatory agencies which are involved.

Technical Questions to Be Addressed

Dispersant use may be preferred over other options if winds and currents would cause undispersed oil to impact a sensitive area, especially if there is insufficient time for mechanical recovery of the oil before impact. If use of dispersants will prevent, or substantially aid in preventing, environmental damage that could occur if they were not used, dispersion of the spilled oil should be strongly considered. Also, if dispersion of oil can reduce or eliminate hazardous conditions, use of dispersants is recommended. The technical questions that should be addressed when considering dispersant use as an oil spill countermeasure include the following:

• Is any countermeasure needed? Or will the spill be dissipated by natural means (evaporation, mechanical dispersion, biodegradation, photooxidation, and so forth) before it could impact a sensitive resource? Natural dissipation can be expected if the seas are rough, if the oil is very thinly spread on the water surface, if the spill has occurred relatively far from any shoreline, or if the oil spill volume is relatively small.

• Is the use of a chemical dispersant (on any portion of the spill) appropriate? Would the dispersed oil result in less environmental damage than would be caused by the untreated oil? How reliable is the prediction that the application of dispersant will ameliorate the environmental consequences of the spilled oil, for the particular spill situation? The answers to these questions will include consideration of the populations and habitats that may be impacted by an oil spill and the current understanding of the relative impacts of dispersed oil and untreated oil on specific populations, communities, and habitats (that is, specific ecosystems). The answers should also include an estimate of the probability of dispersing a significant fraction of the spilled oil. It should be recognized that increased damage may result from inaction as a result of uncertainty, in effect, a decision not to disperse.

• Is the oil dispersible? If the oil is dispersible when initially spilled, how long will it remain dispersible? As discussed above, oil becomes progressively less dispersible with time after spilling owing to increased viscosity which results from evaporation of the lower molecular weight compounds and also from formation of water-in-oil emulsions. As a general guide, oil is readily dispersible if the viscosity is less than about 2000 cSt (2000 Mm²/s) and becomes progressively less easy to disperse as the viscosity increases above this value. If its viscosity is greater than 10 000 cSt (10 000 Mm²/s), an oil or a water-in-oil emulsion (mousse) is usually fairly difficult or impossible to disperse. Oil should be fluid, that is, the water temperature should be above the pour point of the oil. Lindblom² contends that oils are dispersible providing they are fluid (Newtonian in behavior) and will spread on the water. Canevari [6] suggests that oil composition may be as important as oil viscosity in determining whether or not the oil can be dispersed. Indigenous surfactants and other compositional variables such as asphaltene content may affect dispersant performance.

• Are available dispersants appropriate for use in dispersing the oil which has been spilled? Note that it is not necessary in most situations to use the dispersant that is optimum for a particular oil. In most cases, experience with use of dispersants on a variety of oils will be sufficient to indicate that the spilled oil can be dispersed using available dispersants. However, in some cases, it may be worthwhile to ensure that an available dispersant is able to disperse the spilled oil adequately under expected sea conditions. For example, for a major offshore oil field, laboratory testing of dispersants in advance of any spill might be done to select a dispersant that will be effective. If testing has not been done before an oil spill, simple field tests [7] can be made to estimate dispersability if a representative sample of oil can be recovered in timely fashion from the spill. Alternatively, effectiveness can be estimated by visual monitoring of the spill as treatment is in progress. (Note that recovery of a representative sample from a spill at sea will usually be difficult and may not be realistically possible; for this reason, visual monitoring is usually preferred.) Finally, if a new dispersant becomes available, it may be desirable to test it with a

²G. P. Lindblom, personal communication, 1986.

variety of oils to determine those on which it would work well and also to compare it with competitive products.

• Are the weather conditions appropriate for chemical dispersion of the spilled oil? Is visibility adequate to allow aircraft or boats to apply the dispersant efficiently onto the oil? Is the sea sufficiently turbulent to cause the oil to disperse after treatment? In general, oil will be dispersed more readily when the sea is rough than on calm seas. Mackay [8] suggests that chemical dispersion may be relatively ineffective at wind speeds under about 7 m/s, although this is not a precise threshold nor is its value firmly established. This does not mean that dispersants should not be applied unless the wind is blowing at least 7 m/s, but dispersion will likely be less on calm seas or unless the seas become more rough after treatment. Conversely, if the seas are very rough (Sea State 5 or higher), it is usually not necessary to use any treatment because wind and wave action will be adequate to remove the spilled oil from the water surface quickly and application may not be practical under these conditions. However, two other factors should be considered if the seas are rough: (1) the spill will move relatively quickly (rapid advection) at high wind speeds, so that time available for response may be less, and (2) the mechanically dispersed oil may resurface when the weather moderates and the seas become more calm.

• Is equipment available that can apply the dispersant properly? Dispersants can be sprayed on the oil slick either from boats or from aircraft. With either type of equipment, the spray apparatus should be designed, calibrated, and adjusted so that the dispersant is applied efficiently to the oil, with the least possible losses owing to windage (that is, small droplets). Also, the dispersant should be applied to oil and not wasted by spraying onto seawater which is not covered by oil; trained personnel are needed. If possible, the dispersant should be sprayed preferentially onto the thicker oil patches rather than on thin oil layers or sheens. Current thinking is that a volume median droplet diameter of the order of 0.3 to 0.4 mm is appropriate for aerial application [9]. For boat spraying, the spray nozzles should be mounted sufficiently far forward to avoid the bow waves produced by the boat, and the spray pattern should be such as to assure overlapping spray patterns from adjacent nozzles.

• Is the oil thickness appropriate for use of chemical dispersants? If most or part of the oil is in relatively thick patches, these patches might need a very high dispersant dosage rate (gallons per acre) for effective dispersion to be realized. For example, oil thickness in the thicker portions of a spill on cold water may be on the order of 1 to 3 mm, compared with an average of 0.1 mm for most oil spills in temperate zones; the dispersant application rate under cold weather conditions might then need to be on the order of 500 to 1500 L/ ha versus 50 L/ha (100 ha = 1 km²) which has typically been used elsewhere.

• Can other countermeasures be used and are they available to use? If other countermeasures can be used, would they be effective? Would the use of these countermeasures result in more or less oil removal from the water surface than if dispersants were used? Note that mechanical containment and recovery are relatively ineffective if the oil layer is relatively thin, that is, less than about 0.5 mm, or the sea is moderately rough, typically Sea State 4 or greater.

• Will the cost of spill mitigation be less if dispersants are used? In general, it appears that use of dispersants may result in costs that are lower than for mechanical recovery or for shoreline cleanup, based on the volume of oil treated or collected. However, chemical dispersion at sea could require treatment of far greater volumes of oil (with attendant increased cost) than the volumes that would be collected.

As already noted, some of the information that is relevant to a dispersant use decision can only be obtained at the time of a spill, such as the date, time, volume of spill, product spilled, weather conditions, and so forth. However, some of the most critical information, such as environmental sensitivity data, can be obtained well in advance of an actual spill. If not obtained in advance, the long time needed to acquire this information at the time of a spill may make it impossible to render a dispersant use decision in a timely fashion.

Components of a Dispersant Use Plan

In view of the above, a dispersant use plan should include the following.

1. Information about the spill—what oil was spilled and the properties of the oil, how much was spilled, where the spill occurred, and what are the wind, wave, and ocean current conditions? Most of this information can only be obtained at the time of the spill. However, information on the properties of oils produced in and transported through the area of interest can be obtained before any spill. An example of oil property information is shown in Table 3, which was taken from a study made recently for the American Petro-leum Institute [10]. Additional and more detailed oil property information is available for many oils in the open literature, such as the oil composition data reported in the Oil and Gas Journal in 1983 [11] and the properties of oil products incorporated in ASTM Specification for Fuel Oils (D 396) and ASTM Specification for Diesel Fuel Oils (D 975).

2. Trajectory analysis—information on winds (speed and direction) and ocean currents noted above is needed at the time of a spill to estimate the spill trajectory and to determine what sensitive resources, if any, are likely to be impacted by the spilled oil, whether treated with dispersants or not. Many oil spill trajectory analyses have been proposed [12], but one of the most flexible is that used by the National Oceanic and Atmospheric Administration (NOAA) [13]. For planning purposes, historical wind and current data may be used, but measured values would be preferred for most actual spill situations. The dispersant use plan should provide for both types of information.

3. Resources available for dispersant application—inventories should be maintained of dispersant supplies and of equipment available for dispersant application. These inventories should include information on dispersant properties and may include information on the effectiveness of the available dispersants when used to treat the different oils that are produced in and transported through the area of interest. The inventories should also include information about calibration and testing of the dispersant application equipment.

4. Dispersant use plans—a dispersant use plan should include details of planned application rates, which may depend on the oil that was spilled and its thickness on the water surface. The maximum allowable rate of application may sometimes be limited by the water depth, that is, a low maximum rate of application may be specified for shallow water depths [14]. Dispersant application procedures have been described in several publications [15–17].

5. Monitoring and control—the rate of application of a dispersant not only should be planned, but procedures should be established in advance of a spill for controlling the rate of application and for monitoring the operation. Monitoring and control procedures may include calibration of the spray equipment; preparation of record forms on which to record the actual settings of the flow rate and of other instruments; and information on the speed, elevation, and direction of the spray plane (assuming aerial application) or spray boat. In most cases, visual observation and photographic documentation of the application process will be part of the monitoring and control procedures. One plan for monitoring and control of a dispersant application is given in Appendix A.

6. Training—for greatest effectiveness, personnel involved in all phases of a dispersant operation should be properly trained, preferably using the equipment which is actually planned for field use. There is a need to develop this type of training program.

	Counter of		c16	Pour	CST			M	B/D			IMM	3/YR	
Crude or Product	Origin	API API	wt%	Ŗ Ĵ	$100^{\circ}F^{b}$	Factor	USEC	USG	USWC	Total	USEC	USG	USWC	Total
CRUDE AND COND.	ENSATE													
Alaskan	United States	26.5	1.06	0	15	3L	105.0	494.0	934.0	1533.0	38.3	180.3	340.9	559.5
Algerian blend	Algeria	45.5	0.05	-20	9	I	6.0	9.6	1.4	17.0	2.2	3.5	0.5	6.2
Algerian condensate	Algeria	65.0	0.10	-80	ŝ	I	13.0	51.2	:	64.2	4.7	18.7	:	23.4
Arabian light	Saudi Arabia	33.4	1.79	-30	9	3L	8.6	28.0	:	36.6	3.1	10.2	:	13.4
Arabian medium	Saudi Arabia	30.8	2.40	S	10	3L	8.0	35.8	:	43.8	2.9	13.1	:	16.0
Arabian heavy	Saudi Arabia	27.9	2.85	-2	19	3L	4.7	21.7	:	26.4	1.7	7.9	:	9.6
Ardjuna	Indonesia	35.2	0.11	75	4	2H	:	6.1	1.6	7.7	:	2.2	0.6	2.8
Arun condensate	Indonesia	54.0	0.10	-54	-	Π	:		22.5	22.5	:	:	8.2	8.2
Attaka/Bedak	Indonesia	42.3	0.09	- 10	9	2L	:	:	13.8	13.8	:	•	5.0	5.0
Basrah	Iraq	33.7	1.95	14	7	3L		2.4	•	2.4	:	0.9	0.0	0.9
Bass Strait/other	Australia	44.4	0.10	99	30	2H	0.6	6.5	26.4	33.5	0.2	2.4	9.6	12.2
BCF 13	Venezuela	12.9	2.70	25	8 458	4	:	2.3	:	2.3	:	0.8	:	0.8
BCF 17	Venezuela	16.9	2.40	- 10	295	4	:	63.6	:	63.6	:	23.2	:	23.2
BCF 22	Venezuela	22.0	1.85	- 60	58	3L	:	17.6	:	17.6	:	6.4	:	6.4
Beatrice	United Kingdom	38.7	0.05	55	×	2H	•	15.0	•	15.0	:	5.5	:	5.5
Bekapai	Indonesia	40.0	0.08	9	7	2L	:	3.5	0.5	4.0	:	1.3	0.2	1.5
Bern	Saudi Arabia	37.8	1.19	-25	4	2L	:	10.3	:	10.3	:	3.8	:	3.8
Bombay high	India	39.4	0.17	86	e	3H	:	16.1	6.2	22.3	:	5.9	2.3	8.1
Bonny light	Nigeria	36.7	0.12	60	ę	3H	52.9	21.0	:	73.9	19.3	7.7	:	27.0
Bonny medium	Nigeria	25.2	0.23	-17	12	3L	8.9	14.4	• • •	23.3	3.2	5.3	:	8.5
Boscan	Venezuela	10.1	5.50	50	19 400	4	14.0	3.7	:	17.7	5.1	1.4	:	6.5
Brass River	Nigeria	40.9	0.09	35	17	2L	4.2	32.0	:	36.2	1.5	11.7	:	13.2
Brent	United Kingdom	38.2	0.26	27	4	2L	72.1	18.4	:	90.5	26.3	6.7	:	33.0
Cabinda	Angola	31.7	0.17	65	18	3H	3.1	19.1	:	22.2	I.I	7.0	:	8.1
Camar	Indonesia	35.6	0.10	8	20	2H	:	8.1	:	8.1	:	3.0	:	3.0
Ceuta	Venezuela	31.8	1.20	-35	Π	3L	:	1.7		1.7	:	0.6		0.6
Coban blend	Guatemala	26.5	2.80	50	15	3H	:	1.4	:	1.4	:	0.5	:	0.5
Djeno blend	Congo	26.9	0.33	37	38	3L	3.1	7.4	:	10.5	1.1	2.7	:	3.8
Dubai	Dubai	31.1	2.00	16		3L			:	0.0	• •	: •	:	0.0
Ekohsk	Norway	43.4	0.14	10	7	2L	5.1	10.4	••••	c.cI	1.9	3.8	•••).C

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^{*a*} The data shown above were taken from Ref 10. ^{*b*} 1° F = 17.2° C. 7. Environmental impacts—the species and habitats which may be exposed to spilled oil or to dispersed oil should be identified and procedures developed for comparing the relative impacts of dispersed oil and of untreated oil on populations which may be at risk at the time of a spill. This work should be done well in advance of a spill. The analyses of impacts can also be made well in advance of a spill to identify areas and seasons when dispersant use should be considered as well as areas and seasons when dispersants would likely not be appropriate. As described in two recent papers [18, 19], there are at least three systems available for use in addressing the questions of environmental impacts: (1) the ASTM guidelines in Table 4, (2) the mapping system developed by Research Planning Institute for API [20], and (3) the system developed by S. L. Ross Environmental Research Ltd. to analyze and compare the effects of both dispersed oil and untreated oil on populations at risk [19].

8. Decision making procedures—although the NCP specifies that the Federal On-Scene Coordinator, the EPA, and the affected states must concur in a dispersant use decision, the NCP does not specify procedures to make the decision, who should provide the necessary information on which to base the decision, nor criteria for making the decision. A well designed dispersant use decision making system (or plan) should involve consideration of whether or not use is acceptable from an ecological perspective and appropriate from an environmental perspective, as well as consideration of practicality (can the spilled oil actually be dispersed with available dispersants, is application equipment available, are personnel trained in use of the equipment, and so forth).

Thus, a dispersant use plan should include the following components:

- 1. Spill information form:
 - (a) spill specific information—what oil was spilled, where, how much, and relevant oceanographic and atmospheric data;
 - (b) spill trajectories and oil fate projections (spreading, evaporation, and so forth); and
 - (c) dispersant use plan—what dispersant will be used, application equipment to be used, and planned rate of application.

 nesponse.
 Marine mammals (F 929) Rocky shores (F 930)
Seagrasses (F 931)
Coral reefs (F 932)
Mangroves (F 971)
Nearshore subtidal (F 972)
Tidal flats (F 973)
Sandy beaches (F 990)
Gravel/cobble beaches (F 999)
Salt marshes (F 1008)
Offshore (F 1009)
Bird habitats (F 1010)
The Arctic (F 1012)

 TABLE 4—ASTM guides for ecological considerations for the use of chemical dispersants in oil spill response.

2. Oils that may be spilled—names of crude oils, oil properties (viscosity, pour point, API gravity), plus information on dispersibility based on oil viscosity versus temperature and pour point data.

3. Dispersant resources—suppliers, sizes of available stockpiles, how to access these supplies, and product information.

4. Dispersant application equipment—what equipment is actually available for use, where it is located, and how to obtain access to it; logistics information should be included.

5. Dispersant use decision making procedures—this has two parts:

- (a) Analysis of the relative environmental impacts which might be anticipated from dispersed oil and from untreated oil and development of dispersant use recommendations based on these impacts.
- (b) A prearranged system for informing the appropriate government agencies, for assembling the information needed to make a dispersant use decision, and procedures for arriving at the final decision. An outline of the information sources and agencies which might be involved as shown in Table 5.

6. Quality assurance/quality control procedures (QA/QC)—guidance on calibration and use of dispersant application equipment and on monitoring the effectiveness and effects of a dispersant application.

Responsibility for Preparing the Plan

In principle, either the party responsible for spill cleanup (usually, the spiller) or the regulatory agencies could prepare a dispersant use plan. The regulatory agencies will inevitably need to be involved, for they must accept the plan for use in the approval process. However, the most productive approach is for industry (the potential spillers) and the agencies to cooperate in preparation of the plan. This is because industry sources will normally have much of the needed information about oil production and shipments, oil properties, availability of dispersant supplies and application equipment, dispersant properties, and dispersant use technology. Government agencies will usually be the primary source of information on species and habitats which may be at risk in the event of an oil spill and the relative priorities for protection of these resources, whether dispersants are used or not. Both government agencies and industry sources will have information on the fate and effects of spilled oils, whether dispersed or not. And of course the government regulatory agencies must accept the decision making process which ultimately is used.

Application of the Dispersant Use Plan

The use of the technical information discussed above may be illustrated by decision diagrams. Several of the diagrams that have been developed for dispersant use decision making are shown in Figs. 1 through 4. These diagrams have been selected from the large number that are available in the literature. These diagrams are similar to each other in some ways, but each tends to emphasize different aspects of spill response. Brief descriptions of the diagrams follow.

1. EPA Dispersant Use Decision Tree—See Fig. 1 [21]. This is one of the more detailed and complete decision making procedures that is available. It has been programmed for use on a personal computer such as an IBM PC. At each node in the decision diagram (tree) the user may ask (that is, through a help menu) for an explanation of the factors involved in each of the decision options which are available. The help menus include infor-

TABLE 5—Sources of information and agencies responsible for dispersant use decision making.^a

Techniques used to respond to an oil spill may include mechanical recovery, use of chemical dispersion, allowing for natural recovery, or a combination of these. The technique(s) actually used for any particular spill will depend on the spill conditions (size of spill, oil spilled, location, sea state, and so forth). For illustration, the steps involved in deciding which technique(s) to use are indicated in the EPA Oil Spill Countermeasures Decision Tree, which is shown in Fig. 1. The agencies or individuals involved in each part of this diagram or decision tree are shown below.

Item or Event H	Primary Responsibility	Concurrence (C) or Alternate Responsibility (A)	Sources of Information
Report of oil spill	spiller		spiller; third parties
Surveillance	spiller	OSC (C)	SSC
Assessment of possible hazards to personnel	spiller	OSC (C)	SSC
Trajectory analysis	OSC	spiller (A)	NOAA; spiller computer facilities
Oil thickness estimate	OSC	spiller (A)	SSC
Sea state estimate	OSC	spiller (A)	SSC, USCG, NOAA, NWS
Availability of resources for mechanical cleanup	spiller	OSC (A)	Cooperatives, contractors, suppliers
Effectiveness of mechanical cleanup	OSC	spiller (C)	SSC
Dispersant use plan			
 Notifications 	spiller	OSC (A)	observers at spill site
 Spill specific information 	spiller	OSC (A)	observers at spill site
• Is dispersant use appropriate	SSC	state or federal agencies (A)	charts or maps showing distribution of species which may be affected by spilled oil
 Is dispersant use allowable 	RRT	MMS (A)	Subparts H of NCP and of the Regional Contingency Plan; MMS policies on use of dispersants
• Is oil dispersible	SSC	spiller (A)	oil property data plus ambient water temperature
 Are dispersant supplies available 	spiller	SSC (A)	inventories of dispersants
• Will dispersants work with the spilled oil	SSC	spiller (A)	technical data on available dispersants; field tests
 Is dispersant spray equipment available 	spiller	SSC (A)	inventories of dispersant application equipment
 Has the equipment been calibrated 	spiller	SSC (A)	QA/QC procedures
 Have personnel been trained to apply dispersants properly 	spiller	SSC (A)	QA/QC procedures; training programs
• Are trained observers/monitors available	SSC	spiller (A)	QA/QC procedures; training programs

Item or Event	Primary Responsibility	Concurrence (C) or Alternate Responsibility (A)	Sources of Information
Dispersant use plan (con	tinued)		
• Is dispersant use acceptable	states	EPA (C)	technical data on toxicity and effectiveness of available dispersants
Dispersant use authorization	OSC	EPA (C) + states (C)	NOAA
Monitoring cleanup	OSC	····	SSC

TABLE 5—(cont'd.).

^{*a*} OSC = Federal On-Scene Coordinator

SSC = Scientific Support Coordinator

NOAA = National Oceanographic and Atmospheric Administration

QA/QC = Quality Assurance/Quality Control procedures (see Appendix A)

USCG = United States Coast Guard

NWS = National Weather Service

MMS = Minerals Management Service

mation on mechanical containment and recovery, on observation techniques and needs, and on those conditions that would lead to a decision to let natural processes clean up the spill. Consideration is given to the effectiveness of different countermeasures. Weather conditions, spill site, oil type, and other spill related factors are considered in the program. It is explained in the text of the program but is not clear in the diagram (Fig. 1) that simultaneous use of more than one countermeasure may be appropriate or needed. In the description of the dispersant use decision, recommendations are given for dispersant application rates based primarily on water depth. These rates have been chosen to be low enough that no environmental damage is likely if the recommended application rates are used. Thus, the rates are "safe." Little or no guidance is given as to how to evaluate the tradeoffs which must usually be made between possible impacts as a result of untreated oil versus possible impacts as a result of use of dispersants.

2. API Dispersant Use Decision Diagram—See Fig. 2 [22]. Primary emphasis is placed on decisions regarding dispersant use; the limitations of mechanical containment and recovery are noted. Simultaneous use of mechanical recovery and dispersants is recommended. No guidance is given regarding regulatory acceptance or application rates, but consideration is given to the effects of spill volume, oil products that have been spilled, condition of the oil (that is, weathering), weather conditions, and the effectiveness of countermeasures.

3. SLR Dispersant-Decision Making Workbook—See Fig. 3 [23]. Gives methods for characterizing on a numerical basis the environmental impacts on populations which may be at risk from either dispersed or untreated oil. Using these computed values, methodical and objective decisions can be made regarding the advisability of dispersant use or nonuse from an environmental perspective. Other aspects of spill response (mechanical recovery, natural removal) are deliberately not considered, because these are considered to be separate parts of the oil spill countermeasures problem. No guidance is given as to dispersant application rates nor is consideration given as to the effects of weather conditions, spill size, oil condition, and so forth. The objective of this decision making method is solely to indicate whether dispersant use is appropriate to consider or not.



FIG. 1—Flowchart of the EPA oil spill response decision tree.



- It is unlikely that sufficient mechanical equipment will be available to clean up a large split.
- With the approval of the Federal On-Scene Coordinator and the concurrrence of the EPA and the state(s). 8£ 9
 - Small spills normally should be completely controlled, particularly it both mechanical and chemical
- methods are used. However, under some conditions some oil may need to be removed from the shore. (d) Large spills, particultity 10,000 to 30,000 bbls per day, will be difficult to control. Only large aircraft spray systems are suitable and some oil may still strand. However, oil that is kept off the shore will
- lessen adverse eflects.
- Appropriate methods should be used to clean shorelines and sensitive habitals. See, for example, AP1 (1985) ٩

FIG. 2—API dispersant use decision diagram.



- regulatory agencies in terms of "High", "Medium", and "Low"; the determine is based on local priorities.
 - b) Quantitative impact on resources is calculated using environmentally-based algorithms; these algorithms yield a quantitative estimate of the degree of impact on each resource in terms of "Major", "Moderate", "Slight", or "Negligible".
 - c) The dispersant use decision is based on a comparison of the impacts on affected resources by the spilled oil if chemically dispersed vs. the impacts (usually on a different set of affected resources) by the untreated oil.

FIG. 3—SLR decision making method.

4. State of Alaska Dispersant Use Guidelines—See Fig. 4 [24]. No details are given of the factors that may be involved in the decisions at each node in the decision tree; appears to assume fairly high level of expertise by user. Accompanying the decision tree are maps on which are shown the zones in which dispersants (a) may be used with approval by the federal On-Scene Coordinator (OSC), (b) may be used only with concurrence of the EPA and the State of Alaska plus consultation with the Regional Response Team (RRT), or (c) may not be used. Note that the OSC must notify the EPA and the State of Alaska as soon as possible if he authorizes dispersant use. These zones are defined by bathymetry and currents, biological parameters, nearshore human use activities, and time required to respond. The definitions of the zones were developed by a subcommittee of the Alaska RRT. The zones were not evaluated by procedures such as those in the SLR workbook method described above. In the event that dispersant use may be authorized, no guidance is given as to dispersant application rates, nor is guidance given as to the effects of weather



FIG. 4-State of Alaska dispersant use decision matrix.

conditions, spill size, oil condition, and so forth. The objective of this decision making method is solely to indicate whether dispersant use is appropriate to consider or not, from a regulatory perspective.

In these dispersant use decision making procedures, it is clear that there are considerations not only of operational aspects (that is, will dispersants work effectively and would dispersant use be an environmentally appropriate countermeasure), but also there are considerations of whether dispersant use is acceptable from a regulatory viewpoint and whether use would be allowed by local regulatory agencies. However, some of these decision making procedures are more complete and explicit than others in dealing with the many questions that are usually raised regarding dispersant use.

Conclusion

The U.S. National Contingency Plan allows the use of dispersants for oil spill mitigation but stipulates that authorization for such use requires concurrence of the federal On-Scene Coordinator, the EPA, and the affected states. Such concurrence is only likely to be obtained in a timely fashion if a carefully designed plan can be presented which shows (1) that dispersants will be applied under good control and (2) that dispersant use can be expected to result in less environmental damage than if no dispersant were used. Preparation of such a plan takes time. Fortunately, most components of a dispersant use plan can be prepared well in advance of a spill. This includes analysis of the relative impacts of dispersed oil versus the impacts of untreated oil. The components of a complete dispersant use plan include:

(1) Spill specific information (what oil, where, how much was spilled, and weather and oceanographic data),

(2) dispersant resource inventories,

(3) information on dispersant application equipment and how to use it properly,

(4) plans to observe and control the application of the dispersants and to monitor the effectiveness of the application,

(5) analysis of the relative effects on populations at risk from dispersed oil and from untreated oil, and

(6) procedures for making the dispersant use decision.

Most of the components of such a plan can be completed well in advance of a spill, and only a few spill specific details will need to be added at the time of the spill. Use of this type of plan will enable dispersant use decisions to be made quickly, the decisions can be documented fully, and the decisions are likely to be more appropriate than if they are made without such a plan. For greatest acceptance and use, a dispersant use decision making plan should be the joint product of a cooperative effort by both industry and government.

APPENDIX A

Quality Assurance/Quality Control Program for Dispersant Application to Spilled Oil

Objective

Within realistic limits of calibration, operation, measurement, and observation, to assure that the correct amount of dispersant is applied to the spilled oil in a timely fashion.

General Comments

The following should be accomplished well in advance of a spill:

(1) perform calibrations with the equipment to be used and maintain the equipment (including periodic recalibration),

(2) train the operators and observers, and

(3) obtain any measuring instruments and train operators in their use.

Realistically, it must be recognized that it will be necessary to:

1. Accept qualitative observations in some cases.

2. Accept field observations and measurements as being sufficiently accurate for the job that must be done; do not attempt to achieve extremely precise measurements. It is unreal-

istic to expect high precision under the conditions which usually are found at the time of an oil spill and under field conditions.

3. Accept visual observations and estimates, in some cases, rather than striving for instrumental measurements, for example, of oil dispersed into water or of oil thickness before dispersion.

Elements of Program

Distribution of Oil on Water-(that is, measurement of areal coverage, thickness of oil, and thickness distribution):

Use visual observation, preferably from aircraft. Use notes from ITOPF Technical Information Paper 1 [25] as a guide. Spilled oil will usually be nonuniformly distributed on the water surface, and it is usually extremely difficult to make accurate estimates or measurements of the amount spilled.

Calibration of Systems for Dispersant Application—(the procedures that are adopted must be related to systems that are available):

All systems (meters, metering pumps, nozzles) should be calibrated using the fluids (dispersants) to be sprayed. For the total system during field operation, a reasonable calibration can be obtained by measuring the total amount of dispersant sprayed in a given time period and simultaneously noting the speed of travel and the width of the spray swath. (Note: The accuracy of the total system calibration will probably be no better than $\pm 10\%$, but this should be adequate.) If individual meters, metering pumps, nozzles, and so forth must be calibrated, the usual procedure would be to time the passage (throughput) of a known volume of liquid, usually at constant throughput rate and at about the rate expected to be used during dispersant application.

Monitoring of Dispersant Spray Field Operation—(that is, speed of travel, pump settings during operation, pumping time, wind speed and direction, direction of travel during application, altitude if aerial application or height of nozzles above water if boat application, and accuracy of application of dispersant to oil on water):

This involves two parts. (1) A reliable log of operating variables and operations aboard the spray craft. (Note: Log sheets should be prepared in advance, taking into account the specific equipment to be used.) (2) Aerial observation and direction of the dispersant spraying operation. See also the final paragraph on p. 4 of ITOPF Technical Information Paper 4 [16]. The observer/director should preferably be in radio contact with the spray operators to provide guidance. The observer should note the position and appearance of the spill, position of the spray craft during operations, apparent accuracy of dispersant application (is the dispersant hitting the target), and apparent effectiveness of the dispersant on the oil (in subsequent flights, is it apparent that the oil is dispersing within previously treated areas). See also the second paragraph in the second column of p. 7 of ITOPF Technical Information Paper 3. [15]. The observer should also make note of the sea conditions during dispersant application for future reference.

Effectiveness of Dispersant—(that is, how much oil is dispersed into the water column as a result of the dispersant application):

It is difficult to make quantitative measurements of the effectiveness with which a dispersant actually disperses oil into the water column. This is because (1) the concentrations to be measured of oil in water are usually small (for example, 0.1 to 10 ppm), (2) the available analytical apparatus is fairly delicate and therefore not practical for field use, (3) the analytical apparatus should be calibrated with the oil that is being dispersed, which may be difficult under field conditions, and (4) knowledge of the thickness of oil on the water surface is usually poor. For these reasons, it is likely that the most appropriate means of evaluating the effectiveness with which the dispersant actually disperses the oil may be visual observation by a trained observer, as described in ITOPF Technical Information Paper 3, p. 7 [15]. Use of a trained observer avoids the many problems associated with making field analyses and, owing to the limitations of such field analyses, may actually be as accurate and as effective as the analyses could be. Use the checklist in Appendix B to record observations. If, in spite of the problems outlined above, it is desired to make field measurements to try to determine the amount of oil dispersed into the water column, there are instruments available to do this. The best approach is likely to be use of a submersible pump to take water samples from various depths below the water surface and to analyze the samples directly in the field using a fluorometer. Sampling equipment and sampling procedures are available.

APPENDIX B

Checklist for Dispersant Observations

Note to observers: Record any information that is available; if information is not available, or not relevant, leave that space blank.

- I. Observer
 - 1. Name
 - 2. Business address and phone number
- II. Spill background
 - 1. Spill date
 - 2. Spill time
 - 3. Where spill originally occurred and source
 - 4. Specific type of oil (if known)
 - 5. Quantity of oil spilled (if known)
- III. Situation at time of dispersant application
 - 1. Date
 - 2. Time
 - 3. Location where dispersant was applied
 - 4. Spill area
 - 5. Spill description (continuous slick? windrows? scattered patches?) and area of sea surface covered
 - 6. Wind speed and direction
 - 7. Air and water temperature
 - 8. Visibility and precipitation
 - 9. Sea state
 - 10. Wave height and length
 - 11. Swell height and length
 - 12. Percent of waves breaking
 - 13. Significant tides and currents
 - 14. Description of floating oil:
 - a. Viscosity
 - b. Emulsification (percent oil in water or water in oil)
 - c. Weathering (percent of light ends evaporated)
 - d. Oil thickness (both average in oil patches and in thickest patch
 - e. Obtain a sample if possible

(Please note that the information requested in Item 14 may be difficult to obtain at many spill sites.)

- 15. Brief description of spill control and recovery efforts thus far (including successes and problems)
- IV. Dispersant use
 - 1. Full name of dispersant used (obtain a 1-pt [0.473-L] sample)
 - 2. Source of dispersant used (including name, address, and phone number of contact)

- 3. Method of dispersant application and type of equipment
- 4. Location relative to oil where dispersant was applied (for example, inshore edge of slick? sheen? thickest patches?)
- 5. Application rate (dosage, not dilution, in U.S. gallons per acre)
- 6. Estimated dispersant:oil ratio
- 7. Swath width and speed of application unit (boat or aircraft)
- 8. Dispersant pump rate and total amount of dispersant used
- 9. Time dispersant application began
- 10. Time dispersant application ended
- V. Observations
 - 1. What happened when the dispersant contacted the spill—immediately? after 10 min? after an hour?
 - 2. Percent of oil dispersed
 - 3. Percent (or amount) of oil resurfacing after a time interval
 - 4. Effects on floating oil? on biota? on sea color? on wave pattern? on other physical features?
 - 5. Please take color photos through a polarizing filter at regular intervals, and make written notes about each one (including the date and time, film and shutter speed, film type). A videotape record of the event would also be valuable.
 - 6. List any problems during application
 - 7. Did sea or weather conditions change much during the dispersant operation? How? (Refer to III.7 to III.14)
 - 8. For any oil/dispersant/water sample collected, label each sample carefully and on the data sheet list:
 - a. Geographic location
 - b. Depth
 - c. Location relative to spilled oil
 - d. Time
 - e. Notes (why was the sample taken here and now? What was it typical of or different from?)

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Dispersant Use Considerations

REFERENCE: Lavache, M. L., "Dispersant Use Considerations," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 135–143.*

ABSTRACT: The development of dispersant use guidelines and decision-making criteria are complex interagency activities. The use of dispersants as an oil spill response option in United States' waters occurs as the result of a decision process established by the National Contingency Plan (NCP), a federal regulation. The NCP requires a recommendation from the federal predesignated On-Scene Coordinator (OSC) to the U.S. Environmental Protection Agency (EPA) representative to the Regional Response Team (RRT). The recommendation is simultaneously made to State RRT representative(s) whenever state(s') waters are affected. The approval necessary for dispersant use is concurrence with the OSC's recommendation by the EPA RRT representative and, as appropriate, the State RRT representative(s). The U.S. Departments of Commerce (DOC) and the Interior (DOI) have related authorities and are also RRT member agencies. The NCP recommends that EPA and state RRT representatives consult with their DOC and DOI counterparts, as appropriate, during the decision process. Such consultation may become mandatory following a pending revision of the NCP, and where federal trusteeship interests are involved.

KEY WORDS: contingency plans, decision processes, dispersants, oil spills

This paper addresses elements of the three major categories of dispersant use decision considerations. The categories are technical issues, planning activities, and human resources. Technical issues may be either scientific or operational and include an assessment of the oil's dispersibility, estimation of the adequacy of available dispersants and application equipment, identification of resources at risk, estimation of treated and untreated oil trajectories, establishment of communications procedures, and the development of logistics data and operational guidelines. Planning activities include the process of developing both the Regional Response Team (RRT) Regional Contingency Plan (RCP) and the On-Scene Coordinator (OSC) Local Contingency Plan (LCP). These plans specify the respective concurrence and recommendation processes and should adequately address each major technical issue to the extent that regional guidance is appropriate. The human resources involved in the planning and operational phases of dispersant use decision making include the OSC, various RRT representatives, the oil spiller, and others with either environmental, economic, or political interests. The number of parties participating in the planning process will undoubtedly exceed the number of parties required in the decision process. The effectiveness of dispersant use decision making is proportional to the collective planning efforts of the regional and local response communities and the efficiency of their emergency communications network.

The opinions or assertions contained herein are those of the author and are not to be construed as either official or reflective of the views of either the Commandant or the Coast Guard in general.

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Discussion Points

OSC Data Compilation

The U.S. Coast Guard (USCG) provides OSCs in the coastal zone. The Environmental Protection Agency (EPA) provides OSCs in the inland zone. The boundaries between the two zones are developed regionally and are documented in the RCP. The OSC's jurisdiction within each zone extends from the inland sources of navigable water out to the extent of United States' interests, approximately 200 miles (322 km) to seaward.

The first requirement for dispersant use authorization is a favorable recommendation from the OSC to the RRT. Such a recommendation is formed after the accumulation and thorough assessment of information in a number of different data categories. The OSC must have the most accurate and complete information on spill location, weather, water temperature and salinity, tide and current, resources at risk, type and volume of oil, surface and subsurface trajectories, and the availability of dispersant and application equipment. The ability of the OSC to collect adequate data is influenced by the time of day (day or night), time of week (weekday, weekend, or holiday), weather, his familiarity with and the availability of his information sources, and the size of the OSC staff. If the OSC determines that a cleanup is warranted, he must then choose between mechanical removal and dispersant use, or some combination of each method. Occasionally, there are no physical or biological resources at risk and no cleanup is required. When specific resources are threatened, however, the OSC must form his best professional judgment concerning the relative hazards of an undispersed slick on the surface versus a dispersed plume in the water column. This judgment is based on the premise that dispersants should be considered as a defensive weapon and used only to protect specific resources threatened by surface oil. When dispersants are recommended, it is also assumed that those resources which may be affected by the subsurface dispersant plume have a lesser social or economic value.

Regional Response Team Concurrence

The extent to which an RRT participates in the dispersant authorization process is initially dependent on the adequacy of the Regional Contingency Plan. Comprehensive preplanning results in considerable efficiencies in incident-specific decision making. The best contingency plan is one that allows the consideration of all aspects of a situation as quickly as possible. Deficiencies in preplanning may result in high levels of decision-making activity, but with a diminished probability of timely consensus.

Although not a designated member of the RRT concurrence network, the USCG RRT member (who serves as the RRT chairman for coastal zone incidents) generally coordinates the delivery and interpretation of incident and dispersant information to EPA, U.S. Department of Commerce (DOC), U.S. Department of the Interior (DOI), and the state(s). The governor of each state in a region has designated a particular agency or department to represent the state on the RRT (Fig. 1). Frequently, however, the functions of public health, emergency management, water quality, and wildlife management are performed by different elements of state government. This routinely creates the necessity for the lead state agency to initiate a second round of concurrence deliberations among those other state agencies with a jurisdictional interest in dispersant use. The passage of information from the OSC into the RRT network, and sometimes into secondary loops, introduces the problem of time multiplication into the decision process. A similar multiplication follows the delivery of inaccurate or incomplete data from the OSC to the RRT. Carefully developed regional and local contingency plans maximize the opportunity for good decision making (Fig. 2).



FIG. 1-The dispersant use authorization concept.

National Contingency Plan (NCP) Product Schedule

EPA maintains a list of dispersants and other chemical and biological products that may be authorized for use on oil spills in accordance with the current NCP guidelines [1]. The list is called the NCP Product Schedule and may be obtained by written request to EPA Headquarters: Emergency Response Division, U.S. Environmental Protection Agency, Washington, DC 20460.

The following information is required for a dispersant to be listed in the Product Schedule: identity of manufacturer and distributor, special handling and occupational safety requirements, shelf life, recommended application procedures, toxicity, effectiveness, flash



FIG. 2-The dispersant use decision process.

point, pour point, viscosity, specific gravity, pH, component formulation, heavy metal concentrations, and the identity of the laboratory that performed the required tests. Similar prerequisites are itemized for surface collecting agents, biological additives, and burning agents. OSCs may not use substances that do not appear in the Product Schedule except, in an emergency, to prevent or reduce a hazard to human life. Substances that do appear in the Product Schedule are otherwise subject to the RRT authorization process.

Special Forces

The NCP provides for several special forces which are available at the request of an OSC to assist major oil or chemical spill response operations. These special forces arrive from different locations and serve as adjunct OSC staff members for the duration of the response.

The National Strike Force (NSF) is a USCG element consisting of the Atlantic Area Strike Team in Mobile, Alabama and the Pacific Area Strike Team in San Francisco, California. The NSF has a combined strength of 65 men and women. Members are extensively trained and well equipped for major pollution incidents. The categories of their employment during dispersant operations include equipment preparation, dispersant application, observation, and documentation.

The Public Information Assist Team (PIAT) is another USCG element. Its purpose is to complement the OSC's media and public relations capabilities during major pollution response incidents. PIAT is dispatched from USCG Headquarters in Washington, DC and concentrates on maintaining a coordinated flow of timely and factual information from the OSC to the public through the media. Team members have considerable knowledge of the NCP and the national response mechanism, and are conversant on a variety of issues relating to dispersant use. They have a clear understanding that the best time for public education is during a major pollution response incident.

The third special force available to an OSC is through the position of Scientific Support Coordinator (SSC). The SSC is a member of a group of highly skilled technical advisors and communicators who serve in each USCG district. The SSCs are employed by the National Oceanic and Atmospheric Administration (NOAA) and are linked by electronic mail to various technical support services. The SSC generally coordinates the assembly of resource sensitivity, weather, and trajectory data for the OSC during a spill response. SSCs synthesize technical information from a variety of sources into operational recommendations for the OSC.

Communications

Advances in communications technology have been adopted within the oil spill response community to the extent that each of the 48 coastal zone OSCs, each of the 12 to 18 members of the 13 RRTs, and each of the 14 NRT members are linked through an electronic mail system. The various data files developed by the OSC's staff in each of the dispersant decision categories can be merged into a summary document for simultaneous transmission to each member of the RRT concurrence network and other interested parties. The 2 obvious advantages of this approach are speed and accuracy. Electronic mail can be sent both ways in the system, and all account holders are interconnected. Comments, suggestions, objections, additions, and deletions may be entered at any point. Both federal and commercial telephone systems are also used for verbal exchanges, with conference calls often following the distribution of electronic mail files. The electronic mail system operates from a NOAA computer in Seattle, Washington.
Preauthorization of Dispersant Use

The NCP encourages RRTs to develop contingency plan guidance that considers the designation of preauthorization areas or conditions which would allow an OSC to apply dispersants without the delays of the formal RRT concurrence process. The preauthorization may be defined by geographic limits, volume of dispersant, biological season, or some other discrete measure. This form of specialty planning involves extensive training and public education, is heavily dependent on the capabilities of the local USCG and RRT agency staffs, and is generally successful in proportion to the local logistics situation.

One of the first steps in developing a preauthorization strategy is to establish and evaluate an area with finite physical or political boundaries and then add inclusive resource sensitivity subdivisions. Several of the RRTs and various industry groups have adopted this approach. There are four zone descriptions which are representative of the majority opinion.

1.	Dispersant use is ENCOURAGED	(> mechanical).
2.	Dispersant use is RECOMMENDED	(= mechanical).
3.	Dispersant use is CONDITIONAL	(< mechanical).
4.	Dispersant use is PROHIBITED	(mechanical only).

The identification of Zones 1 and 4 is particularly important to OSCs; the former so that necessary planning details and data can be developed, and the latter to highlight the need to evaluate alternative removal strategies.

Some RCPs do not include an allowance for PROHIBITED zones. This may prove to be a costly omission if an OSC's limited staff resources are devoted to planning for an event which an RRT concurrence agency knows it cannot authorize. Preauthorization becomes a more attractive option when RRTs approach the issue as a group to ensure consistency, but also one state at a time for the purpose of developing jurisdiction-specific RCP annexes.

Logistics

The availability of an adequate supply of effective dispersant, application equipment, delivery vehicles, and trained personnel are the main components of a dispersant use logistics plan.

Each of the dispersants listed in the NCP Product Schedule is available in different quantities, from different locations, and at various prices. Not more than several brands form the bulk of available United States' stockpiles. Industry oil spill cooperatives and large pollution contractors are the most likely sources of an initial dispersant supply. Some manufacturers have indicated the possibility of additional production in response to a demonstrated operational requirement. Start-up costs for a special production run, elapsed time for production, and subsequent transportation costs may become additional factors in the decision process.

Dispersant application equipment is usually available for purchase or lease from a wide variety of sources. Some configurations require assembly or modification. Dispersant application equipment includes spray booms, flow meters, nozzles, pumps, eductors, tankage, and so forth. Each specific application ensemble is designed around a given over-thesurface speed of delivery and sweep width. Contingency plans must identify the availability of both application equipment and the types of corresponding delivery vehicles. There are two general categories of dispersant delivery vehicles: boats and planes. Boats range in size from small outboard driven craft to large offshore supply vessels. The advantages of boat application include a long on-scene residence time and significant tankage capabilities. Simple pumping arrangements can be prefabricated at little expense and are easily stored for rapid installation. The shortcomings of boat application include poor visibility, which requires the use of a spotter aircraft, and relatively low areal coverage per unit of time. Boat applications are best suited to small spills of opportunity, operation in confined areas, or where a number of boats can operate in different patches of oil as a task force under the guidance of a single spotter aircraft.

There are three major classes of airborne dispersant delivery vessels: helicopters and small and large fixed-wing aircraft. Helicopters may be used either with installed tankage and spray booms or with an underslung bucket and boom arrangement. They perform well in confined locations and do not need an airfield for other than refueling. Cargo weight is an important factor in helicopter operations since the maximum dispersant capacity is generally limited to approximately 400 L per trip. Helicopters are used at best efficiency with buckets when full spares are available for immediate pickup at the staging site. Pilot training with both the remote spray controls and the quick-release feature for buckets is essential before operational deployment.

Small fixed-wing aircraft have a larger (800 to 1200 L) capacity and can operate from small airstrips. Although the airspeed of a small plane is greater than that of a helicopter, there are trade-offs between tankage, airspeed, and the proximity of the staging site to the location of the incident. Many of the available small fixed-wing aircraft may require nozzle changes to switch missions from crop dusting to dispersant application. Planes with altimeters and navigational equipment are preferred. The use of a separate spotter aircraft at an altitude offering the best opportunity for observation is recommended.

Larger multi-engine fixed-wing aircraft types include DC-4, DC-6, and C-130 models. Their respective tank capacities range from 6 000 to 20 000 L. The larger payloads and faster application speeds allow for greater coverage than with smaller planes or boats. The use of this type of aircraft is the logical choice for dispersant application on major spills in offshore waters. Cost considerations relating to start up, standby fees, and operating expenses, however, may affect a spiller's timely agreement to underwrite dispersant operations unless the local and regional contingency planning processes account for the development of an incident-specific resources-at-risk analysis and other supporting data. Another consideration is the assignment of a probability factor for equipment failure to each major mechanical component in the dispersant application system. A plan that relies on a single type of delivery vehicle may not adequately address the opportunity for system failure, thereby leaving the OSC without the dispersant use option.

Monitoring

There are two types of dispersant monitoring plans. One type is used at the time of dispersant application and is intended to yield operational intelligence as a quality control and effectiveness measure. Trained observers may be asked to record pre- and post-application observations with video, photo, and narrative documentation. The other type involves the accumulation of operational, biological, physical, and/or chemical data for subsequent analysis and publication. This type of research effort has a generic emphasis, and is not necessarily intended to contribute to the spill of opportunity.

The development of an acceptable monitoring plan can be one of the most difficult aspects of the contingency planning process. The selection of monitoring guidelines offers the opportunity for polarization within the regional and local contingency planning communities and should be addressed with care. The OSC has two principal responsibilities during an oil spill response:

(1) to assess the situation and monitor acitvities throughout the response to ensure that the spiller is responding satisfactorily to the incident and

(2) if that is not the case, or if the identity of the spiller is unknown, to assume supervision of all or part of the response activities using the Federal Pollution Fund [FWPCA, Section 311(k)].

If the half-dozen operational incidents which form the body of United States' dispersant use experience are used as an indicator, it can be inferred that dispersant use will—for some time—remain a federally funded activity. The OSC will contract for commercial response services for most operational functions and will develop reimbursable agreements for the employment of supplemental or unique government resources. The OSC's contracting authority, however, is limited to oil containment, removal, and disposal activities. Dispersant application and real-time effectiveness evaluations are appropriate Pollution Fund categories; research monitoring is not.

Resource management and trusteeship agencies have species and habit-specific responsibilities that make research-type dispersant monitoring activities a high priority consideration during contingency plan development. These special resource interests, combined with the near certainty of federal funding for dispersant use can create a situation wherein dispersant use, which may be the preferred response alternative, is not recommended because research monitoring requirements—which cannot be funded by the OSC—have been included in the RCP.

The resolution of this dilemma is dependent on the development of the most comprehensive monitoring strategy that can be financed through the Pollution Fund, with the agreement of all parties that the primary objectives of the national response mechanism are to accomplish the containment, removal, and disposal of spilled oil. In some regions it may be worthwhile to develop a standby research monitoring plan in the event that a spiller is willing to underwrite the cost of such activities as a part of the spill response.

Where regional interests require research monitoring, dispersant use should not be recommended to the RRT unless the spiller, or a third party, agrees to finance the research in a manner described in the RCP by the special-interest agencies. During the development of such an agreement, however, note that the time-critical period of effectiveness for dispersant use is quite short—probably shorter than the time necessary to activate a research monitoring plan.

Training

A variety of training opportunities exist to serve some of the needs of the various parties throughout the dispersant planning, decision-making, and application processes:

- locally developed USCG training exercises and contingency planning meetings,
- local exercises sponsored by industry oil spill cooperatives,

• NSF Strike Team training visits to local USCG field offices for workshops on operations and planning preparedness,

- RRT working groups on dispersant use and observer training,
- semi-annual RRT meetings held by each of the 13 RRTs,

• USCG sponsored OSC/RRT exercises, in six locations per year, to focus on communications and resource-tasking issues,

- industry sponsored technical and planning workshops,
- long-term federal agency participation with industry dispersant use committees,

• development of training and research materials by any of the sources listed above, either in-house or through contracts, and

• attendance at oil spill conferences, dispersant use symposia, or similar events.

Levels of organizational awareness and support, funding, and the availability of the appropriate personnel are principal considerations in the development of dispersant training opportunities. Care should be exercised when designing a training event to ensure that technical data presentations, policy discussions, and operational demonstrations each involve a specific target audience.

Observations

Boundaries

RRT boundaries are formed by the state boundaries of member states. Coastal zone boundaries are those of the USCG local field offices. Because the Coast Guard performs a number of maritime functions other than pollution response, the USCG boundaries often conform to the physical boundaries of water bodies rather than to political lines. This situation often leads to an extended number of interested parties in the OSC-to-RRT recommendation and concurrence process. It is essential to establish the identities of the concurrence network members during the contingency planning process.

Prerequisites for Effective Dispersant Use

Five critical elements are: a thoroughly designed and developed logistics capability, comprehensive local and regional contingency plans, an efficient and well-exercised RRT concurrence process, active training programs within the local and regional response communities, and a specially developed public information strategy.

Spills of Opportunity

The use of dispersants on small oil spills is likely to involve fewer complications with application equipment, logistics support, and overall coordination. Application by boat or helicopter is usually associated with small spills. The greatest opportunities for developing operational experience with dispersants may occur—at least in the near term—with the use of these relatively inefficient delivery vehicles. This concept is consistent with the NCP encouragement for RRT consideration of preauthorization for OSC dispersant use in specific circumstances.

Effective Regional Coordination

Three common elements of effective regional dispersant coordination are: an agreement that the total dispersion and/or recovery of the spilled oil is not possible; an agreement that the selection of response method(s) involves OSC's "best professional judgment" to *minimize* damages, and that the choice of dispersant use as a response option should be made as a *defensive* measure to protect specific resources; and an understanding that the success of the dispersant use coordination process is dependent on aggressive advance planning and decision making.

Probability

Dispersant use becomes a low probability event, given the relatively small number of eligible oil spills in any region, and in consideration of the related planning, logistics, data collection, and decision-making requirements. The coordination of dispersant activities requires more collective effort per unit of probability than any other category of pollution response planning.

Benefits of Dispersant Planning

Comprehensive local and regional dispersant use planning appears to require a disporportionate resource commitment in comparison to the probability of plan execution. The development of a fast and reliable OSC/RRT communications system, and the personal familiarity among the individuals involved in the interagency planning effort are significant and positive side effects. The intangible benefits of dispersant use planning are likely to enhance progress in other areas of activity in both the local and regional response communities.

Reference

 [1] National Oil and Hazardous Substances Pollution Contingency Plan, 40 CFR 300, Subpart H— Use of Dispersants and Other Chemicals, U.S. Environmental Protection Agency, Washington, DC. Carol-Ann Manen,^{1*} Paul Š. O'Brien,^{2*} Brad Hahn,^{3*} Howard Metsker,^{4*} Lyle B. Fox, Jr.,^{5*} David Kennedy,^{6*} Charles Getter,⁷ Lynn Tomich,^{8*} Michael Conway,^{9*} John Whitney,^{10*} and Lori Harris¹¹

Oil Dispersant Guidelines: Alaska

REFERENCE: Manen, C.-A., O'Brien, P. S., Hahn, B., Metsker, H., Fox, L. B., Jr., Kennedy, D., Getter, C., Tomich, L., Conway, M., Whitney, J., and Harris, L., "Oil Dispersant Guidelines: Alaska," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018*, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 144–151.

ABSTRACT: The Alaska Regional Response Team (RRT) is in the process of developing preconsultation and preapproval plans allowing for the limited use of dispersants on oil spills in Alaskan marine waters. "General Alaska Dispersant Use Criteria" briefly reviews the present data base for oil dispersing chemicals and establishes a three-part classification system for the use of dispersants in Alaskan coastal waters. This system is being applied to Alaskan areas in a site- and resource-specific manner. The general criteria and the application of the classification system to Cook Inlet have been subjected to public comment from the oil and fishing industry, approved by the RRT, subjected to public comment from the oil and fishing industry, approved by the RRT, and incorporated into the Alaska Regional Contingency Plan. At present, this classification system is being used to develop dispersant use guidelines for Prince William Sound, a much different regime, both physically and biologically, from Cook Inlet.

KEY WORDS: Alaska, dispersant use, oil spills, Alaska Regional Response Team, classification system

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The State of Alaska has coastal resources unparalleled in the rest of the nation. Alaska's tidal shoreline is 70 500 km long, 53% of the total shoreline of the entire United States [1]. This area encompasses vast, productive ecosystems and is a generous source of renewable and nonrenewable resources. Because of the size of this coastline and the difficulties involved in responding to spill incidents in remote, isolated, sparsely populated areas, which difficulties are often compounded by darkness and severe weather, a Regional Response Team (RRT) Working Group, consisting of representatives of the U.S. Environmental Protection Agency (EPA), State of Alaska, National Oceanic and Atmospheric Administration (NOAA), U.S. Fish and Wildlife Service, and the U.S. Coast Guard, has been exploring the possibilities of using dispersants as a response mechanism to oil spills in Alaska marine waters.

Decisions concerning dispersant use must be based on an evaluation of potential impacts from dispersed versus undispersed oil or the effects of oil on the water surface versus the effects of oil in the water column. If dispersants are used, the impact of spilled oil on organisms or systems using the water surface can be decreased or eliminated, but will be increased on those organisms within the water column. Examples of such compromises include untreated oil threatening highly aggregated populations of surface-using organisms (migrating or staging populations of seabirds; breeding sites of birds or mammals) and dispersed oil threatening aggregated populations of water column organisms (migrating salmon; fish or crab eggs or larvae).

The effects of oiling on marine birds and fur-bearing marine mammals are well known; the extremely long residence time of stranded oil and the resulting high probability of chronic impact on the subtidal benthos as the stranded oil leaches off the beach have been illustrated by the Baffin Island Oil Spill experiment [2]. Alternatively, even though the effects of chemically dispersing oil into the water column are not as well documented, available data indicate that these effects, although they may be severe, will be transient [3].

The "General Dispersant Use Criteria" states that, in all cases where a response action is deemed necessary, the mechanical removal of oil from the water surface is the preferred method of control. Only in those instances where the feasibility of physical containment and collection of the oil is limited, and it has been determined that the impact of dispersants or dispersed oil will be less harmful than that of nondispersed oil, will the use of dispersants or other chemicals be considered. In addition, any dispersants being considered for use must be currently on the National Contingency Plan Product Schedule.

Three dispersant use zones were developed for the general dispersant use criteria. These zones are defined by: (1) physical parameters, such as bathymetry and currents; (2) biological parameters, such as sensitive habitats or fish and wildlife concentrations areas; (3) nearshore human use activities; and (4) time required to respond to a spill incident.

Zone 1

The use of dispersants in Zone 1 is acceptable and should be evaluated, after consideration of mechanical means, as a response tool to mitigate oil spill impacts. The Federal On-Scene Coordinator (OSC) is not required to obtain approval from EPA or the State of Alaska before the use of dispersants in this zone. However, the OSC will notify EPA and the State of the decision as soon as practical.

Zone 1 is defined as an area in which dispersant use should be considered as a means to

prevent or reduce the amount of oil reaching the shoreline or other sensitive resources, including:

(1) endangered or threatened species protected by Federal and State governments;

(2) nesting, spawning, breeding, and nursery areas for mammals, birds, fish, and shellfish;

- (3) fish and wildlife concentration areas where these animals feed, rest, or migrate;
- (4) sensitive marine habitats, including:
 - (a) seagrass beds,
 - (b) kelp beds,
 - (c) shellfish beds,
 - (d) tidal flats,
 - (e) marshes,
 - (f) shallow subtidal areas,
 - (g) low-energy bays and harbors, and
 - (h) rocky intertidal areas;

(5) aquaculture and commercial areas which are shallow enough to allow impacts from oil spills; and

(6) recreational and industrial areas.

Zone 1 areas are characterized by water conditions (depth, distance, and currents) that will allow dispersed oil to be rapidly diluted to low concentrations. These areas are far enough away from sensitive resources that dispersant operations would not cause disturbances. Because it is likely that spilled oil will impact sensitive resources in this zone, an immediate response is required to mitigate environmental consequences.

Zone 2

The use of dispersants is conditional in Zone 2 to protect sensitive wildlife and other resources. The OSC is required to consult with the RRT and obtain the approval of EPA and the State of Alaska before the use of dispersants in Zone 2. A spill in Zone 2 must be continuously monitored and the need for dispersant response actions reappraised accordingly.

Zone 2 areas are characterized by water conditions (depth, distance, and currents) that will allow rapid dilution of dispersed oil to low concentrations. These areas are far enough away from sensitive resources that dispersant operations would not cause disturbances, so an immediate response is not necessary.

Zone 3

The use of dispersants is not recommended in Zone 3. Dispersants may be used in Zone 3 if, on a case-by-case basis, it is determined that the disturbance of the organisms or direct exposure to dispersant or dispersed oil or both would be less deleterious than the impact of spilled oil. As in Zone 2, the OSC is required to consult with the RRT and obtain the approval of EPA and the State of Alaska before the use of dispersants in Zone 3.

Zone 3 is defined as the area immediately in or around the resources requiring protection, including the resources themselves. Dispersant use in this area may disturb resources, may not have adequate time for effectiveness, may expose the resources to dispersants directly, or may expose other resources to unacceptable high levels of dispersed oil. See the above definition of Zone 1 for examples of these resources.

This classification system is conservative, especially in light of recent data on the effects of dispersants and dispersed oil in shallow water [4]. Moreover, this classification system is not being generally applied to the state's coastline and marine waters, but is being tailored to respond to specific physical settings and biological resources. The variety of marine and coastal habitats in the Alaskan Arctic and Subarctic coastal regimes (estuaries, barrier islands and lagoons, exposed high-energy coasts, rocky islands and sea cliffs, wetlands, and tideflats), and the permutations possible within these categories require that this system be applied in a site- and resource-specific manner.

Areas for which it has been considered reasonable to develop dispersant use guidelines have been ranked in order of probability of an accidental release of oil and include Cook Inlet, Prince William Sound (considered with the Copper River Delta), and Prudhoe Bay (considered with the Sagavanirktok River Delta area).

Specific Guidelines: Cook Inlet

The dispersant use classification system was first applied to Cook Inlet, a large tidal estuary in south-central Alaska (Fig. 1). More than half of the population of the State of Alaska is concentrated around Cook Inlet. The major port for the City of Anchorage and southcentral Alaska is located at the head of the inlet. The inlet supports commercial fisheries for all five species of salmon; king, tanner, and Dungeness crabs; halibut; and shrimp, and is the most popular and accessible sportfishing area in Alaska. In contrast, 14 offshore oil



FIG. 1—The coastline of Alaska. The locations and sizes of the tentatively identified dispersant preapproval areas, Cook Inlet, Prince William Sound, and Prudhoe Bay are indicated.

and gas production platforms are located in Cook Inlet. The volume of petroleum products shipped through Cook Inlet has reached as much as 95×10^5 m³ oil and over 60×10^5 m³ of liquid natural gas annually [5].

Tides in Cook Inlet are among the highest in the world and currents are very swift; circulation is primarily tidally driven. The physiography of the inlet amplifies tidal flow, with the result that while by strict definition Cook Inlet is an estuary, its physical behavior is more like that of a large embayment [6].

The mountain ranges surrounding Cook Inlet contain glaciers which are the sources for most of the stream systems discharging into the inlet. The glacial flour transported by these streams is the source of the large suspended sediment load occurring in the inlet. In the Upper Inlet, dynamic, very fine, highly fluid bed loads associated with this glacial flour cause low-standing crops of benthic invertebrates. There are extensive intertidal mudflats at the mouths of the major glacially fed rivers. Ice, up to 4 ft (1 m) thick and a ¼-mile (0.4 km) in diameter, forms in the Upper Inlet in the winter and is transported throughout the upper and middle portions of the inlet by tides and currents.

Most of the southwestern shoreline is rocky and highly indented, while the northwestern shoreline contains extensive mudflats and coastal wetlands. The eastern shoreline is characterized by raised plateau-like topography, that is, high cliffs footed by sand/gravel beaches and mudflats and having little indentation.

The application of the dispersant use criteria to this area was made easier by the large amounts of environmental information collected during the last two decades to plan for and assess the effects of the rapid industrial and population growth in Anchorage. In general, a Zone 3 designation was applied inshore of the 20-m isobath (Fig. 2). However, where the shoreline consists of rocky headlands and the nearshore depth increased rapidly, this designation was changed to "an area extending one mile out from the shoreline." This distance allows for ample dilution of dispersed oil before its impacting the shoreline or shallow water area.

In lower Cook Inlet, Zone 1 was identified as an approximately five-mile (8-km) wide buffer area outside Zone 3; this width would provide adequate time to conduct a dispersant response before oil enters the sensitive Zone 3 area. In the middle and upper Inlet, all waters outside of Zone 3 were designated Zone 1 as a result of the Inlet's reduced width in this area. The remaining waters in the lower Inlet were designated as Zone 2. Exceptions to this are:

1. The area north of Anchor Point is classified as Zone 3 during 1 July through 15 August as a result of the large salmon migrations during this period.

2. Zone 3 is narrower around the Port of Anchorage, Nikiski docks, and Drift River offshore loading facility to make it easier to use dispersants in these areas where mechanical containment is difficult and the probability of an oil spill is high.

3. The most northern areas of the inlet are wetlands, which are heavily used for nesting and staging by waterfowl. Under this dual zone classification, this area is designated as Zone 1 during the first 3 h of the ebb tide and Zone 3 during the rest of the tidal cycle. This dual Zone 1/Zone 3 designation was adopted to prevent extreme tidal fluctuations from transporting high concentrations of dispersed oil into mudflats and marshes.

Specific Guidelines: Prince William Sound

Prince William Sound, a series of bays, inlets, islands, and fjords, is one of the largest tidal estuarine systems on the North American continent not presently influenced by coastal urbanization. The mainland coast is mountainous and deeply carved by glaciers,



FIG. 2—Dispersant use zones in Cook Inlet. The use of dispersants is acceptable in Zone 1, conditional in Zone 2, and not recommended in Zone 3. The area north of Anchor Point (Kachemak Bay) is classified as Zone 3 during 1 July through 15 August as a result of the presence of large numbers of migrating salmon during this time. The area north of Point Possession is designated as Zone 1 during the first 3 h of the ebb tide and Zone 3 during the rest of the tidal cycle.

many of which, like the Columbia Glacier, are still active. River systems are short and with few branches, reflecting the close proximity of the mountain ranges to marine water. Bayhead deposits of mud, sand, and gravel are common, as well as glacial outwash deltas and moraines of sand and gravel. Eelgrass beds are common where streams empty into the Sound.

Although all of Prince William Sound can be characterized as estuarine, the conditions from one fjord to the next vary, depending on the amount of freshwater input, degree of seasonal icing, turbidity, and the tidal mixing (or flushing) rate. These factors exert a strong control over the marine flora and fauna on a local scale, as well as Prince William Sound as a whole.

The renewable resources of Prince William Sound include prodigious stocks of king, tanner, and Dungeness crabs; razor, butter, and littleneck clams; scallops; and commercially important fish such as salmon, halibut, herring, flatfish, ocean perch, cod, and hake.

Mammals are represented by seals, sea lions, sea otters, and whales. The local bird population is diverse and abundant. At various times of the year, the area is inhabited by over 130 avian species, of which about 60 species contain tens of thousands of individuals, and another 7 species have numbers in the millions.

Prince William Sound is comparable in size to Puget Sound, Washington; the coastline totals approximately 5000 km, yet is populated by less than 5000 permanent inhabitants in the remote communities of Valdez, Cordova, and Whittier. Valdez is accessible by road and air, Whittier by railroad and air, and Cordova by air only. The economy of these communities is based on commercial fishing, tourism, and oil. The terminus of the Trans-Alaska Pipeline is in Port Valdez, a fjord in the northeastern portion of Prince William Sound. Oil received from Prudhoe Bay is stored in tanks at the terminal until it can be loaded aboard tankers for shipment to ports on U.S. West Coast and elsewhere. At the current throughput rate of 240 000 m³ a day, nearly three tankers load oil at Valdez every day.

Application of the dispersant use classification system to this highly indented coast is being tailored to Prince William Sound's fjord geomorphology and focused on the tanker traffic lanes which extend out of the Port of Valdez, through the central portion of Prince William Sound, and south through Hinchinbrook Entrance (Fig. 3). Preliminary discus-



FIG. 3—Prince William Sound. The dispersant use guidelines for Prince William Sound will be focused on the tanker traffic lanes. At present, the Dispersant Functional Working Group has initiated the tentative identification of zones.

sions have tentatively identified the traffic lanes themselves, and an area extending on either side of the lanes to within 1 km of the coast as Zone 1 area (Fig. 3). In the main body of Prince William Sound itself, areas to the east and west of this zone have been tentatively designated as Zone 3 because of their complex geomorphology and rich fishery resources. Outside of the sound and seaward of the 5.6-km (3-mile) territorial limit, the Zone 1 designation is continued as a 9-km (5-nautical-miles) band to the north and south. Shoreward of this band has been tentatively designated as Zone 3; seaward of this band as Zone 2. Review of these tentative designations has just been initiated (Spring 1988). These tentative designations will be revised depending upon the reviews and comments from the resource agencies, industry, and the environmental community.

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Letters of Agreement for the Use of Dispersants

REFERENCE: Hart, T. E., "Letters of Agreement for the Use of Dispersants," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 152–156.*

ABSTRACT: Subpart H to the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) authorizes the On-Scene Coordinator (OSC) to use dispersants on oil discharges if certain conditions have been met. Primary among these is the requirement that the U.S. Environmental Protection Agency (EPA) representative to the Regional Response Team (RRT) and the affected state concur regarding dispersant use. However, obtaining concurrence after a spill can be so time-consuming that optimal dispersant use is no longer possible.

Since the effectiveness of dispersants is time-critical, the sooner that concurrence can be obtained and the dispersant applied, the more effective such application should be. Thus, planning can significantly increase the performance of dispersants.

One way to expedite the decision making process is in agreements that preauthorize the OSC to use dispersants. The NCP encourages RRTs to plan for such use and to have preauthorizations in place. The Region IV RRT has developed an agreement for the use of dispersants in Florida. Two similar agreements have been developed by the Caribbean RRT for Puerto Rico and the U.S. Virgin Islands. While none of these agreements allows the unrestricted use of dispersants, each specifies areas where the OSC can use dispersants and areas where dispersants cannot be used without further discussion with the EPA and the state. The Caribbean RRT has also included provisions in the agreements for a monitoring strategy to assess the effectiveness of dispersants when they are used.

The key to an effective and successful response is having an organization and contingency plan in place. Such arrangements are an integral part of the Region IV and Caribbean RRTs' contingency plans and will result in a more timely and informed decision on whether dispersants will be used.

KEY WORDS: dispersants, letters of agreement, contingency plans, oil spills

Today, the use of dispersants on oil spills that threaten coastlines or offshore resources are not always automatically ruled out. Contrast this to a few years ago where, if a spill occurred offshore, the typical response would be to track its movement and wait for it to come ashore before initiating cleanup actions. Use of dispersants that might break up the slick offshore would most likely have been prohibited. Although many of today's responses would be similar, there is more of a willingness to use dispersants since they are generally accepted to be less toxic than those of the 1960s and 1970s. Furthermore, there is an increasing amount of scientific data on dispersants and their effect on marine organisms.

Subpart H of the National Oil and Hazardous Substances Pollution Contingency Plan

The views expressed herein are those of the author and are not to be construed as official or reflecting the views of the Commandant or of the U.S. Coast Guard.

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specifically authorizes the predesignated Federal On-Scene Coordinator (OSC) to use dispersants under certain conditions. One of these conditions is that the OSC must obtain the concurrence of (1) the Environmental Protection Agency (EPA) representative to the Regional Response Team (RRT) and (2) the affected state(s). Since the effectiveness of dispersants is largely dependent upon how soon the dispersant can be applied to the spill, it is essential that the required concurrences be obtained as soon as possible. Timely response is always a key element, but especially so with dispersants, since the effectiveness is usually adversely affected by the weathering of oil. Delays would also result in the slick spreading out and breaking up into smaller slicks, making uniform dispersant application more difficult. Having to obtain the required concurrences at the time of a spill leaves one vulnerable to the availability of the individual(s) who have the authority to make that decision on the EPA and state level. Subpart H provides for a mechanism to obtain these concurrences beforehand:

RRT's should consider, as part of their planning activities, the appropriateness of using dispersants.... If the RRT and the states which jurisdiction over the waters of the area to which a plan applies approve in advance the use of certain products as described in the plan, the OSC may authorize the use of products without obtaining the concurrence of the EPA representative to the RRT or the states.

The solution that the Seventh Coast Guard District has been pursuing is to develop letters of agreement (LOA) with the EPA and states/territories in its geographical area. These LOA identify geographical areas where the OSC has been given the concurrence to use dispersants without the need to obtain further approval for dispersant use at the time of a spill.

Before discussing development for our dispersant agreement, a word as to the federal spill response organization may be appropriate. The federal response organization can be broken down into three major levels: the National Response Team, Regional Response Team, and the predesignated Federal On-Scene Coordinator. The National Response Team (NRT) is responsible for developing the national policy and is comprised of members representing twelve different federal agencies with specific responsibilities in response activities. The Regional Response Team (RRT) is comprised of members of the federal agencies represented on the NRT as well as persons from the various states and, in some cases, municipalities, located in the federal region. The RRT serves as a regional planning body and is responsible for developing regional contingency plans which will ensure prompt spill response actions. During an actual, or potential, pollution incident the RRT may assist the predesignated Federal On-Scene Coordinator by offering technical advice and coordination in removal activities. The predesignated On-Scene Coordinator (OSC) is generally a representative from the EPA for inland spills and the Coast Guard for the spills occurring in coastal and offshore waters. The OSC is responsible for investigation of pollution incidents and for monitoring of cleanup operations when undertaken by the spiller. When the spiller does not take proper action, or is unknown, the OSC initiates a federal cleanup response using the 311(k) pollution fund.

The Seventh Coast Guard District cochairs two RRTs; the Region IV RRT encompassing the southeastern United States and the Caribbean RRT which includes Puerto Rico and the U.S. Virgin Islands. It was through the Region IV RRT that the Seventh Coast Guard District initially began planning activities for the use of dispersants. The proposal was set forth in late 1982 that the RRT appoint a dispersant committee to determine beforehand where and under what conditions accepted dispersants could be used by our Federal OSCs. Throughout 1983, members of this committee gathered information on dispersants, attended dispersant workshops being held around the country, and in doing so, developed a greater awareness of potential uses of dispersants and their limitations. In January 1984 this committee held a meeting in Atlanta with the express purpose of identifying those situations in which the RRT could preauthorize the OSC to use dispersants. The following recommendations came from the meeting.

1. Dispersants should be given consideration along with other cleanup techniques when responding to offshore oil spills which pose a potential threat to coastline shorelines.

2. The Coast Guard along with EPA and the State of Florida should enter into discussions to determine if a prototype agreement on "preapproved" usage of dispersants could be reached. It was hoped that if this agreement could be developed it would serve as a basis for similar agreements with remaining Coastal Region IV states, Georgia and South Carolina.

Almost immediately after this meeting, work began on a dispersant agreement. These efforts were successful and the agreement was jointly signed by the Seventh Coast Guard District, EPA Region IV, and Florida on 17 Sept. 1984. This was the first such arrangement develped which preauthorized the OSC to use dispersants. In the document the three parties agreed that physical removal of oil was still the preferred response method but recognized that in some cases this would not be feasible. In these instances, the effective use of dispersants should be considered to minimize serious environmental/economic damage or to prevent the loss of human life. The LOA sets forth criteria under which dispersants can be used on or in waters off the coast of Florida which are also within the boundaries of the Seventh Coast Guard District. Note that the LOA does not include the entire state of Florida since the Florida Panhandle west of 83 50"W longitude is in the Eighth Coast Guard District.

The decision to use dispersants rests solely with one of the three predesignated Coast Guard OSCs in Florida. With certain noted exceptions no further approval or consultation with the EPA or the state on the part of the OSC is required. We believe that this agreement provides the OSC with a mechanism to consider and decide upon the use of dispersants and actually commerce dispersant application in a much more timely manner than would be possible if the agreement did not exist. In addition to providing the OSC with authority to use dispersants, the agreement provides the OSC with specific guidelines regarding deliberations as to whether he/she should authorize the use of dispersants. Guidelines specified in the agreement include:

1. The decision to use dispersants shall be made only after consulting the State of Florida Oil Spill Dispersant Atlas to ensure that an environmentally sound decision is made. Each of the OSCs has a copy of the atlas and is familiar with its contents. In the event of a spill, the atlas can be consulted to ascertain readily whether the spill is in/or threatens an area where dispersant use is restricted or prohibited.

2. Dispersants may be used in open waters at least 3 miles (5 km) from any shoreline where the water depth is at least 65 ft (20 m) deep. Use inside 3 miles (5 km) may be considered where the water depth is at least 32 ft (10 m) deep and the economic/esthetic value of the recreational area is substantially greater than the environmental value.

3. Prior approval from the EPA and state are required if use of dispersants is contemplated in shellfish propagation or harvesting waters, over reef areas, in coastal marshes, or mangrove forests.

4. Sinking agents are expressly prohibited.

To date, the Coast Guard OSC's in Florida have not had occasion to invoke the LOA to use dispersants. However, with Florida's port traffic and her location adjacent to the shipping lanes between the Gulf ports and the southeastern Caribbean, Europe, and East Coast ports, the potential for a serious marine casualty off Florida is always present. Two examples illustrate the risks of spills along the Florida coastline. In August of 1985, Hurricane Eleana passed south of the Florida Keys and northward into the Gulf of Mexico. In its path was the tankbarge Texas loaded with 4 million gal (15 million L) of oil. The barge broke loose from its towing vessel a few miles north of the Dry Tortugas and remained adrift for about 36 h before the tow was reestablished. In February 1987 the Liberian car carrier, Fernpassat, struck the entrance jetty to the St. Johns River in Mayport, Florida. In this mishap the vessel's fuel tanks were ruptured and resulted in the release of over 100 000 gal (400 000 L) of fuel oil. After it was determined that the vessel was in no immediate danger of sinking, it was directed out beyond the Gulf Stream where any remaining leakage would be caught in the current and dissipated. The OSC considered the use of dispersants in the first hours of the casualty, but darkness and fog prevented an accurate assessment of the spill and its location. By daylight the majority of the oil that would impact the coastline had already come ashore making the question of dispersant use immaterial. Incidents such as these underscore the desirability and necessity of having an effective, coordinated contingency plan including plans for the use of dispersants immediately available and ready to be placed into effect. We consider the Florida LOA a vital element of our overall contingency planning process even though it does not provide prior concurrence for all spill possibilities.

In mid 1985 the Seventh Coast Guard District began discussions with Puerto Rico and EPA Region II to develop an agreement similar to the Florida LOA. While the formats of these agreements are essentially the same, the specifics regarding where and when prior concurrence has been given differ in each. In the Puerto Rico agreement which was signed on 16 Jan. 1986, the OSC may use dispersants ½ nautical mile (926 m) from shore where the water depth is over 60 feet (18 m) deep. This compares to the 3-mile (5-km) preapproved area in the Florida LOA. Inside of ½ mile (0.8 m), or where the water depth is less than 60 ft (18 m) deep, the OSC must obtain concurrence from EPA and the Puerto Rico Environmental Quality Board (PREQB). If a decision cannot be obtained from these entities within 12 h, dispersant can be applied if the OSC determines that it is desirable. If PREQB and EPA cannot reach a consensus, the decision of PREQB shall take precedence. A significant addition to the Puerto Rico LOA is the requirement that if dispersants are used, a debriefing, chaired by the PREQB, will take place within 45 days of the use to gather information concerning the effectiveness of the dispersants and to assess whether any changes to the LOA should be made.

The LOA with the U.S. Virgin Islands was signed on 22 May 1986. Again, it too differs from the Florida and Puerto Rico agreements in specifying areas where concurrence has been given. Dispersants may be used in waters that are at least 1 mile (1.6 km) from any shoreline or reef (where the reef is less than 20 ft [6 m] from the water's surface) and the water depth in the application area is at least 65 ft (20 m) deep. Provisions have been incorporated into the LOA addressing the possible situation where the Virgin Islands Department of Conservation and Cultural Affairs (DCCA) and the EPA cannot provide the OSC with an answer or do not agree as to whether dispersants should be used in areas where prior concurrence has not been given. One major addition to this LOA is the inclusion of the Department of the Interior (DOI) as a party. Subpart H to the National Contingency Plan states that, "... the OSC shall consult with other appropriate Federal agencies as practicable ..." when considering the use of dispersants. Because of the amount of

landholdings that DOI has in the U.S. Virgin Islands, it was deemed desirable that they participate in the dispersant agreement. The Virgin Islands LOA also includes a provision to insure that a monitoring strategy to identify the effectiveness of dispersants is accomplished. The monitoring strategy to be followed is contained in Subpart H to the Caribbean Regional Contingency Plan.

I would recommend that each region develop contingency plans for dispersant use. Ideally these plans will identify areas where dispersants can be used. They should also provide for the required concurrences eliminating the need for the OSC to obtain concurrences at the time of the spill. Agreements can be tailored to each region or state, depending upon what people are comfortable with.

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Field Measurement of Effectiveness: Historical Review and Examination of Analytical Methods

REFERENCE: Fingas, M. F., **"Field Measurement of Effectiveness: Historical Review and Examination of Analytical Methods,**" in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018,* L. Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 157–178.

ABSTRACT: Data are provided on 106 separate offshore experimental spills to determine dispersant field effectiveness. Effectiveness ratings for 25 of these spills were assigned by the experimenters; they vary from 0 to 100% and have an average of 33%.

Measurement techniques used for these experiments are reviewed and described. The techniques include: subsurface measurements to determine oil in the water column, surface sampling to determine oil remaining, dispersant application amount or distribution, and the use of remote sensing to observe visually the results or to quantify the area of surface oil. Existing means of detection and quantification appear to be effective.

Most experimenters have used subsurface oil data in an attempt to establish a mass balance and thereby an effectiveness value. This technique is critically examined using values from historical trials, and it is shown that the subsurface oil does not have a regular distribution in relation to the surface slick. Correlation cannot be established between concentrations at depth or with time and distance. This lack of correlation implies that mass balance values based on subsurface oil concentrations in relation to the surface slick are not reliable. Effectiveness results claimed in the literature are also suspect because they do not correlate well with the maximum oil concentration seen at a given depth.

The mathematical relationships used to provide the integrated amount of oil in the water column are also examined. It is shown by simulation that effectiveness claimed is highly sensitive to both assumptions and mathematical treatment. Historical data are used to show that effectiveness values can vary over an order of magnitude depending on the algorithm used. Values in the literature are generally the highest one would obtain using reasonable algorithms.

A number of phenomena have been observed at spill sites. Herding of oil occurs immediately after dispersant application and has sometimes been misinterpreted as dispersion.

Examinations of spills where slicks were monitored for longer than 3 h show that extensive resurfacing of oil occurred. Resurfacing is particularly problematic because, depending on current and wind, resurfacing may occur outside slick boundaries. When this occurs, resurfaced oil is not included in subsequent calculations, and consequently, effectiveness is overestimated.

Field effectiveness cannot be reliably determined by using only measurements of oil in the water column. The distribution of oil in the water column is not known nor does it necessarily bear a relationship to surface slick boundaries. Furthermore, in the initial hours—perhaps as many as 7—the oil concentration in the water column may be transitory as significant amounts of oil resurface. Remote sensing over a long term such as two or three days is suggested as the primary technique for monitoring experimental spills and for attempting to establish a mass balance.

KEY WORDS: dispersants, dispersant effectiveness, field effectiveness, oil spill treatment, field measurement

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Review of Past Field Trials

Over the past 11 years, 106 spills have been laid out deliberately to test the effectiveness of oil spill dispersants [1-20]. These spills are summarized in Table 1. They do not include spills smaller than 0.2 m³ (1 barrel). Many more of these types have been conducted than of the larger scale experiments, but have not been well documented in many cases [18,21-25].

The purpose behind most large-scale experiments has been to document the effectiveness of oil spill dispersants in the field. The specific motive was to establish an effectiveness value or the percentage of the oil removed, attributed to the application of chemical dispersants versus that of slicks acted on by natural processes alone. Of the 106 slicks documented, 23 are controls used to establish a comparison. Percentage effectiveness is reported in 25 spills, and the average for these values is 33%. Values range from 2 to 100%. Most authors have not assigned effectiveness values because, as will be demonstrated later in this paper, effectiveness values are difficult to establish and variances are high. All values reported were made on the basis of water column oil measurements followed by attempts to obtain mass balance based on distance estimations and distribution extrapolation between measured points.

Additional points of interest are that 34 of these spills were conducted in French waters, 24 in American, 17 in Canadian, 17 in Norwegian, 9 in Dutch, and 5 in British waters. As a percentage of treatment methods, 37% were performed by ship spray systems, 32% by fixed-wing aircraft, 22% by helicopter, and 8% were premixed with dispersants.

Previous authors have analyzed field experiments, in lesser numbers, and have generally concluded that field tests show effectiveness problems with dispersants [1,26]. Others have noted the variety of analytical techniques used and the problems associated with conducting these field operations and obtaining data to determine the actual effectiveness [7,27].

Analytical Aspects of Field Trials

Table 2 is a summary of the analytical means employed at the field trials summarized in Table 1. This table lists the means used to measure oil content in the water column, sampling the oil or dispersant on the water surface, and for remote sensing. Notably absent are techniques used for the measuring of dispersant in oil; reliable means still do not exist to measure the amount of dispersant in oil, especially in the case of field trials [28]. This means that the actual loss of dispersant to water is not known, as well as the amount of dispersant retained in the oil, both on the surface and in the water.

Reviews of oil-in-water analytical techniques have been published [29-31]. In recent years, at field trials, most oil in the water column has been measured using fluorometers or turbidimeters. Both instruments possess the ability to measure the dynamic range of the encountered concentrations [30,31]. The accuracy of the measurements, in both cases, is dependent on the accuracy of calibration. Obtaining accurate calibration results is difficult since an instrument's response for a given amount of oil is sought, and oil will largely cling to the walls of the calibration pipes and vessels or float to the surface. This can be partially alleviated by adding dispersants or other surfactants, although in the author's laboratory it was found that a maximum of 70% of the oil in the range of 1 to 30 ppm was actually in the water, even with large amounts of dispersant. Without dispersant this amount was as low as 10%, depending on the oil type. The effect on the final measurement, of this loss of oil, is to overestimate the oil during the actual measurement. Calibrations made in the author's laboratory and used with field fluorometric data resulted in overestimations by as much as an order of magnitude. Commonly, measurements in the field are double or triple the actual value. This is due to lack of compensation for oil loss during calibration. With

Location/ Identifier	Reference	Year	Number	Oil Type	Spill Amount, m ³	Dispersant	Application Method	Dose Rate, D:0	Sea State	Claimed Effectiveness,
North Sea	Cormack and Nichols	1976	-	Ekofisk	0.5	10% conc.	ship, WSL	:	-	:
Wallops Island	McAuliffe et al. [1.3]	1978	0 N	Kuwait Murban	1.7	10% conc. Corexit 9527	ship, WSL helicopter	1:20 1:5	2-3 1	100
	.		4 v) v	La Rosa Murban	1.7	Corexit 9527 Corexit 9527	helicopter helicopter	1:1 1:11		100
South California	Smith et al. 141	1978	5	La rosa North Slone	1.7	Control later Control later	nencopter control then heliconter	>1:1 >1:5	-I-0	05
	2		×	North	3.2	Corexit 9527	airplane, Cessna	>1:5	0-I	:
			6	North	1.7	Recovery +	helicopter	>1:5	0-1	•
			10	North	0.8	BP1100WD	ship, WSL	>1:5	0-1	•
			Ξ	Slope North Slope	0.8	Corexit 9527	ship	>1:5	0-1	:
South California	Smith et al.	1978	12	North Stone	3.2	Corexit 9527	airplane, Cessna	>1:5	1-2	÷
			13	North Slone	0.8	Corexit 9527	ship	>1:5	1-2	:
			14	North	0.8	BP1100WD	ship, WSL	>1:5	1-2	:
			15	North	0.6	several,	several,	• • •	1-2	
Victoria	Green et al.	1978	16	North Slond	0.2	demonstration 10%, 9527	demonstration ship, WSL	I :1	7	•
	[04]		17	North	0.4	10%, 9527	ship, WSL	Ŀ	-	
			18	stope North Slope	0.2	10%, 9527	ship, WSL	l:1	Π	÷

TABLE 1—Data from dispersant effectiveness trials.^a

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(cont'd.).
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FABLE 1

Location/ Identifier	Reference	Year	Number	Oil Type	Spill Amount, m ³	Dispersant	Application Method	Dose Rate, D:0	Sea State	Claimed Effectiveness, %
Long Beach	McAuliffe et	1979	19	Prudhoe	1.6	control	control	:	2-3	0.5
	[<i>C</i> '7] .18		20	Prudhoe	1.6	2% conc.	ship	1:67	2–3	8
			21	Day Prudhoe Ray	1.6	2% conc.	ship	1:67	2-3	5
			22	Prudhoe	3.2	conc.	airplane, DC-4	1:20	2-3	78
Long Beach	McAuliffe et	1979	23	Prudhoe	1.6	conc.	airplane, DC-4	1:25	2-3	45
	[רינ] וש		24	Prudhoe	1.6	control	control	:	2-3	1
			25	Prudhoe	3.2	conc.	airplane, DC-4	1:27	2-3	60
			26	Prudhoe	1.6	2%	ship	1:11	2–3	11
			27	Prudhoe Rav	1.6	2%	ship	1:11	2–3	62
Mediterranean, Protecmar I	Bocard et al. [7]	1979	28-41	light fuel	3 each	BP1100X BP1100WD Finasol OSR- 5 Corexit	ship, helicopter, various and airplane CL215		1-3	÷
Mediterranean, Protecmar II		1980	42-49	light fuel	1-5.5	BP1100X BP1100WD Finasol OSR- 5 Corexit	ship, helicopter, various and airplane CL215	÷	1–3	÷
Mediterranean Protecmar	Bocard and Gatellier	1981	50	light fuel	6.5	Dispolene 325	airplane, CL215	1:3	1-2	50
Newfoundland	Gill et al. [9]	1981	52 53 53	light fuel light fuel ASMB	6.5 6.5 2.5	Shell control control	airplane, CL215 control control	1:3	2-3 1-2	:::
			54	ASMB	2.5	Corexit 9527	airplane, DC-6	1:10	-	:

Norway	Lichtenthaler and Daling	1982	55	Statfjord	0.2	control	control	÷	2-3	0.6
			56 57	Statfjord Statfjord	0.2 0.2	10% conc. 10% conc.	ship ship	1:10 1:10	2-3 2-3	6 17
			58	Statfjord	0.2	control	control	:	2-3	2.6
			59	Statfjord	0.2	10% conc.	ship	1:17	2–3	19
			60	Statfjord	0.2	10% conc.	ship	1:18	2-3	22
			61	Statfjord	0.2	10% conc.	ship	1:13	2-3	2
North Sea	Cormack	1982	62	Arabian	20	control	control	•	1	' :
			63	Arabian	20	Corexit 9527	airplane, Islander	1:2	Т	÷
			64	Arabian	20	Corexit 9527	airplane, Islander	1:4	1	:
Mediterranean Protecmar V	Bocard et al. [1,12]	1982	65	light fuel	3	10% Dispolene	ship	1:2	3	•
			99	light fuel	5	Dispolene 325	aimlane CL215	1-74	"	
Protecmar V	Bocard et al.	1982	67	light fuel	5	Dispolene 325	ship	1:2.8	9.0	: :
			89	liaht fial	v	Dismelane 375			c	
			00	light fuel	0 0 V	Dispolene 325	airplane, CL215	1:2.8	7,	•
			56	light fuct	C.C.	Dispolene 323	sup	1:2.0	7-1	:
			2:	light rue	4 (Dispolene 325	helicopter	1:2.9	1-2	:
			5	light tuel	7	premixed	premixed	1:20	1-2	40-50
			77	light tuel	5	control	control	:	2	:
Holland	Delvigne	1983	73	Stattjord	7	control	control	:	1-2	2
	أحدثها		74	light fuel	2	control	control		1-2	ć
			75	Statfjord	2	control	control		¦	10
			76	Statfjord	7	Finasol OSR-5	airplane	1:10-30	·	10
			77	light fuel	2	Finasol OSR-5	airplane	1:10-30	·	10
			78	Statfjord	7	Finasol OSR-5	premixed	1.20	- <u>-</u> 2	10
Holland	Delvigne [1.13]	1983	79	light fuel	2	control	control	:	2-3	7
	-		80	Statfjord Statfjord	77	Finasol OSR-5 Finasol OSR-5	airplane airplane	1:10-30 1:10-30	1-2 1-2	20

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Location/ Identifier	Reference	Year	Number	Oil Type	Spill Amount, m ³	Dispersant	Application Method	Dose Rate, D:0	Sea State	Claimed Effectiveness,
Halifax	Swiss and Gill	1983	82	ASMB	2.5	Corexit 9527	helicopter	1:20	-	2.5
			83	ASMB	2.5	control	control		-	-
			84	ASMB	2.5	Corexit 9550	heliconter			
			85	ASMB	2.5	control	control	1.10		<u>.</u> -
			86	ASMB	2.5	BP MA700	beliconter	1.10	2 <u>-</u> 3	10-41
			87	ASMB	2.5	control	control	01.1		
Norway	Lichtenthaler and Daling [16]	1984	88,	Statfjord	10	control	control	• • • • • •	, -	· :
	-		89	Statfjord	10	Corexit 9527	airplane,	1:75	I	:
			60	Statfiord	10	control	Islander control		ç	
Norway	Lichtenthaler and Daling	1984	16	Statfjord	10	Corexit 9527	airplane	1:80	10	• • • •
	[07]									
			92 93	Statfjord Statfiord	12	Corexit 9527 Corexit 9527	premixed	1:33	2	:
Brest, Protecmar	Bocard [7,17]	1985	94	fuel oil	5	control	control		:-	
VI			95	fuel oil	28	Disnolene 355	heliconter	0.1	-	
			96	fuel oil	part of above	Dispolene 355	ship-spray	1:9		· · ·
			67	fuel oil	part of	Dispolene 355	ship-aerosol	1:9	I	:
Haltenbanken	Sørstrøm [19]	1985	86	topped Statfjord	12.5	control	:	:	1-2	:
			66	crude topped Statfjord crude	12.5	Finasol	premixed, injected 3 m below surface	1:50	1–2	÷

:	:	:	:	:	:	:	: :	
1-2	1–2	1-2	1-2	2-3	2-3	2-3	2-3	
•	250 ppm	:	:	1:10	1:1	1:1	:	
:	premixed	:	:	helicopter	helicopter	helicopter	:	orings Laboratory.
control	alcopol (demulsifier)	control	control	BP MA700	BP MA700	Corexit CRX-8	control	id WSL-Warren Sp
12.5	12.5	2.5	2.5	2.5	2.5	2.5	2.5	entrate, an
topped Statfjord crude	topped Statfjord crude	topped Federated crude	topped Federated crude	topped Federated crude	topped Federated crude	topped Federated crude	topped Federated crude	end, concconc
100	101	101 (CA)	102 (CB)	103 (C1)	104 (T1)	105 (T2)	106 (C)	Mixed Ble
1985		1986						a Sweet I
Sørstrøm [19]		Swiss et al. [20]						s: ASMB-Albert
Haltenbanken		Beaufort Sea						^a Abbreviation

FINGAS ON FIELD MEASUREMENT OF EFFECTIVENESS

				New concentration and	ndem m m	istant from to take			
			Wate	er Sampling	Surfa	ice Sampling		Remote	e Sensing
Reference	Trial Location	Method	Depths, m	Analysis	Method	Use	Uispersant Sampling	Sensors	Use
Cormack and Nichols	Britain—North Sea	Knudsen bottles	2-15	fluorescence	grab	water content, emulsification	Krome- cote cards	:	:
ادا McAuliffe et مرادعا	U.S.A.—New Interest	pumping to bottles	1,3,6,9	FT-IR	:	: : :		color	documentation
Green et al. [6]	Canada- Victoria	pumping to fluorometer and to bottles,	1,3.5	fluorometer, GC	•		:	photo	documentation
Smith et al.	U.S.A.—Long	towed fluorometer pumping to bottles	1,3,6,9	IR, GC	:	÷		color	documentation
14J McAuliffe et al. [5]	Beacn U.S.A.—Long Beach	pumping to bottles	1,3,6,9	IR	:	:	pans	pnotographs color photographs	documentation
Bocard and Gatellier	France—Toulon (Protecmar	pumping to bottles and instrument	0.2,0.6,1,2.	5• IR (bottles)• turbidimeter	sorbent	:	:	and video IR	slick area
[7,8] Gill and Ross [9]	1&3) Canada—St. John's	pumping to fluorometer and bottles	1,2,4	(direct) bottles not done—spoiled	sorbent	thickness	Krome- cote cards	IR,UV	slick area surface tension
Lichtenthaler and Daling	NorwayNorth Sea	sample bottle	1,2.5,5,9	GC	÷	÷		laser fluorosensor photo	documentation
[10] Cormack [11]	Britain—North Sea	pumping to bottles	1,3,6,9	GC, fluorometer	sorbent	thickness	Krome- cote	IR	documentation
					skimmer	weathering	cards		

TABLE 2—Monitoring methods used at dispersant field trials.

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Bocard [12,17]	France—Toulon (Protecmar 4&5)	pumping to bottles and instruments	0.3,0.7,1,2	 IR (bottles) fluorometer and turbidimeter (direct) 	sorbent	:		IR	documentation
Delvigne [13]	Holland— North Sea	pumping to bottles	1,1.5,2,3,7,10	GC, IR	sorbent	weathering	 sorbent paper 	IR, UV	slick area
		towed fluorometer pumping to instrument	various	fluorometers droplet size analyzer			• GC analysi of	e o	
Swiss and Gill	Canada— Halifax	pumping to bottles and instrument	1,2,5,10	(marvern) • fluorometer (direct)	sorbent	thickness	filter paper	IR, UV	slick area
[07:47]		radioactive tagging (tritiated octadecane)		 GC IR fluorometer counting (bottles) 				SLAR	experimental
Lichtenthaler and Daling	Norway—North Sea	acoustic spectrometry pumping to bottles and instrument	0.5,1,2,3 (5,10)	• GC (bottles)	sorbent	thickness	:	IR, UV	slick area
[07]				• turbidimeter				SLAR ^a	
Dickinson et	Canada— Basiifort San	pumping to bottles	0-4	• GC	sorbent	oil remaining	:	:	:
au. [10] Sørstrøm [19]	Norway— Haltenbanken	in situ fluorometer and	most		:	:		IR, UV microwave	slick area and plume
Swiss et al. [20]	Canada— Beaufort Sea	in situ fluorometer	Ι			:	:	pilotography IR, UV photography	slick area, effectiveness
^a Side-looki	ng airborne radar.								

this being the major source of error for fluorometric and turbidimetric measurements, results from these instruments tend to be high rather than low. Both instruments, especially the turbidimeter, however, have a tendency to provide useful measurements over a range of two orders of magnitude with respect to a given instrument range. Lower concentrations may not be accurate when instruments are calibrated at high levels. Turbidimeters, by nature of their construction, are not capable of measuring low quantities of oil in the water column [31].

Earlier field trials often used grab samples and subsequent gas chromatographic (GC) analysis to determine oil in water. These types of measurements tend to be low, as the greatest sources of errors are oil loss in the sample jar as a result of loss of the volatiles or adhesion to the walls.² These types of losses have been avoided by some investigators by putting a chlorinated extractant directly into the bottle before the water sample is added [7, 14]. The difficulty in pumping specimens to the surface, the questions of accuracy associated with this pumping, and the difficulties in handling sample bottles has diminished the use of this method in recent years.

Infrared (IR) analysis of oil in water has occasionally been used. It is believed to be as accurate as GC in the range of 0.05 to 20 ppm [29].

One experimenter used a unique analytical scheme of tagging the oil with a radioactive tracer and subsequently counting the samples [32]. Results using this sophisticated method correlated very well with fluorometric data. Note that the fluorometric data was 70% of the radioactive data, the same factor that the author noted previously in this paper, as a minimum loss for the calibration of a fluorometer.

Several investigators have tried to determine the deposition rate of dispersant from aircraft sprays by catching the spray on Krome-cote cards or absorbent sheets [1,9,11,13,14]. The cards or sheets are then washed with a solvent and the amount of dispersant determined in the solvent. Since analytical methods of determining dispersants are not readily available, the dispersant is usually dyed to perform this experiment. The dye is an oilsoluble dye such as "Oil Red B" (used in North America to color gasoline for tax purposes). With the addition of dye, the solvent washing of the Krome-cote cards can be analyzed directly by colorimetry. Few results have been published; however, deposition rates have ranged from 30 to 80%. The use of Krome-cote cards also enables the measurement of droplet size. Constant droplet spreading rate can be calibrated and used to read droplet size directly. Again, few results have been published because many cards have been spoiled by sea spray or subsequent handling. The same fate has applied to many sorbent pads in past field trials. In addition to sea spray, other problems with this technique have been noted, including the pitching and yawing of any device or craft holding the sorbent pad and the large unexplained lack of homogeneity in values from those cards or pads actually recovered.

Surface oil has been sampled by a number of investigators to determine the extent of weathering or slick thickness [1,7,8,9,11,14,16,18]. Methods to obtain the specimen include sorbents, dipping, and the use of skimmers. Analysis on these samples have generally included viscosity, density, or GC analysis to determine degree of weathering. Analysis of amount of water present has also been included. This is to estimate the extent of water-in-oil emulsification. Samplers have also been devised which can be calibrated to estimate slick thickness [33]. Results from this procedure are very scattered both as a result of the lack of homogeneity of the slick and because of difficulties in obtaining a "clean" specimen.

² D. Mackay and S. Abernethy, "Measurement of Oil in Water," unpublished report, Environment Canada, Ottawa, 1982.

Remote sensing has increasingly become the means to monitor dispersant field trials [34-37]. Slicks can be monitored without the usual perils and limitations of surface craft. Remote sensing can provide a synoptic view of the entire slick, positional records, and thickness profiles of the slicks. Photographs, which need little explanation, have been used at most field trials. Similarly, video recording is now coming into vogue and provides analogous capability. Infrared (IR) scanners have been used at many trials. IR imagery provides a thickness profile map of the slick [36]. The correlation of these profiles to slick thickness has been attempted. However, variances in which a particular signal level occurs is thought to depend on sun angle, air and water temperature, wind speed, and oil type [36].³ A number of investigators have used the loss of IR imagery as an indication of the rate of disappearance of the thick slick, since IR only shows the thick slick (cutoff at 10 to 50 μ m is estimated). A recent experiment in the Arctic, however, showed that the rate of disappearance of the IR image (thought to be equivalent to the thick slick) was faster or as fast in the three control slicks as in the three treated slicks [20]. The reason for this particular phenomenon may be that the treated slicks formed "herdy balls" or "pea flock" in the thick oil area and these may have been interpreted by the IR scanner as thick oil [20]. Generally, the IR image disappears after a few hours, more rapidly if the oil is dispersed. Another anomaly was also observed in this field trial when, after the disappearance of the IR image in the first few hours, the reappearance in IR imagery of the slick the next day.⁴ Clearly, even this method is not completely understood, nor can one make definitive statements using IR imagery alone.

Ultraviolet (UV) imagery has been used frequently at spill tests. UV imagery offers a view of the entire slick down to very small thicknesses. The limit is suspected to be around 0.01 μ m or that of a monomolecular layer of oil [36]. UV scanners have also been coupled with IR scanners to provide an overall map of the oil. UV imagery represents the sheen portion and IR imagery represents the thicker portions [36]. Anomalies for UV imagery include the detection of natural oils and phytoplankton as oil; hwoever, false imaging is much less for UV than IR [36].

Oil on the surface damps the microcapillary waves and thus provides a means of detection by radar [36]. Radar has been used at a few spill trials; however, it does not provide thickness information, and imagery is generally not as good as that for IR or UV. Furthermore, radar is susceptible to many false images resulting from phytoplankton, wind slicks, freshwater slicks, and calm areas on the sea. The advantage of radar is its ability to detect slicks at long range (from 40 to 100 km depending on the type of radar and altitude of the aircraft) [36]. Its usefulness at dispersant field trials is questionable.

Microwave thickness measurements have been attempted at one field experiment, however, the use was experimental and the results were inconclusive [38].

Phenomenological Observations

A review of the literature on field trials reveals an interesting feature, that is, most experimenters were struck with an unusual occurrence or observation which occurred at their trial. Some of these have been further investigated and processes defined, others have not. Many of these occurrences interfere with the assessment and evaluation of the effectiveness of dispersants.

The most important phenomena discovered at field trials, and later described in detail

³ R. C. Belore, "Calibration of UV-IR Line Scanner for Oil Thickness Using Measured Field Data," Environment Canada, unpublished report, Ottawa, 1982.

⁴ R. H. Goodman, private communication, Esso Resources Canada, Calgary, June 1987.

in laboratory studies, is that of herding [39-41]. This is the movement of oil by the dispersant. The dispersant has a greater surface tension with water than the oil. When large droplets of dispersant break through the oil layer, the greater surface tension in that area enables the dispersant to push the oil aside until all the forces are balanced. This usually means that most of the spray swath is affected and the oil is pushed into narrow ribbons or pools within the area. The process is transitory. The dispersant is largely soluble in water and is carried away and the oil is allowed to respread over the area. The entire process generally takes 2 to 10 min. Workers at early field trials observed herding and felt that this was actually dispersion. In fact, workers have since discovered that when herding takes place, dispersion effectiveness is low, as most of the dispersant was lost to the water column [39].

Herding is thought to occur only when the applied droplets of dispersant are large enough to penetrate the oil layer. The size at which this occurs is not clear and was originally thought to be 500 μ m, but recent investigations have shown that there may be other factors involved as well [41]. Herding clearly does not occur all the time even though circumstances may be similar. Bocard has recently reported and documented an interesting phenomena observed during a field trial in France.⁵ Herding was observed to occur both upwind and downwind of a dispersant spray boat. Investigation of the phenomenon has failed to reveal any obvious cause of the herding upwind.

Herding is important from a remote sensing point of view. When herding occurs, a discontinuous area is seen. Since the herded ribbons and pools of oil are too small to be detected from the air, the oil appears to have suddenly disappeared. When the oil respreads, it again appears. This was observed and documented in the series of images of one oil spill dispersant trial [34].

Resurfacing of dispersed oil has been observed in a number of trials [7]. Bocard has indicated that resurfacing is generally observed after 3 h; however, evidence of resurfacing has appeared in the form of expanded sheen areas as early as 1.5 h [32]. Resurfacing of dispersed oil would only be observed if one was monitoring the sea surface for several hours, and the dispersed plume from which the oil was surfacing is near the original slick. Long-term (for example, up to 12 h) remote sensing is generally required to show evidence of resurfacing. Those who have monitored in this manner suspect that much of the dispersed oil resurfaces [7]. It is questionable then, if this is the case, how effective a particular application is if the dispersed portion resurfaces and the phenomena is difficult to measure. Many field tests surveyed in this paper did not include remote sensing surveillance or other provision for measuring resurfacing nor did most field work last beyond 3 h. Long-term (for example, 24- or 48-h) measurements may be necessary to take in the effect of resurfacing.

Another phenomenon observed at field trials is the formation of oil-emulsion-like objects in the thick portion of the slick.⁵⁻⁷ These have alternatively been called "Pea Floc" and "Herdy Balls." The author observed these at the 1986 Beaufort Sea dispersant trials. The appearance of these is similar to a dried pea; however, they are brown and "mushy" looking. In the case of these above-mentioned trials, much of the area once occupied by the thick slick was covered by these objects.⁷ Initial work at the Esso laboratory in Calgary has suggested that these may be a three-way oil-in-water-in-oil emulsion.⁸ Such an emul-

⁵ C. Bocard, private communication, Institut Francais du Petrole, Paris, Nov. 1986.

⁶ T. Turner, private communication, Warren Springs Laboratory, Stevenage, England, Nov. 1986.

⁷ M. F. Fingas and D. Kittle, private communication, Environment Canada, Ottawa, July 1986.

⁸ J. S. Tang and R. H. Goodman, private communication, Esso Resources Canada, Calgary, March 1987.

sion has been formed in the Esso laboratory. It requires an excess of dispersant (as high as 1:1) to form. This emulsion is unstable, also as observed at the field trials, and requires a monomolecular layer of oil or dispersant to hold it into place; if not, rapid breakdown of this emulsion occurs. These objects, although few in number and apparently few in distribution, have been interpreted from the IR imagery as being thick oil [20,37]. This effect may have led to the result that the thick areas for all three control slicks appeared to disappear faster than the thick areas of the treated slicks [20]. This result, in itself, is rather unlikely since it would imply that dispersants had the reverse effect of that intended.

Another phenomenon observed at field trials is the presence of "lace" or sheen areas where small circular areas of open water are evident. These areas are thought to be areas of sheen sprayed by dispersant. Explanation of the holes in the sheen is that they were caused by herding or that they represent oil lost by dispersing into the water column.⁵ The presence or formation of lace is not felt to be important to the measurement of effectiveness.

Discrepancies in observations and impressions between observers from surface vessels and aircraft are numerous [7]. The last two phenomena noted are not observed from aircraft as a result of the small size scale. Observers on surface vessels often do not observe macro features, such as the formation and movement of the dispersed oil plume. In most field trials it has been recognized that resolution of observations from the surface and air is a task to be done before data can be properly interpreted.

Attempts to Determine Mass Balance

A number of workers have attempted to measure dispersant effectiveness by performing a mass balance of oil in water [3,5,32]. A number of assumptions are necessary to construct such a mass balance.

1. The distribution of oil in the water column has a known or measurable distribution, geometry or function.

2. The distribution of this oil in water can be measured with respect to the slick.

3. The oil-in-water-column measurements taken at different points in time are useful. Technology does not exist to measure a large number of oil-in-water concentrations in a synoptic fashion, although it has been attempted [42].

4. Some water column oil concentration data can be used to form an entire picture of the oil concentrations beneath a slick using mathematical algorithms. Generally, this implies that one takes concentrations in a "block" and adds the various blocks together. Additionally, the implication is that averages are a good estimation of depth concentration profiles.

The first assumption, that the oil has a known or measurable geometry in the water column, is difficult to establish. However, a geometry or distribution must be known before integration can be accomplished [43]. Brown and coworkers have performed a series of tests in a wave basin with fixed geometry of all discharges, sampling ports, and cameras, and have noted two interesting results [27]. First, the shape and geometry of the underwater plume varied widely. Secondly, the direction(s) that the plume or, in some cases, plumes travelled also varied dramatically. No correlation to wind or induced current was established. This result implies that the geometry and movement of subsurface plumes is poorly understood and integration of subsurface concentration data is not valid mathematically.

Data analysis on numerical results in the literature from these trials did not reveal any

uniform structure to oil concentration in the water column with respect to either time or space.

Subsurface concentrations with depth at 30 min after dispersant application fit square root or log function equally well. A series of these are shown in Fig. 1, along with the name of the primary author from whose paper the data was derived. The correlation coefficient for both curve fits ranged from 0.82 to 0.96 and were approximately equal over the 14 sets of data used. A number of other functions were attempted with a significantly poorer fit. Note that only at 30 min after dispersion did these functions form such a unified set of curves, and also that the actual values of oil concentration varied over two orders of magnitude for a given depth. The presence of this correlation of depth and concentration is probably due to the similarity of process (dispersion here), whereas the lack of correlation after 30 min is that the process is oceanographic and turbulence transport and is different in every case. Figure 2 shows the lack of correlation in concentration with depth versus time for the Canadian Offshore Aerial Applications Task Force (COAATF) experiment near Halifax [32]. Similar correlations were performed with data from McAuliffe, Lichtenthaler, and Bocard, all showing the lack of correlation.

The second assumption is that the oil concentration can be measured with respect to an x, y coordinate system, such as position below the slick. Since surface slick movement and subsurface plume movement are not necessarily coupled and are due to different forces,



FIG. 1—Correlation of oil concentration with depth.





FIG. 2—Correlation of concentration and time after dispersion.

such an assumption is not fully valid. As the oil originates from the surface slick, the plume will for some time pass under the slick depending on the differential velocity between slick and plume.

Figure 3 presents a correlation between concentration and distance along the windward axis of a slick. Figure 4 presents the same correlation, however, along the slick axis perpendicular to the wind. Distance in both figures refers to relative distance where 100 is on one edge, -100 another edge, and 0 the center of the slick. The data are taken from McAuliffe and Lichtenthaler as noted [5,10]. In both cases, there is an obvious lack of correlation between concentration and the distance along a slick's axis, nor is there any apparent structure to the data.

The third assumption, that data at various times can be used, has been dealt with above. It has been established that there is poor correlation between time and concentration.

The fourth assumption made in attempting a mass balance is that an appropriate mathematical function can be found to relate subsurface concentrations and dimensions to an overall measurement of oil in water. Two schemes to perform this are in the published literature. McAuliffe and coworkers used the total of four layers beneath the slick [5]. The first layer was the body of water 0 to 2 m below the slick. The concentration taken was the average of all the 1-m depth concentrations. The second layer was the body of water 2 to 4 m below the slick. The average concentration was taken to be the average of all 3-m depth concentrations. The third layer is the 4- to 7.5-m layer and uses measurements at the 6-m depth. The fourth layer is from 7.5 to 10.5 m and uses the measurement from the 9-m depth of water. The volume of each layer is evaluated using the main slick length and $\frac{2}{3}$ of the slick width.



FIG. 3—Correlation of concentration and relative distance along slick windward axis.

The second scheme in the literature is that reported by Swiss and Gill [14,15]. Four layers are also used: 0 to 1.5 m represented by the concentration at 1 m, 1.5 to 7.5 m represented by the concentration at 2 m, 3.5 to 7.5 m represented by the concentration at 5 m, and 7.5 to 12.5 m represented by the concentration at 10 m. The scheme is not remarkably different from that of McAuliffe's, which is noted above.

Both schemes are compared in Fig. 5. The data is that published by McAuliffe and coworkers for a slick laid during the 1979 South California trials [5]. In the paper the authors give a value of 45%. In applying the method from the same paper one gets essen-



FIG. 4—Correlation of concentration and relative distance perpendicular to the wind.

tially the same result (43%). These results are equivalent, since the exact value of background oil and roundoff errors will make the difference. Using the scheme proposed by Swiss and coworkers, a value of 41% is obtained. The difference is minimized because of the same area used as in the McAuliffe scheme. In the Swiss scheme, the actual area is used in practice rather than % of the width times the length. To illustrate further the variances caused by using different integration schemes, Fig. 5 shows a scheme using all the areas under the slick and integrating 28 compartments rather than just 4. This results in the value of 33% instead of the published 45% effectiveness result. Integrating each individual compartment will yield more accurate results than averaging values, given that the compartments are of different sizes and, secondly, that the values of concern are different. Figure 6 illustrates this basic mathematical concern. Average values will produce the same values as the sum of individual same size compartments. However, when the compartments are of different sizes, the integral is very sensitive to method of treatment.

Some authors have given estimates of effectiveness based on maximum concentration achieved in the water column [44]. Values using this assumption and other values are shown in Table 3. Effectiveness would vary a great deal depending on which scheme is chosen. Since concentrations of oil in water vary widely and appear to have little structure, use of maximum concentration estimates are not likely to be reliable. The correlation of maximum concentration of oil at the 1-m depth and the claimed dispersant effectiveness is shown for a number of field trials in Fig. 7. The correlation is very poor indicating probably both a variety of approaches for the assessment of effectiveness and the lack of relationship between both.

	SLICK GEOMETRY	SUE	SUR	FACE	CON	CENT	RATIC	<u>NS (</u>	opm)	
4	600 m	DEPTH (m)		S	TATIC	<u>n nu</u>	MBE	3		AVE.
			1	2	3	4	5	6	7	
1 f	(6) _ <	1	.58	1.62	4.87	3.76	3.09	.83	.17	2.13
	(2) (3) (4) (5)	3	.75	1.23	4.09	2.65	2.87	.82	.27	1.81
		6	.33	1.0	.82	1.23	1.33	.60	.11	.//
STATI	ONS (7)	9	.04	.44	.04	.49	.04	.30	.04	.21
T	OP VIEW OF SLICK			AL	L DA	TA A0	CTUAI		UES	
OIL SPILLEI OIL REMAIN	$D = 1.6 \text{ m}^3$ (10 BARRELS) IING AFTER EVAPORATION = 1.	22 m ³		FF	ROM N	ACAUL	IFFE	1981		
CALCULAT	ION BY METHOD OF MCAULIF	FE				_				
· VOLUME IN	EACH LAYER = AVERAGE COM	CENTRATION	× ⅔	×C	ALCU	LATE	D ARI	EA ×	DEP	тн
• LAYER	DEPTH REPRESENTED (m)	MEASURED DE	PTH	(<u>m)</u>	OIL	IN E	ACH	AYE	R (m	<u>3)</u>
1	0 - 2	1					.20			
2	2 - 4	3					.17			
3	4 - 7.5	6					.12			
4	7.5 - 10.5	9					.03			
					т	TAL	= .52	=>	43%	
						_		EFF	ECII	VENESS
	TION BY METHOD OF SWISS									
	I EACH I AVER - AVERAGE CO	NCENTRATION	× A	CTUA		FA x	DEP	тн		
• LAYER	DEPTH REPRESENTED (m)	MEASURED DE	ЕРТН	(m)	OIL	. IN E	ACH	LAYE	R (m	³)
1	0 - 1.5	1		<u>, , ,</u>	_		.15	;		<u></u>
2	1.5 - 3.5	2					.17	,		
3	2 1,5-3,5 2 117 3 3,5-7,5 5 .14									
4	4 7.5 - 12.5 10 .04									
	*USING SA	ME DATA AS		/F	тс	TAL	= .50		41% ⁴	(
	05114 54	DATA AU		-				EFF	ECTI	/ENESS
						·				
CALCULA	TION BY INTEGRATING EACH	COMPARIME								
SLICK SUE	COMPARTMENTS AND THEIR D	IMENSIONS								
120 18	30 360 420 600 m	-								
1		-	ĽA'	YER*	<u>O</u> IL	. IN E	ACH	LAYE	R (m	<u>3)</u>
E O				1			.19	1		
			:	2			.16	i		
11	$\mathbb{Z}(\overline{p}) \geq \mathbb{Z}$			3			.08	}		
¥ <u> </u>			. 1	4	_		.02			
	* USING SAME CRITERIA AS	DEPTHS AND MCAULIFFE			т	DTAL	= .45	EFF	37% ECTI	VENESS
	FIG. 5—Example	of mass bal	ance	e calc	ulati	on.				

EXAMPLE SITUATION

Summary and Conclusions

A large number of dispersant field trials have been conducted worldwide. Methods and results from these vary significantly. Measurements of effectiveness at these trials were, in early years, attempted by integrating water column concentrations. This was based on the assumptions that a regular distribution of oil in the water column existed, that this was spatially oriented with the surface slick, that oil in the water column would not resurface, and that a simple integration scheme could accurately sum the amount of oil in the water


FIG. 6—Example of variances in handling data similar to oil spill measurements.

			and the second	
Concentration in ppm at 1 m	Effectiveness ^b (%) if Equally Distributed to 1 m	Effectiveness (%) if Equally Distributed to 2 m	Effectiveness (%) if Distributed as a Square Function to 2 m	Effectiveness (%) if Distributed as a Square Function to 5 m
1	- 1	2	3	5
2	2	4	6	9
5	5	10	14	23
10	10	20	29	45
20	20	40	57	91
30	30	60	86	
50	50	100		
75	75			
100	100	•••	•••	• • •

TABLE 3—Effectiveness estimators using maximum water column values alone.^a

^a The use of these estimates is not suggested as oil has been shown not to form a uniform downward plume. This table is presented here only as an example of this technique.

^b All examples assume a starting slick thickness of 100 μ m.



FIG. 7—Correlation of concentration and claimed effectiveness.

column. This paper has shown that none of the assumptions are entirely true, and that measurement of effectiveness using water column oil concentrations is not an accurate or reliable means. Recent measurements of oil remaining on the surface using remote sensing data are more accurate. However, they depend on the assumption that thickness of the slicks are identical. Tests of this type have been performed only on the short term and the accuracy of slick thickness measurements is poor.

There exist no empirical relationships between slick position, subsurface plume concentrations, and time. Subsurface concentration of oil 30 min after application of dispersant does, however, follow a square root or log function equally well. There appears to be no correlation between maximum subsurface concentration and dispersant effectiveness.

Analytical means appear to be adequate for subsurface concentration measurement, but are lacking for surface thickness measurements, and for dispersant in oil or in water measurements.

Experimenters have observed a number of phenomena during field trials. These include herding, resurfacing of dispersed oil, and formation of emulsion particles. All of these interfere with the assessment or measurement of effectiveness.

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A New Pair of Eyes II. Looking at Dispersants from a Different Point of View

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ABSTRACT: Those concerned with managing oil spills have been struggling for the past 15 to 20 years to improve the application and effectiveness of dispersants. Progress has been slow and uneven, especially in the United States where the attitude of regulatory agencies has been to downplay the use of dispersants. This paper takes a serious (occasionally irreverent) approach to the problem of dispersing oil, using some different viewpoints than have been used in the past.

KEY WORDS: air blowers, air cushion vehicles, chemical treatment of spilled oil, dispersant(s), dispersant application methods and equipment, equipment cleaning, helicopters, homogenizers (mixer-emulsifiers), hydrofoils, low toxicity chemical agents, oil spills, submarines, viscoelasticity

A number of years ago the author wrote a paper entitled "A New Pair of Eyes" [1] which was concerned with spill prevention. It looked at familiar problems from a different point of view than those concerned with day-to-day contact with the equipment and procedures of specific facilities. By asking questions such as, "What if this happened to us," or "What if we did this instead of that," or "What if... whatever," a productive approach was made to oil and hazardous material spill prevention. Hence "A New Pair of Eyes II" about oil spill dispersants, in the best tradition of movie makers! Not all "IIs" are as successful as the original; hopefully this one will be.

Here is a warning in advance of reading this paper. It is NOT a highly scientific paper, It is NOT the result of years or months or weeks or even days of painstaking laboratory or field research, nor is it based on a comprehensive survey of the literature, to see who has done what, and where it was done. It IS the result of a long association with the oil spill control industry, personal observations, a lot of listening and talking, plus an overactive imagination—all in the United States.

What this paper will do, hopefully is change the way some people think about the problem of dispersing oil spills. The flights of fancy contained herein may not be new to everyone in the world. But the ideas, most of them, are new to the author. They are solely his responsibility, except for two suggested by two friends whose names are suppressed to protect their professional reputations. (Unless, of course, someone wishes to offer larger bribes to disclose their names than were proffered to keep them quiet.)

The ideas to be considered, in varying amounts of detail, are shown in Table 1.

What does it take to disperse oil in water? The answer to that question is energy. For a specific oil, in a specific amount, on a specific kind of water (fresh, saline, brackish), at a

¹ President, Illinois Chemical Corp., P.O. Box 2116, Highland Park, IL 60035.

I.	Low toxicity chemical agents
II.	Mechanical energy sources
	A. ACV air stream
	B. gas turbine exhaust
	C. VTOL exhaust
	D. helicopter downdraft
	E. air blowers
	F. homogenizers (mixer-emulsifiers)
III.	Improved application equipment
	A. large helicopters
	B. hydrofoils
	C. submarines
IV.	Chemical treatment
	A. in situ reactions
	B. in situ additions
V.	equipment cleaning

TABLE 1—New approaches to dispersing oil spills.

specific temperature, it takes a specific amount of energy to form a dispersion of the oil in water with droplets of a specific size (or size range). The exact amount of energy cannot easily be measured, since few of the above "specifics" are easily measurable in a spill incident.

The required energy can be provided in a number of ways. There are several sources of mechanical energy. Most is naturally supplied by the action of wind and waves. Some comes from spraying dispersants from aircraft or a boat. Some may be supplied by propeller action from boats, or from high pressure water jets.

Mechanical energy from these sources has generally been insufficient, so the chemical energy of dispersants has been used to provide what is missing. The amounts of money and man-hours that have been expended in dispersant research over the world the past 10 to 15 years are very large. Dispersants have become more "effective." Some so-called "third generation" dispersants require little or no mechanical energy to cause dispersion.

Table 2 shows that most of the papers on dispersants presented at the major biennial oil

Year	Theory, Use, Planning, Cost	Toxicity Effectiveness	Application Methods	
1969	1	5	0	
1971	1	3	Ō	
1973	1	1	Ō	
1975	1	0	0	
1977	3	3	1	
1979	2	7	2	
1981	1	8	ō	
1983	8	11	3 3	
1985	5	15	6	
1987	9	10	9	
Total	32	63	21	

TABLE 2—Number of dispersant papers and subject matter.^a

^a Compiled from *Proceedings of the Joint Conferences on Prevention and Control of Oil Spills*, American Petroleum Institute, U.S. Environmental Protection Agency, and U.S. Coast Guard, 1969–1987 (alternate years).

Theory, Use, Planning, Cost	Toxicity Effectiveness	Application Methods	
7	10	5	

TABLE 3—Number of dispersant papers in ASTM STP 659 [4].

spill conferences in the past have been concerned with toxicity and effectiveness [2,3]. There has been relatively little attention given to application methods for dispersants, and such papers that are available have been concerned primarily with spraying systems, either by boat or from aircraft.

In October of 1977, ASTM Committee F-20 held a dispersant seminar in Williamsburg, VA. There were 22 papers, published in a single volume [4]. The distribution of topics is given in Table 3.

These two tables do not represent all the published papers for the period 1969 to 1987, obviously. There are undoubtedly many papers in foreign journals which the author has not seen. The use of dispersants outside the United States has been considerably greater than within the United States, because restrictions in this country have almost entirely precluded dispersant usage. The subject matter of the papers in Tables 2 and 3, and the content (if you read them), shows a rather restricted viewpoint of when to use, how to apply, and what a dispersant should be.

Can we disperse oil using high amounts of mechanical energy alone, or assisted by chemical agents of low toxicity? What do I mean by "low toxicity" chemical agents?

Hydrocarbons apparently differ widely in their toxicity to organisms. And different organisms appear to take up hydrocarbons at different rates, depending both on the organism and the hydrocarbon structure [5,6]. The toxicity of hydrocarbons to certain algae appears to correlate well with solubility [7]. This suggests that one might be able to produce (by a refinery process?) hydrocarbon fractions of low toxicity, which could be used either as a solvent for dispersants, or as a diluent for spilled oil which is too viscous to disperse easily or both. The use of such low toxicity materials to reduce the viscosity of spilled oil to the point where it could be dispersed by mechanical means alone, without any other chemical dispersants being used, might increase measurably the amount of externally supplied energy to effect dispersion. This would require evaluating a trade-off between reduced toxicity and increased cost for dispersion energy.

Let us examine several potential sources for such mechanical energy. Could we use any of the following for this purpose?

Air Cushion Vehicles (ACVs)

One paper on the use of an ACV was presented at a previous ASTM F-20 seminar on dispersants [8]. That paper reported on field trials using a small Hovercraft[®]. It dismissed, rather out of hand, application of the dispersant in the fan downdraft, and was concerned primarily with the more or less conventional use of spray bars.

While the air pressure required to support an ACV is surprisingly (to the author) low, there is nevertheless a large amount of energy expended by the fans, together with considerable movement of air sideways across the surface of the water over which the ACV is passing. A test of actually applying dispersant into the fan downdraft stream would seem worthwhile. Vanes to promote surface mixing might be installed at the ends of the ACV curtain without affecting AVC performance too severely. If application of the dispersant



FIG. 1—Air cushion vehicles can operate over water or land.



FIG. 2—An air cushion vehicle (load capacity 15 tons [14 Mg]) being hoisted onto a larger vessel.



FIG. 3—Specifications of the Bell Voyageur ACV.

into the fan downdraft is not effective, spray bars mounted UNDER the ACV might be more effective than extending from sides outboard of the vessel.

Small ACVs would be required for confined spill areas, but larger vehicles, such as are used to transport people across the English Channel, would provide a stable platform for storing really large amounts of dispersant. These vehicles can operate in the open ocean, and close to shore in shallow water, if there are no obstructions in the way.

ACVs have an impressive capacity for sustained operation. They can operate over land as well as water (Fig. 1), which allows easy restocking if a staging area is available close to a spill site. The smaller ones can be hoisted onto a larger vessel for transport to a spill area (Fig. 2). One built for use by the U.S. Army (Fig. 3) is approximately 75 ft long (23 m) and 36 ft (11 m) wide, with a payload capacity of over 30 tons (27 Mg); it can operate at a cruising speed of 45 mph (72 km/h). Power is supplied by twin gas turbines, using jet or light diesel fuel; 2000 gal (7571 L) suffice for 8 to 10 h of operation.²

² Technical data and literature, Bell Aerospace Division of Textron, Buffalo, NY.

Jet Engine Exhaust

There is considerable pressure exerted by the exhaust of jet aircraft engines. One or more such engines, mounted vertically between the hulls of a catamaran or trimaran, could provide both mixing energy and heat to the oil surface, reducing viscosity and thus aiding dispersion. Dispersants might be applied through a nozzle system directed into the water immediately ahead of, or perhaps even in, the gas exhaust stream.

This same process might be used to ignite the oil film, since the heat from such an exhaust is considerable. There would be much detail to consider in how to mount and operate safely such engines. The advisability and practicality of in situ ignition of oil spills has been the subject of much discussion and a number of papers, in part because of the potential for air pollution, and in part because of the difficulty of igniting oil on water. The author takes no position, but has not seen any mention of using jet engine exhaust as a means of ignition.

VTOL Exhaust

As an extension of the idea above, perhaps the jet engine need not be mounted on a boat. The author has little information on the operation of vertical takeoff and landing (VTOL) aircraft. Might it be possible to "dance" such an aircraft across the surface of small spills in hard-to-reach areas to agitate simultaneously the surface and apply dispersant?

Helicopter Downdraft

Helicopters have been used to apply dispersants from a spray bar slung beneath the aircraft [9]. Very large helicopters are now manufactured, able to lift as much as 14 500 kg.³ Is there sufficient agitation from the downdraft of such a large aircraft to provide the needed energy for dispersion (see Fig. 4)? If the downdraft is too spread out, could an air deflection system, something like the "egg crate" diffusers used in fluorescent light fixtures, be carried beneath a helicopter to concentrate surface agitation, without interfering with the operation of the helicopter?

Air Blowers (Large and Small)

Many companies now make portable electric or gasoline powered leaf blowers or spray equipment.⁴ One company makes units powered by 100-V AC current. One model, no longer manufactured (remaining stock available at the time of writing this paper through a catalog house for under \$50) has an attachment to inject fertilizer through a venturi into the air stream. Another company manufactures a backpack unit (loaded weight 32 lbs [14.5 kg]) powered by a 3-HP (2.2-kW) gasoline engine capable of dispensing either liquid or powder, with a 50-ft (15-m) horizontal and 40-ft (12-m) vertical throw (Fig. 5). They also make smaller, hand powered units.

For small spills, such a portable system could be used to apply dispersant, and perhaps, with a specially designed nozzle provide agitation as well.

On larger spills, the same idea of using air or water jets for both application and agitation is worth considering. Water jets have been studied for controlling oil spills [10]. The idea of injecting dispersant into the water jet was not mentioned in this paper. Using water jets

³ W. Drury, Sikorsky Aircraft Corp., Stamford, CT, private phone communication and literature.

⁴ R. Daly, Chicago Turf & Irrigation, Inc., Itasca, IL, private phone communication and literature.



FIG. 4—Downdraft from a Sikorsky CH53A helicopter.

to apply dispersant from above, or air jets from just below the surface, seems worth some testing.

Homogenizers (Mixer-Emulsifiers)

Rather than use a dispersant at all, could we disperse a spill entirely by mechanical means, using a low-toxicity hydrocarbon solvent only if necessary to reduce the viscosity of spilled oil sufficiently so it will flow easily?

Some vessel, perhaps an oceangoing barge (which has compartments that could carry the low-toxicity solvent) or an ACV, could be equipped with a number of homogenizers which would take up the floating oil and some water, emulsify (disperse) the oil, and eject the mixture from the rear of the vessel as it moved through the spill area. The low-toxicity solvent could be sprayed onto the oil before sending it through the emulsifier, or it could be injected into the emulsifier at the same time as the oil. So could a dispersant, for that matter.

Single in-line continuous mixer-emulsifiers are available from at least one manufacturer with a capacity of up to 100 000 gal (378 540 L) per hour of water. Such a mixer in a



FIG. 5—Backpack gasoline powered blower for powders or liquids.



FIG. 6—One-hundred horsepower (74.5-kW) mixer-emulsifier.

horizontal configuration (Fig. 6), driven by a 100-HP (74.5-kW) 1200-RPM explosion proof motor, 230/460-V operation, with an 8-in. (20-cm) diameter inlet and a 6-in. (15-cm) outlet, cost about \$35 000 in mid 1986.⁵

Papers on dispersant effectiveness are generally concerned with how much of the oil present is dispersed, rather than the concentration of dispersed oil in the water. There is usually a lot of water present, so concentrations are presumably quite low. Data are needed

⁵ Technical data and literature, Charles Ross & Son Co., Hauppauge, NY.

Vessel Type	Capacity Range, Tons	Capacity Range, BBL ^b
River and lake barges	10 000-20 000	60 000-120 000
Coastal barges	40 000	240 000
Small tankers	75 000	450 000
Large tankers	120 000	720 000
Super tankers	220 000	1,320 000

TABLE 4—Capacities of oil carrying vessels.^a

^a Private communication from a major oil company.

^b 42 gal/barrel (159 L/barrel).

on dispersion concentrations to see how high a concentration could be effected mechanically by equipment such as just described.

One major oil company operates a variety of vessels with the load capacities shown in Table 4. Assuming a 10% concentration of oil in water, a single 100-HP (74.5-kW) emulsifier could process about 250 barrels of oil per hour. At 50% concentration, 1250 barrels could be processed. Five such units could therefore handle from 1250 to 6000 barrels per hour.

A single 100-HP (74.5-kW) mixer emulsifier measures about 5 by 2 by 2 ft (1.5 by 0.6 by 0.6 m), and weighs a bit less than 1 ton (907 kg).⁵ Five-hundred horsepower is equivalent to 375 kW, so a 500-kW diesel driven generator should have sufficient capacity to run five such units. A generator this size weighs about 5 tons (4536 kg), and measures about 13 by 6 by 7 ft (4 by 1.8 by 2.1 m).

The cost of a skid mounted 500-kW diesel powered generator is about \$75 000; trailer mounted, with fuel tanks, around \$175 000. Fuel requirement for the generator at full load is about 40 gal (151 L) per hour.⁶ A 500-gal (1893-L) storage tank would contain less than 2 tons (1814 kg) of fuel.

This array of equipment, with necessary piping, seems well within the 35-ton (32-Mg) load capacity of an ACV (Fig. 3). A processing capacity of 6000 barrel per hour (22 712 L/h) would handle a full barge load spill in a day or two, and might even make a substantial dent in spillage from a super tanker disaster, if this capacity is attainable in practice.

Now let us consider dispersant application equipment.

Helicopters

Helicopters have been used for survey work, and for small scale application of dispersants from containers carried beneath the aircraft. This kind of equipment is currently being suggested by a major dispersant manufacturer for helicopter application.⁷

Early methods for application of dispersants from the air used fixed wing aircraft. The American Petroleum Institute funded some testing of a spray system developed by Biegert Aviation, designed to slide into a C-130 Hercules Aircraft. It is known as ADDSPACK, or Airborne Dispersant Delivery System. It consists of a 5500-gal (20 820-L) tank and associated equipment, and weighs, fully loaded, around 25 tons (23 Mg). Field tests of low level flights [11] indicated difficulty in accurately depositing dispersant where desired, and a

⁶ Technical data, Indeck Power Co., Wheeling, IL.

⁷ Oil Spill Chemicals Application Guide, 3rd ed., Exxon Chemical Americas, Houston, TX.

considerable effect of turbulent air from the flight path on the spray pattern at low levels (50 to 75 ft [15 to 23 m]).

Some of the problems associated with fixed wing aircraft are the need for a landing strip, long distances to travel to and from spill sites, relatively high speed during application, and lack of maneuverability. It should be possible to use a large capacity helicopter, operating either from shore close to a spill site, or even from a vessel at the spill scene, for improved dispersant application. It is the understanding of the author that current worldwide practice is now to use helicopters.

Sikorsky Aircraft Corporation manufactured a helicopter known as a "praying mantis" or "flying crane."³ The military version was designated CH54 (Fig. 7). Some 40 are still in use by the U.S. Army, and 6 are in civilian use for logging and other purposes. This aircraft has 4 legs which can attach to and lift a rectangular pod large enough in 1 configuration to seat 50 passengers (Fig. 8). It also has a cargo sling that allows lifting practically anything of any size or shape within its design capacity.

The empty weight of the CH54 is 10 tons (9 Mg), and the lift capacity 10 tons (9 Mg) (Fig. 9). The total loaded weight of 20 tons (18 Mg) makes landing on cargo ships possible. The rotor diameter is about 60 ft (18 m), which might limit ship landings, but would pose no problem at a shore staging area. A smaller dispersant capacity would be available than with the ADDSPACK, but a helicopter could set an empty "HADDSPACK" (new acronym) down, pick up a full one, and be back on scene in a matter of minutes. The maneuverability and slow speed should overcome some of the problems that appear to arise with fixed wing aircraft.

Sikorsky makes a still larger helicopter, the CH53A, with a 79-ft (24-m) rotor diameter, and a cabin measuring 30 ft (9 m) long by $7\frac{1}{2}$ ft (2.3 m) wide by $6\frac{1}{2}$ ft (2 m) high. It also



FIG. 7-Sikorsky "Flying Crane," the CH54.



FIG. 8—Passenger module for the CH54.

PERFOI	MANCE, WEIGHTS AND DIMENSION F THE CH-54A BELICOPTER	ONG
(At Maximum Gross We	Performance ight in NASA Standard Air,	Except as Noted)
BIOH SPHED at Sea Level, 42,00	0 1bs.	95 Knots
HIGH SPEED at Sea Level, 38,00	0 1bs.	110 Knots
BEST RATE OF CLIMB, Sea Level, 3	Continuous Power,	95 Knots
2 Engines		1,330 fpm
stround cleanance)	rect (10 ft. wheel to	A 1 4 4 4 1 1
HOVERING (TETLING OUT OF Ground	Prent	6,400 Feet
MAXIMUM TEMPERATURE, for Hovert	ing Out of Oround	2,400 Feet
Effect at Sea Level	and one or mouth	050 #
SERVICE CEILING, Continuous Pow	Ner	9.000 Feet
AVERAGE FUEL CONSUMPTION (Cruis	te Two Engines Operating)	3.615 Lbs./Hr.
RANCE with 1320 gallons, usable	fuel (10% Reserve)	200 N.M.
MAXIMUM GROSS WEICHT WEICHT EMFTY USEFUL LOAD	<u>Veights</u>	CH-54A U.S. Army Eqpt. 42,000 Lbs. 19,234 Lbs. 22,766 Lbs.
	Dimensions	
LENGTH OVERALL (blades extended	1 Contraction of the second	BRICH
WIDTH OVERALL	A CONTRACTOR OF THE OWNER	21*10#
HEIGHT OVERALL (to top of tail :	rotor)	2514.7"
MAIN ROTOR DIAMETER (blade tip	circle)	72"0"
TAIL ROTOR DIAMETER (blade tip	circle)	16'0"
WHEEL BASE (nose wheel to main . GROUND CLEARANCE (without pod)	landing wheels)	19'9" 24'5" 0*1"
INTERNAL DOD DESCRIPTION		March States 16
Length	6407-20600	6420-67400
Width	RITOR	30 6.
Height	6169	11 - 6"
DATE AND A STREET AND A		0 0.

FIG. 9—Specifications of the Sikorsky CH54.



FIG. 10—Sikorsky CH53A towing a mine detector.

has an external one-point or two-point suspension sling. This craft weighs 15 tons (14 Mg) empty, and has a load capacity of approximately 15 tons (14 Mg) in addition.³

The CH53A has been used to tow a mine detector (Fig. 10). This suggests the possibility of towing a dispersant application system which would simultaneously eject dispersant and provide mechanical mixing energy. When the unit is empty of dispersant, it could be towed back to a supply ship for refilling, while the helicopter picks up another unit to continue dispersant application.

Hydrofoils

Tests have been conducted using a large hydrofoil vessel to carry and spray dispersant on an oil spill [12]. There are several potential advantages to such a system. The spill area can be reached quickly, and a large application area covered at relatively high speed. The application system in these tests was the usual spray bar, with the usual problems associated with spray bars. There is no mention of the possibility of applying the dispersant through the submerged portion of the foil. The dispersant could be pumped out through nozzles on the back side of the foil, or from within the foil itself. This would prevent evaporation, discharge the dispersant from below or into the oil, and provide a large amount of agitation, all simultaneously.

Subsurface Application of Dispersants

Dispersion of oil takes place at the interface of the oil and water. Application of dispersant from above, either by surface or aerial spraying, requires the dispersant to mix with the oil, or sink through it, to reach the water/oil interface.

Application from below, through the use of either large manned or small remotely controlled unmanned submarines, might be a way to apply dispersant right at the oil/water interface where it is needed.

Small remote control and manned submarines currently are used in the oil industry for a variety of undersea tasks^{8,9} (Fig. 11). Large submarines (many of which have been "moth-

⁸ W. Hughes, Ocean Systems Engineering, Houston, TX, private phone communication.

⁹ D. Stroud, Market Manager, Perry Co., Riviera Beach, FL, private phone communication.



FIG. 11—A remote controlled submersible.

balled" by the U.S. Navy), should be available to be custom fitted for oil spill dispersant application. Any of these vessels could be fitted for carrying dispersant in ballast tanks, or in auxiliary containers either on-board or towed by the vessel. Discharge of dispersant through underwater spray bars or other devices could enable more timely and effective dispersant action.

This idea requires more thorough investigation. A dispersant for such use would necessarily be hydrocarbon based rather than water based. Not only are there questions about the effect of hydrocarbon based dispersants on pumps, seals, and other equipment, but there is the question of whether or not such a vessel could operate effectively so near the surface. Both manned and unmanned small submersibles are designed to have neutral buoyancy; they might bounce around a lot near the surface. Hence some kind of a towed system might work better, but accuracy of application could be a problem. Sensing of the oil layer from below, by sonar, ultraviolet, or infrared detection methods, should not be a problem.⁸

Chemical Treatment

In Situ Chemical Reaction

Chemical treatment of oils can make them water soluble. Despite obvious difficulties and safety problems, it might be possible to treat an oil spill in place with a chemical agent to make the oil water soluble or to form a self-emulsifying mixture of treated and untreated oil.

One possible treating agent is sulfur trioxide, SO_3 . This material can be shipped as a stabilized liquid. It is highly corrosive, reacts violently with water and organics, forms a mist of sulfuric acid in air, and would require a lot of protective equipment to apply in the field, if indeed such application is possible at all.¹⁰ (The white smoke screen used by the U.S. Navy is SO_3 , titanium tetrachloride [TiCl₄], and chlorosulfonic acid [ClSO₃H].) Chlorosulfonic acid is another possible agent which could sulfonate oil in place.

Portable chemical processing plants have been built to manufacture fertilizer products in some third world countries. Models of these and other chemical process plants have been exhibited from time to time at the Offshore Technology Conferences or the Petro-

¹⁰ R. Estes, Tennessee Chemical Corp., Atlanta, GA, private phone communication.

chem Shows of the American Institute of Chemical Engineers. These plants are usually barge mounted. A barge mounted sulfonation plant could be transported to a spill site, and the reactions to sulfonate the spilled oil conducted on board, skimming some untreated oil from the water for processing, and discharging the reaction product, after neutralization, back onto the spill as a made-on-scene dispersant. One of the materials necessary would already be on site!

In Situ Chemical Agent Additions

Adding Dispersant when Loading—Chemical treatment of all oil shipped, rather than just that spilled, would be expensive. But the problems of dispersant application to spilled oil would be eliminated, and the costly effects of a spill and cleanup might be drastically reduced. Selective treatment for high risk areas, such as barge loads of refined product in a heavy industrialized area, might be a worthwhile preventative cost.

Pretreatment with dispersants is not a new idea. It has always been considered too costly, since most oil shipments do not result in spills. On the other hand, a shipper usually insures the value of his cargo, and the addition of dispersants to a shipment can be considered a form of insurance. Certainly application effectiveness would be greatly improved over field application methods; the application equipment would consist of a metering pump in the loading line.

Consideration would need be given to the shipping path, and en route environmental exposure if a spill occurred, the possible effect of the dispersant on product (in crude, any effect would usually be refined out), and of course, cost. It is doubtful if such treatment would be made voluntarily; it would probably require legislation to make it effective.

Adding Other Treating Agents when Loading—A new product that imparts viscoelasticity to hydrocarbons is now available.¹¹ This material not only enhances pickup of spilled oil by skimmers and vacuum equipment, and raises the drain-under velocity of containment booms, but it exhibits definite herding effects on spilled oil, reducing the spread on water. The amount needed varies, depending on the product to which it is added, from about 0.03 to 0.3% by weight. At present this would add from 10¢ to \$1 per gallon to the oil, probably too high a cost. It is quite possible that with increased production, costs might be reduced sufficiently to make this a feasible approach.

Equipment Cleaning

The author has never seen a paper on the difficulties of cleaning vessels and equipment that have been involved in spill cleanup. A large crude oil spill at sea must foul all the vessels engaged in entering the spill for operational or monitoring service, and there must be some contamination of clean areas as those vessels move around.

A small submersible used in the Ixtoc I well blowout in the Bay of Campeche, Mexico, in 1979–1980, had great difficulty in this regard. The vessel was used to monitor progress of attempts to cap the well. The oil not only fouled the vessel, but attacked the plastic coating of control cables and other equipment. Cleaning was a tremendous task.⁹

There are materials available, many based on silicone resin chemistry, that prevent wetting of surfaces by either oil or water. Many require baking the surface after the resin is applied, a procedure rather impractical for an entire ship. But at least one material, formerly sold under the tradename Pan Shield[®], was sprayed on and air-dried to provide the "nonstick" surface.¹²

¹¹ Elastol, General Technology Applications, Inc., Manassas, VA.

¹² M. Barr, Dow Corning Co., Midland, MI, private phone communication.

Such a material, if sprayed or painted on vessels and equipment before use in or on an oil spill might greatly simplify cleanup after the spill, and might provide protection against attack by the spilled product.

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Measurements on Natural Dispersion

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ABSTRACT: In the case of an oil spill, knowledge is needed of the natural dispersion behavior of the oil in the particular situation for decision making on the application of chemical dispersants. Small-scale and full-scale laboratory measurements were performed on the natural dispersion rate Q, droplet size distribution $d_0(f)$, and intrusion depth z_i for a surface oil slick broken up by breaking waves and the breakup of submerged oil (submerged spill) in a turbulent ambience. Empirical relations were derived for Q, $d_0(f)$, and z_i as a function of oil type, weathering state, oil layer thickness, breaking wave energy, temperature, and water salinity.

KEY WORDS: natural dispersion, laboratory measurements, droplet size, oil, water, oil spills, waves

Whether or not to use chemical dispersants in the case of an oil spill is an important choice especially in rough sea conditions where mechanical removal of oil is impossible and natural dispersion can be considerable. Application of chemical dispersants can affect in several ways the natural dispersion of a surface oil slick. They can, for example:

- shorten the lifetime of oil on the sea surface,
- increase the oil concentration in the water, and
- decrease the droplet size of the dispersed oil.

The oil concentration and droplet size are important to, for example, the uptake of oil by marine life and the absorption of oil by suspended particulate matter and its subsequent sedimentation to the sea floor.

Relatively little research has been performed on the natural dispersion of oil [1-10]. The present paper discusses small-scale and large-scale laboratory measurements of natural dispersion that were carried out on the volume of oil entrained in the water column as the result of a breaking wave, the droplet size distribution of the entrained oil, and the depth of initial intrusion. The experiments were performed with different conditions with respect to the following parameters:

- energy of breaking wave,
- type of oil,
- oil-weathering state,
- oil layer thickness,
- water salinity, and
- temperature.

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The measurements were made in three different laboratory facilities:

• a grid column was used to study the breakup of submerged oil in a turbulent ambience with turbulence levels on field scale;

• a small-scale flume (water depth 0.43 m) was used for an extensive series of measurements on the entrainment of oil by a breaking wave and the resulting droplet size distribution in different conditions; and

• five of the small-scale experiments were transformed to a large scale and were repeated in a flume with a water depth of 4.3 m and with "full-size" breaking waves.

Oil Droplet Size in Turbulent Ambience

The mechanical action of breaking waves and turbulence in the water flow causes spilt oil to break up into small droplets and the droplets to diffuse in the water mass. The effect of turbulence on the oil droplet size was determined by measurements in a laboratory grid column. The column is shown in Fig. 1. The oscillating grid generates homogeneous tur-



FIG. 1-Grid column experimental layout.

bulence in the column, the small-scale structure of the turbulence being similar to ocean conditions if the energy dissipation rates in the column and in the ocean are equal. The energy dissipation rate e in the column can be varied in the range $e = 0 - 3.5 \times 10^3$ J/s·m³. Values of e in field conditions are:

deep sea	$e = 10^{-4} - 10^{-2} \mathrm{J/s} \cdot \mathrm{m}^3$
estuary	$e = 10^{-1} - 10^0 \mathrm{J/s} \cdot \mathrm{m}^3$
surface layer	$e = 10^{\circ} - 10^{\circ} \mathrm{J/s} \cdot \mathrm{m}^{3}$
breaking wave	$e = 10^3 - 10^4 \mathrm{J/s} \cdot \mathrm{m}^3$

This means that measurements of oil droplet size in turbulent conditions can be made in the grid column at full-scale turbulence and that it is not necessary to model the parameters involved.

The oil was generally introduced into the grid column as large oil droplets near the bottom. In some tests the oil was introduced at the water surface. The turbulence grid was switched on for a period t_{grid} . Oil/water samples were withdrawn continuously during this period and led through a laser beam particle sizer. Oil droplet size distributions were measured in the column as a function of the following parameters:

• oil type: PB = Prudhoe Bay crude (Alaska), viscosity $\nu_0 = 92 \times 10^{-6} \text{ m}^2/\text{s}$ (at 20°C), and Eko = Ekofisk crude (North Sea), $\nu_0 = 8.0 \times 10^{-6} \text{ m}^2/\text{s}$;

• oil-weathering state: $PB_0 = fresh oil$, PB_3 , $PB_{10} = oil$ weathered by evaporation for three and ten days ($\nu_0 = 122 \times 10^{-6}$ and 220×10^{-6} m²/s, respectively), and $PB_{em} = emulsified oil, oil/water ratio = 0.3 (non-Newtonian viscosity behavior);$

• turbulent energy dissipation rate e from 0 to $3500 \text{ J/s} \cdot \text{m}^3$;

• $t_{\text{grid}} = 5$ s (simulation of a single breaking wave) and $t_{\text{grid}} = 600$ s (steady state, submerged oil spill);

• temperature T = 4, 12, and 20°C;

• water salinity S = 0, 15, and 30%; and

• oil introduction: surface and subsurface.

The laser beam particle sizer was unable to resolve the complete droplet size distribution because the relatively low concentration of small droplets could not be measured in the presence of a high concentration of larger droplets. The measurements in the grid column were therefore mainly used to derive the influence of various parameters on the mean droplet size d_{50} . The d_{50} measurements on submerged oil in a turbulent ambience are summarized in Fig. 2. The d_{50} value is given as a function of the oil viscosity v_0 , where v_0 depends on oil type, weathering state, and temperature. The results are given for various turbulence levels and turbulence durations and lead to the following conclusions.

1. The value d_{50} increases with increasing oil viscosity ν_0 according to the empirical equation:

$$d_{50} = c_1 \, v_0^{0.34} \tag{1}$$

The constant c_1 depends on the turbulence intensity e and the turbulence duration t_{grid} . The value d_{50} depends on oil type, weathering state, and temperature only as far as these variables influence the viscosity v_0 .



FIG. 2—Droplet size d_{50} versus oil viscosity for submerged oil in a turbulent ambience with different turbulence intensities, e, and duration of turbulence, t_{grid} . Grid column experiments.

2. The value d_{50} decreases with increasing turbulence level in high-turbulent water according to

$$d_{50} = c_2 \, e^{-0.50} \tag{2}$$

The constant c_2 depends on oil type, viscosity, and turbulence duration. The value d_{50} in low-turbulent water is smaller than according to Eq 2 as a result of the additional breakup caused by the shear on droplets rising in low-turbulent water. (See also the Results of the Oil Dispersion Experiments section and Fig. 7.)

Other results (not shown in Fig. 2) are below.

3. The value d_{50} is independent on water salinity.

4. The value d_{50} for the droplet distribution caused by the breakup of oil introduced under the surface is the same as that for droplets entrained from an oil layer by the turbulent eddies. (Surface oil introduction was done only with $t_{grid} = 600$ s.)

5. A d_{50} steady state was obtained at about 5 min indicating that the droplet size distribution generated by a shortlasting breaking wave will depend on a time parameter.

Small-Scale and Large-Scale Experiments on Oil Breakup by Breaking Waves

Experiments were also performed in a laboratory wave flume, 15 m long, 0.5 m wide with a water depth of 0.43 m. The experiments dealt with the effect of breaking waves on a surface oil layer measuring the following parameters:

- ratio of dispersed oil and surface oil,
- droplet size distribution $d_0(f)$ of dispersed oil, and
- vertical intrusion of oil droplets in the water mass.

The flume was equipped with a programmed wave board. Seven wave trains were selected, characterized by a specific wave height and energy dissipation of the single breaking wave.

An oil layer with a thickness h_0 (generally about 0.5 mm) was introduced into the test section of the flume. The entire wave breaking process took place in water covered by the oil layer. Figure 3 shows the passage of a breaking wave through the oil layer. The initial intrusion depth of the oil droplets was observed by taking photographs of the oil droplets (or of dye sprayed on the water surface) immediately after the wave passage. The droplet size distribution in these experiments was not obtained with the less suited laser beam particle sizer, but with a series of nine samplers. A sampling device is shown in Fig. 4 and consists of a small glass cylinder (content 50 cm^3) with a flat top. The cylinder is provided with a flexible silicon tube which is closed when it is bent by pulling on a rope. The glass was filled with heavy brine. In open position in the flume, flow exchange took place between the glass and the ambient water. The exchanged volume was derived by measuring the water density in the glass. After sampling, the device was taken out of the flume and kept vertical in stationary position during many hours. The oil droplets rose to the top glass. Photographs were taken of the top glass to enable the number of oil droplets in large size classes ($d_0 \gtrsim 100 \ \mu$ m) to be counted. Droplets with $d_0 < 100 \ \mu$ m were measured and counted by placing the sampling device directly under the microscope. The design of the apparatus enabled oil droplets to be measured down to $d_0 = 3 \ \mu m$.

Oil droplet samples were withdrawn in experiments in which nine samplers were mounted at three different depths below the water surface. Samples were taken at various times after the wave passage. The samplers could be moved on a carriage which enabled samples to be taken on a trajectory covering the entire length of the oil droplet cloud. The total amount of oil dispersed in the breaking process could, therefore, be observed.

Experiments were performed under the following conditions:

- oil type: Prudhoe Bay (PB) and Ekofisk oil;
- weathering state: PB₀ and PB₁₀;
- seven breaking waves with different energy dissipation;
- temperature: T = 2, 8, and 15°C; and
- oil layer thickness $h_0 = 0.2, 0.6, \text{ and } 1.2 \text{ mm.}$

Figure 5 shows a photograph of large oil droplets in a sampler. Figure 6 shows the droplet size distributions of three samples taken at the same time but at different depths. (A, B, and C samples taken at 0.1, 0.2, and 0.4 m below the water surface, respectively.) The graphs are drawn for $N(d_0)$ versus d_0 where $N(d_0)$ is the number of droplets on a droplet size interval 0.7 to 1.4 d_0 .

Some of the small-scale flume experiments were also performed in a large-scale flume, with a length scaling factor of $n_1 = 10$. This means that the water depth was increased

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FIG. 3—Passage of a breaking wave through oil slick in the small-scale flume.

from 0.43 to 4.3 m, and the wave height from, for example, 0.2 to 2 m. In many respects, the experiments in the large flume can be considered as full-scale experiments.

The experiments in the large-scale flume were as similar as possible with the small-scale flume, taking into account the length scaling factor $n_1 = 10$. Both PB₀ and Ekofisk oils were used. The layer thickness h_0 was about 1 mm since the scaled up value of $h_0 = 5$ mm was unfeasible. (It is concluded in the Results of the Oil Dispersion Experiments section



FIG. 4—Sampler in closed and in open position.



FIG. 5-Large oil droplets from breaking wave experiment in sampler.



FIG. 6—Oil droplet distribution in breaking wave experiment.

that $d_0(f)$ and Q are independent on h_0 .) The same samplers were used, but samples were only taken within the droplet cloud. The total amount of dispersed oil was obtained by extraction of oil/water samples using a tube-pump-bottle system. Samples were taken along the entire length of the oil droplet cloud. The oil concentration in the samples was measured by infrared spectroscopy.

The large flume was equipped with a wave generator similar to that in the small flume. The wave generators were steered by the same wave train signals, with an amplitude scaling of $n_a = 10$ and a wave period scaling $n_{Tw} = \sqrt{10}$. The results of the large-scale experiments confirm those obtained with the small-scale experiment on the droplet size distribution, the entrainment ratio of Ekofisk and PB oil, and the relative entrainment as a function of the wave type.

Results of the Oil Dispersion Experiments

The grid column experiments and the small-scale and large-scale flume experiments lead to empirical relationships for oil entrainment, droplet size distribution, and intrusion depth which appear to be valid for very different conditions.

All experiments confirm the droplet size distribution given by

or

$$N(d_0) = c_1 d_0^{-1.3}$$

$$N_u(d_0) = c_2 d_0^{-2.3}$$
(3)

where

- $N_{u}(d_{0})$ = number of droplets in unit droplet size interval around d_{0} ,
- $N(d_0)$ = number of droplets on an interval proportional to d_0 , for example, 0.7 to 1.4 d_0 (see Fig. 6), and
- $c_1, c_2 =$ proportionality constants.

This distribution holds in all conditions for small droplet sizes down to at least $d_0 = 3 \,\mu m$ (limit of measurements). The largest droplet size, d_{max} (generally on the order of magnitude of 1000 μm), depends on oil characteristics, turbulence level, and resurfacing and diffusion processes,

Equation 3 implies the following equation for the volume of dispersed oil is true:

$$V_t(d_0) = 1.45 \ V(d_0) \tag{4}$$

where $V(d_0) =$ volume of oil droplets in the size interval 0.7 to 1.4 d_0 and $V_1(d_0) =$ volume of oil droplets smaller than 1.4 d_0 .

The total volume of dispersed oil depends on the value of c in Eq 3 and on the maximum droplet size d_{max} . When a breaking wave passes through a (thick) oil surface layer, it is assumed that d_{max} is very large, say several millimetres, in the first instance. However, large droplets are unstable in the residual turbulence of the ambient water and resurface quickly. In principle, d_{max} can be found from diffusion calculations for the particular condition with a turbulent vertical diffusion coefficient ϵ_z and the terminal velocities of the droplets $W(d_0)$. The largest droplets in the small flume and in the large flume (with $\epsilon_z = 0$) were equal when the time of measurement, after the breaking wave has passed, was ten times larger in the large flume than in the small flume (scaling of intrusion depth).

The grid column simulated the breakup of submerged oil (submerged spill). In this case, d_{max} depended on the turbulence level in the ambient water. The measurements gave the d_{max} values shown in Fig. 7 for different oil types (PB₀ and Ekofisk) and different turbulence levels. The value d_{max} satisfies Eq 1, $d_{\text{max}} \sim v_0^{0.34}$ in high-turbulence conditions.



FIG. 7—Maximum droplet size, d_{max} versus turbulence level, e, for the breakup of submerged oil (grid column experiments).

Breaking waves caused an initial oil droplet intrusion depth z_i on the order of 1.5 to 2.0 H_b (H_b = wave height of breaking wave) or 2 to 4 h_{wc} (h_{wc} = whitecap height of breaking wave). The oil concentration and the droplet size distribution are homogeneous over the intrusion depth in the first instance, but inhomogeneities arise in the course of time as a result of resurfacing and diffusion processes. (The example in Fig. 6 shows a homogeneous distribution over the intrusion depth for oil droplets with $d_0 \leq 100 \ \mu m$ and an inhomogeneous distribution for larger droplets as a result of resurfacing.)

The oil entrainment as a result of breaking waves, Q, is related to a characteristic breaking wave energy by

$$Q \sim D_{ba}^{0.57} \tag{5}$$

in which Q = volume of entrained oil per unit surface area and D_{ba} = breaking wave energy dissipation per unit area (J/m²).

Equation 5, with the empirical exponent 0.57, was valid over the wide range of D_{ba} values in both the small-scale and large-scale experiments, where D_{ba} varied over a factor of 900.

The oil entrainment rate per droplet size class $Q_t(d_0)$ can be described empirically by:

$$Q_{t}(d_{0}) = c(0) D_{ba}^{0.57} d_{0}^{1.7} S_{cov} F_{wc}$$
(6)

where

- $Q_t(d_0) =$ Volume of entrained oil droplets in a size range interval Δd around d_0 , with $\Delta d \sim d_0$ (for example, interval 0.7 to 1.4 d_0), per unit area (m²) and per unit time (s);
 - $S_{\text{cov}} = \text{fraction of (sea) surface covered by oil } (0 < S_{\text{cov}} \leq 1);$
 - F_{wc} = fraction of surface covered by breaking waves ("whitecaps"), per unit time; and
 - c(0) = proportionality constant, depending on oil type, weathering state, and temperature.

Empirical values of c(0) for size intervals 0.7 to 1.4 d_0 , for various oil types are:

$$c(PB_0) = 0.65,$$

 $c(PB_{10}) = 0.40,$ and (7)
 $c(Ekofisk) = 1.58$

in which $Q_r(d_0)$ is expressed in metres per second and d_0 in metres.

The c values in Eq 7 were derived from experiments performed at a water temperature of about 13°C. The influence of the temperature on Q_r , as far as could be derived from the experiments carried out in the range of 2 to 15°C, is given by

$$c(0) \sim \nu_0^{-1}$$
 (8)

in which $v_0 = \text{oil viscosity}$ which varies with temperature. Measurements are shown in Fig. 8.

The oil entrainment Q, as a result of breaking waves, appeared from the experiments to be independent of the oil surface layer thickness h_0 , within the applied values $h_0 = 0.2$ to 1.2 mm (see Fig. 9). The maximum droplet size d_{max} may be considerably larger than h_0 .



FIG. 8—Flume measurements on oil entrainment, Q, versus temperature, T.

Application of Dispersion Relations in Oil Spill Trajectory and Fate Modelling

The transport of oil droplets in numerical oil spill models may be calculated by the advection-diffusion equation after establishing the droplet concentration profile and droplet size distribution as a result of the breakup of surface oil and initial intrusion in the water column:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = \frac{\partial}{\partial x} \left(\varepsilon_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left(\varepsilon_z \frac{\partial c}{\partial z} \right) + W \frac{\partial C}{\partial z} \quad (9)$$



FIG. 9-Measurements on oil entrainment, Q, versus oil surface layer thickness, ho.

where

 $C = C(d_0)$, oil concentration per droplet size;

u,v,w = advection velocity components in x,y,z direction;

x, y, z = longitudinal, lateral, and vertical directions;

 $\varepsilon_{x}, \varepsilon_{y}, \varepsilon_{z}$ = coefficients for diffusion in x, y and z direction; and

 $W = W(d_0)$, terminal velocity of oil droplets with size d_0 .

The present study assumes that the surface oil enters the water column directly as a result of breaking waves within the slick-covered area, as quantified by Eq 6. The Eqs 6 and 9 need the environmental parameters D_{ba} , F_{wc} , and the diffusion coefficients ε . The value ε_z is the most important diffusion coefficient, influencing the vertical spread and resurfacing of the oil droplets.

Much literature quantifies D_{ba} , F_{wc} , and ε_z in terms of more easily known environmental parameters as the windspeed U_w , bathymetry of the sea and the surf zone, currents, and wave statistics. (See the literature review [4]).

Field measurements of ε_z in arbitrary sea conditions show a wide range of values over several orders of magnitude. One of the reasons is the occurrence of vertical density gradients as a result of temperature or salinity differences. Reasonably reliable estimates of ε_z can be made only for simplified sea conditions without any stratification. Ichiye [7] has described the vertical diffusion coefficient in a deep unstratified sea as a function of the sea state related to the wave conditions. Empirical relations for a shallow unstratified sea with wind, waves, and currents have been derived by Veth [11]; the relations need the wind velocity and the current velocity. Stive and Wind [12] related ε_z in the surf zone with spilling breakers to the water depth and the phase velocity of the waves.

The fraction of breaking waves and the energy dissipation per breaking event in a specific wind field must be derived from wave statistics. Examples of relations are given in the following.

Field observations of Holthuysen and Herbers [6] and Toba et al. [13] lead to a simple empirical relation for spilling breakers in deep water:

$$F_{wc} = c_b (U_w - U_{wi}) / T_w$$
(10)

where

 F_{wc} = fraction of sea surface hit by breaking waves per unit time;

 T_w = wave period;

 U_{wi} = initiation of breaking wind speed, ≈ 5 m/s; and

 $c_b = \text{constant}, \approx 0.032 \text{ m/s}.$

A semi-empirical relation for the energy dissipation per unit surface area in a breaking event is given by:

$$D_{ba} \approx 0.0034 \,\rho_w \,g \,H_{\rm rms}^2 \tag{11}$$

where

 $H_{\rm rms}$ = root mean square (rms) value of the wave height in the wave field,

 ρ_w = water density, and

g = acceleration as a result of gravity.

Battjes and Janssen [2], and Stive and Dingemans [12] formulated a model for the prediction of D_{ba} and ε_z from a random wave breaking on a beach. The values D_{ba} and ε_z are related to H_{rms} , T_{w} , and the water depth h in an implicit set of equations. In many cases, the values of D_{ba} will be within the range of the performed experiments or within a relatively small extrapolation. However, extensive oil slicks may considerably reduce the wave spectrum and the breaking of waves in field conditions. In extreme conditions, wave breaking takes place only along the edges of the slick. These effects can hardly be quantified yet.

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Laboratory Studies on Oil Spill Dispersants

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ABSTRACT: Laboratory tests of oil spill dispersant effectiveness are used around the world to select dispersants for application to specific oils. These tests are presumed, by some, to represent real sea conditions and to provide the user with a result that is representative if not identical to a real dispersant application at sea. A number of tests have been developed over the years. At this time, the two most widely used tests are the Mackay test, otherwise known as the Mackay-Nadeau-Steelman (MNS) test, and the Labofina test, otherwise known as the Warren Springs or rotating flask test. The Mackay test employs a high velocity air stream to energize 6 L of water, whereas the Labofina test uses rotation of a separatory funnel with 250 mL of water. Both tests apply a large amount of energy to the oil/water system.

This paper compares test results from these apparatus with those from two lesser known devices, the oscillating hoop and the swirling flask. Both devices are relatively new, and protocols for their use have not been finalized. The oscillating hoop apparatus uses a hoop which is moved up and down at the water surface. The concentric waves serve both to energize the oil in the hoop and to contain it. Thirty-five litres of water are used in this test. The swirling flask test makes use of a 125-mL Erlenmeyer flask. The flask is rotated using a standard chemical/biological shaker to produce a swirling motion in the contents.

The results obtained using all 4 apparatus with a number of oils and dispersants are presented. A total of 121 oil/dispersant combinations were tested in the 4 apparatus.

The correlation of numeric values between the Mackay, Labofina, oscillating hoop, and swirling flask is low. The correlation of effectiveness ranking is also poor. An oil that disperses more readily than another, according to one test, is less readily dispersable according to one or more of the other tests. Similarly, a dispersant that is more effective by one test is less effective by another. The results from the oscillating hoop correlate poorly with all other test results.

Specific tests were also conducted to ascertain the effect of settling or rising time (the time the oil-in-water mixture is allowed to sit unagitated before a sample is taken). Longer settling times alter the oscillating hoop test results dramatically, improve the correlation for results with different apparatus, and enhance correlation with physical data such as viscosity. Differences in the effectiveness results are still apparent.

Results show that all the high energy tests (the Mackay, the Labofina and the oscillating hoop) produce unique dispersant effectiveness results and those correlate poorly with the physical properties of the oil.

KEY WORDS: dispersants, laboratory tests, effectiveness testing apparatus

A variety of dispersant tests have been employed in the past [1-4]. Reviews have listed a total of 35 tests using a number of different test apparatus. The primary function of these

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tests is to provide a numeric value of dispersant effectiveness. This is alternatively defined as the percentage of oil put into the water column or the percentage of oil not left on the surface. These definitions may appear to be equivalent, but in certain cases, can lead to rather different percentages because of losses such as evaporation or the amount that clings to walls.

The objectives in determining dispersant effectiveness are:

(1) to determine whether a particular product is acceptable in terms of a regulation or guideline procedure and value for acceptability,

(2) to screen oil and dispersant types to ascertain the best combination for field use,

(3) to provide data on whether a type of oil with a given evaporation exposure will disperse, and

(4) to measure chemical/physical parameters for experimental purposes or mathematical model inclusion. The objective may indeed indicate the type of test or apparatus needed.

A variety of apparatus are now in use around the world. The more common types of these are listed and described in Table 1. This paper will provide results and comparison for four of these apparatus: the rotating flask or Labofina apparatus, the MNS or Mackay apparatus, the oscillating hoop, and the swirling flask apparatus. The first two apparatus are the most commonly used in the world for regulatory testing of dispersants. The oscillating hoop has largely been used for scientific purposes and the swirling flask test is a new experimental concept. Three very important factors differentiate dispersant effectiveness apparatus:

- (1) the amount of energy input,
- (2) the oil-to-water ratio, and
- (3) the inclusion of rising/settling time in the protocol.

The method of adding dispersant to the oil has been shown to be very important as well [16]. Test results reported in this paper eliminate this variance by adding premixed oil and dispersants. The MNS test has been described in the literature [7,8]. In the test a 310-mmdiameter by 310-mm-high glass tank in which 6 L of seawater are placed is used. A Plexiglass[®] lid, tightened on the top of the tank, has separate ports for collecting oil, adding oil, placing thermometers, and admitting and releasing air. Air flow into the tank is used to generate a wave which varies from 2 to 6 cm in total height. Ten millilitres of oil are added to a containment ring after a wave is established on the water. In normal operation, the dispersant is then added to the oil with a syringe. After 1 min, the time to allow the dispersant to mix with the oil, the containment ring is lifted and the oil allowed to spread with the waves. After 10 min of agitation, a 500-mL specimen of water is withdrawn using suction applied to a sample tube inserted into the test vessel. The specimen is extracted with methylene chloride and this extract is analyzed colorimetrically for oil. Wave lengths used for the determination have recently been reviewed [17]. Sampling as described above is performed dynamically—this is with energy still being applied to the oil/water system. No rising/settling time is normally allotted. Problems with this procedure include the measurement of large, unstable droplets as being actually dispersed [16].

The rotating flask or Labofina test is the most common test in the world and has several basic variants [1,5]. The test vessel is a 500-mL conical separatory funnel which is rotated at 33 rotations per minute (rpm) about its vertical axis. Two-hundred-and-fifty millilitres of seawater are placed into the separation funnel. Five millilitres of oil are then added. In

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TABLE

Apparatus Description	Alternate Names	Reference(s)	Primary ^a Use	Water Amount, L	Oil: Water Ratio	Source of Mixing Energy	Energy Rating ^b
Rotating flask	Rolling Flask, Warren Springs,	5,6	M	0.250	1:50	rotating vessel itself	ŝ
MNS (Mackay- Nadeau-	Labolina Mackay	7,8	W	6.0	1:600	high velocity air stream	ŝ
Steelman) Oscillating hoon	:	9	Ь	35.0	1:200	hoop beating water	3
SET (simulated environmental	EPA test	10,11	R	119	1:1190	dund	ŝ
Dilution test	IFP	12,13	0	4 or 16 L initially	initially 1:800, constant replacement at 0.5 vol/h	oscillating hoop	7
Cascading weir	Mackay flume	4,14	പ	0.5 L/s constant flow	N	gravity fall over weir	2
Concentric tube	Bobra apparatus	15	Р	constant flow	constant replacement	water flow	1
New EPA Swirling flask	::	с 16	шш	2 to 4 L 0.125	1:100 to 1:300 1:1200	propeller vessel movement	1 2

^a R = regulatory testing of dispersants,
P = physical and experimental measures,
E = experimental apparatus only,
M = multipurpose, and

O = testing of dispersants for operational use.

^b Energy rating is classified by present author: 5 = ultra high, 4 = very high, 3 = high, 2 = medium, and 1 = low.^c R. Griffiths, private communication, Environmental Protection Agency, Leonardo.

most tests, 0.2 mL of dispersant is added dropwise to the oil surface and then the vessel is rotated for 5 min. The separatory funnel is allowed to stand for 1 min, during which time large, unstable oil particles rise to the surface. Then a 50-mL specimen of water is released from the bottom stopcock. The oil is analyzed in a manner similar to the MNS test.

The oscillating hoop test was developed by Dr. Mackay at the University of Toronto and has been used in a variety of physical experiments [9]. Its main advantage is that the oil is contained on the surface by the inward concentric waves. This allows access to the oil layer for physical experiments and also minimizes contact and loss to the vessel walls. A variety of protocols have been used for this oscillating hoop. No standard procedure has been defined. This paper reports results using the procedures and apparatus described by Buist et al. [9]. A test vessel of 50-L capacity is used. Thirty-five litres of water are placed in the vessel for each run. A metal hoop, of a diameter just less than the test vessel, plunges up and down at a rate of 60 to 150 rpm to form inwardly moving concentric waves. The vessel normally has a sample port at its bottom through which 100 mL of specimen is withdrawn. Colorimetric analyses are again performed. In practice, the hoop oscillation is started, 200 mL of oil placed in the center, dispersant added, and agitation continued for 30 min before a specimen is taken.

The swirling flask test was developed in Environment Canada's laboratory to provide a rapid and simple alternative to other tests [16]. In the test, a 125-mL Erlenmeyer flask to which a side spout has been added to decant water specimens without disturbing the surface oil layer. The source of agitation is the movement of the entire flask using a standard chemical/biological shaker at 150 rpm. A run begins by putting 120 mL of saltwater in the vessel, placing 0.1 mL of the oil/dispersant mixture on the water, and agitating for 20 min. The flasks are allowed to sit quiescent for 10 min and then a 30-mL water specimen is poured from the side spout. The specimen is extracted with methylene chloride and analyzed colorimetrically for oil.

Comparison of Effectiveness Results

Several investigators have performed comparison tests with two or more different apparatus [1,2,18-22]. The conclusion from these studies is that the numerical results of laboratory results do not correlate well, but do agree on the rankings assigned to dispersants. A recent study by the author on three test apparatus using one dispersant, but many different oils, concluded similarly that the ranking of oil dispersability is relatively the same with different tests [16]. In this paper, a comparison of dispersants and oils for four different effectiveness tests is presented.

Table 2 presents the effectiveness results with the MNS apparatus and Corexit 9527^{\circ}. Test runs are performed at a dispersant-to-oil ratio of 1:25 and at a temperature of 15°C. All other parameters are operated as described in the literature [8]. A blank run value is presented for each oil. This is to highlight the unique feature of the MNS test; that some oils will show very high blank or no dispersant effectiveness results.

Table 3 presents a series of the Labofina tests results done according to the protocol described by Martinelli [5]. All experiments had a dispersant-to-oil ratio of 1:25 and were run at a temperature of 15° C. As with all of the results presented in this paper, values are the average of at least two runs.

Table 4 presents the results of dispersant effectiveness testing using the oscillating hoop apparatus. Tests were done in accordance with the detailed protocol described in the appendix. Experiments were all performed using a dispersant to oil ratio of 1:25 and at a temperature of 20°C. Samples were taken during agitation and 5 min after agitation ceased (settling time of 5 min).
Oil Type	Chemical Dispersability with Corexit 9527	Blank Run
Adgo	96	20
Adgo (2.6% evaporated)	74	10
Amauligak	71	15
Amauligak (13.4% evaporated)	65	28
Amauligak (19.4% evaporated)	67	6
Automotive diesel	94	5
Automotive gasoline	46	38
Bent Horn	68	5
Bent Horn (20.4% evaporated)	80	0
Bent Horn (32.9% evaporated)	69	9
Bunker C	3	0
Electrical lubricating oil	28	14
Electrical transformer oil	94	21
Fuel oil No. 2	75	24
Hibernia	48	0
Hibernia (18.2% evaporated)	46	0
Hibernia (23.0% evaporated)	19	0
Issungnak	91	34
Issungnak (15% evaporated)	99	0
Issungnak (25% evaporated)	85	0
Lago Medio	81	2
Lago Medio (8.8% evaporated)	69	5
Lago Medio (14.8% evaporated)	85	2
Norman Wells	75	8
Tarsiut	81	30
Tarsiut (12.4% evaporated)	53	22
Tarsiut (16.4% evaporated)	72	39
Transmountain blend	84	1 .
Transmountain blend (18.5% evaporated)	80	0
Transmountain blend (28.5% evaporated)	83	0

 TABLE 2—Dispersability results for MNS apparatus.

 TABLE 3—Dispersant effectiveness using the Labofina apparatus.

	Effectiveness, %			
Oil Type	With Corexit 9527	With Enersperse 700		
Adgo	87			
Alberta Sweet Mixed Blend	41	49		
Amauligak	98	62		
Amauligak (13.4% evaporated)	77	70		
Automotive diesel	63	44		
Bent Horn	18	24		
Hibernia	39	49		
Issungnak	52	40		
Lago Medio	45	71		
Norman Wells	52	51		
Tarsiut	86	40		

			Effectiveness, %	
			Dispersant	
Oil Type	Sampling Procedure	Corexit 9527	Enersperse 700	CRX-8
Alberta Sweet Mixed	• dynamic	50	92	82
Blend	• 5-min	26	81	21
Avalon	• dynamic	84	53	87
	• 5-min	40	16	18
Norman Wells	• dynamic	62	68	67
	• 5-min	29	57	17
Prudhoe Bay	• dynamic	87	63	82
	• 5-min	52	59	46

TABLE 4—Dispersant effectiveness using the oscillating hoop apparatus.

Table 5 presents the results of the effectiveness tests conducted with the swirling flask apparatus. Procedures followed for this test are detailed in the appendix. Experiments were conducted with an oil-to-dispersant ratio of 1:25 and at a temperature of 20°C.

Dispersants were obtained from the manufacturers or their associated companies. Corexit 9527 is a very common dispersant and is manufactured by Exxon Chemicals. CRX- 8° has the same source but is a new, experimental product. Enersperse 700°, formerly known as BP MA-700°, is a product of British Petroleum and is sold in Canada by PetroCan Chemicals. Oils were obtained from petroleum companies and names are designated by the company who provided them. The properties of these oils are described in Table 6 [23].

	Effectiveness, %					
	Dispersant					
Oil Type	Corexit 9527	Enersperse 700	CRX-8			
Adgo	61	67	42			
Alberta Sweet Mixed Blend	30	48	37			
Amauligak	48	54	56			
Atkinson	7	8	9			
Avalon (19.8% evaporated)	8	13	10			
Federated	39	38	23			
Gear oil	29	10	40			
Hibernia (11.7% evaporated)	11	6	12			
Issungnak	24	42	42			
Kuwait	5	7	4			
Lago Medio (19.9% evaporated)	0	2	7			
Norman Wells (12% evaporated)	23	31	37			
Prudhoe Bay	7	17	5			
Tarsiut	53	63	52			
Uvilik	52	64	11			

 TABLE 5—Dispersant effectiveness using the swirling flask apparatus.

Oil Type	Kinematic Viscosity, mm ² /s at 15° C or cst	Density, 15°C	Oil-Seawater Interfacial Tension, mN/ m at 15° C
Adgo	68.0	0.953	6.9
Alberta Sweet Mixed Blend	7.7	0.839	8.4
Amauligak	15.7	0.890	2.9
Amauligak (13.4% evaporated)	23.4	0.898	15.0
Atkinson	57.3	0.911	17.9
Avalon	13.5	0.844	20.5
Avalon (19.8% evaporated)	95.0	0.885	26.7
Bent Horn	14.8	0.818	26.6
Federated	5.2	0.826	22,2
Gear oil	172.9	0.883	2.8
Hibernia	67.7	0.865	21.0
Hibernia (11.7% evaporated)	120.1	0.880	19.0
Issungnak	3.6	0.828	16.8
Kuwait	19.0	0.870	22.9
Lago Medio	47.1	0.872	12.4
Lago Medio (19.9% evaporated)	295.0	0.897	22.5
Norman Wells	7.2	0.832	16.4
Norman Wells (12% evaporated)	24.0	0.855	
Prudhoe Bay	43.0	0.902	9.7
Tarsiut	8.5	0.875	14.1
Uvilik	15.7	0.879	12.2

TABLE 6—Properties of test oils.

Corexit 9527 was used on all four test apparatus. These results are shown in Table 7 and illustrated in Fig. 1. The latter compares the effectiveness in other apparatus versus the swirling flask (SF) apparatus. Both the numerical results and the graphical representation show that there is little correlation between the test results. The rank at which the oil performed in each test is shown in Table 8. Except for the oscillating hoop results, which are the exact inverse of the swirling flask results, rank correlates somewhat. The correlation is poor, however, and could not be relied upon to give a definitive answer. Comparisons of Table 2, Table 3, and Table 5 show that the same rank comparisons hold for a variety of oils and two dispersants.

	Effectiveness, %						
Oil Type	Swirling Flask	Oscillating Hoop	Settling and Oscillating Hoop	Labofina	MNS		
Alberta Sweet							
Mixed							
Blend	30	50	26	41	90		
Avalon	8	84	40	38	10		
Norman Wells	23	62	29	52	75		
Prudhoe Bay	7	87	52	35	80		

TABLE 7—Comparison of results for Corexit 9527.



FIG. 1-Effectiveness comparison for Corexit 9527.

A comparison of the effectiveness of different dispersants in the same apparatus, the swirling flask, is shown in Fig. 2. As can be seen, most effectiveness results correlate well; however, with some oils, specific effects occur. An examination of Table 5 shows that, generally, Enersperse 700 shows greater effectiveness than the other products except with Amauligak, Atkinson, gear oil, Hibernia, Lago Medio, and Norman Wells. These represent very light and very heavy oils. For these oils, CRX-8 shows greater effectiveness than the other dispersants. Corexit 9527 shows greater effectiveness than CRX-8 for most oils other than the above-mentioned exceptions. For Uvilik, CRX-8 shows only 11% effectiveness compared to 52 and 64% for the other dispersants. This result was tested repeatedly, as it appeared anomalous. This example illustrates the oil and dispersant specificity of some combinations. Oil composition synergism with dispersant type is suspected to be the cause of this.

The effect of settling time with the oscillating hoop apparatus was measured. The concentrations of oil in water were first measured while the energy was still applied and then

	Effectiveness Rank in Apparatus ^a				
Oil Type	Swirling Flask	Oscillating Hoop	Labofina	MNS	
Alberta Sweet Mixed Blend	1	4	2	1	
Avalon Norman Wells Prudhoe Bay	3 2 4	2 3 1	3 1 4	4 3 2	

TABLE 8—Comparison of effectiveness rank for various oils.

^a 1 is the most dispersed, 4 is the least dispersed.



FIG. 2—Dispersant effectiveness in swirling flask.

5 min after the energy was removed. Figure 3 illustrates the comparison between both sets of effectiveness results. There is little correlation between the two sets of results. It appears that those dispersions that are very stable show little decrease in effectiveness with settling time. Similar results were found by Daling and Nes using both the Labofina and MNS apparatus [19]. The lack of settling time in the test protocol can lead to very different conclusions about the effectiveness of any particular oil/dispersant combination.







FIG. 4—Effectiveness as a function of viscosity.

The author has shown, in a previous paper, that test results from the swirling flask test correlate well with the oil viscosity [16]. The same paper showed that the correlation with the other apparatus was poor. Figure 4 shows the correlation for the swirling flask data in this paper. The correlation is not as good as that presented in the previous paper, but is still better than that for the other apparatus. Compositional differences in the oils would account for some of the variation observed.

Other observations on the data include the high values and lack of discrimination in the MNS and oscillating hoop tests when dynamically sampled. The majority of values of any dispersant/oil combination that disperse are 80% or higher. Values for nonfunctioning combinations are generally lower than 20%. Few values appear between these two ranges. This is suspected to be due to the artificially high dispersions caused by the high energy levels. Also, the Labofina test has a low oil-to-water ratio. This has been shown to be a factor by Byford,² who has found that effectiveness was changed little, whether the dispersant was placed in the oil or water. With the small oil-to-water ratio, the dispersant has full contact with the oil as a water solution with sufficient surfactant content to disperse oil. This is true also if the dispersant is premixed with the oil and surfactant leaches into the water. In other apparatus, such a small oil-to-water ratio would not occur.

Summary and Conclusion

A large number of tests were performed using four apparatus, three dispersants, and, in some cases, different operating modes. These tests show that there is little correlation between the numerical data generated by such a wide variety of apparatus. The oscillating hoop results, in particular, correlate poorly with those of other tests. The rank of effectiveness of oil/dispersant combinations correlate only weakly between tests. The oscillating

² D. C. Byford, private communication at Dispersant Workshop, Toronto, 1983.

hoop test again showing the poorest correlation of the devices tested. However, very poor and very good oils/dispersant combinations will show up throughout all types of testing.

The effectiveness results for various dispersants tested in the same apparatus do correlate somewhat. Some oil/dispersant combinations do, however, produce unique and unexplained results. These are probably due to compositional synergism between the oil and dispersant. This implies that each oil be tested with each dispersant to determine what the actual effectiveness is.

Settling time is important in dispersant effectiveness tests. Allowing large, unstable droplets to rise and be eliminated from analysis, ensures that results are true for stable emulsions.

The MNS and oscillating hoop tests operated without a settling time provide very high or very low results with little discrimination between oil/dispersant combinations in both groups. This may be due to high mixing energies, as well as lack of settling times. The Labofina test has a high oil-to-water ratio which may cause anomolous results.

APPENDIX

Detailed Operating Procedures for the Swirling Flask Apparatus

• Standards of 97.6, 75.2, 56.4, 37.6, 18.8, and 9.2% dispersability are made by pouring 30 mL of artificial saltwater (33-g table salt/1-L water) into a separatory funnel and adding the following quantities of oil:

97.6% dispersability:24.4 μ L of oil 75.2% dispersability:18.8 μ L of oil 56.4% dispersability:14.1 μ L of oil 37.6% dispersability:9.4 μ L of oil

18.8% dispersability:4.6 µL of oil

9.2% dispersability: 2.3 μ L of oil

• Extract with three 5-mL volumes of methylene chloride (dichloromethane).

• Let the solution settle in the separatory funnel for about 2 min before draining the organic phase to the 1-mL indication line. After each extraction there should remain 1 mL of organic phase in the separatory funnel.

• The absorbance of the standards are measured at the following wavelengths: 400, 370, and 340 nm.

• Standard calibration curves are then drawn.

• Place 120 mL of artificial seawater, (33-g table salt/1-L water), in a 150-mL spouted Erlenmeyer flask. Carefully float 0.10-mL premixed oil/dispersant mixture (25:1 by volume) on top of the saltwater, and place the flask in the thermo-controlled Brunswick shaker, preset at 20°C, and set for 150 rpm.

• Shake for 20 min, then remove and let stand on the shaker shelf for 10 min.

• Discard first 1 to 2 mL in the spout, then transfer 30 mL into the separatory funnel through the spout, using a 50-mL graduated cylinder.

• Extract the oil as in the calibration curve procedure, using the same times, volumes, and wavelengths, rinsing out the transfer vessel (graduated cylinder) with the extractant.

Detailed Operating Procedures for the Oscillating Hoop Test

• Prepare standards by placing 100 mL of saltwater (33-g table salt/1-L water) in a 500-mL separatory funnel.

• Add appropriate amount of oil with a syringe:

Percent Dispersion	Volume of Oil, µI
10	42.9
25	107.3
50	214.6
75	321.9

• Add 100 mL of methylene chloride, mix thoroughly, allow to separate.

• Remove oil/methylene chloride layer down to the 50-mL indication line. Repeat two more times, which should result in 250 mL of solution.

• Analyze with an ultraviolet/visual (UV/VIS) spectrophotometer at appropriate wavelengths (340, 370, and 400 nm).

• Plot absorbance versus percent dispersion on linear graph paper for each wavelength.

• Perform an experimental run by filling tank with 35 L of saltwater (33-g table salt/1-L water), set hoop oscillating at 150 rpm.

• Pour 150 mL of oil/dispersant mixture (25:1 ratio) into the center of the hoop.

• After 30 min, draw off 100 mL of water from the central sampling port while hoop is still oscillating, transfer to 500-mL separatory funnel.

- Stop hoop, wait 5 min, then sample again.
- Add 100 mL of methylene chloride, mix thoroughly. Let stand for 10 min.
- Remove oil/methylene chloride layer down to the 50-mL indication line.
- Repeat two more times, which should result in 250 mL of solution.

• Analyze this fraction with a UV/VIS spectrophotometer at appropriate wavelengths (340, 370, and 400 nm).

• Obtain percent dispersion from prepared standard curves.

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Design and Evaluation of a Large Boat-Mounted Dispersant Spraying System and Its Integration with Other Application Equipment

REFERENCE: Onstad, L. A. and Lindblom, G. P., "Design and Evaluation of a Large Boat-Mounted Dispersant Spraying System and Its Integration with Other Application Equipment," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L.* Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 220–228.

ABSTRACT: Oil spill response groups have recognized that it is essential to have the ability to apply dispersants properly when they are needed. Some of these organizations have developed unique application equipment as part of their total capability. Two California industry cooperatives have designed dispersant spray systems that are attached to existing advancing recovery devices, thus providing the largest spray systems yet developed for any surface vessels.

Detailed calibration of the systems has been done and has provided tables and charts which can be used by both management and operators for direction of dispersant application programs. Close control of dispersant dosage is a requirement for successful dispersant application and also for accurate documentation for regulatory authorities. The calibration work reported here has also shown the variability that can be found in very similar systems and indicated the need for careful evaluation of educator performance, as well as the value of use of accurate metering pumps for dispersant, whether used diluted or undiluted.

KEYWORDS: dispersants, application, calibration, dispersant spray systems

In the early 1980s, offshore oil exploration and production in California became an important public issue as a result of new lease sales and the known potential of significant reserves. Regulatory agencies, such as the Minerals Management service, U.S. Coast Guard, and the California Coastal Commission, began to look seriously at the ability of the oil industry to respond to an offshore oil spill [1]. The agencies promulgated policies regarding oil spill preparedness, which dictated equipment type and capabilities, response times, training requirements, and (most importantly for this paper) the requirement to have dispersant application capability and an available stockpile of dispersant chemical.

Most offshore operations had a limited amount of dispersant on board and some type of device, such as a backpack sprayer, to apply them. The three California oil industry spill cooperatives had a large stockpile of dispersants, a large airplane on a standby contract, helicopter bucket spray systems, and several small boats equipped with spray arms.

During this period, the Clean Seas and Clean Coastal Waters cooperatives acquired several large offshore supply boats and converted them to dedicated oil spill response vessels. Each of these vessels was outfitted with containment boom and skimmers designed for use

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in both skimming and stationary modes. The advancing mode skimmers operated offsweep arms which extended 40 to 50 ft (12 to 15 m) from the sides of the vessels.

Dispersant System Design

It was apparent that these vessels might be used effectively to apply dispersants if the sweep arms could in some way be used as part of an application system. This idea was further developed by both cooperatives in designing such systems. The general requirements for spray system design and the need for accurate calibration are well known [2].

The Clean Seas vessels are equipped with a skimming system manufactured by Offshore Devices, Inc. (ODI). This system contains two 13.7-m $(45-ft)^3$ aluminum sweep arms, each equipped with a foam-filled float on the outboard end. The ODI arm, made of 20.3-cm (8-in.) diameter aluminum pipe, pivots on a bracket mounted on the bulwark of the vessel. When deployed, it is held in place perpendicular to the vessel by lines and is designed to travel through the water at speeds of up to 5 kn (2.5 m/s).

Dispersant spray booms were designed to be permanently attached to the ODI sweep arms (Figs. 1 to 3). The sprayboom sections were made of 5.01-cm (2-in.) standard 6061 aluminum pipe and coupled using 5.01-cm, 2000# full couplings. Nozzle outlets were 1.9cm (%-in.) 2000# full couplings, internally threaded to accept the nozzle bushings. Nine nozzles were fitted to each boom, the inboard nozzle at about 2 m (6 ft) from the ship's rail, and the others at an internozzle spacing of 1.2 m (4 ft). Two 5.01-cm aluminum 90° swivel joints were used to offset the shipboard end of the sprayboom from the sweep arm. A standard camlock fitting was placed on the inboard end of the sprayboom to allow for attachment of a water hose.

Eight sets of brackets (0.95 by 7.6 cm) (% by 3 in.) were designed to attach the sprayboom to the sweep arm using standard 6061 aluminum flat bar. These were heated and bent around a 20.3-cm pipe to give them proper form. Another eight sets of brackets were designed to hold the sprayboom using the same material bent around a 5.01-cm pipe.

A set of spacers of varying lengths were built to hold the spray boom away from the ODI arm at an outboard slope less than that of the arm itself. This was to make the sprayboom approach a more horizontal attitude with respect to the water surface.

Nozzles were selected to give a slightly overlapping spray pattern (at a system pressure of 207 to 276 kPa [30 to 40 psi]) and so that spray from the inboard nozzle would hit the side of the ship just above the water. Spraying Systems 6530 and 5030 nozzles, equipped with jet stabilizers, were selected. Because the final configuration of the spraybooms still had some slope—from approximately 2.1 m (7 ft) above the water at the inboard end to 1.1 m (3 $\frac{1}{2}$ ft) above the water at the outboard end—it was necessary to change from 50 to 65° nozzles in some positions. The first (inboard) nozzle and the three most outboard nozzles were 65°, and the other five nozzles were 50°. With this configuration, the swath width sprayed on each side of the vessel is about 11.6 m (38 ft). With both port and the starboard arms extended, the total swath width sprayed is 23.2 m (76 ft).

Seawater supplied from the ship's fire pump is used as the carrying fluid for the dispersant. A small, portable pump is used to add dispersant to the system. (For maximum efficiency and dosage control it is now planned to install a metering pump for addition of the dispersant chemical.) The initial calibration reported in this paper was done with the eductor and portable pumps aboard each vessel.

Each of the response vessels is equipped with tanks (1893 to 3785 L) (500 to 1000 U.S.

³ All original measurements in this paper were in English units.







FIG. 2-ODI arm with attached sprayboom in deployed position.



FIG. 3-ODI arms float with sprayboom detail.

gal each) for storing dispersant in bulk. The tanks have pressure-relief valves and are internally coated to protect against any undesirable effect of corrosion on the chemical.

After calibration of the systems was completed, training in their use was necessary. Practice spraying operations were accomplished by requiring the boat crew to simulate applying dispersants in various dosages, using calibration charts provided. This type of practice is necessary so crews will be able to follow dispersant application requirements and directions even if no technical expert is present to assist.

The system developed by Clean Coastal Waters is similar in concept to the Clean Seas system. It, however, was designed to attach to the sweep arm of a Troilboom Oil Recovery system. Since this arm is held horizontal to the water and has no float, there was no necessity to allow for a slope offset. This system, however, mounts 2.4 to 3.0 m (8 to 10 ft) above the water, so drop pipes were inserted. These allowed the nozzles to be positioned only about 1.5 m (5 ft) from the water and the spray patterns to be less subject to relative wind and motion of the vessel. The Clean Coastal Waters system is equipped with a metering pump to allow for absolute control of dosage with change in the ship's speed.

CONICAL CONTAINER MEASUREMENTS





EQUATIONS FOR CALCULATION OF FLOW VOLUMES AND RATES

The volume of water collected in each pail is determined from the relationship for the volume of the frustum of a right circular cone, which is given by:

 $V = (\pi h) x (R^2 + r^2 + (R x r)) / 3000$

- where: V = volume in liters h = measured depth of water in centimeters R = radius of pail at level h in centimeters r = radius of pail bottom in centimeters
 - and: R = h tan A + r, where A is the angle of deviation from vertical measured at the pail base.

The rate of flow in USGPM is determined by multiplying V by (15.85/t), where t is the collection time in seconds.

FIG. 4—Equations and measurements used in calibration.

Calibration Procedures

Water was used as the calibration fluid in all cases. All nozzles were operating for all tests. The water was collected in identical calibration plastic pails (Fig. 1). Test runs were timed to 0.1 s from the time the pails were placed under the spray to the time they were removed. Collection times usually varied between 40 and 70 s, depending on the time required for the pails to become $\frac{1}{2}$ to $\frac{8}{5}$ full. After collection, the water depth was measured (to the nearest 0.1 cm) with a plastic ruler inserted into the center of the water. For each nozzle the data were converted to volume collected and flow rate using the equation in Fig. 4. The sum of the individual nozzle data gave similar information for the entire run. The three or more replicates for each determination were averaged.

Eductors were calibrated by timing removal of water from a pail through the chemical suction line. The calculated pump rate to fill the final level was subtracted from the calculated pump rate to fill to the initial level to give the rate of chemical delivery at the test setting of the eductor.

Results

All data obtained were tabulated, plotted, and analyzed. This showed there was a distinct difference between the three Clean Seas systems. A summary of the results, showing averages for the booms and nozzles, is given in Table 1. The differences obviously represent variation in the output of the three pumps or the adjustments of the fire water systems feeding the pumps. However, the data obtained will be accurate if the same operating conditions are used as those at the time of calibration of each system. Also, and most importantly, any differences will not be of concern *if dispersant is added to a system by a metering pump rather than through an eductor*. In this latter case only enough water to maintain the spray nozzle patterns under the vessel's operating conditions is necessary, and whatever amount of dispersant is required for a given dosage per unit area can be added. Table 2 shows the dispersant pump rates required for different swath widths and applies to any method of chemical addition.

The results of the eductor calibrations showed that the actual amounts of fluid added to the system varied from 75 to 105% of the eductor setting and that some performance was very erratic (Table 3). Comparison of this data with Table 2 shows that use of the current eductors can greatly limit the dosage capabilities of the three systems. Although operating tables and reference charts have been prepared from this data, it is recognized that use of

			Port	St	arboard	
Vessel	Pressure, psi ^b	Total	Per Nozzle	Total	Per Nozzle	Booms)
Mr. Clean	20	17.78	1.975	17.98	1.998	35.76
	30	20.73	2.303	20.32	2.258	41.05
Mr. Clean II	20	19.36	2.151	19.97	2.219	39.33
	30	23.77	2.641	23.58	2.620	47.35
Mr. Clean III	20	12.57	1.397	12.24	1.360	24.81
	30	14.13	1.570	14.42	1.602	28.55

 TABLE 1—Summary of average water rates in U.S. gallons per minute (USGPM) measured for three boat systems.^a

 a 1 U.S. gal = 3.785 L.

 b 1 psi = 51.7 mm Hg.

		Dispersant Dosage, USGPA ^b				
Speed, kn	Swath, ft	2	3	5	7	10
3	75	1.05	1.57	2.62	3.66	5.30
	105	1.47	2.20	3.67	5.12	7.42
	115	1.61	2.41	4.02	5.61	8.13
5	75	1.74	2.62	4.36	6.10	8.72
	105	2.44	3.67	6.10	8.54	12.21
	115	2.67	4.02	6.69	9.35	13.37
7	75	2.44	3.66	6.10	8.55	12.21
	105	3.42	5.12	8.54	11.97	17.09
	115	3.74	5.61	9.35	13.11	18.72
10	75	3.49	5.23	8.72	12.21	17.44
	105	4.89	7.32	12.21	17.09	24.42
	115	5.35	8.02	13.37	18.72	26.74

 TABLE 2—Chemical addition rates in USGPM for various

 dosage requirements at three swath widths and speeds of 3, 5, 7,

 and 10 kn.^a

^a A general equation for all dosage calculations is:

$$D = 430 P/(S \times V)$$

where

D = dosage in USGPA, P = chemical pump rate in USGPM, S = Swath width in feet, and V = speed of boat or aircraft in knots. The equation can be easily rearranged to solve for any variable. 1 U.S. gal = 3.785 L, 1 ft = 0.3048 m, 1 acre = 4047 m², and 1 kn = 0.5144 m/s. ^b USGPA = U.S. gallons per acre.

metering pumps to add the dispersant chemical is by far the most accurate and dependable way of operating, and plans for implementing this on the Clean Seas ships are underway.

Calibration of helicopter spray systems has also been conducted. Two Simplex Model 2000 systems are owned by Clean Seas. These have 65 nozzle ports each, with a varying number of nozzles fitted in each unit depending on the desired dosage and the speed of the helicopter. Spraying Systems 8355 0.64-cm (¼-in.) nozzle bodies of 90° configuration, fitted with D10 orifices and #45 cores, are currently used. Changes in nozzle type and numbers, as well as speed of the helicopter, will allow for dosage variation as required (Table 4). The addition of a flowmeter with a variable control pump can provide positive control of dispersant flow when in flight.

Summary and Conclusions

Dispersant spray systems have been designed for permanent attachment to mechanical recovery systems on several large response vessels used in California. These have been calibrated in detail so that accurate control of dispersant use is possible. The advantage of metering pumps over eductors for introduction of dispersant has been indicated. Operating tables and charts have been developed for individual boat and aircraft application systems for rapid reference in providing guidance and achieving known dosage during response

	CLEAN SEAS EQUIPMENT CALIBRATION (EDUCTOR) (TEST 11) (MR. CLEAN) 30 psi					
Flowmeter Setting						
LPM ^a	USPGM	Test	Amount Educted, USGPM	Average USPGM	Performance Percent of Setting	
4 4 4 4	1.06 1.06 1.06 1.06	A B C D	0.87 0.94 0.87 0.57	0.89	83.9	
12 12 12	3.17 3.17 3.17	A B C	2.42 2.44 2.43	2.43	76.6	
26 26 26 26	6.87 6.87 6.87 6.87	A B C D	7.37 7.67 7.13 7.31	7.37	107.3	

TABLE 3—Eductor calibration data for three boat systems.

CLEAN SEAS EQUIPMENT CALIBRATION—EDUCTOR

(MR. CLEAN II) 33 psi

Setting, USGPM	Test	Amount Educted, USGPM	Average USGPM	Performance Percent of Setting
2	Α	1.79		
	В	1.70		
	С	2.00	1.83	91.5
4	Α	3.92		
	В	3.83		
	С	3.55	3.77	94.3
5	Α	4.79		
	В	4.38		
	С	4.60	4.59	91.8

CLEAN SEAS EQUIPMENT CALIBRATION (EDUCTOR) (TEST 12) (MR. CLEAN III) 30 psi

Flowm	eter Setting				D
LPM	USGPM	Test	Amount Educted, USGPM	Average USGPM	Performance Percent of Setting
8	2.11	A	2.06	2.06	97.6
6	1.59	Α	1.64		
6	1.59	В	1.70	1.67	105.0
5	1.32	А	1.32		
5	1.32	В	1.17	1.25	94.7
4	1.06	Α	1.11		
4	1.06	В	1.11	1.11	104.7

^{*a*} LPM = litre per minute.

		Swath	= 50 ft			Swath	= 40 ft	
D D-4				Speed	, knots			
USGPM ^b	50	60	80	100	50	60	80	100
17.77 27.62 36.81	3.06 4.75 6.33	2.55 3.96 5.28	1.91 2.97 3.96	1.53 2.38 3.17	3.82 5.94 7.91	3.18 4.95 6.60	2.39 3.71 4.95	1.91 2.97 3.96

 TABLE 4—Dispersant dosage using helicopter units as calibrated, without flowmeter or variable pump in U.S. gallons per acre.^a

^a 1 U.S. gal = 3.785 L, 1 acre = 4047 m², 1 ft = 0.3048 m, and 1 kn = 0.5144 m/s.

^b The pump rates in this table are the total rates obtained in the calibration of the 20-nozzle test of UNIT "B," and the 34- and 44-nozzle tests of UNIT "A." The 44-nozzle test of UNIT "B" was essentially identical to that of UNIT "A." Nozzle specifications: Spraying Systems 8355 ½-in. (6.35-mm) nozzle bodies, 90° configuration, D190 orifices with #45 cores.

operations. Such preparation by any response group will add significantly to the chances of success in dispersant use.

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Tropical Oil Pollution Investigations in Coastal Systems (Tropics): The Effects of Untreated and Chemically Dispersed Prudhoe Bay Crude Oil on Mangroves, Seagrasses, and Corals in Panama

REFERENCE: Ballou, T. G., Dodge, R., Hess, S., and Knap, A., "Tropical Oil Pollution Investigations in Coastal Systems (Tropics): The Effects of Untreated and Chemically Dispersed Prudhoe Bay Crude Oil on Mangroves, Seagrasses, and Corals in Panama," in *Oil Dispersants: New Ecological Approaches, ASTM STP 1018, L.* Michael Flaherty, Ed., American Society for Testing and Materials, Philadelphia, 1989, pp. 229–256.

ABSTRACT: A multidisciplinary long-term field experiment was conducted to evaluate the use of chemical dispersants as a means of reducing adverse environmental effects of oil spills in nearshore, tropical waters. Three study sites whose intertidal and subtidal components consisted of mangroves, seagrass beds, and coral reefs were studied in detail before, during, and after exposure to untreated crude oil or chemically dispersed oil. This study was intended to simulate an unusually high, worst-case exposure level of dispersed oil and a moderate exposure level of untreated oil. The third site served as an untreated reference site. Assessments were made of the distribution and extent of contamination by hydrocarbons over time, and the short- and long-term effects on survival, abundance, and growth of the dominant flora and fauna of each habitat. The whole, untreated oil had severe, long-term effects on survival of mangroves and associated fauna and relatively minor effects on seagrasses, corals, and associated organisms. Chemically dispersed oil caused declines in the abundance of corals, sea urchins, and other reef organisms; reduced coral growth rate in one species; and had minor or no effects on seagrasses and mangroves. Conclusions were drawn from these results with respect to decision making at the site of the actual spills based upon trade-offs on the consequences of dispersing or not dispersing the oil.

KEY WORDS: oil spills, dispersants, crude oil, nearshore, tropical, mangrove, seagrass, coral, effects, field experiment

The primary objective of this study was to evaluate the application of dispersant to spilled oil as a means of reducing adverse environmental effects of oil spills in nearshore, tropical waters. To accomplish this objective, a two-and-one-half-year field experiment was designed in which detailed, synoptic measurements were made of representative intertidal and nearshore subtidal habitats and organisms (mangroves, seagrass beds, and coral reefs) at one reference and two experimental sites before, during, or after exposure to untreated

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crude oil and chemically dispersed oil. The results were intended to give guidance in minimizing the ecological impacts of oil spills through evaluation of trade-offs in the relative impacts of chemical dispersion to tropical marine intertidal and subtidal habitats.

This report deals only with the major results of the study. A large number of parameters were monitored, but in the interest of brevity, only the most important aspects of the study are reported here. In particular, results are reported for the experimental sites only, unless the reference site data are particularly important to the interpretation of results.

General Scenario Development

This study was intended to simulate an unusually high exposure level of chemically dispersed oil and a moderate exposure level of untreated oil. This level of dispersed oil would be approached only if fresh oil were dispersed directly adjacent to coral and seagrass habitats in shallow, nearshore waters. The exposure level chosen for the untreated oil was based on field observations of estimated amounts that caused mangrove tree mortalities.

The target concentration of dispersed oil in this study was to simulate the chemical dispersion of an oil slick with an average thickness of 0.1 mm. The slick was to be large relative to the surface area of the receiving waters, which in turn were to be slowly flushed. The slick was to be dispersed before stranding; therefore, the dispersed oil was subject to dilution by intervening water. Thus, the concentration that reached shore would be diluted to about 15 parts per million (ppm) or less, lasting for three days. However, it was not technically feasible to release dispersed oil at this concentration for such a long period. Thus, a target concentration of 50 ppm released over 24 h was selected, producing an exposure of 1200 ppm-hours. The untreated oil was released into the study site at an application rate of 1 L/m². This would represent the amount of oil that would strand from a 100- to 1000-barrel spill (1 barrel = 42 gal = 158.9 L), depending on wind and current conditions. This concentration was based on levels known to have caused adverse effects on mangroves [1,2].

The experimental scenarios used in this project were developed on the basis of the collective experience of the American Petroleum Institute (API) Task Force members and the project scientists, and the oil and dispersed oil volumes selected were uniformly acknowledged as being very strong tests of the potential impacts of each.

Site Selection

The sites selected for the experiment were in the northwestern Laguna de Chiriqui, located on the Caribbean coast of Panama. The study sites were chosen on the basis of presence and condition of nearshore, microtidal tropical marine habitats typical of much of the Caribbean basin and other areas. The intertidal portion of each site consisted of well-developed red mangrove (*Rhizophora mangle*) forests. The subtidal portion consisted of turtle grass (*Thalassia testudinum*) beds and coral reefs composed primarily of *Porites porites* and *Agaricia tennuifolia*. In addition, consideration was given to the physical layout of each site with respect to proximity to other sites and human inhabitants, fetch, longshore currents, and relative location of each habitat. Each site was 30 by 30 m and was approximately one half covered by mangroves and one half covered by coral and seagrasses. Water depths averaged 0.48 m over the seagrasses and 0.63 m over the corals.

Two of the study sites were located on one island, approximately 0.5 km apart, and the third site was located on a separate island about 5 km to the east. This latter site was designated as the reference site (Site R). The other two sites were designated as the dispersed oil site (Site D) and the untreated oil site (Site O).

Site Preparation and Treatment

Prespill biological, chemical, and physical parameters were collected in March 1984 and again in late November and early December 1984. Methods used to characterize each site are described in later sections of this paper. Immediately following the November 1984 survey, preparations were begun for the treatment of each site according to a preestablished protocol described below.

Before release of oil or dispersed oil, study Sites D and O were enclosed within a 45-cmdeep containment boom drawn through a channel cut through the mangrove prop roots around the perimeter of the mangrove study area, extended across the edge of the seagrass and coral habitats, and joined in the middle at a point just outside the seawardmost part of the coral reef. This enclosed the area around the study site and helped restrict the movement of untreated oil and dispersed oil to allow a controlled exposure to the habitats and organisms present in the site.

Immediately outside the enclosed area, a small, shallow-draft barge was anchored perpendicular to shore. This barge served as a work platform, and it functioned as the oil delivery vessel during the spills.

A large workboat was positioned adjacent to the barge. This vessel served as the main work area and observation area during the spills. It provided an area from which to observe, monitor, and document the progress of site treatment. The water sampling and hydrocarbon monitoring system was located on the stern of this vessel.

Following placement of the booms, barge, and workboat, the oil delivery and monitoring systems were set up. The oil delivery system consisted of a battery-powered electric pump with six outlet valves. Each valve was connected to a length of 13-mm polyethylene tubing that was connected at the other end to a 1.0-m section of 19-mm polyvinyl chloride (PVC) pipe with a row of small holes drilled into it. This tube was fastened to a section of wooden board that was loosely anchored to the bottom with a short section of cord. Two of these oil-release devices were located in the coral area, two in the seagrass area, and two in the outer fringe of the mangrove area. The release rate was 10 L/min (0.167 L/s).

The oil monitoring system consisted of a Turner Designs field fluorometer, a batterypowered electric pump, a six-way gang valve, and six lengths of 13-mm polyethylene tubing. The ends of the tubing were located at six points in the study site and were anchored approximately 10 cm above the bottom. The oil monitoring points were located within approximately 3 to 5 m of the oil release points. This apparatus allowed water to be sampled from six different locations within the study site for analysis by the fluorometer or for analysis of discrete water samples. These were subsequently analyzed for volatile hydrocarbons (C_1 to C_{10}) and for intermediate-range carbon number hydrocarbons by gas chromatography (GC) or gas chromatography/mass spectrometry (GC/MS) in the laboratory.

The oil used in this study was Prudhoe Bay crude oil. The dispersant used was a commercial nonionic glycol ether-based dispersant concentrate. All of the oil used in the study was obtained directly from Petroterminale de Panama (PTP) and placed into clean, metal drums. Dispersant was added directly to each barrel in a 20:1 oil-to-dispersant ratio. In addition, hexadecane was added as a chemical label to aid in the identification and quantification of the dispersed oil. Octadecane was added as a chemical label to the untreated oil.

The undispersed oil was released over a 24-h period starting at 1430 h on 28 Nov. 1984 and ending at 1445 h on 29 Nov. 1984. A total of 4.5 barrels (715 L) of oil was released. The release of oil was governed by continuous measurements from a fluorometer monitoring system.

Four barrels of untreated oil were released from 1250 to 1700 h on 1 Dec. 1984. On 2 Dec. 1984, an additional two barrels were added between 1245 and 1500 h, making a total

of 953 L released into the 900- m^2 site. The whole, untreated oil was allowed to remain within the area enclosed by booms until 1630 h on 3 Dec. 1984, at which time the free, floating oil was removed with sorbents.

Analytical Methods

Chemical Sampling and Analyses

An intensive analytical survey was conducted at each site before treatment, during treatment, and following treatment to determine the chemical characteristics with reference to petroleum hydrocarbons. This analytical program was intended to establish baseline levels of naturally occurring (biogenic) and petroleum hydrocarbons; determine real-time concentration of petroleum hydrocarbons during site treatment; and conduct postspill analyses of water, sediments, and biota to determine exposure levels and uptake.

Water Sampling—Analyses of water were conducted by obtaining large- and small-volume water samples for GC and GC/MS analysis and continuous fluometric analysis during site treatment. Large-volume samples were collected by pumping approximately 75 L (15 L/h for 5 h) through glass columns packed with Amberlite XAD-2 resin. Large-volume samples were taken before and after site treatment. Small-volume water samples were obtained during site treatment using an outlet valve on the monitoring system described above and collected in 1-L separatory funnels and extracted twice with dichloromethane. Extracts were stored in clean glass ampoules and analyzed later for total extractable organic matter. Small-volume samples were also taken for analysis of low-molecular-weight (LMW) hydrocarbons (C_1 - C_{10}). Continuous fluometric analysis was conducted using the oil monitoring system.

Sediment sampling—Sediments were collected in the intertidal area at low tide using 10cm-diameter by 30-cm-long aluminum corers. Three replicates were taken at each sampling point and stored separately. Other samples were taken using a stainless steel knife to cut the peaty material to a depth of 0.5 cm. These are called "surface scrapes." One sample is made up by combining five scrapes from an area within a 1-m radius from a central sampling point. All samples were treated with saturated mercuric chloride solution.

Sampling of biota—Mangrove leaves and seagrass leaves were collected from each site in triplicate and then later pooled at the Bermuda Biological Station (BBS) laboratory to create fewer samples.

The coral tissue was sampled with an air-pik [3]. The tissue was dissociated from the carbonate matrix using a stream of air, blown into a clean beaker, and then transferred to a glass jar. Mercuric chloride was added to prevent sample degradation.

Analytical techniques—The dichloromethane extracts of the water samples extracted in the field were analyzed by scanning and fixed wavelength ultraviolet (UV) fluorometry on a Perkin-Elmer 650 10S scanning spectrofluorometer. Selected samples were analyzed further by capillary GC and capillary GC/MS after further purification and separation using a Hewlett-Packard 5840 gas chromatograph equipped with a capillary injector and flame ionization detector.

The XAD-2 resin was removed from the column and extracted twice with aqueous acetone (1:1) and then *n*-hexane. The extracts were run on a Florisil[®] column and then analyzed by GC and GC/MS.

Sediment samples were sieved to remove all debris over 1 mm. Three replicates from each site were pooled to give one sample from each habitat (mangrove, seagrass, and coral). The sediments were alkaline digested, and the nonsaponifiable lipids were partitioned into n-hexane, subjected to Florisil cleanup, and analyzed by GC and GC/MS. Plant and animal

samples were homogenized, subjected to alkaline digestion, and analyzed for hydrocarbons as described above for sediments.

Verification of compound identification in sample extracts was carried out using a Hewlett-Packard 5970 quadrupole mass selective detector with a capillary direct interface. This was coupled with a 5790 Hewlett-Packard capillary gas chromatograph and a Hewlett-Packard 59970A data system with the National Bureau of Standards (NBS) Reference Library. Unknown peaks that did not correspond with known samples were identified by interpretation of their mass spectra as well as by library data searches.

Biological Studies—Intertidal Systems

The intertidal area of the study sites were moderately developed mangrove forests typical of sheltered coastal areas throughout the Caribbean Sea. The mangrove communities were dominated by red mangroves (R. mangle). Molluscs, echinoderms, and crustaceans dominated the fauna of the mangrove forest. Prop roots of R. mangle were colonized by several species of oysters. Within the forest, the mangrove tree snail (Littorina angulifera) was the dominant macrofaunal species.

A variety of biological parameters were monitored during the course of this study. The objectives of these analyses were to evaluate possible changes in the macro- and microstructural characteristics of the mangrove forests and effects on mangrove fauna. The parameters used to describe the macrostructural characteristics of the mangrove communities were individual tree location, species composition, diameter at breast height (DBH), tree height, and canopy density.

Within the mangrove forest at each site, three transects were established running perpendicular to the water's edge, each incorporating three sample stations. The transects were used for measurements of canopy density, phenology, and other measurements. All trees within the study sites were identified as to species and numbered; their location, trunk diameter, and total height were determined and recorded. Forest canopy density measurements were determined with a spherical densiometer.

Three trees along the center study transect were chosen for determination of the functional and microstructural characteristics of individual trees. Each tree was evaluated for leaf production rates, leaf length and width, and growth of respiratory organs. Several aerial roots were tagged and measured in each site and monitored for growth rate (cm/day) and density of lenticels (gas exchange organs present on the roots).

Detailed transect surveys of the density and distribution of *L. angulifera* were conducted during each survey period. Observations were made at nine permanent stations established on the three transects previously described. At each station, the number of snails present in six vertical compartments from the sediment surface to the canopy was counted. All snails present within a 5-m radius of the station were counted.

At each site, five separate prop roots were permanently marked, and the number of each species of mangrove oyster present was counted. The survival of these groups of oysters was monitored throughout the study period.

Subtidal Systems—Coral Studies

The subtidal ecosystem of the study sites is composed of fringing seagrass beds and coral reefs that parallel the outer mangrove fringe. The most common seagrass species is *T. testudinum* (turtle grass). Living corals occur on the crest and landward reef portions, consisting predominantly of *P. porites, Millepora alicicornis,* and *Siderastrea* spp. with lesser abundance of *Agaricia* spp., *Porites astreoides,* and occasional *Oculina* spp.

The seagrass- and coral-associated fauna and flora are very diverse and abundant. The

most common organism is the colonial anthozoan, Zooanthus pulchellus. Sponges, anemones, sabellid worms, starfish, urchins, and sea cucumbers are also common.

In addition to the large faunal assemblage, many species of algae are present in these areas. *Halimeda, Dictyota, Caulerpa, Acanthophora, Penicillus, Udotea, and various bluegreen algae are found throughout the nearshore zone from the mangrove prop roots to the outer slope of the coral reef.*

Reef Coverage Assessment—To evaluate epifaunal and epifloral coverage of the coral reef substrates, the point plotless line transect method was chosen. The point plotless line method is described in detail in Dodge et al. [4]. At each site, four locations for semipermanent line transects were established. Each transect line was 10 m in length. Two transect lines were laid parallel to the reef crest and were established in water depths of approximately 1 m. Two other lines were laid parallel to the first in depths of approximately 1.3 m.

Data were collected from the transect lines by a diver swimming over the line and recording the identity of the substrate which lay beneath points established at 10-cm intervals. The substrate was identified as either bare substrate or as one of several categories of living organisms. Organisms were subcategorized into epifaunal and epifloral groups. Stony corals were identified to species. Other animals were classified to phylum or order. The anthozoan *Zooanthus pulchellus* was identified to species. Fleshy and calcareous algae were distinguished. In addition, seagrass was identified when present.

The data set obtained allowed derivation of percentage of coverage for the various animal and plant components as a measure of relative abundance. For each site, major parameters were averaged over transects for a mean representation. These parameters were total organisms, total corals, total animals, and total plants.

Coral Growth Assessment—The coral species Montastrea annularis, Agaricia tennuifolia, Porites porites, and Acropora cervicornis were chosen for growth assessment following treatment by oil or dispersed oil. Approximately five specimens of each species were fixed to cement blocks with underwater quick-setting cement. Cemented specimens were placed at 1- to 2-m depth in the central portion of each site.

At least seven days before treatment with oil or dispersed oil, specimens at each site were stained with alizarin red S dye [5] for approximately 5 h. Staining was accomplished by securing a clear plastic bag around cemented corals, injecting a mixture of alizarin red S dye and distilled water at sufficient concentration to bring the alizarin concentration to between 10 and 15 ppm, and closing the bag opening securely around the coral base.

At the start of the following survey, coral specimens were then collected, air-dried, labeled, and packaged for shipment to the laboratory at Nova University (Dania, Florida). The techniques used to measure growth parameters varied from species to species. New growth is measured by quantifying the amount of new calcareous skeleton deposited on top of the stained skeletal layer.

Subtidal Systems—Seagrass Studies

To determine the impact of crude oil and dispersed crude oil on subtidal grass beds (*Thalassia testudinum*) and the associated infauna and epifauna, a variety of parameters were monitored in situ. These are listed below:

Floral Assessments

- Growth rates
- Blade area
- Plant density

Faunal Assessments

- Macroepifauna
- Macroinfauna

Seagrass Growth and Density Assessment—For the purposes of *Thalassia* growth studies, three plots were established within each of the study sites. Plots were 0.5 by 0.5 m and were permanently marked with iron rods driven into the substrate at each of the four corners. Within each study plot, ten plants were selected at random and marked with nylon tie-wraps.

Subsequent to marking each plant, the length and width of all blades for each plant were recorded. Measurements were made in situ using clear, plastic millimetre rules. Approximately 72 h after the initial length measurements, the central blade of each numbered plant was remeasured. Actual growth rate data were calculated from the difference of these two values divided by the number of hours separating measurements and then multiplied by a factor of 24. This provided a per-day growth rate for each plant.

Plant density data were taken using a 0.5- by 0.5-m PVC quadrat subdivided into 25 cells (each cell = 100 cm^2) was placed at random within the grass bed. Counts of the number of plants per cell were made for 16 cells within each quadrat. A total of 4 quadrat replicates were conducted within each site during each sampling period. Plant densities are reported as the number of plants per square metre.

Descriptive statistics (means, standard deviations, ranges), analyses of variance (ANOVA) statistics, and Student-Newman-Keuls (SNK) multiple-range tests were used to provide a statistically valid assessment of the effects, if any, of crude oil and dispersed oil of subtidal grass beds.

Seagrass Faunal Assessments—A wide variety of organisms were present in the seagrass beds, including echinoderms, holothurians, polychaetes, poriferans, coelenterates, and calcareous and noncalcareous algae. Two species of sea urchin (Echinometra lacunter and, to a lesser degree, Lytechnius variegatus were by far the most abundant macroepifauna present at all study sites and, for this reason, were chosen for detailed evaluation before, during, and after site treatment.

Sea urchin abundance was assessed using two techniques: (1) linear transects and (2) random quadrats.

Three 30-m line transects were conducted within the seagrass community at each study site during each sampling period except March 1984. Transect lines consisted of 30-m fiberglass tapes. Data were recorded in 2-m increments over the length of the transect.

Areal densities of sea urchins also were assessed at each site during each sampling period. This was accomplished using the same 0.5- by 0.5-m quadrat locations used to determine plant densities.

Results

Baseline Chemical Characterization—Analysis of the samples collected during the first sampling trip (March 1984) indicated that the sites were free of petroleum hydrocarbons. Hydrocarbons present in water samples taken from the three sites ranged from 0.1 to 0.2 μ g/L. The GC pattern of hydrocarbons indicated a biogenic origin. Sediment and tissue samples also were free of oil hydrocarbons.

Chemical Monitoring During Site Treatments—Tables 1 and 2 summarize the water sampling data obtained during site treatment. The concentrations of oil were taken at arbitrary time intervals by switching sampling ports and reading the concentrations in terms of fluorescence intensity. These readings then were converted to ppm oil using a calibration graph. The concentrations achieved were time-averaged at 1-h intervals. The results in Table 1 show variability, and generally, the concentrations at Site D were lower over the coral area and higher over the seagrass area. The readings listed as 80 ppm are actually higher as the fluorometer quenched at this reading; thus, these readings are 80 ppm plus. Figure 1 shows the measured concentration of dispersed oil at two sampling locations over

Hours After Dosing	Area 1 (Coral)	Area 2 (Coral)	Area 3 (Seagrass)	Area 4 (Seagrass)	Area 5 (Mangrove)	Area 6 (Mangrove)
0		3.0		4	•••	
1	5.3	2.0	4.3	5.5	4.2	4.5
2	5.0	4.5	6.0	8.5	8.0	10.5
3	27.5	21.0	39.0	26.3	48.0	24.0
4	27.0	35.3	63.3	48.5	58.3	36.0
5	33.7	26.0	40.7	56.7	67.3	49.3
6	13.0	27.7	49.3	62.0	34.7	54.0
7	7.0	19.7	73.3	63.3	28.0	44.7
8	4.0	13.0	70.0	60.0	54.0	32.5
9	7.1	19.0	29.8	39.3		
10	4.3	21.0	76.7	80.0+	20.0	55.0
11	11.3	33.0	40.5	80.0+		
12	9.7	35.3	80.0+	80.0+		
13	6.5	31.0	80.0+	70.0		• • •
14	7.1	16.8	80.0+	80.0+	• • •	
15	12.6	10.6	80.0+	80.0+	20.5	42.0
16	20.0	10.0	80.0+	80.0+	49.3	43.3
17	10.8	11.2	80.0 +	80.0 +	23.5	34.0
18	18.2	5.0	65.0	80.0+	67.0	35.7
19	22.0	24.8	70.0	80.0+	27.5	50.0
20	6.3	21.3	80.0+	80.0+	15.0	53.3
21	5.0	19.3	80.0+	70.0	23.3	65.0
22	7.5	18.5	48.0	49.0	40.0	47.3
23	6.8	28.5	65.0	44.0	52.7	70.0
24	12.3	19.0	39.5	33.5	52.5	64.0
48	3.0	4.6	7.7	8.0	5.3	8.4
For 0 to 2	4 h:					
Mean	12.1	19.1	59.0	57.6	36.5	42.9
(SD)	(8.3)	(9.7)	(23.0)	(25.0)	(18.9)	(16.7)

 TABLE 1—Fluorometry readings as oil equivalents (in ppm) during dosing period at the dispersed oil site (Site D). Concentrations of dispersed oil were somewhat variable over the site, with highest concentrations present over the seagrass areas.

the seagrass bed. Table 3 presents the exposure concentrations in ppm-hours for each sampling location. Table 3 shows that the dispersed oil target exposure of 1200 ppm-h (50 ppm \times 24 h) was exceeded at the mangrove and seagrass sampling locations, and the overall average exposure for the entire site was about 1470 ppm-h, or about 20% higher than the planned exposure. Table 2 shows the hourly averaged concentrations under the oil slick at Site O. Concentrations are less than 3 ppm and are fairly uniform. Total exposure to subtidal habitats ranged from 65 to 165 ppm-h.

Samples taken during the dosing period at Site D and analyzed by GC and GC/MS indicate that the measurements reached concentrations as high as 222 ppm. Qualitative analysis showed a full range of oil hydrocarbons present in the extracts. Discrete water samples taken during the oiling of Site O indicate much lower levels of exposure to hydrocarbons, ranging from 0.01 to 0.09 ppm during the dosing period. The qualitative analysis indicated no cross-contamination between sites.

Water samples taken during the dispersed and untreated crude oil releases were analyzed for LMW hydrocarbons. LMW hydrocarbon concentrations were high at Site D, ranging between 293 and 684 parts per billion (ppb). At Site O, LMW hydrocarbon concentrations

Hours After Dosing	Area 1 (Coral)	Area 2 (Coral)	Area 3 (Seagrass)	Area 4 (Seagrass)	Area 5 (Mangrove)	Area 6 (Mangrove)
0	1.6					
1	1.9	3.0	2.2	1.8	2.5	2.5
2	1.8	2.9	2.7	2.0	3.0	3.5
3	1.5	4.0	3.1	2.7	3.6	3.3
4	1.5	4.0	3.1	2.7	3.6	3.3
5		2.0	2.2	2.5	3.5	3.4
23	1.3	1.4	1.9		2.3	2.5
24	1.3	1.8				
26	1.0	2.1	1.8	1.3	2.0	2.6
27	1.2	2.1	1.9	1.8	2.3	3.1
28					2.3	3.4
48	1.1	2.1	1.9	1.3	2.1	2.8
49	•••	1.9	1.7	1.2	2.0	2.8
Mean	1.4	2.5	2.3	1.9	2.6	3.0
(SD)	(0.3)	(0.9)	(0.5)	(0.6)	(0.6)	(0.4)

 TABLE 2—Fluorometry readings as oil equivalents (in ppm) during dosing period at the oil site (Site O). Oil concentrations were much lower and more uniform at this site.

ranged from 33 to 46 ppb. The aromatic hydrocarbons benzene, toluene, the xylenes, and the trimethyl benzenes had the highest concentrations at Site D. The cycloalkanes were next which fits well with expected solubility data. As with the higher-molecular-weight hydrocarbons, it is obvious that the chemical dispersant significantly increased the concentration of oil hydrocarbons for the whole molecular-weight range to which the organisms were exposed.



FIG. 1—Total oil in water over seagrasses at Site D during site treatment (0 to 24 h) and 24 h after termination of treatment.

	Dispersed Oil Site	Untreated Oil Site	
Mangrove sample Location 1	1515	150	
Mangrove sample Location 2	1915	166	
Seagrass sample Location 1	1930	103	
Seagrass sample Location 2	2235	165	
Coral sample Location 1	475	65	
Coral sample Location 2	755	106	

 TABLE 3—Total hydrocarbon exposures in the water column expressed as ppm-hours (area under the curves for the dispersed and untreated oil releases).

Three days after site treatment, 8.9- and 10.2-ppb total hydrocarbons (collected by largevolume sampler) were measured in the water at Sites D and O, respectively, and these concentrations slowly decreased through the end of the study. Concentrations of hydrocarbons in the water column were very low and comparable at both sites through the 20month postspill survey.

Sediment Analysis—After discharge, oil was found in the mangrove sediments at both treatment sites. Not all of the chemically treated oil was completely dispersed in the water. There was always some surface slick which moved into the mangrove forest. The oil coverage was not uniform and was reflected in the very high variability between samples that were analyzed for hydrocarbon content. In general, more oil was found in the sediments at Site O than at Site D (Table 4).

Hydrocarbons in the seagrass sediments were very much lower than in the mangroves. At three postspill sample times (December 1984, March 1985, and December 1985), the concentrations ranged from 20 to 45 ppm at Site D and from 1 to 6 ppm at Site O.

Oyster Tissue Analysis—Samples of Crassostrea rhizophorae taken to determine uptake and depuration of hydrocarbons show a rapid tissue uptake of 506 and 679 ppm for oyster

	v		
	Site D	Site O	Site R
Prespill (November 1984)			
Mangrove sediments	0.6 ± 0.3	0.9 ± 0.6	0.6 ± 0.6
Seagrass sediments	0.3 ± 0.1	0.4 ± 0.3	0.3 ± 0.0
Coral sediments		• • •	0.9 ± 0.7
3 Days postspill (December 1984)			
Mangrove sediments	16 ± 27	93 ± 47	0.5 ± 0.2
Seagrass sediments	45 ± 33	1.2 ± 0.7	0.5 ± 0.2
4 Months postspill (March 1985)			
Mangrove sediments	89 ± 77	140 ± 136	0.8 ± 0.4
Seagrass sediments	21 ± 10	6 ± 4	0.4 ± 0.1
7 Months postspill (June 1985)			
Mangrove sediments	179 ± 263	229 ± 281	
12 Months postspill (December 1985)			
Mangrove sediments	125 ± 66	552 + 713	
Seagrass sediments	27 ± 4	2 + 1	
Coral sediments	7 ± 2	0.4	
20 Months nostenill (August 1986)			
20 Wollins posispin (August 1960) Manarova sediments	185 + 88	254 + 307	
	105 ± 00	237 1 307	• • •

TABLE 4—Petroleum hydrocarbon results for sediment samples (ppm wet weight).

tissues in Sites D and O, respectively. At the four-month postspill period, there is a reduction to 161 and 134 ppm, respectively. However, after twelve months, most of the oil hydrocarbons were no longer present in the tissue of oysters from both sites.

Effects on Adult Mangroves—Figure 2 presents the canopy coverage data. Canopy coverage proved to be a much more sensitive measure of defoliation than Leaf Area Index (LAI) measurements, and only this parameter will be discussed here.

Inspection of the data plotted in Fig. 2 shows that the canopy coverage at Site D did not change appreciably during the entire study period. These measurements supported on-site observations of the forest canopy, which remained dense, with no observable changes between prespill and postspill conditions.

The canopy coverage measurements at Site O increased dramatically following site treatment, but the distribution of affected trees within the site was not uniform. This is reflected in the increase in mean open canopy and the increase in standard deviation of the means. Inspection of Site O showed that most of the defoliation occurred in the eastern half of the site behind the outer fringe trees, where much of the oil accumulated during site treatment. All of the trees in this area were completely defoliated. Individual trees scattered throughout the remainder of the site also were defoliated, but there were a substantial number of trees (especially in the outer fringe and the extreme western edge of the site) that were only slightly defoliated and still contributed to the overall canopy coverage.

Estimates of the percentage of defoliation of each tree were made at Site O during each postspill survey. Most of the observed defoliation occurred during the 4-month period after oiling, during which time 18 trees were completely defoliated. The average defoliation for the entire site was 43.1% after 4 months. The number of dead trees increased slightly during the following year and a half, to 25, and the average defoliation increased to 47.5% by the end of the study at 20 months postspill.

The relationship between the analytical chemistry data on sediment hydrocarbon concentrations (presented in Table 4) and the effects seen on adult mangroves at Sites D and O was somewhat unusual. While Site O levels were consistently higher than at Site D, the difference in measured hydrocarbon concentrations is less than the measured differences in biological effects, especially in mortality and defoliation of adult mangroves. This would suggest that the dispersant may in some way reduce the toxicity of crude oil to mangroves.

Effects on Juvenile Mangroves—Following site treatments in December 1984, 3 groups of 25 propagules each were planted at each site. In the following surveys, it was not possible to locate all planted groups, which prevented detailed analyses of toxic effects from site treatment, but inspection of those propagules present 4 months after treatment indicated that the whole oil had a more severe effect than did the dispersed oil.

Naturally colonizing propagules were counted during each site visit to determine the survival rates of those propagules that successfully sprouted within each site. Mangrove propagules typically have very high sprouting rates in intertidal habitats, but their long-term survival is dependent on their ability to compete with larger trees for light. In mature mangrove forests, propagules usually survive only in areas where adults have been removed by fire, cutting, or some other cause.

The total number of seedlings increased at each site during the period from November 1984 to August 1986, with most of the increase occurring after June 1985. The reason for this increase is unknown but may be a result of seasonal or yearly variations in propagule production in the study area. A very large increase in live seedlings at Site O was seen in December 1985 and August 1986 (12 and 20 months postspill, respectively). This increase represented an almost tenfold increase in the number of live seedlings at Site O. Most of the seedlings were growing in the area of greatest impact to adult trees. The defoliated adults opened up a large area within Site O that became suitable for colonization by man-



FIG. 2—Percent open canopy coverage of mangrove forests at Site D, Site O, and Site R. Arrow indicates site treatment date.

grove propagules. Significant reduction in canopy cover had occurred as early as March 1985 (4 months postspill), but contamination of the sediments by whole oil possibly prevented successful colonization until after June 1985 (7 months postspill).

As mentioned above, increases in seedlings were measured at Sites D and R, but the magnitude of increase was much less than at Site O, and the ratio of live to dead seedlings (L/D) also was much lower. A ratio at or near 1.0 indicated that mortality of seedlings was about equal to successful sprouting of new propagules. Site D appeared to be near this equilibrium (L/D = 1.31), with little or no net increase in new mangroves; Site R appeared to be increasing slightly (L/D = 1.91); Site O was increasing very rapidly in terms of new mangroves filling in areas opened by the death of adults (L/D = 14.1). All L/D data are for the final survey period.

Effects on Mangrove Fauna—Tree snail (L. angulifera) surveys indicated that the site treatments had a significant effect on both the density of tree snails and their vertical distribution within each site. A two-way ANOVA was used to detect differences in total abundance and distribution. Treatment of Site D with oil and dispersant was followed by a 48% reduction (significantly less than prespill levels, P less than 0.05) in the snail population four days later. When this site was resurveyed four months later, the snail population within the site had increased but was still 23% below the prespill level. For the duration of the study, the number of Littorina within Site D remained approximately equal to or greater than during the prespill period. A significant change (P less than 0.05) in the distribution of Littorina over time at Site D was measured only during the December 1985 survey (one year postspill). This change was manifested by an increase in snail density at the middle level of the forest.

At Site O, treatment with oil was followed by a significant reduction in the tree snail population (p less than 0.05). Snail density dropped 51% during the four days after site treatment. Unlike Site D, however, snail density remained highly reduced after four months when snail density had increased by only 19%. By June and December 1985, tree snail abundance had increased substantially and was only slightly below prespill levels.

The vertical distribution of tree snails changed at Site O following site treatment. The relative abundance of tree snails was significantly increased (p less than 0.05) in the upper levels of the mangrove forest and reduced in the lower levels. This upward shift in the remaining population persisted through the 20-month postspill visit.

Survival of the mangrove oysters was very high at all sites and at all sampling times. Very high short-term survival rates were observed at Sites O and D four days after site treatment. Survival of *Crassostrea rhizophorae* at Site D was 96.9%, and 100% for *Isognomon alatus* and *Pinctada imbricata* for the period from the beginning of site treatment to four days later. Survival of oysters at Site O for the same period also was very high. *C. rhizophorae* was the only species to have any reduction in survival (87.5% survival). All oysters at Site R had 100% survival for this period.

When these oysters were examined during the 4-month postspill revisit, overall survival still was quite high. At Site D, survival of C. rhizophorae was 60.9%; I. alatus, 95.8%; and P. imbricata, 50.0%. The survival rates of P. imbricata are based on a change from 2 individuals to 1 individual present on the marked roots. At Site O, the numbers of I. alatus had increased 26.4% (from 53 to 67 individuals). C. rhizophorae had 81.2% survival and P. imbricata had 100.0% survival. At Site R, C. rhizophorae had 100.0% survival, I. alatus had 88.5% survival, and P. imbricata had 66.6% survival after 4 months. These data suggest that the mangrove oyster species are quite resistant to the short- and long-term toxic effects of exposure to fresh oil and dispersed oil.

The high survival rates of oysters at Sites D and O occurred in spite of the high levels of petroleum hydrocarbons present in the oyster tissues. This would indicate a relatively high resistance to the toxic effects of whole and dispersed oil. The addition of dispersant appeared to make no difference in the uptake of oil.

Reef Coverage Assessments—Tables 5 through 7 summarize the results for all survey periods obtained from each of the four plotless line transects at Sites D, O, and R, giving the means and standard deviations of each assessment category for each site.

Two-way ANOVA was used on data from each site for each of the four parameters (total coral, total animal, total plant, and total organism coverage). A fixed-model ANOVA was used. This statistical analysis evaluates differences between the six assessment periods and accounts for the variance component of transects within each site and replication of each transect.

If the ANOVA test indicated a significant period difference was present, further testing was conducted using the SNK test to isolate specifically those periods which were significantly different from each other.

Site D: dispersed oil treatment—The mean values (± 1 standard deviation) of each of the major assessment categories (total coral, total organism, total plant, and total animal coverage) for each assessment period are graphed in Figs. 3 and 4.

Nearly all major assessment categories declined abruptly in the first posttreatment assessment period and continued to decline through December 1985 (twelve months postspill).

Total coral coverage declined over the entire postspill study period. Two-way ANOVA for total coral coverage indicated a significant difference between assessment periods (p less than 0.05). SNK testing revealed that the November 1984 pretreatment period was significantly greater than the December 1985 and August 1986 periods (12 and 20 months postspill, respectively). This decrease in total coral coverage was the result of a 67% decrease in *P. porites* coverage and the complete elimination of *A. tennuifolia* from the transect locations.

For total animals, ANOVA indicated significant period differences at the *P*-less-than-0.01 level. SNK testing revealed that the prespill period was significantly greater than all other periods. Total animal coverage was affected primarily by the loss of sponges during the immediate postspill period. Sponge coverage declined by 40% during this time. On-site observations indicated that sponges were severely affected by dispersed oil; sponges in the treatment area were covered by a white, fungus-like layer and were very friable. As mentioned above, *P. porites* coverage also declined, contributing to the overall decrease in total animal coverage.

For total plants, ANOVA did not reveal any significant period effects. For total organisms, ANOVA revealed significant period differences. SNK indicated the prespill period was significantly greater than all postspill periods. Total organism coverage declined by almost 50% between November 1984 and August 1986 (3 days prespill and 20 months postspill, respectively), accompanied by a 40% increase in bare substrate.

Site O: oil only treatment—The mean values (± 1 standard deviation) of each of the major assessment categories (total coral, total organism, total plant, and total animal coverage) for each assessment period are graphed in Figs. 5 and 6.

In general, while there appears to be a slight decline for some parameters following site treatment, the overall impression is one of fairly stable conditions over time. Total plant coverage appears to decline; however, this organism category was scarce and, consequently, is represented by relatively few data points.

No significant differences in total coral coverage between sampling periods were detected using ANOVA. Inspection of the data in Table 7 indicates that coral coverage appears to decline gradually over the entire study period, but none of the between-period means are significantly different. Therefore, within the range of measured variability at Site O, it is not possible to detect (using ANOVA) any overall effect on corals.

	March (8 Moi Presm	1984 nths vill	Noven 198. (3 Da Presp	nber 4 ays	Decembe (5 D: Poster	er 1984 ays	March (4 Mo	1985 inths	June (7 Mo	1985 anths	Decembe (12 Mc	ar 1985 onths	August (20 Mo	1986 nths
Assessment Period	Mean %	SD	Mean %	SD	Mean %	S	Mean %	SD SD	Mean %	SD SD	Mean %	SD SD	Mean %	SD SD
ASSESSMENT CATEGORY Porites porites A garicia tennuifolia	32.50 1.00	11.73	26.13 1.13	13.91	20.25 1.38	14.51	19.38	11.96	16.13	12.57	9.50	10.78	8.63	9.40
Millepora alcicornis Total corals	33.50	11.73	27.25	13.79	21.63	14.15	19.38	11.96	0.13 16.26	12.57	9.50	10.78	8.63	9 40
Zooanthids	7.25	2.63	14.63	5.15	13.25	2.92	6.50	2.78	6.75	3.24	6.50	3.38	12.25	5.73
Sponges	9.50	7.05	12.38	6.84	7.38	5.04	6.13	3.52	6.63	3.89	6.38	3.78	6.25	1.67
Anemonies Total other			0.50	0.76	0.13	0.35			0.25	0.46	0.50	0.53	0.38	0.74
animals	16.75	7.54	27.50	9.24	20.76	5.97	12.63	2.20	13.63	5.73	13.38	2.62	18.88	4.76
TOTAL ALL ANIMALS	50.25	8.30	54.75	7.55	42.39	9.68	32.00	10.43	29.88	8.51	22.88	8.27	27.51	10.45
Calcareous algae	3.75	2.22	2.00	2.93	1.88	2.10	1.13	1.55					0.38	
Fleshy algae					0.63	1.06			0.25	0.46	0.25	0.46	0.50	0.83
Total algae	3.75	2.22	2.00	2.93	2.51	3.02	1.13	1.55	0.25	0.46	0.25	0.46	0.88	0.83
DCABLASS TOTAL DLANTS	375	ccc	2 M	2 03	7 51	3 07	1 13	1 55	20.05	0.46	0.75	0.46	0.00	000
TOTAL ORGANISMS	54.00	6.48	56.75	7.38	44.90	9.70	33.13	10.63	30.13	8.34	23.13	8.17	28.39	10.57
Rubble/bare substrate	46.00	6.48	43.25	7.38	55.10	9.70	66.87	10.63	69.87	8.34	76.87	8.17	71.61	10.57
Grand total	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

TABLE 6—Percent	age of cove	rage of t	he reef sub	strate by	the listed	organism	categorie	s at the o	il site (Sit	e O) at ea	ich of the c	newssess	t categori	·S.
	March (8 Moi Presp	1984 nths dil)	Noven 198 (3 Da Presp	nber 4 iys iill)	Decembe (5 D	er 1984 ays pill)	March (4 Mo Posts	1985 nths pill)	June (7 Mo Posts	1985 inths pill)	Decembe (12 Mc Posts	er 1985 onths pill)	August (20 Mo Postsj	1986 nths nill)
Assessment Period	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD
ASSESSMENT CATEGORY Porites porites	28.25	17.73	25.00	11.44	21.75	7.81	21.38	11.11	24.88	7.32	19.50	8.67	15.63	10.72
Agaricia tennuifolia Millepora alcicornis	0.75 1.50	0.50 3.00	1.25	1.19 1.39	1.38 0.88	1.30 1.25	1.13 0.88	1.55 1.64	0.13 0.63	1.19	0.79 1.13	0.71 1.64	1.38 1.63	1.06
Total corals	30.50	18.72	27.63	13.21	24.01	9.35	23.39	12.08	25.64	7.80	21.38	9.04	18.64	11.87
Zooanthids	11.00	3.37	19.38	5.01	20.25	8.56	15.38	5.10	21.38	7.07	25.38	12.30	31.63	8.25
Sponges	8.75	5.56	8.63	1.77	7.38	1.51	9.38	3.46	10.00	2.56	7.63	2.69	10.25	4.13
Anemonies Total other					0.13	0.35								
animals	19.75	7.23	28.01	5.66	27.76	9.24	24.76	7.46	31.38	6.50	33.01	9.75	41.88	4.88
TOTAL ALL ANIMALS	50.25	19.09	55.64	13.27	51.77	10.57	48.15	11.83	57.02	11.10	54.39	16.89	60.52	15.35
Calcareous algae	5.50	0.58	12.00	4.60	9.88	3.64	5.00	2.93	2.88	2.23	3.25	2.31	1.50	1.41
Fleshy algae	1.50	16.1	1.50	1.93	2.75	2.31	0.50	0.76	0.88	1.64	0.38	0.74	1.50	1.31
Total algae	7.00	I.4I	13.50	4.50	12.63	2.50	5.50	3.30	3.76	2.43	3.63	2.00	3.00	2.56
Seagrass	7 00	141	13 50	4 50	17 63	2 5U	5 50	3 30	376	243	242	00 6	3 00	7 56
TOTAL ORGANISMS	57.25	18.57	69.14	10.99	64.40	10.21	53.65	10.62	60.78	12.22	58.02	17.27	63.52	17.57
Rubble/bare substrate	42.75	18.57	30.86	10.99	35.60	10.21	46.35	10.62	39.22	12.22	41.98	17.27	36.48	17.57
Grand total	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

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TABLE 7—Percei	ntage of cc	overage .	of the reef s	ubstrate i	by the list	ed organ	isms at the	ereference	e site (Site	R) at eac	h of the as	sessment	categories	
	March (8 Moi Presp	1984 nths vill)	Nover 198 (3 Dz Presp	nber 14 ays vill)	Decen 198 (5 Di Posts	nber 14 ays pill)	March (4 Mo Postsj	1985 nths pill)	June 1 (7 Moi Postsp	985 aths aill)	Decembe (12 Mo Posts	er 1985 onths oill)	August (20 Mo Postsp	1986 nths dill)
Assessment Period	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD	Mean %	SD
assessment category Porites porites Agaricia tennuifolia	21.25	2.50	15.25	4.74	15.75	5.44	8.38	4.81	13.88 0.25	5.03 0.46	8.63	6.55	7.25	6.54
Mutepora auctoruts Total corals Zooanthids Sponges Anemonies	21.25 23.00 5.00	2.50 7.79 2.94	15.25 34.75 3.63	4.74 6.76 2.00	15.75 32.88 5.00	5.44 6.64 2.51	8.38 27.38 6.75	4.81 3.38 4.40	14.13 27.75 5.00	5.44 3.92 2.07	8.63 28.25 6.88	6.55 4.06 2.80	7.25 22.63 7.13 0.38	6.54 7.56 1.25 0.74
Total other animals	28.00 40.75	6.32 7 89	38.38 53 63	5.37	37.88 53.63	4.70 3.54	34.13 47 51	4.45 7 58	32.75 46 88	5.44 10.22	35.13 43.76	5.46 10.42	30.14 37 39	7.32
Calcareous algae	4.00	0.82	4.75	4.13 8.45	4.13	3.14 8 06	2.88	1.73	0.88 0.88 23.88	0.83	4.25	2.87 2.87	1.50	0.93
Total algae	5.25	1.89	15.50	10.66 6.29	14.50	7.98	23.88	16.75	24.76 14 88	18.30	25.50 16.50	16.12	22.50	10.18
TOTAL ORGANISMS	19.25 68.50	4.11	29.63 83.26	7.50 5.99	27.38 81.01	4.75	37.63 80.14	16.12	39.64 86.52	16.22 7.84	42.00 85.76	11.89	39.75 77.14	8.56 6.53
Kubble/bare substrate Grand total	UC.16 100.001	0.00	10.00	66.c	18.99 100.00	c/.4 0.00	19.80	0.00	100.00	/.84 0.00	14.24 100.00	4.86 0.00	22.86 100.00	0.00

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FIG. 3—The percentage of reef substrate coverage of total organisms (top) and total animals (bottom) at Site D. Error bars are ± 1 standard deviation.

Significant ANOVA differences in total animal coverage were detected at Site O, but these differences involved increases in animal coverage during the March 1985 to August 1986 period (4 to 20 months postspill). No significant reduction was detected in animal coverage during the postspill period.

For total plants, ANOVA revealed significant period effects. SNK testing revealed the prespill period was significantly greater than all the postspill periods from March 1985 to August 1986 (4 to 20 months postspill).

For total organism coverage, ANOVA revealed significant period effects. SNK testing revealed that only the March 1985 period was significantly less than the prespill period. This appears to be the result of small, nonsignificant decreases in corals, zooanthids, and algae combining to cause an overall reduction in total organism coverage at that time. Four months later, however, total organism coverage had increased to prespill levels.

Reference Site R—The mean values (± 1 standard deviation) of each of the major assessment categories (total coral, total organism, total plant, and total all animal coverage) for each assessment period are graphed in Figs. 7 and 8.

In general, parameters for Site R show relatively uniform values over assessment period times. Variability is high, and there are some apparent period differences.


FIG. 4—The percentage of reef substrate coverage of corals and total plants at Site D. Error bars are ± 1 standard deviation. Arrow indicates date of site treatment.

For total coral coverage, ANOVA indicated significant period differences. SNK testing, however, did not resolve any particular period as significantly different from another. For total animal coverage, ANOVA indicated significant period differences. SNK indicated that the November 1984 pretreatment period was significantly greater than August 1986 period.

For total plants, ANOVA indicated significant period differences. SNK testing revealed the December 1984 period to be significantly lower than the June 1985 to August 1986 period. For total organisms, ANOVA indicated no significant differences between periods.

Additional statistical analyses—A linear regression analysis method [6] was used to determine if a regression line fitted to transect parametric data for each site would have a slope significantly different from zero. The analysis also incorporated an ANOVA to test further inequality of parametric means.

For Site D, only total coral coverage exhibits both statistically significant ANOVA and linear regression (negative slope). Clearly, there is a strong relationship of decreasing coral coverage over the entire study period. Total organism and total animal coverage exhibit significant group differences but not a significant regression.

The overall conclusion drawn from these analyses is that coral coverage was reduced



FIG. 5—The percentage of reef substrate coverage of total organisms (top) and total animals (bottom) at Site O. Error bars are ± 1 standard deviation. Arrow indicates date of site treatment.

and no recovery occurred, and total organism and total animal coverage decreased, but there were indications that recovery of these parameters had begun during the final assessment period 20 months after site treatment.

For Site O, only coral coverage exhibited a significant regression (the accompanying ANOVA did not exhibit significance). There was a slight, but statistically significant, decrease in coral coverage over time. Coral coverage was the only parameter that showed a consistent downward trend over the entire study period, resulting in a regression line that was significantly different from zero.

For Site R, the only parameter that exhibited a significant regression is total animal coverage, which showed decreasing coverage over time. This must be tempered with on-site observations which indicated an increase in fleshy algae over time. Although only significant at the 90% level, the table results for plants tend to confirm this with an increase in the regression line over time. No significant regression was found for coral coverage, indicating that there was no measurable decrease in coral coverage through the duration of the study at Site R.

In summary, regression analysis confirms and provides additional information to the



FIG. 6—The percentage of reef substrate coverage of corals (top) and total plants (bottom) at Site O. Error bars are ± 1 standard deviation.

ANOVA and SNK analyses. Although the data are variable, there is a significant decline in coral coverage over time at both Sites D and O. Note that if data from the last assessment period (August 1986) are omitted from the analyses of Site D, the regression would have been more apparent (and significant) for the parameters of total organisms and total animals.

Coral Growth—The growth rates of four coral species at each of the experimental sites and the reference sites have been evaluated for the first growth assessment period (November 1984 to March 1985). Growth rates of two coral species (*A. tennuifolia* and *P. porites*) were evaluated at two and three additional assessment periods for most sites.

Two coral species, *Montastrea annularis* and *Acropora cervicornis*, showed no effects from the treatment dosing. Growth rates (linear extension rate and tip widths) were similar between sites.

The coral species *Agaricia tennuifolia* showed significantly reduced blade extension rate (length), blade thickness (width), and blade area (mass index) growth at the dispersed oil site with respect to the oil site and the two reference sites at each growth assessment period.

Statistical results for the coral species *Porites porites* are not as clearcut as for the above



FIG. 7—The percentage of reef substrate coverage of total organisms (top) and total animals (bottom) at Site R. Error bars are ± 1 standard deviation.

A. tennuifolia, primarily as a result of the high degree of variability within and between sites. The data suggest a possible small growth effect to this species at Site D from dispersed oil treatment for as much as eight months following dosing.

Seagrass Growth—Table 8 summarizes the results of seagrass growth rate measurements for all survey periods at Sites D, O, and R. At Site O, a statistically significant difference (*p* less than 0.05) was noted between the two pretreatment periods, the March 1984 levels being much lower. The same situation was evident at Site D. Results for Site R were ambiguous, but one analysis showed significant differences between March and November 1984 levels. The exceptionally low growth rates at all three sites in March 1984 was perplexing. A careful review of data gathering, recording, and analysis did not pinpoint any source of error. As a result, the depressed March 1984 growth rates remain enigmatic. It seems advisable, then, that greater reliance should be placed on the November 1984 levels. These rates are closer to those recorded during and well after oiling and probably represent more typical growth.

Growth rates also were recorded during site treatment, during the first four days following treatment, and at four to six days following treatment. At Site D, absolute growth rates showed a slight increase during the spill, but these levels were not statistically significant.



FIG. 8—The percentage of reef substrate coverage of corals (top) and total plants (bottom) at Site R. Error bars are ± 1 standard deviation.

Site D growth rates at zero to four days and four to six days postspill also were slightly elevated but did not prove statistically significant.

Comparison of growth rate means at Site D between the November 1984 pretreatment levels and the next three sampling periods (March, June, and December 1985) revealed no increase in March and slight increases in June and December. None of these, however, were found statistically significant through ANOVA and SNK tests. Growth rates at Site D in August 1986 were significantly greater than any of the levels noted before or after treatment.

At Site O, growth rates during treatment decreased slightly from pretreatment levels (0.49 to 0.41 cm/day). During the first four days postspill, Site O growth was higher than pretreatment values. By the four- to six-day sampling, growth had returned to the prespill levels of November. ANOVA testing of these data showed no significant differences in growth rates from prespill values.

Statistical comparison of growth rates at Site O among the November pretreatment level and all subsequent periods demonstrated no statistically significant changes in growth. Therefore, it would appear that undispersed crude oil has no measurable effect on *Thalassia* growth within the time period and under the conditions of this study.

Sampling Period	Site D	Site O	Site R
Pretreatment			
March 1984	0.16	0.19	0.25
(8 months prespill)	(0.20)	(0.21)	(0.13)
	N = 30	N = 28	$\dot{N} = 5$
November 1984	0.39	0.49	0.46
(1 week prespill)	(0.20)	(0.30)	(0.13)
	N = 29	N = 26	N = 27
During treatment			
December 1984	0.38	0.36	NM^a
(During spill)	(0.13)	(0.10)	
	$\dot{N} = 27$	$\hat{N} = 27$	
Posttreatment			
December 1984	0.46	0.48	NM
(4 days postspill)	(0.34)	(0.23)	
• • • •	N = 25	N = 29	
March 1985	0.39	0.46	0.55
(4 months postspill)	(0.19)	(0.17)	(0.29)
	N = 30	N = 29	N = 10
June 1985	0.53	0.39	0.51
(7 months postspill)	(0.29)	(0.20)	(0.23)
	N = 30	N = 30	N = 30
December 1985	0.50	0.46	0.53
(12 months postspill)	(0.22)	(0.22)	(0.26)
	N = 30	N = 30	N = 30
August 1986	0.69	0.43	0.81
(20 months postspill)	(0.42)	(0.22)	(0.42)
	N = 30	N = 30	N = 30

 TABLE 8—Means, standard deviations (in parentheses), and sample sizes for seagrass growth rates (in cm/day) by site and sampling period.

^{*a*} NM = no measurements.

Seagrass Density—Table 9 summarizes the results of density measurements for each site. ANOVA comparison of plant densities between the two prespill periods showed significant differences at all three sites. Like the situation seen with the growth data, plant densities showed a greater difference between the two prespill surveys than between any other two periods.

Postspill plant densities at Site D were initially reduced but recovered and were found at significantly higher levels in all other postspill periods. At Site O, postspill densities declined gradually but significantly. Levels were not reduced, however, to the low densities found in the first prespill survey.

Faunal Assessments

Site D—Of the two urchin species present, Echinometra lacunter was by far the most abundant at all sites. At Site D, total prespill urchin density was relatively high. Mean density was 14.2 urchins/m² for *E. lacunter*. Both species were evident throughout the site and in all nearby areas. During treatment, these organisms experienced a drastic decline in abundance such that a few days after the release of dispersed oil, no live urchins of either species were present anywhere in the seagrass beds at Site D. Both areal $(\#/m^2)$ and linear (#/m) densities were 0.0 at this time. Numerous dead urchins were evident throughout the site.

Four months after site treatment (March 1985), no live urchins were recorded in any of

Sampling Period	Site D	Site O	Site R
Pretreatment			
March 1984			
(8 months prespill)	422.7	356.0	379.2
November 1984			
(1 week prespill)	816.7	841.7	666.7
Posttreatment			
March 1985			
(4 months postspill)	673.3	682.2	NM^a
June 1985			
(7 months postspill)	922.0	603.0	488.0
December 1985			
(12 months			
postspill)	911.0	598.0	692.0
August 1986			
(20 months			
postspill)	862.5	579.7	720.3

 TABLE 9—Mean seagrass densities (in number/m²) by site and sampling period.

 a NM = no measurements.

the linear transects. Inspection of the site revealed no urchins anywhere (a few urchins were found in the deeper water outside of and adjacent to the site).

By the seven-month postspill survey (June 1985), sea urchins had begun to recolonize Site D. The linear and areal densities of both urchin species were well below the prespill levels of November 1984. Although no size measurements were taken, observations of the urchins present indicated that most were relatively small, suggesting that those present represented newly recruited juveniles. Areal density of *E. lacunter* was $0.3/m^2$ in June 1985.

In December 1985 (twelve months postspill), the density of both urchin species at Site D had increased dramatically to levels three times those of the prespill period (November 1984), followed eight months later by another decline in density. The reason for this decline is unknown but may simply reflect the natural variation in density such as that measured at Sites O and R.

Site O—Urchin density at Site O was highly variable during the prespill period. Comparison of the first prespill and first postspill data (November and December 1984) showed a slight decrease in density (from $1.1/m^2$ to $0.8/m^2$ for *E. lacunter*), followed by relatively similar densities $(1.0/m^2)$ in the seven-month postspill period (June 1985). In December 1984, and especially in August 1986, large increases in density of both species were measured at Site O ($10.0/m^2$ and $54.0/m^2$, respectively).

Discussion

The findings of this study provide environmental managers with experimental data that will allow informed, intelligent decisions regarding dispersant use in tropical areas dominated by the three habitat types studied.

Two important design features must be considered in the interpretation of the results of this study. First, the experimental scenario called for the use of fresh, unweathered crude oil. The use of unweathered oil, while somewhat unrealistic, provided an extreme case study from which the effects of less extreme situations might be extrapolated. The second factor is the duration of exposure at Site D. Under normal circumstances, it would be unlikely that such high concentrations of dispersed oil would be maintained for a 24-h period.

The results of sediment analyses indicated that both sites had relatively high and roughly equivalent levels of contamination of intertidal sediments. This may seem unusual in light of the wide disparity in biological effects on the mangroves at each site. This conflict in results probably is related to the sampling protocol used. Sediment sampling is particularly sensitive to small-scale spatial variations in the distribution of oil because of the relatively small volume of material obtained in each sample. This effect would tend to be greatest during the early posttreatment period before waves and tides have redistributed oil within the site.

Within this context, it is clear that Site D had lower levels of contamination in the intertidal sediments and higher levels in subtidal sediments than Site O.

One ramification of these data is that dispersants somehow may act to reduce the toxicity of oil to mangrove trees. It is evident that the mangroves at Site D were exposed to what appears to be a fairly high level of contamination without any apparent biological effects.

The water chemistry data clearly show that subtidal areas of Site D were exposed to very high dispersed oil concentrations during treatment. Site D also showed the most immediate and prolonged effects both in terms of decreasing coverage of reef substrate by living organisms, decreasing growth rates of at least one coral species, and abundance of sea urchins. The decline in substrate coverage and coral growth persisted for at least one year suggesting that the high initial concentrations of dispersed oil had residual effects on these parameters.

The long-term effects of the whole and dispersed oil on the intertidal and subtidal habitats persisted through the 20-month postspill survey, but there were indications that recovery was beginning at this time. Colonization by juvenile mangroves of substrate below dead and defoliated adult mangroves was very vigorous at Site O after 12 and 20 months, and it appeared that these new plants would eventually replace those killed by the whole oil. Obviously, this process will take many years, and recovery will not be complete until the juveniles have reached adult size (probably 10 to 20 years).

Recovery of the only significantly affected component of the seagrass habitat at Site D (sea urchins) was already complete after one year. Recovery of corals and other encrusting organisms in the coral reef at Site D will be much slower, but there are indications that the decline in abundance of corals was beginning at 20 months postspill. The time to full recovery is unknown but is probably on the order of several years.

The data presented in this report and on-site observations made over the two-and-onehalf years of the project clearly indicate that the intertidal and subtidal habitats studied are highly sensitive to the effects of whole and dispersed oil, respectively. The effects on the *R.* mangle forest from both whole and dispersed oil were not unexpected and are very similar to those measured at a previous study conducted in Laguna de Chiriqui in 1983 [2], as well as numerous accidental oil spills [1]. The effects of oil and dispersed oil on seagrass and coral habitats are much more poorly known. This study provides one of the first detailed analyses of these effects in a controlled field setting. Other previous studies of seagrasses [7–9] showed that *T. testudinum* is relatively resistant to dispersed and whole oil when exposed to 5 to 20 ppm for short periods. The results of the present study confirm these findings and provide the only field experiment data to date on the short- and longterm effects of whole and dispersed oil on seagrasses.

The results of this study also expand upon the presently small database on the effects of oil and dispersants on corals. The Coroil project [10] and similar studies conducted at BBS

have found that one coral reef species (*D. strigosa*) is relatively tolerant to dispersed oil in terms of long-term effects on growth and survival. The present study increases the available data for four additional coral species and supports casual observations of the sensitivity of other reef-inhabiting invertebrates. These noncoral invertebrates of the reef community (and the invertebrates of the seagrass beds) have not been studied in much detail, and as the results reported here have shown, they may be one of the most sensitive components of these habitats.

Conclusions

The purpose of this study was to obtain experimental data to determine if the use of chemical dispersants will reduce or exacerbate adverse impacts of oil spills upon sensitive and valued tropical environments such as mangrove forests, seagrass beds, and coral reefs.

The question of possible trade-offs in effects between intertidal and subtidal habitats was explored to determine if there was a net benefit to be gained, such as reduction in impacts to one or both habitats, or increase in recovery rates of affected habitats. This would allow evaluation of various available response options based on different spill scenarios. These options are discussed below. As mentioned above, the constraints imposed by the experimental design (especially those relating to method and duration of exposure) should be considered in the interpretation of the results.

Option 1—No Action

This option was simulated by the untreated oil scenario (Site O). The experimental data for Site O clearly show that whole, untreated crude oil has severe, long-term effects on the intertidal components of the study site (mangroves and associated fauna) and relatively minor effects on subtidal environments (limited to a slight decline in coral abundance). In those cases where the intertidal environment is highly sensitive to oil pollution, the noaction response option has a relatively high probability of resulting in significant adverse environmental impacts, and therefore, the no-action option is not recommended in these cases. Some form of response is warranted, either chemical dispersion of the oil (within the framework outlined below) or mechanical containment and recovery. In situations in which intertidal environments have low inherent sensitivities, the no-action response option may be an acceptable approach.

Option 2—Apply Dispersants in Shallow, Nearshore Waters Directly Over or Adjacent to Coral and Seagrass Habitats

An extreme case of this option was simulated by the dispersed oil scenario (Site D). The experimental data show that the use of dispersants under this scenario had a positive effect in reducing or preventing adverse impacts to the mangrove forest, but this was accompanied by relatively severe, long-term effects on the coral and seagrass environments.

Under more likely conditions in which the floating, untreated oil has weathered for several hours and is dispersed into the water column over a relatively short period of time, it is reasonable to assume that the magnitude of impacts to subtidal environments would be less than was measured in this study. Under less extreme conditions, one would expect the balance in environmental trade-offs to shift in favor of Option 2; for example, more physical weathering of the oil and shorter exposure periods to the dispersed oil (such as would occur in more realistic conditions) would probably result in fewer impacts to nearshore, shallow-water coral reefs and seagrass beds and, at the same time, reduce or prevent impacts to mangrove forests, even if dispersants were applied directly over coral/seagrass habitats. Therefore, the use of dispersants in shallow waters to protect highly sensitive intertidal habitats should be considered a viable option, with the realization that significant subtidal impacts may occur and that overall environmental damages may not necessarily be reduced. All efforts should be made to apply dispersants in water as deep as possible to promote dilution of dispersed oil.

Option 3—Apply Dispersants in Deep Water, Offshore from Mangrove, Seagrass, and Coral Environments

This option was not directly tested during the study, but the experimental data presented here indicate that this option is likely to result in prevention or reduction of damages to mangroves without significant effects on seagrass or coral habitats. Chemical dispersion of oil in deep water, away from nearshore environments, is likely to allow dilution of dispersed oil such that exposure of sensitive subtidal environments to toxic concentrations is not likely to occur. It is reasonable to speculate that any reduction in exposure of nearshore corals and seagrass habitats to dispersed oil would tend to reduce damages to them. Therefore, it is recommended that the use of dispersants be considered whenever highly sensitive intertidal environments are threatened by spilled oil and that dispersant application is conducted in water as deep as possible.

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Dispersed Oil Effects on Tropical Nearshore Ecosystems

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ABSTRACT: Tropical and subtropical critical habitats are generally more fragile and slower to recover than temperate ones in which the environmental standards and guidelines are made. Fisheries nurseries are found immediately adjacent to shore in seagrass in the tropics, unlike temperate zones where fisheries are most frequently offshore and much of the adult fish catch is in this coastal region (the exceptions are a few highly migrating fish such as tuna). Studies have dealt with oil effects on corals and mangroves; fewer have dealt with seagrass. Very few studies have looked at dispersed oil on any of these habitats. The single dispersant used for mangroves and corals and the primary dispersant in seagrass studies was Corexit 9527, which showed no mortality on subtropical and tropical habitat species between 1 to 50 ppm (1:20 dispersant-to-oil dilution) for short (4 to 6 h) time periods. Higher concentrations of dispersed oil tested on seagrasses showed ranked sensitivity. Other dispersants have only been tested on seagrasses. Ranked sensitivity from nontoxic to very toxic appeared as in animal testing. The time of exposure and concentration of dispersants are important to increasing toxicity effects. Four species of corals were tested to Corexit 9527 1 to 50 ppm. Little difference in response was yet apparent. For mangroves, only the Western Atlantic red mangrove has been reported for the single dispersant Corexit 9527. (This manuscript was prepared in June 1987 when some ongoing experimental mangrove data were not yet published.) The Indo-Pacific basin critical habitat species and Arabian Red Sea species need similar testing for "safe limits." Field testing of various dispersants is necessary. Regulators and planners must stop using the generic "dispersants" in oil spill contingency planning and name a nontoxic substance tested in their ecosystems since some dispersants are toxic and others are not. We must establish a network to disseminate recent work.

KEY WORDS: dispersed oil, dispersants, tropical, subtropical critical habitats, mangroves, corals, seagrasses, oil pollution, oil spill, contingency planning, toxicity testing, tropical coastal ecosystems, fisheries

How Tropical Ecosystems Differ from Temperate Ecosystems

Fragility or Resiliency of Ecosystems

A system of rating the "survival" ability of ecosystems through natural and ecological disaster has been done by Cairns [1], whose recovery index (RI) compares resiliency, stability, elasticity, inertia, and vulnerability of ecosystems to irreversible damage. Thorhaug [2] has rated tropical ecosystems versus temperate, subtropical, and arctic ecosystems on this scale, which Cairns did not do (Table 1).

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		Temperate	Subtropic	Tropic	Arctic
1.	Elasticity existence of epicenters	medium	medium	low	low
	dissemule transport	high	medium	low	high
	habitat conditions	high	medium	low	high
	water quality	high-med.	medium	low	high
	regional management	high	high	low	high
2.	Inertia	high	medium	low	medium
	organisms	medium	medium	high	high
	viability in stable ecosystems	high	medium	medium	medium
	redundancy	medium	medium	high	low
	mixing capacity	high	medium	low	high
	proximity to threshold	high	medium	low	low
	regional management	high	high	low	high
3.	Vulnerability to irreversible damage	high	medium	low	low
4.	Resiliency	high	medium	low	low
	overall recovery index	high	medium	low	medium

TABLE 1—Comparative coastal and estuarine habitat recovery ratings on Cairns (1980) scale.

It can be seen that tropical nearshore ecosystems are low on the recovery index as a result of (1) lack of elasticity and resilience once perturbed, (2) vulnerability to ecosystem irreversible damage with pollutant stress, and (3) inertial factors (proximity to critical thresholds when polluted and low regional management capacities; that is, most third-world countries with much less capacity for managing ecosystems lie in the tropics, which are close to their critical pollution limits, while few first-world countries are situated in the tropics).

To give a specific example, a coral reef takes 10 to 50 years to recover naturally from disasters; mangroves, 20 to 50 years; seagrasses, 6 to 50 years. These recovery rates are all dependent on species and extent of impact. These are dependent on the extent of the damage, water and physical conditions, proximity of disseminule epicenters (islands are longest to recover), closeness to limit of range, high or low energy system, and several other factors.

Several investigators [2-4] have called the tropics "on the brink of disaster" because they are close to the critical threshold (LD₅₀ or LD₁₀₀ which is the lethal dosage at which 50% or 100% of the population being tested will die, respectively).

Fisheries

Much of the fisheries nurseries for the several thousand species fished in the tropics (with the exception of tuna and a few other strictly pelagic commercial species) are found very near to shore in seagrass beds, mangroves, and coral reefs. The adult stages may be captured out to sea, but the juveniles and eggs need these nursery habitats to complete their live stages. The temperate ecosystems have many fewer species and more abundance of these species. Spawning and juvenile habitat frequently occurs in open ocean, so that the estuaries and coastal areas lose a portion of their importance to the food web.

The fragility of tropical fisheries may be based on the reasons stated: that the tropics are

already at the high radiation, high temperature end of line. This "multiple-stresses" organisms so that additional stresses easily push them over the "brink of disaster." The reasons may be far more complex. Moore [3] theorizes that the reason there are so many more species in the tropics is that the radiation level, temperature level, and light are all higher and these cause genetic breakage and speciation. Examples of tropical ecosystems succumbing to pollutants of lower levels than their functional analogues in temperate ecosystems are abundant such as heated waste effects [5] and dredge and fill effects [6].

Toxicity Testing Standards for the Tropics

Because of the fact that most first-world nations are in the temperate zone, most of the environmental protection agencies that have research and development money for standard testing are in the temperate zone, thus the test organisms have been mostly temperate species for pollutant standards. An example is the U.S. Environmental Protection Agency (EPA). Almost all the designated test animals are temperate. Standards were set after elaborate testing in the laboratory and field for elimination of heated wastes. These standards were invalid when taken to tropical parts of the United States such as Miami, Key West, Puerto Rico, Hawaii, Guam, and Samoa. New standards had to be set up with tropical organisms. Rarely, if ever, have tropical organisms been used as standards in North America, Europe, or Japan.

In my opinion, the standardization tests for toxicity of a substance discharged into the environment must be redone using tropical organisms to set tropical standards such as the following outlines.

Critical tropical organisms that are vulnerable to pollution and affect the food chain are the estuarine and coastal matrix organisms. These important matrix organisms are coral reefs, mangrove, and seagrass species. In a few tropical locations, macroalgae (*Halimeda*, *Caulerpa, Laurencia*) or marshes might be included. When these are removed, hundreds to thousands of species have no habitat or nursery and thus are effectively removed from the area, even though they could survive the water quality characteristics.

The temperate zone has a plankton-driven food web in coastal areas, which sometimes dominates even in nearshore or estuarine areas. The tropics have benthically driven systems. The difference in recovery rate of a plankton system is days versus years for tropical food webs (at least two orders of magnitude longer).

Tropical Environmental Management, Standards, and Guidelines

Environmental management in the third world is basically 15 years old, being initiated with the United Nations Stockholm Conference on the Environment in 1972. Many developing nations set up environmental protection agencies in response to the mandates on valuable natural resources being decimated by the thoughtless management set forth at this conference.

The natural progression was to set up a large management agency. Then guidelines or standards and laws or policies to enforce sound environmental management were sought. Frequently the nation examined the set of laws, regulations, and policies from first-world nations. They were impressed with the thoroughness of first-world regulations. These standards were translated into the laws, regulations, policies, and legal frameworks used in that nation. For instance, in the Philippines, much of the environmental law (after Stockholm) appeared during a period of martial law, so it was decreed by Presidential Proclamation as a new set of laws. It bears a strange resemblance to U.S. EPA regulations, laws, and policies. Egypt had a very extensive set of environmental laws, but no agency to manage it until the early 1980s. However, no enforcement funds, personnel, or policies were appropriated for the laws, making enforcement impossible.

Several items must be appreciated about tropical environmental management. In firstworld countries, fairly strict laws, which are well enforced, are now operant. In first-world territories, protectorates, and second-world nations, such as Venezuela, Israel, and Middle East nations, this is also occurring. In third-world nations, which form the bulk of the tropical area, good policies and laws and an organizational structure frequently exist. Often low economic budgets, understaffing, lack of advanced professional training for staff, and other political constraints such as little veto power over the government's own environmentally impacting projects (roads, power plants, and other infrastructures) cause less than optimum resource management.

There is no place this phenomenon is so evident as in oil spills in the third world. Oil spills are frequently well planned for on paper. The process of implementation is entirely different. There, lack of enforcement, personnel, funds, and equipment are manifest. Frequently valuable natural resources are impacted during spills.

The first-world guidelines frequently are meant to protect offshore fisheries such as found in temperate areas and the more capital intensive first-world fishing fleets. The fisheries are nearshore in tropical and artesanal nations, and employment is an important element of fisheries. Present oil spill contingency plans are not calculated to protect the complex nearshore sets of critical habitats. *Offshore* spills are the assumed basis for most sets of guidelines for cleanup now in practice in tropical nations. When spills come close to shore, the trade-off, use of dispersant to protect the resources, while not impacting on others, is not understood or implemented. Spills in harbors or at terminals are particularly repetitive in some nations. Therefore, we see large losses of resources in one tropical spill after another: Nigeria, Panama, Puerto Rico, Jamaica, Bahrain, Indonesia, Egypt, and so forth.

Results

Comparative Dispersant Effects on Tropical Habitats

Tables 2, 3, and 4 show dispersant effects available from the literature. Seagrasses, mangroves, and corals are shown separately to compare dispersant effects within each critical habitat group. Unfortunately, scientists and government workers in the tropics do not publish material at the same rate as the first world, so there may be dispersed oil spills with unpublished results (I would appreciate receiving synopses from the authors of these). For instance, the Philippine Coast Guard was funded by the United Nations for a large dispersant toxicity testing program, but results were not published nor are they available. (Fish were the major test organisms.)

In general, there is more detailed data in laboratory experiments about seagrass than others. There is more field testing on corals. A wider range of dispersants have been tested on seagrasses than on mangroves or corals. More real-life spills have been documented on mangroves than seagrasses or corals.

The clearest point is that all reported testing, with one exception, has been in the Greater Caribbean, and we know nothing of other basins.

Importance of Seagrasses, Mangroves, and Corals to the Tropical World

Seagrasses are found from the tropics to the arctic and therefore differ from mangroves and corals, which are almost strictly tropical and found generally in subtropics close to the tropics (mangroves go to Anclote on the West Florida coast and Daytona Beach on the East Florida coast). Seagrasses are a very critical habitat to tropical systems, forming a chief fisheries nursery for hundreds of commercial species. Seagrasses cover at least 1 million km^2 [7]. They are distributed from the high tide marsh in estuaries to the coastal areas in continental shelves. There are about 50 species worldwide.

Mangroves are found throughout the world's tropics, especially in low energy areas such as estuaries, lagoons, and river deltas. Throughout the world's tropics 500 000 km² are found [8]. There are about 50 species worldwide. The detritus adds appreciably to the productivity. The trees form a major intertidal and upland coastal habitat for hundreds of species.

Coral reefs are well known to be important structural elements to a coastline's integrity and to be habitats for a wide array of important species for fisheries and ecology. Reefs are chiefly coastal, tropical and in some seas are rarely found in estuaries. Reefs can be found on coastlines from the intertidal zone to the edge of the continental shelf. Of the world's tropics 600 000 km² contain corals. They are found in all tropical ocean basins. There are hundreds of species.

Because of the predominance of drilling on continental shelves, reefs and seagrasses are in danger of spills from most drilling sites. In Mexico and some Middle East nations, drilling is in and around mangrove areas. Tanker spills most frequently affect reefs, and secondarily affect seagrasses. Port, harbor, terminal, pipeline, and other "facility based" spills most frequently affect mangroves and seagrasses.

The Tethys Seas of ancient geological times had a worldwide tropical zone which connected through either Mexico or Central America and the Suez area. Species were similar. The uplift of the Central American area cut circulation and further speciation continued, making very different groups in the Red Sea, Indo-Pacific, and wider Caribbean. There are presently very different species of corals, mangroves, and seagrasses in each ocean basin with almost no overlap between the Atlantic and Pacific.

Differences of Toxicity Effects Between Species

Seagrasses—Tropical and Subtropical—In the Atlantic, the seagrass Thalassia testudinum is the most tolerant to high concentrations of oil and dispersed oil [9-12]. The least tolerant is Syringodium filiforme. Halodule wrightii sensitivity usually was similar, but it was slightly more tolerant to oil alone than was Syringodium filiforme. These sensitivity rankings were amazingly constant between concentrations, oil, and dispersant type. We have no data yet on the Indo-Pacific species, but would generally expect cogenetors to behave similarly based on comparative pollutant Atlantic versus Pacific work [13] (Figs. 1 through 4).

Mangroves—It should be pointed out that the tolerance to salt of the various 50 species of trees lumped as "mangroves" does not indicate similar physiology between species. Probably mangroves may be more dissimilar in toxicity response than seagrasses.

The only mangrove that has been dispersant tested for oil toxicity in experimental sites (canals) is the red mangrove *Rhizophora mangle* [14,15]. Several field situations give results for red mangroves [15-17]. Clearly, research on interspecific differences to dispersed oils of various types is called for.

Field results reported from the Atlantic would indicate *Rhizophora mangle* has a higher tolerance than the other species. The final results of the Panama experiment, only reported in abstract form at the time of writing [18], will no doubt resolve some comparative Caribbean tolerances. Other parts of the world beyond the Caribbean are yet to be tested for dispersed oil effects on various mangrove species. An ongoing project in Jamaica (Thorhaug, Teas, and McDonald) may answer questions for the Caribbean.

	Dispersant Effect	oil with dispersant has lower toxicity than without	at medium conc. high	at 5 to 100 h	low to medium low to medium low to medium at 75 and 125 ml	medium to high high
	Impact	LD ₅₀ 12- and 96-h bioassays oil & dispersed	LD ₅₀ vs. time and conc.		LD ₅₀ 5 h 100 h	LD ₅₀ at 5 & 100 h
ts on seagrasses.	Resource Affected	Thalassia estudinum	Thalassia Halodule Syringudium		Thalassia Halodule Syringudium	Thalassia Halodule Syringudium
ia oil effeci	Date	1984	1983– 1984	÷	:	
dispersed oil an	Amount of Spill	50 ppm oil lab.	lab.	:	÷	:
and subtropical	Conc. of Dispersant	50-ppm oil 1:20 24 h	La. crude Murban	La. crude Murban	La. crude Murban	La. crude Murban
LE 2-1 ropical	Dispersant Used and Dilution	Corexit 9527	Corexit 9527 1:20	Corexit 9527 1:20	ARco D-609 1:10	Conco K (K) 1:10
IAB	Type	lab. outdoors	lab. outdoors	lab. outdoors	lab. outdoors	lab. outdoors
	Author and Date	Baca and Getter (1984) [22]	Thorhaug and Marcus (1985) [9]	Thorhaug and Marcus	Thorhaug and Marcus (1987) [11]	Thorhaug and Marcus (1987) [12]
	Location		Miami, FL	Miami, FL	Miami, FL	Miami, FL

TABLE 2—Tropical and subtropical dispersed oil and oil effects on seagrasses.

La. crud exper.	cm ³ SW La. crude 75- and 125- mL oil La. crude 75 and 125 mL in 100 000 cm ³ SW La. crude 75	SP-	Cold Cle 500 Finsol O	lab. OFC-D- outdoors OFC-D- lab. Cold Cle outdoors 500 lab. Finsol O	527 50 ppm at exp. 1985 Thalassia none to no effect on 24 h Prudhoe testudinum Thalassia Thalassia Bay crude	9550 125- and 75- La. crude 1986 Thalassia 100 h low mL oil exper. Halodule medium 1:20 disp. Syringudium low to medium in 100 000 cm ³	607 SW La. La. crude 1986 Thalassia 100 h low crude 75- exper. Halodule low and 125- Syringudium medium mL oil La. crude	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	SP- La. crude 75 1986 Thalassia LD ₃₀ 100 h medlow
16		La. cm ³ SW La. crude 75 15 and 125 mL in 100 000	Finsol OSP- La. crude 75 15 7 and 125 100 000	lab. Finsol OSP- La. crude 75 \dots 15 multin multiplication of 125 \dots 16 multiplication of 120 000 000 \dots	 86 Thalassia 100 h Halodule Syringudium 86 Thalassia 100 h Halodule Syringudium 86 Thalassia LD₅₀ 100 Halodule Syringudium 	 ¹⁸⁶ Thalassia 100 h ¹⁸⁰ Halodule ¹⁰⁰ Syringudium ¹⁰⁰ Thalassia ¹⁰⁰ LD₅₀ 100 ¹⁰⁰ Syringudium 	N6 Thalassia LD ₅₀ 100 Halodule Syringudium		986 Thalassia LD ₅₀ 10 Halodule Syringudium
	experi	crude 75- exper- and 125- mL oil La. crude La. crude 75 and 125 mL in 100 000 cm ³ SW La. crude 75 mL in 100 000 mL in 100 000 cm ³ SW	Find the form of the condition of the co	and 125- experimentation and 125- mL oil lab. Cold Clean La. crude 75 outdoors 500 and 125 mL in 100 000 cm ³ SW cm ³ SW lab. Finsol OSP- La. crude 75 nL in 100 000 nL in 100 000	e 198 198	e 198		198	198
Thorhaug and Marcuslab.OFC-D-607SW La. cm3Marcus (1987) [11]outdoorsOFC-D-607SW La. crude 75-Marcus (1987) [12]outdoorsS00and 125- and 125-Marcus (1987) [12]outdoors500and 125Marcus (1985) [9]outdoors500and 125Marcus (1985) [9]outdoors7and 125Marcus (1985) [9]and 125and 125Marcus (1985) [9]and 125and 125Marcus (1985) [9]7and 125Marcus (1985) [9]7and 125Marcus7and 125	Thorhaug and Marcus (1987) [11]lab.OFC-D-607Thorhaug and Marcus (1987) [12]lab.Cold Clean 500Thorhaug and (1987) [12]lab.Finsol OSP- 7	Thorhaug and lab. Marcus outdoors (1987) [11] Thorhaug and lab. Marcus outdoors (1987) [12] Thorhaug and lab. Marcus (1985) [9]	Thorhaug and Marcus (1987) [11] Marcus (1987) [12] Thorhaug and Marcus (1985) [9]		Miami.	FL	Miami, FL	Miami, FL	Miami, FL

	Dispersant Effect	No effect to brief exposures when oil dispersed 20- ppm polychaetes, bivalves crustacca untolerant.	Unclear after 9 mo. whether dispersant had effect or not.	No death on corals with dispersant	Reports intertidal reefs extensive mortality, subtidal to 2-m mortality.
	Impact	6 to 24 h after, 1 to 50 ppm on <i>Diploria</i> strigosa	No impact immed. Some death after 6 mo. during winter cold	no coral death at 24-h exposure	coral death
S.	Resource Affected	corals	corals	corals, seagrasses, mangroves	corals, scagrasses, mangroves
cts on coral.	Date	1981– 1986	1980	1985	1986
ed oil and oil effec	Amount of Spill	Arabian light crude	Arabian light crude	Prudhoe Bay crude	50 000 med. wt. crude
LE 3—Dispers	Conc. of Dispersant	1:10		50 ppm 20:1	20:1
TAB	Dispersant Used and Dilution	Corexit 9527 BP 1100 WD	Corexit 9527 20:1	Corexit 9527	Corexit 9527
	Type	field and lab.	field exper.	field exper.	spill
	Author and Date	Knap et al. (1985, 1986, 1987) [19]	Le Gore et al. (1983) [20]	Getter and Ballou (1987) [23]	Cubit et al. (1987) [17]
	Location	Bermuda	Arabian Gulf	Panama	Panama

	Dispersant Effect	Dispersed oil before it reached mangroves			no defoliation at sites with dispersant		if dispersed before oil on mangroves, less mortality
	Impact	defoliation death		defoliation death	28% trees defoliated		observed mangrove death
	Resource Affected	mangroves	R. mangle	R. mangle	R. mangle	R. mangle	mangroves
s on mangroves	Date	1984		27 April 1986	1985	1982-1986	fall, 1986
and oil effect	Amount of Spill	exp.	exp.	55 000 to 60 000	exp.	exp.	:
4-Dispersed oil	Type of Oil	50-ppm Prudhoe Bav crude	La. crude	med. wt. crude	Prudhoe Bay crude	50 ppm	med. wt. crude
TABLE	Dispersant Used and Dilution	Corexit 9527 24 h 1:20	Corexit 9527 1:20	Corexit 9527, approx. 21 000 L 1:20	Corexit 9527 1:20	Corexit 9527 1:20	Corexit 9527 1:20
	Type	field	field	accidental	exper.	field	field spill
	Author and Date	Getter (1986) [16]	Teas et al. (1987) [15]	Cubit et al. (1987) [17]	Getter and Ballou (1987) [23]	Teas (1986) [14]	Teas et al. (1987) [15]
	Location	Panama	Turkey Pt. Biscayne Bay, Fl.	Coast on Caribbean side of Panama	Coast on Caribbean side of Panama	South Florida	Panama

THORHAUG ON DISPERSANT EFFECTS ON TROPICAL ECOSYSTEMS

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FIG. 1—Time of exposure (5 h) of three subtropical and tropical seagrasses versus mortality.



HALODULE

THALASSIA



FIG. 2—Time of exposure (100 h) of three species of subtropical and tropical seagrasses versus mortality.

SYRINGODIUM HALODULE THALASSIA



Corals—Several coral species have had dispersed oil spilled on them. Knap [19] mentions several Acropora species. Although several sets of field experiments have been carried out which used various corals [16,19,20], there was not a particular attempt to increase concentration until toxicity differences appeared to occur. Thus, there is not, at present from the publications, a hierarchy of sensitivities. My theory, based on toxicities of other substances, is that there may be various sensitivities among coral species² if experiments are carefully defined.

Differences Between Concentrations

Seagrasses—Large toxicity tolerance differences appeared as increased concentrationraised percent mortality for a species. In each case seen in Figs. 2 and 3, a general range occurred where some species are less than 50% and others (*Syringodium* and *Halodule*) are greater. Time of exposure also influences these sets of curves (Figs. 1 and 2). Statistically significant differences occurred between species at higher concentrations. These ranges are at least an order of magnitude above advised usage levels for dispersants, but useful for small and less controlled spills in bays and harbors in which greater than instructed dispersant concentrations may be used.

Mangroves—No comparative studies between concentrations of dispersants for mangroves could be found. The existing studies used different concentrations between authors, but too many variables occurred to make a comparison.

² Note added in final edit. Jamaica experiments are showing specific differences.



FIG. 4-Oil type versus mortality for Halodule wrightii exposed for 100 h.

Corals—There was some experimental work by Knap and colleagues [19] using concentrations in the range 1 to 50 ppm. The higher concentrations showed sublethal effects of behavioral treatment (tissue contraction, tentacle retraction, and localized tissue rupture); lower concentrations did not show such effects.

Differences Between Dispersants

The EPA toxicity tables indicate large differences among the 20 dispersant products listed with the U.S. Environmental Protection Agency. A biological indicator organism test was done by a scientific group using a temperate Pacific estuarine species. Indeed, large toxicity differences highly correlated with the EPA information were found [21].

Seagrasses—A set of laboratory experiments using three seagrasses and seven dispersants as dispersed oil was run [7]. The seagrasses responded generally in the same relative tolerance order to each of the dispersants. Dispersants could be clumped into three groups: low toxicity, medium, and high. Finasol OSR-7 was least toxic; Cold Clean 500, Conco K (K), Jansolv 60, OFC-D-609 were most toxic; and Corexit 9550 and 9527 fall in between. The difference between dispersants was much greater than differences between species (Fig. 3 and Table 5). This seagrass ranking of dispersed, toxicity oil correlated well with temperate animal toxicity data [21].

	orme	% Mortality	7	7	10	12	25	18	30	63	84	84	100	86	100	98	100
	dium filif	CV%	28	28	35	299	22	18	28	17	41	25	37	46	29	37	52
	Syringou	<u>G</u> ± 95% C.L.	3.98 ± 0.25	3.41 ± 0.26	3.11 ± 0.61	3.05 ± 0.41	2.86 ± 0.35	3.25 ± 0.25	2.80 ± 0.54	1.97 ± 0.35	1.49 ± 0.45	1.39 ± 0.37	0.51 ± 0.45	1.42 ± 0.38	0.44 ± 0.39	0.59 ± 0.35	0.41 ± 0.68
neu seus us	htii	% Mortality	7	7	10	41	57	21	27	58	88	76	100	73	100	67	100
decree, er of	tule wrigh	CV%	24	15	21	64	41	36	45	31	65	60	31	24	38	61	28
OIL ITTEE SHOLLO	Haloe	$\overline{G} \pm 95\%$ C.L.	4.20 ± 0.31	3.64 ± 0.35	3.52 ± 0.29	2.25 ± 0.61	2.11 ± 0.37	3.31 ± 0.28	3.22 ± 0.66	2.05 ± 0.45	1.69 ± 0.55	1.84 ± 0.41	0.66 ± 0.21	1.66 ± 0.31	0.54 ± 0.31	0.76 ± 0.75	0.45 ± 0.25
cunciadem us	mum	% Mortality	0	0	7	10	18	16	26	22	37	26	40	35	51	65	88
ביש עש בירי	ia testudi	$CV\%^{b}$	18	48	37	51	18	6	21	28	35	31	28	24	38	49	37
ייד איני בווב	Thalass	$\overline{G} \pm 95\%$ C.L. ^a	4.51 ± 0.22	4.22 ± 0.55	4.11 ± 0.41	3.98 ± 0.31	3.76 ± 0.24	3.54 ± 0.11	2.95 ± 0.37	3.35 ± 0.31	2.78 ± 0.41	3.28 ± 0.41	2.60 ± 0.33	3.10 ± 0.27	2.73 ± 0.45	2.10 ± 0.41	1.74 ± 0.35
		Dispersants		Finasol OSR-7	Finasol OSR-7	Jansolv-60	Jansolv-60	Cold Clean 500	Cold Clean 500	Corexit 9550	Corexit 9550	Corexit 9527	Corexit 9527	OFC-D-609	OFC-D-609	Conco K(K)	Conco K(K)
		Dosage Oil, mL	0	75	125	75	125	75	125	75	125	75	125	75	125	75	125

 ${}^a \overline{G}$ = mean specific growth rate (% length increase/day) and C.L. = confidence limit. ${}^b CV$ = coefficient of variation.

TABLE 5-The effects of seven dispersants on three subtronical. tranical severasses [12].

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Mangroves—The mangrove studies, both field and experimental, carried out to date have all been with a single dispersant, Corexit 9527. There is no indication of the effect of other dispersants. Since dispersed oil is far better for mangroves than oil alone, it may result that a variety of dispersants are appropriate. These experiments are now ongoing with red, white, and black mangroves [13].

The major finding from experimental studies with Corexit 9527 is that dispersant-treated oil does not cause mass mortality whereas nondispersant treated oil (that is, no dispersant) can cause mass mortality, perhaps by cutting off oxygen from the prop roots [14].

Corals—Most field experiments as well as laboratory tests have dealt with one dispersant product, Corexit 9527. One study [19] tested 9527 (1:20 dilution) and BP 1100 WD (1:10 dilution) and found no statistical difference in the ranges 1 to 50 ppm with 6- to 24-h exposure with light Arabian crude oil.

Differences Between Oil Types

In general, both fresh oil versus "aged oil" and various weights of oil might have a difference in toxicity on habitat organisms. To date, no comprehensive program on any of the three critical habitat types has been carried out using various "ages" and types of petroleum products (Tables 2, 3, and 4).

Seagrasses—Oils and ages used were the following: light Middle Eastern crude, aged for 24 h in sunlight and air, and Louisiana crude, treated in the same manner. Both were tested on three seagrass species. No statistically significant difference between oils was seen. The more toxic "newly spilled" oil was not tested (Fig. 4).

Mangroves—Prudhoe Bay crude and Louisiana crude have been used for mangrove results. No differences have been pointed out by authors [13-16] or are apparent from results.

Corals—"Aged" Arabian light crude and Prudhoe Bay have been tested on corals. The authors [16,19,20] do not point out any differences between them, nor are they apparent from results.

Differences in Times of Exposure

There are several times of exposure that are relevant to tropical coastal oil spills: (1) very short times (1 to 2 h) where a parcel of dispersed or oiled water might flow over a habitat; (2) 6 to 12 h, where a tidal cycle could wash a dispersed or oiled water parcel onto a habitat, especially in an estuary; and (3) longer times where oil might sit in an estuary. The traditional EPA standard of 96 h (near 100 h), not designed for oil spills but for toxicity tests in general, is relevant to this.

Seagrasses—Three tropical Atlantic seagrasses have been tested for time of exposure response to Corexit 9527. Figures 1 and 2 show this result. Clearly, the longer exposure times have a greater toxicity effect, especially at higher concentrations of dispersant and oil.

Mangroves—Mangroves appear not to have had systematic experiments on time of exposure to dispersed oil.

Corals—Corals were exposed from 6 to 24 h to dispersed oil in a continuous flow experiment [19]. No toxicity appeared within this time frame. Field experiments were 24 h [16] and 6 h [20].







FIG. 6-Seasonal effect of two dispersed oils [1].

Seasonal Effects

Seagrasses—Tests were run throughout the year in subtropics. No differences were found.

Mangroves-No data for mangroves.

Corals—Seasonal differences in response to BP 1100 WD were seen in winter. No differences to Corexit 9527 were seen in winter (Figs. 5 and 6).

Conclusions

Management Principles for Use of Dispersants on Tropical Habitats

1. It is now apparent that certain selected dispersants at concentrations recommended by the manufacturer can be used under various sets of emergency conditions for oil spills which frequently occur in the world's tropics: (a) estuarine spills where or when mechanical means are inadequate to control oil from impacting one or more type of habitat, especially mangroves; (b) nearshore coastal spills where environmental conditions are rapidly transporting spills toward one or more critical habitats; and (c) weather conditions when mechanical cleanup is ineffective and there is a danger of impacting corals, mangroves, or seagrasses.

2. All parties must stop using the generic term "dispersants" within the oil spill cleanup plans. Specific tested and nontoxic dispersants must be named or an approved list made as Britain does for spills on each habitat type with their upper concentration limits for use described.

3. Further laboratory tests must be done by nations in tropical areas to test their commonly used and stockpiled dispersants for toxicity effects on their critical habitat organisms such as various species of corals, mangroves, seagrasses, and marshes. It is unrealistic to imagine small third-world nations will find this a priority. Regional multilateral and industrial funding agencies should undertake this.

4. A network of rapid information dissemination to industry, environmental management, and government spill cleanup managers should be organized so that whatever information is derived can be disseminated.

5. Resource maps which must include the *exact* species of mangrove, seagrass, or corals should be included in oil spill contingency plans. Since the toxicity effects differ by more than an order of magnitude between species, present "lumping" resource maps (that is, "seagrasses") are inadequate. As an example, the U.S. Department of Interior is spending a large amount of money for seagrass maps without specifying the species. By integrating the resource maps into planning oil spill cleanup in a manner as Venezuela has, updated information can easily be incorporated into plans on a yearly basis.

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The Behavior of Dispersed and Nondispersed Fuels in a Sewer System

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ABSTRACT: A small-scale model sewer was constructed to determine the behavior of dispersed and nondispersed fuel flushed or spilled into sewers. The system included a headbox containing a concrete pad with a drain in the middle. The drain fed into a sewer pipe. Six vapor sensors were positioned in ports or simulated manholes at intervals along the pipe length. The vapor sensors were connected to a computer which generated a continuous data record of vapor concentrations at each port. Liquid samples were also taken at different intervals under the vapor sensor ports.

Vapors in a sewer system have two distinct origins: the first is vapor evaporating from the liquid fuel as it is transported with the water and the remainder is vapor that formed upstream and is in the process of moving downstream at a slower rate than the underlying liquid. The latter movement is caused by the pumping action of the water flow, but is slower than the liquid flow as a result of the drag of the walls and the low gas-to-liquid friction coefficient. Gasoline, whether treated with dispersant or not, produces two sharply different vapor peaks at the sensor ports because it evaporates rapidly upon entering the sewer and thus produces a slowly moving vapor cloud. Diesel fuel does not evaporate as rapidly and produces only a single vapor peak at the ports.

The use of dispersants at the beginning of the sewer increases the volatilization rate of the smaller fuel molecules and thus increases the amount of vapor present in the sewer system. This occurs irrespective of the amount or brand of dispersant employed. When dispersants are applied, the vapor concentration and duration is increased at each subsequent port. An increasing amount of dispersant or dispersant/water mixture increases this effect. If dispersants are mixed with the fuel in a very vigorous manner the vapor concentration may not be increased in the first ports, but it will not be decreased and the concentrations are increased 5 min downstream. In no case is the vapor concentration at any port reduced by the use of dispersants.

The results from the small-scale model show that dispersants do not reduce the explosion risk of fuels in sewers. In fact, the use of dispersants will in most cases greatly increase the potential for explosions and their magnitude. Dispersants increase the rate of volatilization of small fuel molecules and increase the total amount of those released. This is consistent with the results obtained by other authors who have conducted static experiments of similar nature.

KEY WORDS: fuels, dispersants, sewers, explosions

Dispersants have been used for flushing fuel spills from streets into sewers and have been added to sewers in which fuel has been spilled. Proponents of this technique have claimed

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that this reduces the fire potential and offers a safe, convenient means of dealing with fuel spills in an urban environment [1,2]. The philosophy behind this usage is that dispersants would disperse the fuel in the sewer water and, aided by dilution from any fire-fighting water, would lower the fuel vapor concentration below both the lower flammable limit and the lower explosion limit, thereby eliminating any potential fire and explosion hazard. This method of reducing fire risk is quite distinct from the use of vapor suppression foams. The operative mechanism with foam is the creation of stable bubbles (foam) over a vapor source so that the vapor cannot penetrate and thus is contained. Vapor suppression by foams has been tested by several workers [3-8]. The use of dispersants to reduce vapor formation and fire risk has never been examined for effectiveness and product performance differences. This study was initiated to investigate both aspects and to examine the behavior of fuel vapors and liquid in a sewer system.

Experimental Procedure

A model sewer system was constructed. The basic features of this system are illustrated in the schematic diagram (Fig. 1) and also in the photograph (Fig. 2). The model sewer was a 3.8-cm diameter and 104 m in length pipe, which descended at a constant slope of 0.0048 to a sump. Water was supplied from a constant head tank through a series of valves such that a constant flow rate could be maintained during an experimental run. The origin of fuel spills was a headbox consisting of a concrete pad, designed to resemble a street, sloped into a drain, just above the sewer pipe.

Simulated manholes or ports were placed along the sewer pipe at approximately logarithmic intervals (4.5, 9.0, and so forth) beginning near the headbox and then subsequently at approximately each 18 m. These served as access ports to sample vapors as well as providing vapor space to resemble real sewer systems. Sampler tips of HNU Photoionizer Model PI 101 vapor sensors were placed into the manholes to draw vapor from a distance 10 cm above the sewer pipe. This distance was selected after a series of preliminary tests and represents the best position in terms of repeatability of results.

The HNU sensors were calibrated for measurements of both test fuels, nonleaded automotive gasoline, and automotive diesel fuel, using Tedlar[®] bags of known filled volume [9]. Volumes of fuel necessary to achieve the desired concentration were injected into airfilled bags, and a probe was attached to analyze the vapor directly. At least two HNUs were used per run to ensure that no instrument peculiarities existed. The data from the calibration runs were fitted to a quadratic function. This, in turn, was included in the computer program to provide output directly in parts per million (ppm) gasoline or diesel fuel by volume. Sensors, calibration, software, and computer were checked throughout the study by applying voltages to the HNU outputs and comparing readings to calibration curves drawn manually.

The outputs of the HNUs were directly coupled to a Tecmar Labmate analog-to-digital converter as part of a Compaq 1 portable computer. A software program was prepared to operate the entire system and provide data output. On start-up of each run, sensor voltages were automatically read 100 times to provide an average background voltage. This, in turn, was subtracted from subsequent readings to annul background signals. This corrected signal was then used in the appropriate formula, derived as noted above, to calculate ppm of vapor. Data were recorded on floppy disks and presented as well on a real-time display. The latter is illustrated in Fig. 3. Two of the HNU sensors are in the background. Real-time printing of data was done only in increments of 20 or 30 data points. A second Compaq computer was used to print and analyze data. In addition to calculating the concentration of vapors in the system, the computer calculated the total integral (equivalent to







FIG. 2-Overall view of model sewer.



FIG. 3-Real-time display and HNU sensors.

the total vapor) by summing vapor concentrations over time. Peak concentrations, as presented in Appendix A, were obtained manually using the complete printout and the plot of the real-time graphs.

Three types of dispersant experiments were performed. Most experiments involved direct injections by syringe of 1 mL of gasoline or diesel fuel, followed by 1 to 10 mL (or more in a few cases) of a 5% dispersant-in-water solution. The syringe was released into a center hole of the drain to ensure repeatability and to avoid hitting the side wall of the 10-cm pipe leading to the actual sewer line. This fuel introduction method was found to reproduce the results obtained using other introduction methods and also yielded particularly consistent and repeatable results.

The second method of fuel addition to the sewer was by vigorously mixing the fuel and dispersant solutions in a syringe and then making the injection.

The third method consisted of spilling the fuel on a marked area on the concrete floor of the headbox (spill source box) and then placing the wash solution on a marked area upgradient from the fuel. This then represented the practice of flushing fuel down a sewer.

During early runs of the sewer system, a number of fuel introduction techniques were tried. Many of these made no difference to the final outcome but yielded significant variance in repeatability and were abandoned.

Tests fluids were obtained from commercial sources as outlined in Table 1.

Gas chromatographic (GC) analyses were performed on a Hewlett-Packard Model 5830A with a 3% SP-2100 (6-ft, ½ in. [1.8 m, 32 cm]) column operated with a temperature ramp of 8°C/min beginning at 40°C and ending at 220°C. Samples were withdrawn from Manhole 5 using a gastight syringe and directly injected. The timing of sample withdrawal was based on the known arrival time of the HNU-detected peaks, which were very repeatable under the same operating conditions.

Over 150 runs were performed and recorded. This does not include spoiled runs and trial runs during construction to determine basic operating procedures. After commencement of operation, 41 additional runs were conducted to test the sensitivity of results to varying conditions, including positions of sensors, flow rates, water temperature, fuel quantity, opening size at manholes, method of injection, and method of discharge. None of these variables affected the basic behavior of fuels in the sewer system or the effect of dispersant on the vapor concentration. The first runs were performed with the sewer emptying into a sealed chamber where all vapors were collected. The vapors in this catchment basin appeared to equal the total integral of vapors along the system and, although this provides a useful measurement, the sealed chamber had to be removed from the system

Description	Source
nonleaded regular gasoline	gas station, PetroCan
automotive diesel	gas station, PetroCan
dispersant sold for land and water fuel spills	Metra Chem Corp., Shewsbury, MA
dispersant sold for oil-on-water spills	Exxon Chemical, Houston, TX
dispersant sold for land fuel spills	Illinois Chemical Co., Chicago, IL
dispersant sold for land fuel spills	Sunshine Chemical Co., West Hartford, CT
household cleaning liquid	grocery store
	Description nonleaded regular gasoline automotive diesel dispersant sold for land and water fuel spills dispersant sold for oil-on-water spills dispersant sold for land fuel spills dispersant sold for land fuel spills household cleaning liquid household dishwashing liquid

TABLE 1—Test fluids used in model sewer.

	SAM	PLE POINTS	
Numb	er	Distance from	Headbox, m
1 2 3 4 5		0 4 9 18 51	.5 .0 .0
6		104	.0
	WATE	R FLOW RATES	
Flow Volume, L/min	Flow Rate, m/s	Flow Rate, ft/s	Water Retention Time, min
1 2 3	0.18 0.22 0.24	0.59 0.72 0.79	10.0 7.5 7.1
5 10	0.29 0.34	0.95	6.0 5.1
	WATER TEMPER	ature 12° ± 1°C	

TABLE 2—Operating conditions.

because vapors persisted in it for several hours. The basic operating conditions of the final system are listed in Table 2.

Water flow volumes were measured with a calibrated cylinder and stopwatch. Flow volumes were verified before each experimental run. Flow rates were measured by determining the retention time of a fluoroscein dye.

Water was sampled at taps from locations beneath vapor sampling Ports 3 and 5. Analyses were performed using a Horiba Oil-In-Water Meter Model OCMA-220; however concentrations of hydrocarbons in the water were too low to be detected (less than approximately 5 mg/L).

Behavior of Fuels in Sewers

The most notable phenomenon observed at the outset of the study was that gasoline produced two vapor peaks at sampling ports in the sewer system, whereas diesel produced only one. Figure 4 illustrates the two-peak phenomenon for both gasoline alone and for gasoline plus dispersant in reconstructions of the computer real-time display. Each display presents the vapor concentrations at each port (manhole). The x-axis is the time scale and each horizontal bar represents the vertical scale of 5000 ppm. Sensor 1, in the headbox, does not detect any vapors as the fuel is injected, and the small amount that subsequently escapes is not detected in the large volume of air in the headbox. The diagrams show that in both cases (gasoline only and dispersant flushed) a sharp peak appears first followed by a broader peak. Both peaks flatten out at the last sensor (No. 6) placed at 104 m down from the headbox. The two peaks move at different rates; the second peak becoming increasingly slower with respect to the first one.

To study the composition of these vapor peaks, samples were withdrawn at Port 5 and were analyzed by GC as described above. The results are shown diagrammatically in Fig. 5. It was found that the first vapor peak is due to gasoline evaporating from the fuel riding



CONCENTRATION AT EACH MANHOLE - gasoline only

FIG. 4—Real-time displays.

with the sewer water. That vapor peak moves at approximately the same speed as the water and consists of the higher boiling point fractions of the gasoline. The second vapor peak results from the rapid evaporation of fuel as it enters the sewer system and consists of the low boiling point fractions of the fuel. This peak moves slowly through the sewer system, as its only driving force is friction with the water flow.

Experiments were conducted to examine the flow rates of the water and the flow rates of the second vapor peak. The results of these are summarized in Fig. 6. As water flow rates rise, the vapor flow rate increases to a maximum and then falls. The point at which the vapor flow rate fails to rise with the water flow rate corresponds to the flow at which the water level rises to the radius of the pipe. It is suspected that the decreasing vapor flow rate after this point is due to the decrease in space available for vapor flow. Figure 6 also shows that the vapor flow rates of dispersed spills are slightly less than that of undispersed fuel spills. This may be due to the increased vapor observed with the use of dispersants. Any increase in vapor amount was observed to slow down vapor movement. In fact, the



FIG. 5—Origin and composition of gasoline vapor peaks in a sewer.

addition of 5 mL of gasoline instead of the usual 1 mL results in vapors remaining in the system for several hours rather than the usual 1 h.

Diesel fuel injection resulted in significantly less vapor concentration in the system. The significantly lesser amounts of volatiles in diesel account for this. Gas chromatography of vapor peaks showed only minor fractionation between the leading and trailing edges of the vapor plume. This is to be expected because diesel fuel largely consists of larger compounds which are less volatile. Otherwise, the behavior of diesel fuel in the sewer system was analogous to that of gasoline.

Effect of Dispersants on Fuel Vapor Concentrations

Six dispersants or surfactant agents were used with gasoline during the injection runs with gasoline to measure the effect on vapor concentration. The effect of the different dispersants on the peak concentrations of vapor at various manholes along the sewer system is shown in Fig. 7. In every case, the dispersant increases the peak concentration of gasoline



FIG. 7—Peak concentration at manholes.
vapors observed. This effect is more pronounced at the beginning of the sewer system and decreased towards the end. This suggests that the dispersant acts fairly rapidly, mostly during the 20 s of transit time from the headbox to Manhole 1 situated at 4.5 m. The difference in peak concentrations caused by the various products is not significant.

The total vapor released into the sewer system was also measured by integrating vapor concentrations over time. The results of this integration with gasoline are illustrated in Fig. 8 where the effects of the six dispersant products are displayed. The dilution volume is the ratio of the 5% dispersant in water solution to the volume of fuel. A dilution volume of 1 means the use of 1 mL of a 5% dispersant in water solution for a 1-mL spill of gasoline. The total vapor released into the sewer system is always greater when using a dispersant than when not. Even when a dilution volume as great as 10 to 1 is used, the total vapor released is still greater than it is when the gasoline is untreated with dispersant.

The same studies were performed with diesel fuel, and the results for two dispersants and diesel alone are shown in Figs. 9 and 10. As with gasoline, the use of dispersant increases both the peak concentration at the manholes and the total vapor released into the sewer system.

These results are consistent with earlier studies on the effect of evaporation with and without dispersant application. Wilson and coworkers examined the evaporation of crude oil dispersed in laboratory vessels and observed that evaporation was increased and molecules larger than twelve carbon atoms were largely dispersed [10]. Bowles and coworkers studied the evaporation of crude oils after dispersion in the Mackay-Nadeau-Steelman apparatus and found that dispersants accelerated the evaporation of volatile components and that compounds containing up to eight carbon atoms (C8) were almost absent in the dispersion [11]. McAuliffe and others have conducted several investigations into the dispersed behavior of C4 to C10 compounds and noted that these are diminished in petroleum dispersed into water and were released by evaporation [12–15].



FIG. 8-Total vapor released into sewer.



FIG. 9-Peak diesel concentration at manholes.

The theories presented by these experimenters are that the formation of small oil-inwater droplets, which dispersants are intended to cause, vastly increases the surface area and thus the evaporation rate. A secondary item of note is that dispersants have little effect on smaller molecules such as benzene and hexane, and these will largely evaporate and not disperse.

The effect of increasing the mixing energy applied to dispersant and fuel was also investigated. As noted in the experimental section, this was performed by vigorously mixing the dispersant and gasoline before introduction to the sewer system. Figure 11 shows the total amount of vapor released additionally to that released from a low-energy mixing injection versus the distance downstream. The total vapor released into the sewer system is increased with increased mixing energy. This vapor increase with more mixing energy is attributed to greater effectiveness of the dispersants caused by increased mechanical shearing, resulting in decreased droplet size, increased surface area, and therefore, an increased evaporation rate.

Summary and Conclusions

Fuel oils spilled in a sewer system will evaporate to some extent and flow with water present in the sewer. Volatile components of the fuel will evaporate near the entry point and the resulting vapors will move slowly down the sewer system. Gasoline contains sufficient volatile components to produce two vapor peaks in the sewer system. The first is a



FIG. 11—Increase in vapor concentration with mixing.

more rapidly moving peak which results from evaporation of fuel riding with the sewer water. It consists of the less volatile components. The second peak is formed by the slower moving volatiles resulting from evaporation near the gasoline entry point.

The difference in performance for the dispersant products tested in this study is not significant. In fact, household cleaners give very similar results to those for some of the commercially sold dispersants.

The use of dispersants to flush fuel spills into or along sewers increases the vapor peak concentrations along the sewer, especially in the immediate vicinity of dispersant application. Similarly, the use of dispersants increases the total vapor released in the sewer. Because of this increased vapor, the movement of the vapor is slightly slower with the use of dispersants. The results from the small-scale sewer experiments show that the use of dispersants for flushing fuel spills down sewers is potentially dangerous because it increases the explosion hazard by increasing peak concentrations, total vapor released, and vapor retention time. Despite claims to the contrary, the results prove that dispersants do not aid in reducing the explosion hazard from fuels in sewers. Instead, the use of dispersants will, in most cases, increase the potential for explosions and their magnitude.

APPENDIX A

Summary Data

			С					
Run Description		Run Number	2	3	4	5	6	Total Vapor, ppt/min
		GASOLINE IN	JECTION R	UNS-FLOW	RATE = 2	2 L/MIN		
Gasoline only		44	5.63	2.73	1.28	1.01	1.16	61.4
-		45	5.40	2.70	1.25	0.98	1.17	77.1
		51	4.69	2.62	1.28	0.85	1.09	75.5
		131	5.31	1.96	1.10	0.92	0.72	61.9
		132	4.91	2.04	1.14	0.90	0.62	60.4
		133	4.65	1.97	1.13	0.90	0.60	60.2
Biosolve	1:1	60	6.63	4.26	2.51	1.45	1.01	91.9
	2:1	47	7.92	4.59	2.51	1.47	1.13	99.0
	2:1	54	7.31	4.58	2.69	1.54	1.03	94.6
	5:1	67	5.08	3.97	2.31	1.52	0.74	76.9
	10:1	73	5.71	3.97	2.52	1.70	0.63	84.9
	10:1	134	6.60	3.28	2.11	1.53	0.51	83.8
	10:1	135	6.02	3.02	1.91	1.40	0.48	72.8
	20:1	77	5.69	3.69	2.42	1.73	0.60	77.2
	50:1	80	6.83	3.69	2.52	2.00	0.62	93.5
Corexit [®]	1:1	64	5.49	3.72	2.07	1.16	1.02	78.5
	2:1	52	7.90	4.39	2.54	1.57	0.99	96.7
	2:1	58	6.28	4.25	2.42	1.49	0.95	86.1
	5:1	70	6.15	3.45	2.28	1.55	0.58	89.9
	10:1	76	5.81	3.41	2.18	1.62	0.59	83.9
	20:1	78	5.32	3.31	2.14	1.67	0.55	84.1
	50:1	81	5.78	3.15	2.06	1.77	0.62	92.1

			c					
Run Description		Run Number	2	3	4	5	6	Total Vapor, ppt/min
Icoshine	1:1 2:1 2:1 5:1	63 49 56 69 75	5.43 7.02 5.96 7.74 6.64	3.75 4.27 4.05 4.01 3.55	2.06 2.19 2.24 2.50 2.24	1.13 1.31 1.32 1.54	1.09 1.06 0.99 0.88 0.80	76.2 88.5 81.0 91.4 84.6
Jansolve	1:1 2:1 2:1 5:1 10:1	61 48 55 68 74	6.28 7.24 6.38 5.02 5.69	3.93 4.38 4.02 3.67 3.61	2.24 2.24 2.20 2.16 2.30	1.33 1.32 1.31 1.32 1.46	1.08 1.09 1.03 0.60 0.61	84.0 86.9 90.5 85.0 73.5 80.9
Sunlight	1:1 2:1 2:1 5:1	65 50 57 72	5.42 7.26 6.48 5.64	4.06 4.70 4.48 3.74	2.31 2.57 2.64 2.38	1.30 1.45 1.52 1.50	0.83 0.97 1.05 0.58	80.9 100.4 94.8 99.6
Lestoil®	1:1 2:1 2:1 5:1	66 53 59 71	4.56 6.83 6.32 5.55	3.35 3.95 3.72 3.55	1.74 2.13 2.03 2.21	1.11 1.30 1.23 1.35	0.85 1.04 1.14 0.66	67.6 82.2 81.4 74.0
Casalian ante		GASOLINE IN	IJECTION R	UNS-FLOW	RATE =	1 L/MIN	0.17	50.2
Biosolve	2:1 5:1 10:1	110 112 113	0.20 7.81 7.87 7.83	2.34 2.98 3.36 3.22	2.15 2.36 2.28	0.87 1.35 1.79 1.77	0.17 	59.3 94.4 149.2 136.6
Corexit	2:1 5:1 10:1	115 116 118	7.83 7.84 7.16	2.79 3.13 3.15	1.87 2.09 1.57	1.19 1.37 1.45	0.88	105.5 119.2 112.1
		GASOLINE IN	JECTION R	UNS-FLOW	RATE =	3 L/MIN		
Gasoline only Biosolve	2:1 5:1 10:1	98 102 100 99	3.55 7.89 4.58 5.02	1.67 2.85 2.85 2.94	1.12 2.04 2.16 2.29	0.85 1.26 1.36 1.44	0.66 0.71 0.55 0.57	46.4 69.2 60.0 67.9
Corexit	2:1 5:1 10:1	103 104 105	7.85 6.96 6.94	2.88 2.63 2.70	2.05 1.98 2.09	1.25 1.26 1.30	0.54 0.54 0.52	66.9 70.8 67.7
Gasoline only		gasoline in 160	ijection r 3.78	UNS-FLOW 1.63	RATE = 1 1.18	5 L/MIN 0.58	1.02	45.0
Corexit	10:1	161	6.01	2.83	2.24		0.68	55.2
		GASOLINE IN.	JECTION R	UNS-FLOW	RATE = 1	0 L/MIN		
Gasoline only Corexit	10:1	160 161	3.78 6.01	1.63 2.83	1.18 2.24	0.58	1.02 0.68	45.0 67.8

Summary Data (con't.).

Run Description			С					
		Run Number	2	3	4	5	6	Total Vapor, ppt/min
		GASOLINE HIC	H MIXING	RUNS-FLO	W RATE =	2 L/MIN		
Biosolve	10:1	83	5.08	2.97	2.18	1.39	0.54	54.7
Corexit	10:1	139	5.73	2.30	1.38	1.05	0.59	72.8
Water	10:1	140	4.23	1.79	1.06	0.79	0.64	554
	10:1	141	3.53	1.62	•••	•••	• • •	64.7
		DIESEL INJ	ECTION RU	NS-FLOW F	RATE = 21	/MIN		
Diesel only		42	11.0	7.27	3.63	5.19	4.15	258.5
		43	11.7	6.99	3.65	4.64	3.82	268.0
		46	10.5	6.38	3.72	4.25	3.43	230.9
		95	10.9	4.59	3.42	3.38	1.83	178.5
Biosolve	2:1	88	11.6	4.74	3.76	4.05	2.19	219.8
	5:1	86	12.0	5.04	4.00	4.52	2.31	245.3
	10:1	87	11.1	4.72	3.80	4.33	2.22	226.5
Corexit	2:1	89	11.7	4.65	3.80	4.33	2.46	251.9
	5:1	90	11.4	4.53	3.54	4.02	2.17	287.7
	10:1	92	10.0	3.87	3.11	• • •	2.35	186.4

Summary Data (con't.).

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