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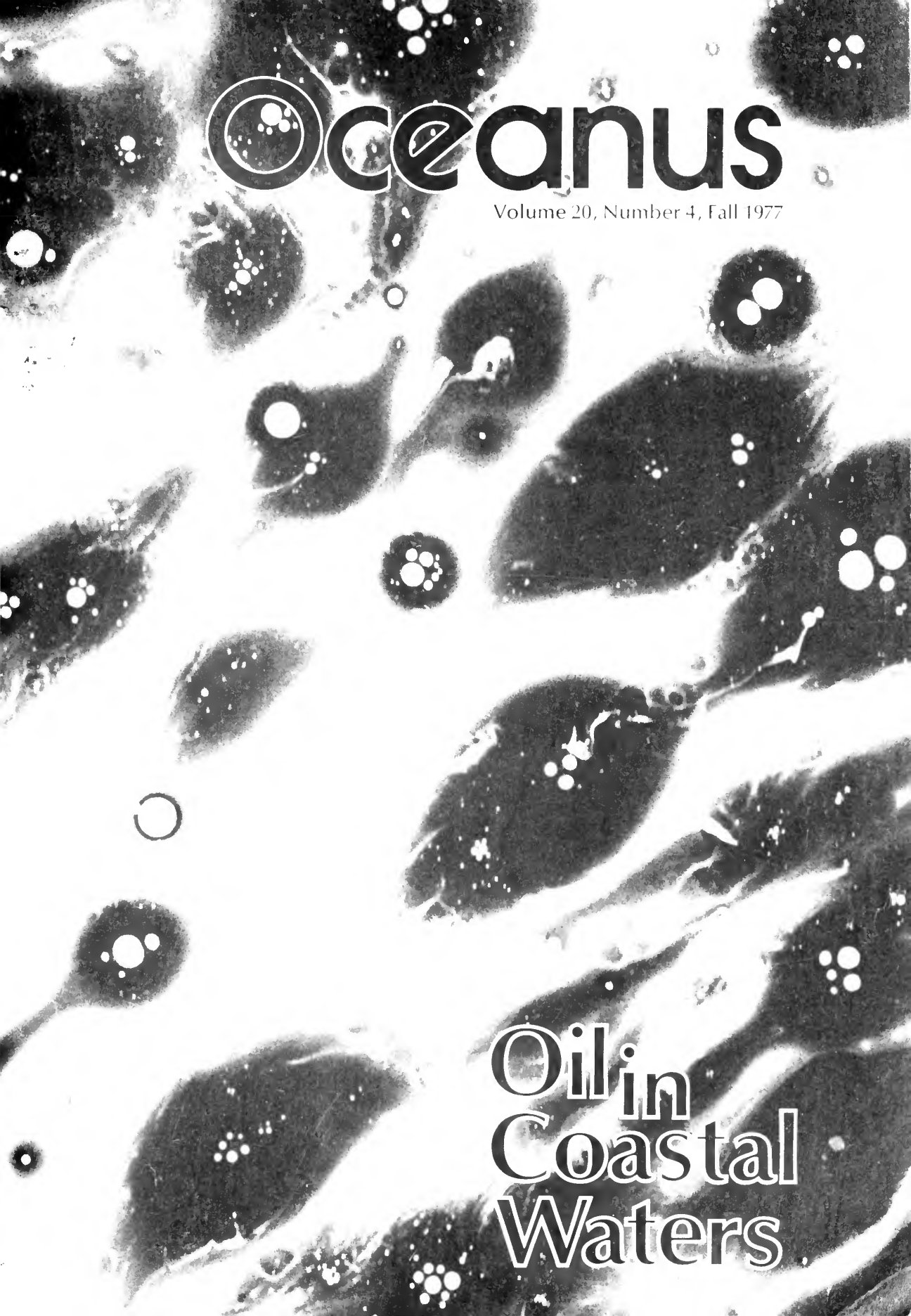

Oil in Coastal Waters

Oceanus®

The Illustrated Magazine of Marine Science

Volume 20, Number 4, Fall 1977

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a bowl. The photograph was taken at the Exxon research laboratories in Linden, rmine the effects of certain chemical dispersants on crude oil. (Photo courtesy

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COVER: crude oil mixing with seawater in a bowl. The photograph was taken at the Exxon research laboratories in Linden, N.J., while setting up experiments to determine the effects of certain chemical dispersants on crude oil. (Photo courtesy Exxon U.S.A.)

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Commentary:

As an energy-hungry society, we will continue to depend on petroleum for as long as supplies last or until alternative energy sources become available and economically competitive — decades, perhaps centuries into the future. This continued, probably growing, use of petroleum carries with it the threat of marine oil pollution throughout our lifetimes.

Does oil pollution threaten catastrophe, or is it a minor perturbation, one of the many stresses man imposes on the marine environment? Oil-soaked birds — unable to fly, dead or dying — are a dramatic and deplorable example of the damage an oil spill can do in coastal waters. But is this a fair gauge of the problem? Could those who tell us that fishing is great around offshore oil rigs equally speak the truth? Only sincere and unbiased scientific investigation of the effects of oil in the marine environment can lead to proper evaluation. Social, economic, and political considerations will be major determinants of regulations to protect our environment, and ultimately of how our civilization may develop. But let the decisions be made with full scientific appreciation of the probable effects of our actions.

It is the purpose of this issue of *Oceanus* to report on some of the significant research being done on the effects of oil in our coastal waters, particularly in the Northeast. From a standing start — one could say a late start — a decade or two ago, scientific institutions have made good progress in investigating how petroleum gets into coastal waters, where it goes, and what effects it may have along the way. Much of the work has been done in the last five years, as evidenced by the papers presented at a recent international scientific symposium sponsored by Canada's Bedford Institute of Oceanography (at which five of the authors in this issue presented papers).

Where does this oil — an estimated 6 million tons per year worldwide — come from? Tanker accidents and oil-well blowouts raise the most concern and receive the greatest publicity, but combined they account for only about 4 percent of the total, according to a study published in 1975 by the National Academy of Sciences (see page 6). A much larger share, 30 percent, results from transportation of oil and related activities. The largest share comes from man's terrestrial operations (44%), such as discharges of municipal sewage and wastes from coastal industries, and including a large amount carried by the rivers into which we dump wastes to be carried, eventually, to the sea. Offshore oil production, also of great concern to many, releases only about a third of 1 percent of the total oil reaching the oceans; a greater hazard is involved in getting this oil

A Fair Gauge

ashore. The remaining 22 percent reaches the sea via the atmosphere (about 10%), from oil seeps on the ocean bottom (about 10%), and from ship accidents not related to oil production. Oil pollution from most of these sources could be reduced considerably by stricter regulations. But the chronic dribbling of petroleum wastes down rivers and bays and into the sea is as difficult to control as it is to measure; these discharges constitute a diffuse source more difficult to assess and study than a localized and intense oil spill.

What happens to petroleum after it enters the sea depends on variables almost as complex as the substance itself: the types of oil, the dosage, the physical nature of the locale, the season, the weather, the types of organisms present. Oil pathways in the ocean include evaporation, solution, emulsification, adsorption onto particles, assimilation into digestive systems, deposition in sediments or weathering into tar balls on the surface. The stuff can be long lived, hidden for years in marsh mud or under sand. It can be present with or without the telltale evidence of surface sheen or smell.

The effects of oil on marine life are beginning to yield to analysis. Some organisms appear to live their lives unaffected. Others metabolize petroleum compounds. Still others cleanse themselves, at least partially, when removed to unoiled areas. Some grow more slowly, or suffer reproductive or communicative impairment, or may develop tumors after prolonged exposure. And some, of course, die. Immediate mortality is in many instances measurable. What isn't yet, at least not in any general sense, is the long-term effect of oil on the marine environment. For example, is the pollutant concentrated in the food chain? Evidence so far suggests that it is not, but here, as in so many other areas, follow-up research is essential.

Long-term investigation — of the recovery of affected ecosystems, the sub-lethal effects of chronic exposure — requires a patient and flexible approach not always found among those hard pressed to make immediate, short-term decisions. Yet it is sorely needed, in this as in other instances where our demands press on the ability of the ecosystems to adjust. We cannot know what we are doing in the full and crucial sense without the difficult business of collecting data, testing theories, and keeping cool.

Bostwick H. Ketchum

Dr. Ketchum, Senior Scientist Emeritus, formerly Associate Director of the Woods Hole Oceanographic Institution, has done considerable research in the area of marine pollution.

The Composition of Oil — A Guide for Readers

During the past 600 million years partially decayed plants and animals have become buried under thick layers of rock. It is believed that crude oil (or petroleum) is a product of the remains of these organisms. This substance has been known throughout historical time. It is described by Herodotus and other ancient writers. It was used in mortar, for coating walls and boat hulls, and as a fire weapon in warfare.

Specifically, crude oil is an extremely complex mixture of hydrocarbons. Although compounds made up of hydrogen and carbon predominate, small traces of sulphur, nitrogen, and oxygen also are present. The three main hydrocarbon classes are:

1) *Alkanes* (paraffins). These are known as *the aliphatic compounds.* They include straight- and branched-chain compounds in which each carbon atom is directly linked to four other atoms. Aliphatic compounds frequently account for a large fraction of the components in crude oil and are common in gasoline and many other fuels. An example of an alkane is hexane. In this issue, when authors refer to *n-alkanes* they are talking about *n*ormal (or straight-chain) compounds. An alkane is said to have a continuous (or straight) chain if each carbon atom in its molecule is joined to at most two other carbon atoms; it is said to have a branched chain if any of its carbon atoms are joined to more than two other carbon atoms. The first four straight-chain alkanes are *methane, ethane, propane,* and *butane.* The alkanes are thus a homologous series of saturated (not tending to form additional products) aliphatic hydrocarbons. Generally, hydrocarbons of low molecular weight* — for example, methane, ethane, and propane — are gases; those of intermediate molecular weight — hexane, heptane, and octane — are liquids; and those of high molecular weight — eicosane and polyethylene — are solids. Paraffin is a mixture of high-molecular-weight alkanes.

2) *Cycloalkanes* (naphthenes). These are known as *the alicyclic compounds.* A cyclic compound that chemically behaves like a straight-chain aliphatic compound is said to be alicyclic. The molecules in these compounds contain a number of atoms bonded together to form a closed chain or ring. An example of such a cyclic compound is cyclohexane, which is found naturally to some extent in petroleum but is combined commercially with benzene for use as a solvent.

3) *Aromatics.* These are compounds whose structure contains the benzene ring. The refining process itself creates additional aromatics. Common aromatic compounds other than benzene include toluene, naphthalene, and phenanthrene (all of which are present in oil). Each of these compounds contains at least one ring that consists of six carbon atoms, each joined to at least two other carbon atoms, and each joined to adjacent carbon atoms by one single and one double bond. The resulting hexagonal structure is characteristic of many aromatic compounds. Several of the aromatic compounds and their metabolites have been identified as potent carcinogens (cancer-producing agents) in laboratory animals.

The following hydrocarbons are also present in crude oil, but in much smaller amounts.

Alkenes (olefins). These are known as *the olefinic compounds,* which are unsaturated chain compounds. These are not usually present in crude oil but are produced by the refining process. Here, double or triple chemical bonds between carbon atoms exist, but not the regular arrangements found in the benzene ring.

Naphthenic acids. Alicyclic compounds with carboxylic acid groups.

Sulphur. Present as free sulphur, hydrogen sulphides, and various organic sulphur compounds, such as thioalcohols (mercaptans).

In addition, there are traces of metals, particularly vanadium. Different crude oils vary in such properties as the proportion of paraffinic to naphthenic hydrocarbons, the sulphur and vanadium contents, and viscosity.

The different hydrocarbon components of petroleum vaporize at different temperatures. The portions of the crude oil that vaporize between defined limits of temperature are referred to as fractions. Generally, the fractions vaporize in the following order: dissolved natural gas, gasoline, benzene, naphtha, kerosene, diesel fuel and light heating oils, heavy heating oils, and finally tars of various weights.

The boiling point is an important physical property of the hydrocarbons. Differences in boiling point between various crude oil hydrocarbons are useful in separating the oil into fractions with individual characteristics suited to specific fuels or lubricants. During the refining process, crude oil is separated into what is termed "cuts" of different boiling ranges. These ranges vary widely depending on the nature of the crude oil (which itself varies from well to well and from day to day), but the following table gives an approximation:

Cut	*Approximate boiling range*	*Approximate molecular size*
Refinery gases	up to 25°C	C_3-C_4
Gasoline	40-150°C	C_4-C_{10}
Naphtha	150-200°C	C_{10}-C_{12}
Kerosene	200-300°C	C_{12}-C_{16}
Gas oils	300-400°C	C_{16}-C_{25}
Residual oil	above 400°C	above C_{25}

There is general agreement that the toxicity of crude oil increases along the hydrocarbon series: from paraffins to naphthenes and olefins, to aromatics. Within each series of hydrocarbons, the smaller molecules are more toxic than the larger (octane and decane are very toxic, while dodecane and higher paraffins are nearly nontoxic). Twelve-carbon atom olefins are quite toxic, and 12-carbon atom aromatics are even more so. Many toxic compounds are removed during the refining process by treatment with sulphuric acid, but in many cases the final product is still toxic.

Paul R. Ryan

*Molecular weight is the weight of a molecule in a substance, and is expressed in atomic mass units (amu). The molecular weight may be calculated from the molecular formula of the substance; it is the sum of the atomic weights of the atoms making up the molecule. For example, water has the molecular formula H_2O, indicating that there are two atoms of hydrogen and one atom of oxygen in a molecule of water. Rounded to three decimal places, the atomic weight of hydrogen is 1.008 amu and that of oxygen is 15.999 amu. The molecular weight is thus (2 x 1.008) + (1 x 15.999) = 2.016 + 15.999 = 18.015 amu. Since atomic weights are average values, molecular weights are also average values. On the average, a molecule of ordinary water weighs 18.015 amu.

The Biogeochemistry of Oil in the Ocean

by John W. Farrington

Oil pollution in the marine environment is the subject of many strong political, economic, and environmental quality debates. The advent of new and/or expanding refinery operations, port facilities, deep water oil transfer terminals, offshore drilling and production, pipelines, and tanker traffic requires an understanding of the source, effects, and fates of fossil fuel compounds discharged into the marine environment. Many scientists around the world are studying the biogeochemistry of these compounds. Such studies are necessary in conjunction with research on the lethal and sublethal effects of petroleum compounds on aquatic organisms. In essence, these biogeochemical studies provide information on the routes, rates of transfer, and reservoirs of accumulation of petroleum compounds in the marine environment. Given an oil discharge at point A, how does it get to point B? How fast? What form does it take? Dissolved? Particulate? How long does it stay at point B before moving to point C? How do the myriad chemicals in oil react with other chemicals in the environment? How are they degraded by microorganisms? Where do the marine organisms come in contact with the oil?

Before the reader can grasp the magnitude of this research challenge, it is essential to consider the nature of crude oil and refined products. Crude oil contains tens of thousands of chemicals. Most are hydrocarbons; molecules composed of carbon and hydrogen atoms arranged in a variety of chemical structures. The molecular weight range of these hydrocarbons varies from methane, which is composed of one carbon atom and four hydrogen atoms, to hydrocarbons composed of more than 60 carbon atoms and 120 hydrogen atoms. Stated in other terms, crude oils can contain gasoline and lubricating oils for automobiles, as well as home heating oils — constituting a wide molecular weight or boiling point range of compounds. In addition to the hydrocarbons, crude oils are composed of small but significant quantities of chemicals that contain nitrogen, sulfur, oxygen, and/or trace metals. The extreme complexity of petroleum, along with its wide molecular weight range, has made it difficult to obtain a complete analysis of petroleum. Thus although the major components of petroleum are now well known, there has yet to be a complete analysis of a single crude oil. Added to this is the fact that crude oils can vary in composition from one well to another in a given field and, on some occasions, from one day to the next in the same well.

This complex chemical soup — petroleum — is discharged into the aquatic environment, itself a complex chemical mixture, and then acted on by a variety of physical, chemical, biological, and geological processes, such as wind, waves, heat, light, oxygen, microbial degradation, metabolism by fish, and adsorption onto particulate matter. During and after all this interaction, the geochemist wants to know — where did all the petroleum chemicals go and why?

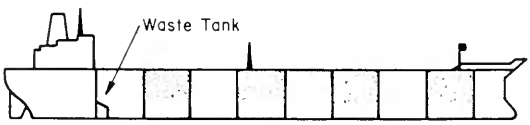
Sources of Fossil Fuel Compounds

The *Argo Merchant,* with its wide coverage on TV and in the press, dramatically reminded the public that shipping accidents cause oil spillage. The subsequent Ecofisk North Sea oil well blowout reminded us that well drilling and production accidents also can cause substantial quantities of oil to be discharged into the sea. These types of accidents, however, account for just a small portion of the total discharge of fossil fuel compounds into the marine environment. Table 1 (taken mainly from a National Academy of Sciences [NAS] study in 1975) gives the sources and amount of petroleum entering the marine environment. Several important points to keep in mind about the table follow:

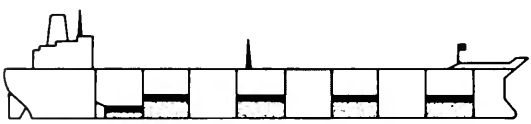
(1) The estimated input rates are in some cases approximations with a wide range of uncertainty. The NAS report ranked the estimates according to the degree of confidence in the value given.

(2) These estimates are global or national averages. The relative importance of the various sources of oil entering the marine environment varies with geographical location and time. For example, a large well blowout would be input of oil to a given location and even when averaged over a 10-year period might result in offshore drilling and production accidents

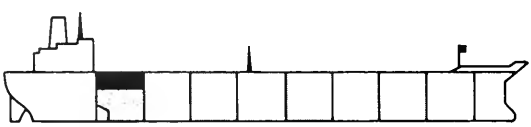
ARRIVING AT DISCHARGE PORT
Full cargo - Clean ballast tank empty



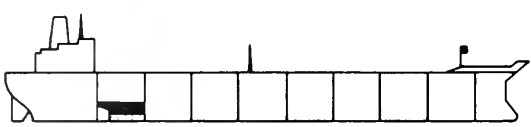
AFTER DISCHARGING CARGO AND PROCEEDING TO SEA
Clean ballast tank full (clean sea water) - Cargo tanks partially full (dirty ballast)



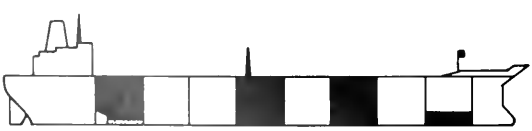
AFTER SEVERAL DAYS AT SEA
Oil settles on top - Clean water pumped from bottom - Tank cleaning of empty tanks - Tank wash water collected in waste tank



AT SEA
Clean ballast for docking - Waste tank containing waste and all residues for separation



ARRIVING AT LOAD PORT
Clean ballast for docking - Waste tank drained of all clean water, leaving only collected residue - Before loading, all clean water pumped into sea



DURING LOADING CARGO
Waste tank loaded on top of residues

Clean sea water Crude oil

Oil contaminated sea water

Figure 1. The load-on-top system. It is used to avoid the problem of washing residues from emptied oil tanks into the sea. Some tanks must be filled with water after unloading or the ship will ride too high in the sea.

dominating inputs for that geographical location.

(3) The largest inputs of oil are from normal operations, and, in fact, are intentional discharges. Accidents related to oil production and transport account for only about 4 percent of the world input. When considering the oil inputs to coastal areas, as opposed to the total marine environment, attention must be given to the location of inputs from tanker operations. Here, the largest input is from ballasting operations; either during cleaning, when some of the unused oil remaining in tanks is discharged, or during the ballast water discharge. In this regard, "load-on-top" tankers discharge less of the oil remaining in cargo tanks than do tankers that do not use this method (Figure 1). Ballast water discharges are usually released offshore, well away from coastal areas. The amount that reaches coastal areas is a complex function of the physical, chemical, and biological weathering and degradation of the oil, plus the water circulation off the coast.

(4) The input from rivers and from land operations contiguous to the coastal waters is

Table 1: Estimate of petroleum and petroleum hydrocarbon inputs to the marine environment.

(Millions of Metric Tons Per Year)

	World	U.S.
Normal Operations		
Offshore Production[a]	0.02	0.003
Transportation[a]		
Load-on-top tankers	0.31	0.05
Non-load-on-top tankers	0.77	0.12
Dry docking	0.25	0.039
Terminal operations	0.003	0.0004
Bilges bunkering	0.5	0.078
Coastal Refineries[a]	0.2	0.03
Coastal Municipal Wastes[a]	0.3	0.10
Coastal Non-Refinery		
Industrial wastes[a]	0.3	0.10
Urban Runoff[b]	0.3	0.10
River Runoff[b]	1.6	0.53
Atmosphere[c]	0.6	0.18
Natural Seeps[b]	0.6	0.12
Accidents[a]		
Offshore production	0.06	0.01
Tankers	0.2	0.03
Non-tankers	0.10	0.02
	6.113	1.510

[a]Estimate with high confidence rating.
[b]Estimate with modest confidence rating.
[c]Estimate with low confidence rating.

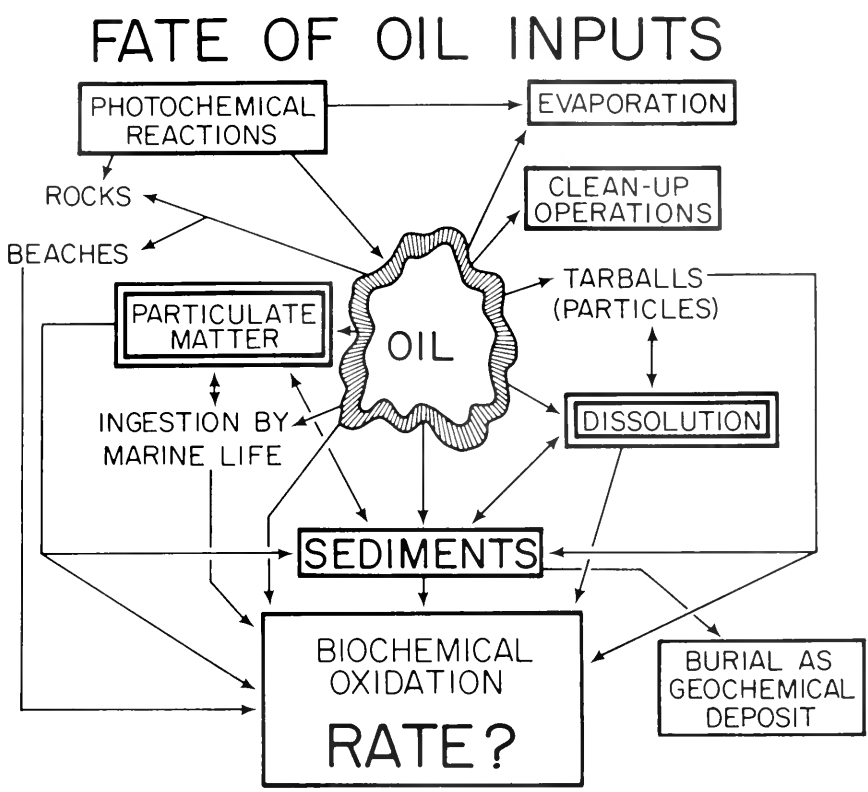


Figure 2. Stylized representation of the fate of oil inputs to the marine environment gathered from several reports in the literature.

substantial, accounting for 57 percent of the total input for the United States and to 44 percent for world inputs.

(5) The marine environment has received inputs of oil from natural seeps for long periods of time. Estimates of this input on a per annum basis are given in Table 1. In some areas, such as Coal Oil Point, Santa Barbara, California, there have been natural seeps for thousands of years, or longer. It is probable that some marine organisms have evolved and/or adapted to these oiled environments over these long periods of time. However, it must be emphasized that the natural seep situation is entirely different from that of discharging oil into areas where no natural seeps have occurred, thus forcing marine organisms to adapt to these inputs over a relatively short time span of 10 years or less.

(6) The effects of the inputs from various sources can be quite different. For example, accidental spills are point source and point-in-time inputs that may have immediate, acute effects, plus long-term chronic effects. On the other hand, municipal or industrial discharges may have no measurable immediate effect, but may have long-term chronic effects as the concentration of the petroleum chemicals builds up in the ecosystem.

A synopsis of the fate of oil in marine ecosystems is given in Figure 2. This information has been gathered from several different studies. There has yet to be a fully balanced study of a spill. Although we know that most of the pathways shown in Figure 2 are important in each spill, we still do not have a quantitative measure of the relative importance of each pathway. However, substantial progress has been made toward this goal.

Buzzards Bay Oil Spill Studies

One of the most comprehensive geochemical studies of a spill was conducted by the late Dr. Max Blumer and his colleagues at the Woods Hole Oceanographic Institution, including Jeremy Sass, and Drs. John M. Teal and Kathy Burns (now at the Ministry for Conservation, Melbourne, Australia). They studied the fate of Number 2 fuel oil that spilled into Buzzards Bay, Massachusetts, in September 1969 (see page 15). Measurements were made over a five- to seven-year period. There is still Number 2 fuel oil in the marsh sediment of Wild Harbor River eight years after the spill (Figure 3). Subtidal sediments still contained components of the Number 2 fuel at least five years after the spill. The lesson learned: if you do not see an oil slick on the water, it does not mean the oil has disappeared from the sediments under the water. Since the

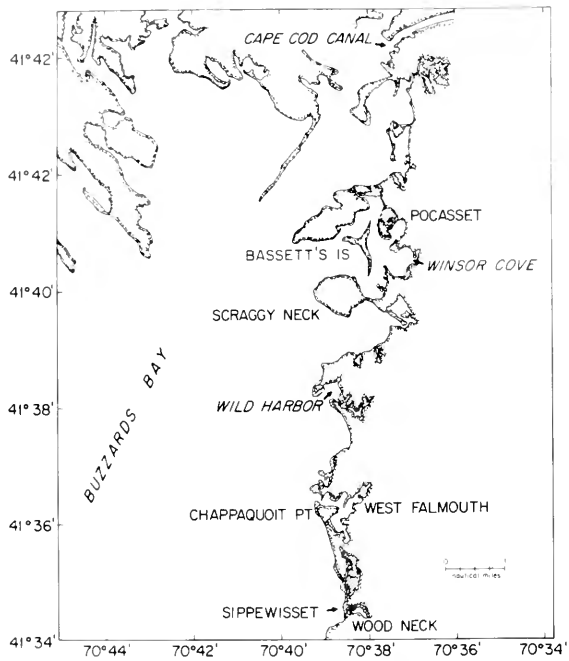


Figure 3. Locations of the 1969 and 1974 Number 2 fuel oil spills at Wild Harbor and Winsor Cove.

sediments and associated bottom-dwelling organisms are an integral part of the coastal marine ecosystem, there is a continued chronic exposure of these ecosystems to components of fuel oil.

Frequently at oil pollution conferences, petroleum industry representatives state that the West Falmouth oil spill was unique and that it is unlikely that another spill will result in such a longevity of oil in sediments. As Dr. Vandermeulen points out (see page 31), the *Arrow* spill involving Bunker C oil resulted in long-term, seven-year contamination of some intertidal areas. Certainly no two spills are exactly alike. There are differences in the compositions of oil and in various other factors, such as the time of year of the spill, the coastal area, weather, the amount spilled, the proximity to shore, and so on. However, the West Falmouth and *Arrow* oil spill studies had a commonality — once oil was incorporated into the sediments, some of the components stayed for a period of five to eight years, or more.

Few, if anyone, would hope for an accidental Number 2 fuel oil spill in Buzzards Bay to study and test the results of the West Falmouth oil spill. However, in October of 1974, the *Bouchard Barge No. 65* hit bottom in Buzzards Bay and was towed to an anchorage at the west end of the Cape Cod Canal. From there, oil spread to shore areas around Basset's Island and Scraggy Neck. Oil slicks entered several areas, one of which was a small region called Winsor Cove (Figure 3). Since the time of the spill, we have sampled an intertidal marsh area in the cove every fall and spring. Our objectives were limited; we wanted to compare the fate of the oil incorporated into the intertidal marsh sediments, and then compare those findings with the West Falmouth spill studies. Our May and June 1977 analyses of the marsh sediments show that weathered Number 2 fuel oil is still present two and a half years after the spill (see page 25). The changes in the composition of the oil, resulting from weathering and microbial attack, closely parallel the fate of the oil spilled into the Wild Harbor area in 1969.

Thus two spills of Number 2 fuel oil entered nearby marsh areas of Buzzards Bay at about the same time of year, and the resulting fate of the oil has been the same for at least two and a half years. These two spills are an example of chronic spillage of oil into coastal areas. During the winter of 1977, the same barge — the *Bouchard 65* — again spilled Number 2 fuel oil into Buzzards Bay. For the year 1975, the U.S. Coast Guard listed 10,141 oil pollution incidents, ranging from small spills of a few gallons to very large ones in the thousands of gallons. A critical question is whether or not areas receiving repeated small spillages will be able to cleanse themselves of oil prior to the next spill, and the next. . . . Will the benthic community, for instance, recover from one spill before being subjected to the next?

Fossil Fuel Hydrocarbons

Estimates of petroleum inputs show that the type of spills we have been discussing are a small part of the total input of oil to the marine environment (Table 1). Slow, chronic dribbling of oil from sewage effluents contribute larger quantities of fossil fuel hydrocarbons. Do these inputs result in contaminated sediments, with subsequent long-term exposure of the overlying waters to toxic petroleum compounds? During my thesis research (1968-1971) with Professor James G. Quinn at the University of Rhode Island Graduate School of Oceanography, we investigated sediments and hard-shell clams

from a number of stations in Narragansett Bay (Figure 4). These stations ranged from the sewage-polluted Providence River area to the mouth of the West Passage of Narragansett Bay, a fairly clean area. From Station C to E_1 (up the West Passage to the Providence River) there was evidence of increasing concentrations of petroleum hydrocarbons in the surface sediments and hard-shell clams.

In trying to locate the source of these petroleum compounds, we searched the records of oil spills in the areas we sampled. We also measured the Field's Point Sewage Treatment Plant effluent for hydrocarbons. The concentration of hydrocarbons was 2 to 16 milligrams per liter. Gas chromatographic analyses showed that the hydrocarbons were predominantly of petroleum origin. Calculations of the concentration of the flow of sewage effluent showed an estimated 130 to 650 metric tons of petroleum hydrocarbons per year are discharged into the Providence River area of Upper Narragansett Bay. After comparing these values with the low estimates of oil input gathered from the spill records, we surmised that the sewage effluent discharges were the source of the petroleum compounds found in the surface sediments and shellfish in the upper part of Narragansett Bay, and might be the source of the compounds found in the surface sediments and clams of the West Passage area around stations C and D, although numerous small spills in that area also were likely contributors.

Since that time Professor Quinn has directed thesis research by several students investigating petroleum contamination in Narragansett Bay. They have conducted some very excellent, detailed experiments which confirm that petroleum hydrocarbons are discharged by the Field's Point Sewage Treatment Plant, primarily in association with particulate matter. These are transported to the upper bay area. Laboratory studies have shown that partitioning of the petroleum compounds between particulate matter, sediments, and water is significantly influenced by sediment type, organic matter content of sediments and seawater, and the chemical structure of the petroleum compounds. Furthermore, the uptake of petroleum compounds by hard-shell clams is also influenced by many of the same parameters.

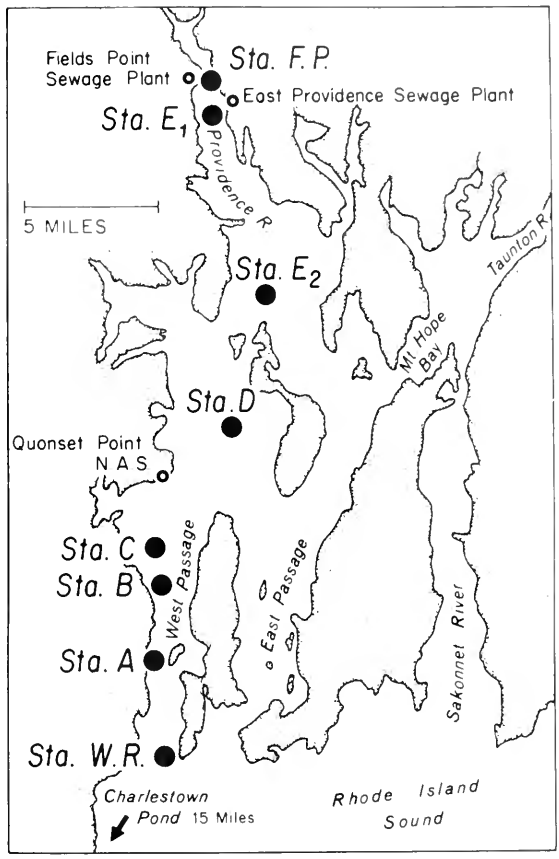


Figure 4. Station locations in Narragansett Bay, R.I., where surface sediments (all stations) and hard-shell clams (stations A, C, and E) were obtained and analyzed for hydrocarbon concentrations and composition. (From Farrington and Quinn, 1973)

Petroleum contamination of surface sediments resulting from effluent discharges and/or repeated small spills is not restricted to Narragansett Bay. During the last five years, several similar situations have been reported in West Germany, Britain, France, and Italy, not to mention other estuaries and harbors in the United States.

New York Bight Sewage Sludge

Since 1972, my laboratory has obtained surface sediments from a number of locations in the western North Atlantic with support from the National Science Foundation, the Office of Naval Research, and the Environmental Protection Agency (Figure 5). These samples have been analyzed for concentration and composition of alkanes and cycloalkanes, some of the principal hydrocarbons of petroleum. Several alkanes are also

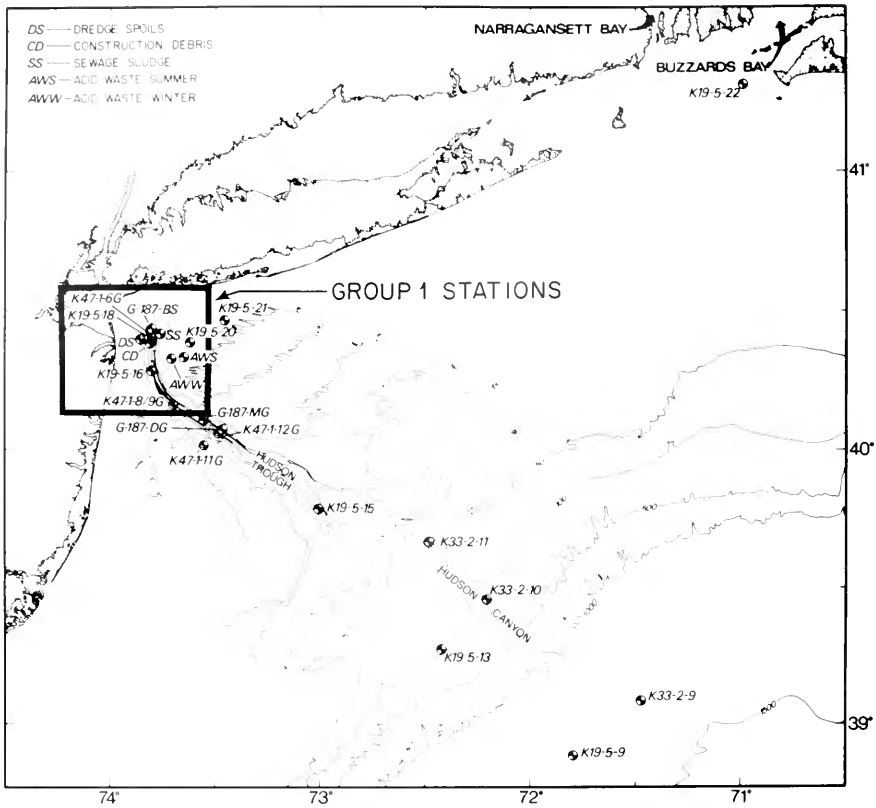


Figure 5. The western North Atlantic, showing stations where surface sediments were obtained for analysis of concentration and composition of hydrocarbons. Group 1 stations were found to be the most polluted with fossil fuel hydrocarbons and are also in or near the ocean dumping sites in the New York Bight. (From Farrington and Tripp, 1977)

biosynthesized by marine organisms, but they can usually be easily distinguished from petroleum compounds, except when petroleum is present at extremely low concentration levels. The results of the analyses show that there is no more than 1 to 10 micrograms (μg) of petroleum hydrocarbons per gram of dry weight for Continental Margin sediments — that is, all others except Group 1 stations in Figure 5. At this time, it is impossible to tell where these petroleum compounds came from, although long-term weathering of ancient sediments (a natural process) or tar particle flux to surface sediments in the Sargasso Sea (a pollution process) are candidates for further investigation. Hydrocarbon concentrations in surface sediments from stations marked Group 1 in Figure 5 have concentrations of hydrocarbons ranging from 50 micrograms per gram dry weight at stations K47-1-8/9G to 2 milligrams per gram dry weight at the dump site locations, such as station G-187-BS. This is a two order of magnitude increase in concentration of hydrocarbons compared to stations outside Group 1.

Analyses of the wide molecular weight range and extreme complexity of the hydrocarbons' composition show that petroleum pollution is causing the elevated concentrations of hydrocarbons. Further evidence is obtained by measuring the carbon-14 radioactivity. The concentration of hydrocarbons in the New York Bight dump site areas is high enough to make it practical to extract about 2 to 5 kilograms of surface sediments and obtain a sufficient amount of hydrocarbons to measure the C-14 radioactivity of the carbon portion of the hydrocarbon molecule. If the hydrocarbons were recently biosynthesized by marine organisms using carbon sources present in the contemporary marine environment, the hydrocarbons would have a young "age," as determined by C-14 geochronology. Hydrocarbons from petroleum have no measurable C-14 activity because the carbon comes from organic matter deposited in sediments many hundreds of thousands of years ago, and all the C-14 has undergone radioactive decay. Thus there should be little if any measurable C-14 activity if the hydrocarbons are from petroleum.

Dr. Elliot Spiker of the U.S. Geological Survey determined the C-14 activity of the hydrocarbons isolated from the dump site sediments. His measurements indicated that there were no more than 10 to 20 percent recently biosynthesized nonpetroleum hydrocarbons, and probably less than 10 percent.

Thus the high concentration of hydrocarbons in the surface sediments, the analyses of the composition of the hydrocarbons, and the C-14 determination all provided evidence of petroleum contamination in these dump site area surface sediments. There also were elevated hydrocarbon concentrations in the area of the Hudson Channel near the dump sites, indicating that some dump site material was being transported to this area. This also was true for measurements of fecal coliform bacteria and trace metals as reported by other researchers. The extent to which these dump site materials and associated pollutants will be spread around the New York Bight area is under investigation by the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA).

The major sources of hydrocarbons from the dump site area are contaminated dredge spoil and sewage sludge. Sewage sludge accumulates hydrocarbons from industrial discharges into municipal sewers, and from atmospheric fallout and rain. Dredge spoil from harbors are contaminated by innumerable small spills and effluent discharges. We have estimated that dumping in the New York Bight area contributes 3.6×10^3 tons of hydrocarbons per year to Continental Shelf sediments.

The proposed Georges Bank Outer Continental Shelf drilling and production area (OCS) is directly adjacent to the north and northeast of our stations, and the Baltimore Trough or mid-Atlantic OCS area is immediately to the south. The estimated global discharge of petroleum from routine operations and spills associated with OCS operations is 180×10^3 tons per year. Thus the rate of pollutant hydrocarbons discharged by dumping in the New York Bight alone is at least 2 percent of the 1973 global OCS discharge rate (see *Oceanus*, Summer 1976). Since there are other dump sites on the Continental Shelf off the East Coast of the United States, the input of petroleum hydrocarbons into the shelf area from this source is certainly greater than the New York Bight input alone. The fate and effect of the hydrocarbons from dumping activities and the fate and effect of OCS discharges may not be the same. However, it is important to consider that even before OCS activities have begun, significant, measurable quantities of petroleum hydrocarbons are being delivered to the Continental Shelf areas off the eastern United States. This must be taken into account when assessing potential environmental impacts of OCS operations now and in the future.

Hydrocarbon Contamination in Sediments

Every now and then researchers uncover interesting information while searching for something else. Philip Gschwend, a graduate student at the Woods Hole Oceanographic Institution, and I were investigating the distribution of three natural occurring hydrocarbons in a sediment core from Buzzards Bay, when we noticed that the signal in the gas chromatograms of the hydrocarbons indicated that the surface sediments contained about 50 micrograms per gram of dry weight of hydrocarbons, similar to that found in weathered petroleum. More importantly, these compounds decreased in concentration in the deeper sections of the core. Could it be that the sediments collected in this area of Buzzards Bay were depositing at such a rate that they contained a historical record of chronic oil spillage in Buzzards Bay? The literature at that time (1973) reported that sediments from some of the basins off Southern California contained historical records of certain trace metals and DDT that had been discharged into the environment by man.

Dr. Vaughan T. Bowen and his co-workers in the Chemistry Department at the Woods Hole Oceanographic Institution investigated another area of Buzzards Bay sediments for the depth distribution of radionuclides from bomb fallout. Their results suggested that if we obtained about a 1-meter core at their study site the bottom 4-centimeter section would contain sediment deposited about 1700-1750. We obtained such a core and enlisted the aid of Dr. Michael Bacon, also of the Chemistry Department, and Robert Anderson, another graduate student, to assist us. They applied Pb-210 geochronology dating to estimate the sedimentation rate, thereby providing a means for placing a time scale on the core sections analyzed for hydrocarbons. The analyses of these sections showed again that there was a decreasing concentration of petroleum alkanes and cycloalkanes with increasing depth in the sediment, and the concentrations had started to increase in the

time interval about 1900 to 1940. Thus we thought we were seeing a historical record of chronic oil spillage into Buzzards Bay.

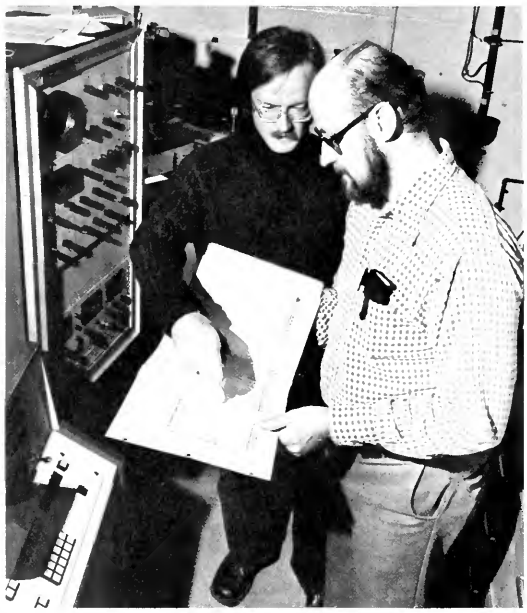
Our hypothesis was short lived. Dr. Blumer and Dr. Walter Giger of the Swiss Federal Institute of Water Research had just completed a study of polynuclear aromatic hydrocarbons in surface sediments of Buzzards Bay. These compounds are the second major class of compounds of petroleum after alkanes and cycloalkanes. Their data showed that the aromatic hydrocarbon composition was not that found in petroleum but resembled compositions of polynuclear aromatic hydrocarbons reported for pyrolytic sources, such as forest and grass fires. Because the composition of these compounds was the same in a variety of samples of New England soils and sediments, they suggested, along with co-worker Dr. William Youngblood, that these compounds were from pyrolytic sources.

Why was there an indication of a historical record of pollutant alkanes and cycloalkanes from chronic oil spills and no record for aromatic hydrocarbons, generally found to be equally stable over the time span investigated? With hindsight, the answer seems simple. Let me first explain how we arrived at the answer.

Dr. Nelson Frew, a Research Specialist in the Chemistry Department, applied quantitative mass spectrometric analysis to the hydrocarbon fractions from the core sections to measure phenanthrenes, a class of aromatic hydrocarbons. These analyses again indicated that the source of the hydrocarbons was predominantly pyrolytic. However, there was a decreasing concentration of phenanthrenes with increasing depth in the core, which paralleled the decreasing concentration of the cycloalkanes and alkanes. Professor Ronald A. Hites and Dr. Robert LaFlamme of the Department of Chemical Engineering at the Massachusetts Institute of Technology measured the concentrations and compositions of several other polynuclear aromatic hydrocarbons obtained in three sections of another core from the same station in Buzzards Bay. The core section with sediment deposited prior to 1900 had lower concentrations of polynuclear aromatic hydrocarbons than did the sections of surface sediments that contained an order of magnitude higher concentrations, plus compositions indicating a pyrolytic origin. We searched the literature and found that there were a few reports on alkanes and cycloalkanes in urban air that matched our data on these compounds. Professor Hites had measured urban air and found that the polynuclear aromatic hydrocarbons data also fit with a pyrolytic origin in urban air, especially if one considered that the dissolving action of water on hydrocarbons adsorbed to sediment particles slightly alters the composition of polynuclear aromatic hydrocarbons deposited there and in soils.

Thus the simple answer and our current hypothesis from all of these collective studies is: The sediments of the study area of Buzzards

Gas Chromatography — Mass Spectrometry



Author, right, consulting with Dr. Nelson Frew, who operates the gas chromatograph-mass spectrometer (GC-MS) facility for chemists at the Woods Hole Oceanographic Institution. The GC-MS provides a detailed analysis of the fuel oil composition after the oil has been extracted from seawater and chemically separated into aliphatic and aromatic fractions. Each fraction is further separated into individual components in the GC by gas-liquid phase partitioning. These components are then bombarded with electrons in the MS to produce fragmentation patterns characteristic of the components' molecular structures. (Photo by Frank Medeiros)

Bay contain a historical record of the fallout of urban air hydrocarbons. These are incorporated into the sediments directly through the overlying water column and also by soil washing into the bay from surrounding areas. These findings are similar to ones arrived at by colleagues who have simultaneously studied freshwater lake sediments. Dr. Gerhard Müeller and co-workers at the University of Heidelberg, West Germany, who have studied the sediments of Lake Constance, a part of the Rhine River system, arrived at the conclusion that there was a historical record of urban air hydrocarbon fallout in that lake's sediments. Dr. Stuart Wakeham, currently at the Swiss Federal Institute of Water Research, also reported similar findings for Lake Washington, Seattle, Washington.

It is highly likely that urban air fallout in the Greater New York area reaches the sediments at the New York Bight dump sites. This fallout comes from combustion processes in automobiles, power plants, home heating furnaces, and industrial plants, where it is then deposited on streets and washed into storm and sanitary sewers. Professor Hites and his co-workers measured the polynuclear aromatic hydrocarbons in one of our samples from the New York Bight and found that these hydrocarbons were of pyrolytic origin.

At present, we do not know if concentrations of polynuclear aromatic hydrocarbons from urban air fallout (found in surface sediments of Buzzards Bay and elsewhere) are causing stress in the ecosystem where they reside. We do know that several of these compounds or their metabolites (see page 59) are known or suspected carcinogens or mutagens. Their concentration in surface sediments has increased over the last several decades. This presumably reflects an increased exposure for the ecosystem through which they pass on their way to the sediments, as well as the benthic ecosystem where they reside. An important question is whether or not a switch in the mix of fossil fuel combustion used for energy — for example, more coal combustion and less petroleum — would result in an increased release of polynuclear aromatic hydrocarbons to world ecosystems. It may well be that ecosystems can adapt to these low concentration levels of polynuclear aromatic hydrocarbons. Certainly, over geological time such compounds have been released into the environment as a result of oil seeps, and forest and prairie fires. Perhaps a key question can be phrased here: How much can we add to the natural background level and how fast can we increase the concentration before there are adverse effects?

Some Future Research Questions

We have established that petroleum and urban air hydrocarbons are found in surface sediments of the New York Bight in very high concentration levels and at lower concentration levels in some areas of Buzzards Bay. We now need to know more about how these hydrocarbons move through these ecosystems and what threats they pose. Present research, funded by the Energy Research and Development Administration, focuses on the interaction of benthic organisms with petroleum-polluted sediments and water. New benthic study chambers will be constructed, allowing us to measure various petroleum pollutants as they are released from sediments under a variety of bottom current conditions. Other research with the chambers will focus on the influence of benthic organisms, such as small worms and bivalves, on the release of the petroleum from the sediments, with the subsequent incorporation of compounds into their tissues.

At the Marine Ecosystems Research Laboratory (MERL) at the University of Rhode Island researchers are studying large controlled ecosystems in tanks on the shoreline of Narragansett Bay. Scientists at other universities and institutions are participating in these studies, too. They are comparing the biological and geochemical responses of Narragansett Bay ecosystems (including sediments and bottom-dwelling organisms) to chronic additions of petroleum. The initial experiments have been underway for about a year. A great deal of effort has been focused on making sure that the control tanks are as close as possible (in biological and chemical composition and function) to the study area. The use of controlled ecosystems for pollution studies was initiated by CEPEX (Controlled Ecosystems Pollution Experiment) under the auspices of the Office of the International Decade of Ocean Exploration, National Science Foundation. MERL is the next generation of these types of experiments.

Others have developed independently in Scotland, West Germany, and France. These experiments are complicated and expensive — MERL, funded by the Environmental Protection Agency, is budgeted to spend a few million dollars over a three-year period.

What do studies using controlled ecosystems accomplish? A detailed answer to that question would require another article. It is sufficient to use the following analogy, one I feel comfortable with as a chemist. In the chemical industry, new product discoveries are usually developed in laboratories. Before going into full-scale production, industry builds pilot plants because it is not easy to go from laboratory chemical reactions to a production plant. After testing is done in the pilot plant, a full-scale plant is developed. Often, even after extensive tests, problems develop in the production plant. Many times these are researched and corrected at the original pilot plant.

In many respects, the controlled ecosystem is a pilot plant for marine biologists and geochemists. It allows us to study and control certain parameters and observe cause-and-effect relationships on large segments of the marine environment. At MERL, we are presently conducting a controlled chronic oil pollution experiment. We have three replicates of a non-polluted system and three of the same system subjected to chronic oil pollution at the 100 to 300 micrograms per liter concentration level. It would be very difficult to find and effectively study as many controls and chronically stressed systems in the natural environment. The MERL systems will be used to provide some answers, which we will then have to verify in real coastal and estuarine ecosystems. Furthermore, we may discover something under these controlled conditions that we will want to investigate further in the natural environment. These experiments will not be limited to oil pollution studies, but will include other pollution stresses as well. Of equal or greater importance, marine scientists want to find out how the natural coastal ecosystems function. Such knowledge would be of immense value in effectively managing coastal and estuarine ecosystems.

In all of these studies, we have to be prepared to move quickly into new areas of research and to take advantage of new knowledge. An example of this is the recent finding by Drs. Arthur Scheier, Richard Larson, and their co-workers at the Stroud Water Research Center of the Academy of Natural Sciences in Philadelphia. These scientists and others have shown that petroleum compounds undergo photochemical attack (Figure 2). Since toxic aromatic hydrocarbons are subjected to photochemical attack, some may have been led to think the compounds were no longer toxic because they had reacted. However, the experiments at Stroud have shown that photochemical reactions of certain petroleum compounds produce mixtures that are more toxic to certain marine organisms than the original petroleum product. As pointed out by Dr. John Stegeman (see page 59), certain marine organisms can metabolize aromatic hydrocarbons. Under certain conditions, the metabolites are excreted from the organism, reducing the danger to it. Under others, the metabolites can have adverse effects. The challenge has been set forth by these results. Marine geochemists and biochemists need to measure these metabolites in ecosystems, determining the present exposure levels for marine organisms and investigating how they and other reaction products move through the marine environment.

John W. Farrington is an Associate Scientist in the Chemistry Department, Woods Hole Oceanographic Institution.

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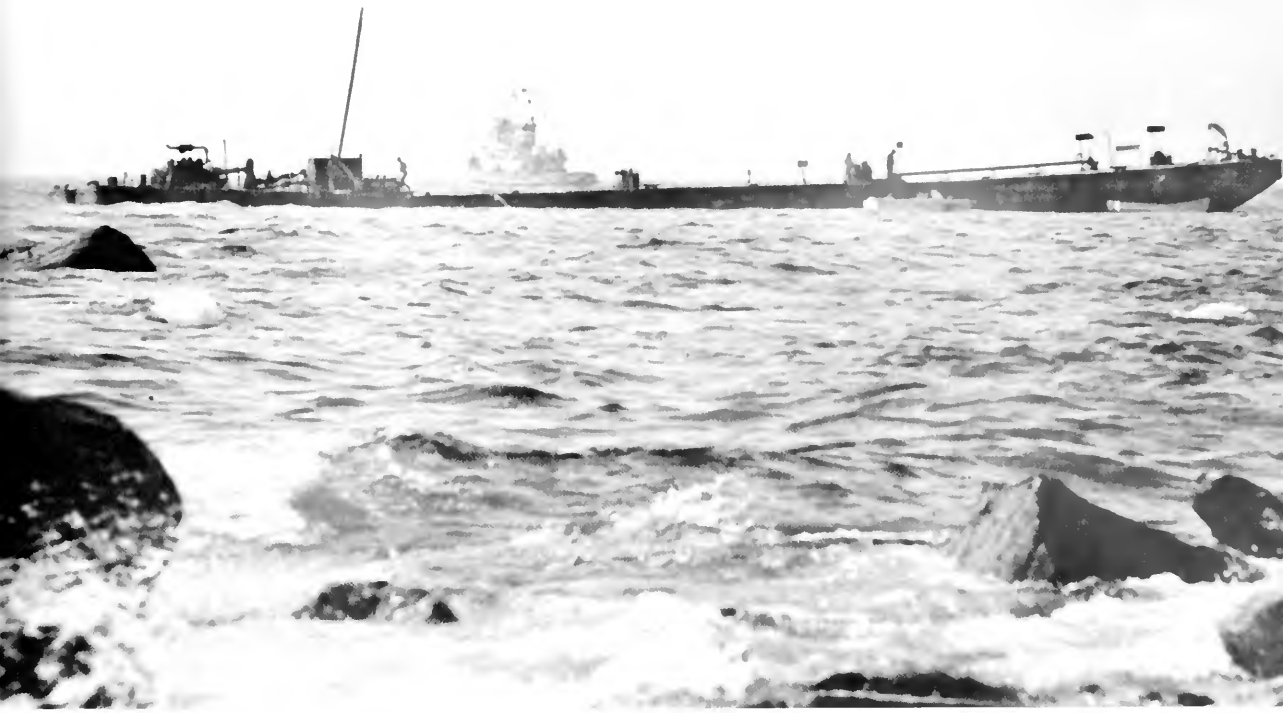


THE WEST FALMOUTH SPILL —*Florida*, 1969

by Howard L. Sanders

Two of the prime objectives of the 200-mile limit bill that went into effect last March were to permit the recovery of the nation's important fishing grounds from overfishing by foreign fleets, and to provide for the proper management of the resources once this was accomplished (see *Oceanus*, Summer 1977). In the case of Georges Bank, it is ironic that these worthy aims may be compromised by proposed oil exploitation. If oil is found there and extracted, oil slicks resulting from chronic low-level oil pollution will become environmental features on Georges Bank, requiring long-term studies of the overall impacts on the fisheries in the area.

Some of the articles in this issue directly concern the *Argo Merchant* oil spill of last December. While the oil from that spill did not come ashore, it might have if the winds had been less favorable. One of the most disturbing results of the spill was its possible effect on fish eggs (see page 46). The slick, more than 100 miles long and about 20 to 30 miles wide, extended on the surface of the sea eastward toward Georges Bank at a time when a number of important commercial fishes, such as pollock and cod, were breeding. Their eggs, confined to the surface, were in direct contact with the spilled oil. The implications of this are obvious.

To put the *Argo Merchant* spill and the potential pollution from oil exploitation into a perspective useful for future decision making, let us consider an exhaustive investigation undertaken by myself and several other scientists on the biological effects of a spill that occurred off West Falmouth, Massachusetts, on September 16, 1969. On that date the barge *Florida* came ashore at Fassett's Point, losing about 650,000 to 700,000 liters of Number 2 fuel oil into the waters of Buzzards Bay. Today, more than eight years after this spill, oil will still pool in your footprints if you walk through some inshore areas at low tide.

Above, the barge Florida *aground at Fassett's Point, West Falmouth, Massachusetts. (Photo courtesy* Falmouth Enterprise)

It should be noted that every oil slick and spill is unique unto itself. Thus the findings in our West Falmouth study do not directly relate to oil exploitation or the *Argo Merchant* accident. They do, however, offer some indications of the long-term residence of oil in benthic sediments and the corresponding reduction of many species of marine fauna. At one reoccupied station near the *Argo Merchant* that was initially unoiled, a set of three sediment samples revealed traces of oil and a three-fold decrease in marine life as compared to those taken 10 weeks earlier. Of course, if the *Argo Merchant* oil had come ashore and even though it would have been a different grade of oil, many of our findings could have had a direct correlation.

Our investigation of the *Florida* accident, entitled "Anatomy of an Oil Spill: The West Falmouth Study," is the most detailed work undertaken thus far on the impact of oil on bottom-dwelling marine life. It is also one of the very few studies of long enough duration to measure long-term effects. The investigation — authored in addition to myself by J. Frederick Grassle, George R. Hampson, Linda Morse, and Susan Garner-Price — documents in 574 pages the initial decimation of organisms in the most severely oiled sites, the pronounced reduction of life at intermediately oiled locations, and the elimination of a few of the more sensitive species at the marginally oiled bottoms. The study incorporates the results of three independent chemical studies: Max Blumer and J. Sass in 1971; K. A. Burns and J. M. Teal in 1971; and A. D. Michael, C. D. Van Raalte, and L. S. Brown in 1975.

Up to 1973, the study of the Falmouth spill was supported by a grant from the Environmental Protection Agency, but since then the investigation has continued without financial aid. The one positive feature of this arrangement is that it freed the investigators from the constraints of bureaucratic overview that often inhibit productive research. Thus the post-1973 research can be viewed as a public service.

The Massive Kill

In the immediate aftermath of the *Florida* grounding, strong winds from the south-southwest moved the oil in a north-northeast direction, carrying much of it into the Wild Harbor and the Wild Harbor River area of North Falmouth. The shoreline soon became littered with continuous windrows of dead fish and marine invertebrates, indicating a massive kill of at least the larger marine animals in the intertidal and subtidal areas of Wild Harbor.

Seven subtidal sampling stations were established and then followed for extended periods of time. These ran from Wild Harbor, where the concentrations of the oil in the sediments were highest and the maximum visual impact on the marine biota was more evident, into the main body of Buzzards Bay along a gradient of decreasingly oiled sediments (stations 31, 30, 9, 10, 20, 5, and 35). The more offshore and minimally oiled stations — 20, 5, and 35 — served as reference sites. In addition, intertidal stations II and IV were established along the axis of severely oiled Wild Harbor River (Figure 1) together with a control site in unoiled Sippewissett

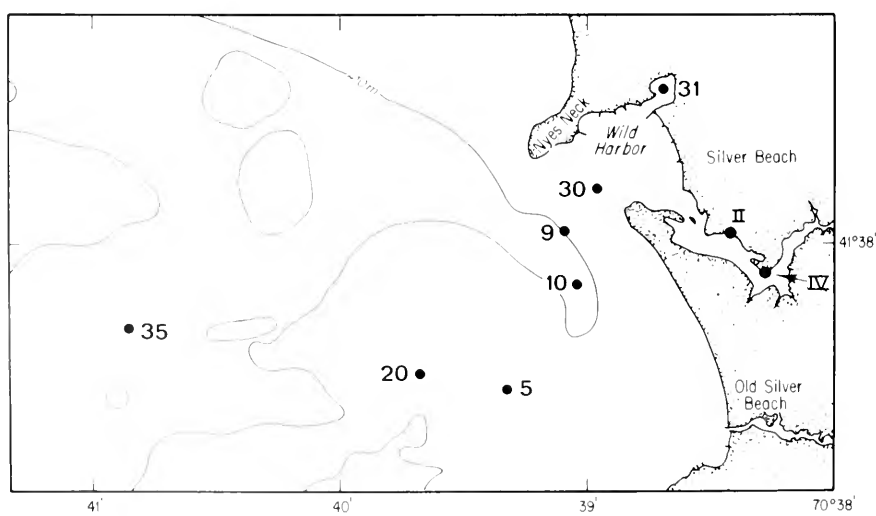
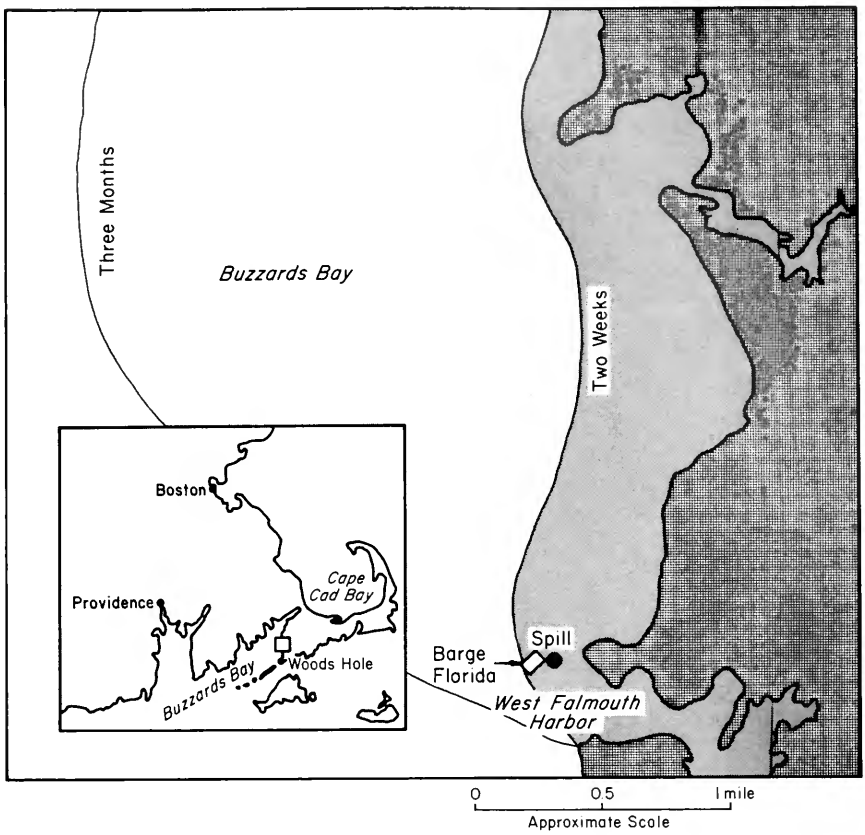


Figure 1. Location of the main subtidal and intertidal stations where faunal samples were collected in Buzzards Bay, Wild Harbor, and Wild Harbor River.



Oil contamination of bottom sediments spreads with time. The approximate boundaries of the oil in the study area at two weeks and at three months after the spill. (Adapted from "A Small Oil Spill" by M. Blumer, H. L. Sanders, J. F. Grassle, and G. R. Hampson, Environment, *Vol. 13, No. 2* © *Copyright 1971. Committee for Environmental Information)*

Marsh. By sampling each station at monthly or bimonthly intervals, changes in oil concentration and composition were carefully monitored. The resultant petroleum hydrocarbon data were then related to the detailed analyses of the biological samples.

On the evening of the day the *Florida* went aground, the company responsible for the clean-up operations added emulsifiers (Aquaclean 100 and Colloid 88, both water-based and claimed to be nontoxic by the manufacturers) at Silver Beach in Wild Harbor and more solutions were added at various points on September 17, 18, and 19. A total of 17,072 liters of emulsifiers were put into the waters before the activity was officially curtailed. The kill of marine organisms, however, was clearly evident by the early afternoon of the 16th, at least four hours before any of the emulsifiers had been added. Thus they could not *per se* have been the immediate causative agents of the kill.

Our conclusions from the initial period of the study included:

1. *In the short period of eight to ten days at the relatively high temperatures of 18 to 21 degrees Celsius, the carcasses of the great majority of animals lacking hard parts rotted and decomposed so that no remnants of their presence remained. Thus there would have been little evidence of the massive kill if a survey had been carried out more than ten days after the spill occurred.*

2. *Whenever oil was detected in sediment samples, there was some mortality in the associated biological samples – the larger the concentration of oil, the greater the mortality. In some samples that were strongly saturated with oil, the kill was almost total.*

3. *Sediments, both intertidal and subtidal, particularly those with a predominantly sandy composition, became more unstable. Apparently this was due to the breakdown and disappearance of animal secretions, tubes, and benthic algae that bound the sediment.*

4. *Marsh grasses that came in contact with the waterborne oil at high tide during the first three weeks after the spill were killed* *(see page 25).*

5. *In much of Wild Harbor River and at subtidal station 31 almost no species of animal life persisted. Among the few surviving forms was the pollution indicator polychaete worm,* Capitella capitata, *which explosively increased in numbers and occupied the bottom in very dense concentrations. By late spring and early summer of 1970, the numbers of this polychaete precipitously decreased as a few other species were able to reoccupy their habitat.*

6. *In the spring of 1970, the gonads of the surviving remnants of the blue mussel,* Mytilus edulis, *were thin, emasculated, hardly more*

than empty sacs. By contrast, the blue mussels from unpolluted Sippewissett Marsh had ripe, well-developed gonads that filled the body cavity.

7. Subtidally, the zone of oil pollution spread. This phenomenon continued to occur for years after the spill.

Chemical Analysis

The techniques of gas chromatography* and, to a lesser extent, mass spectrometry, were the methodologies used to identify the Number 2 oil in the West Falmouth spill. They also were used to monitor the oil's chemical changes over time at a number of sampling stations. Both techniques have been generally employed in the past to distinguish crude oils from different sources, as well as to analytically differentiate the various refinery products of crude oil.

Chemically, oil is a substance of great complexity. The thousands of different molecules of hydrocarbons present in any crude oil, covering a very wide molecular weight range from 16 to more than 20,000 atomic mass units, are the products of diagenesis beneath the surface of the earth under anaerobic conditions over geologic time spans of millions of years. Despite the extreme chemical diversity present in any crude oil, most of the different molecules can be included within a few major homologous groupings of saturated hydrocarbons — straight-chain hydrocarbons (straight-chain paraffins, n-alkanes); branched hydrocarbons (branched paraffins); cycloalkanes (naphthenes); and aromatic hydrocarbons.

In contrast, biologically derived hydrocarbons, being the products of natural evolution, are synthesized from specific rather than randomized processes. Such processes generate a limited and circumscribed suite of hydrocarbons of relatively narrow molecular weight range. Up to at least carbon 22 (C_{22}), such natural hydrocarbons can be resolved into individual compounds by medium resolution gas chromatography. No animal or plant species harbors more than a very limited number of biologically synthesized hydrocarbons, and frequently a single one predominates. Thus petroleum contains a much greater variety of both molecular structures and molecular weights than native or biologically derived hydrocarbons.

The homologous series of n-alkanes (n stands for normal or straight-chain) in petroleum hydrocarbons contain molecules with odd and even numbers of carbon atoms at an approximate ratio of 1.0. Adjacent numbers of a series usually vary little in concentration. In natural hydrocarbons, however, the odd numbered n-alkanes are markedly more dominant. The aromatics present in any crude oil are highly complex mixtures of great variety, containing mono- and poly-benzenes and naphthalenes, a perplexing and nearly infinite array of polynuclear aromatics with multiple alkyl substitutions, and a highly heterogeneous complex of naphthene-aromatics. In contrast, naturally occurring aromatics are rare, simple in structure, and contain, at most, one or two alkyl substitutions.

Cycloalkanes, like aromatics, display considerable heterogeneity in crude oils. Those with substituted rings are more abundant than their parent compounds. Cycloalkanes are uncommon in living organisms, and, when present, occur as simple, one-to-three chain rings. Only the alkenes (olefins) are more abundant in natural hydrocarbons where they often form the major fraction of the biologically synthesized hydrocarbons. This unsaturated hydrocarbon grouping is generally absent in crude oil but can be present in refined petroleum as a product of the "cracking" of long-chain hydrocarbons into shorter hydrocarbon chains. These differences between naturally occurring hydrocarbons and petroleum hydrocarbons can serve as criteria when determining whether a given site has or has not been polluted by oil.

How the Oil Was Altered

Basically, oil can be altered through four processes — evaporation, dissolution, biodegradation, and chemical degradation. Evaporation uniformly depletes the lower boiling point components of the different structural units (n-alkanes, branched alkanes, cycloalkanes, aromatics) which is reflected in a

*Chromatography is the chemical process of separating closely related compounds by permitting a solution of them to filter through an absorbent so that the different compounds become absorbed in separate layers. Earliest applications of these techniques involved colored pigments. Hence chromatography from "chroma."

Table I: Hydrocarbon Content of Buzzards Bay Sediments

in mg hydrocarbons/100 g dry sediment

Year	Month	Station numbers, offshore												River stations	
1969		5	6	7	9	10	20	30	31	35	36	37	90	II	IV	V
	Sept.			6.9			3.9		55					59	45	
	Oct.			19			4.4		110	4.6					55	
	Nov.			14	24	15	2.4		110	5.3	2.0	4.0				
	Dec.			12		25	4.5		110	6.0				76	150	180
1970	Jan.										6.2	4.4				
	Feb.											3.8		51	120	15
	Mar.								12			3.5				
	Apr.			4.8		28	6.2		450	4.2	2.1	5.9			140	190
	May			6.5		25	3.5		210	4.9	2.5	7.0		52	40	77
	June			4.5		18	2.4		400	5.3	2.9	6.7		44	23	78
	July			7.4		14	2.5		240	6.4	4.3	5.7		75	150	40
	Aug.					9.2			120		2.9	4.1				
	Sept.			2.6	5.9	9.4	4.9		210	7.9	6.1	4.2				
	Oct.													63	81	56
	Nov.			4.3		9.8	3.1		300	11	6.8	8.5		22	18	45
	Dec.			5.0	11	8.0	3.4		190					45	35	55
1971	Jan.		4.9						160	5.4	4.0	5.0				
	Feb.			5.4	6.7	9.4	3.4	3.2		3.3	3.1	7.3				
	Mar.								200					39	34	29
	Apr.	1.8	6.6	3.5	7.7	5.6	5.2		200					37	86	
	May															
	June			4.5	5.6	8.8	3.6		230	4.4	4.2	4.6	2.6	15	19	40
	July	3.3		1.1		4.6	2.3				6.0		11	34	27	16
	Aug.	3.7	15	1.3	6.1	5.4	2.0		130	3.5		5.6	13	14	40	32
	Sept.			3.0		8.4	5.4		130	4.5	3.9	4.6				
	Oct.													15	34	19

All data rounded to two significant figures. (From Blumer and Sass, 1972)

uniform reduction of the lower molecular weight envelope. The dissolution process also differentially removes the hydrocarbons of lower molecular weight. However, because of their greater solubility, aromatics are more susceptible to dissolution than are the alkanes. For hydrocarbons with more than 14 carbon units, the effects of dissolution and evaporation processes are minimal for all structural units.

In contrast to dissolution and evaporation processes, biodegradation of oil affects a much wider boiling range of hydrocarbons. Within the same homologous series they are degraded at approximately the same rate. Normal alkanes are the most readily degraded, followed by branched alkanes. Cycloalkanes and aromatics are reduced at much slower rates. Chemical degradation is not well understood, though it is believed that intermediate and higher molecular weight aromatics are the most readily altered by this process.

The Number 2 fuel oil spilled off West Falmouth was a distillate of crude oil with a boiling point range of 170 to 370 degrees Celsius. The normal alkanes ranged from n-decane to n-docosane (C_{10}-C_{22}) with a maximum in the C_{14}-C_{15} region. The numerous isomeric and homologous hydrocarbons present, primarily aromatics and cycloalkanes, produced extensive boiling point overlaps. This phenomenon is expressed in the gas chromatograms as a broad unresolved envelope. Superimposed on this unresolved background are resolved or partially resolved peaks of homologous series of normal and branched alkanes.

Hydrocarbons with a boiling envelope of 170 to 370 degrees Celsius were present only in those sediments in Buzzards Bay that were affected by the 1969 spill (Table 1). The

magnitude of the unresolved envelope revealed in the gas chromatograms was greatest in the region of maximum pollution and highest kill of marine life. The magnitude of the unresolved envelope gradually decreased along a gradient of diminishing biological effects. At all sampling sites along this continuum, the size of the unresolved envelope diminished with time as a response to the gradual degradation of the oil.

The oil impregnated in the sediments from the West Falmouth spill was modified primarily through the processes of biodegradation and dissolution. Evaporation and chemical degradation played little or no role. Gas chromatographic analyses indicated that the straight and branched alkanes were degraded predominantly by bacterial activity (biodegradation), while the depletions among the aromatics occurred largely through dissolution. The more soluble lower molecular weight and less substituted aromatics gradually degraded, while the more substituted and higher molecular weight aromatics were little affected.

The samples used for these chemical analyses of the Number 2 oil were taken whenever biological and sediment samples were obtained. The late Max Blumer of the Woods Hole Oceanographic Institution reported these early findings, along with Grassle, Hampson, Sass, G. Souza, and myself.

Gross Hydrocarbon Concentrations

In a 1972 report covering two years, Blumer and Sass stated that by far the greatest concentration of hydrocarbons were present at station 31. This station remained very heavily impregnated with Number 2 fuel oil during the entire two-year period of the study (Table 1). Only the initial sample (taken in September 1969), registering 55 milligrams of hydrocarbons per 100 grams of dry sediment, contained less than 100 milligrams of hydrocarbons. Thus except for the first sample, the concentrations of hydrocarbons during the study were from one to more than two orders of magnitude higher than the upper limits of the normal environmental background of Buzzards Bay (10 milligrams per 100 grams of dry sediment).

The three intertidal river stations — II, IV, and V — also contained quantities of hydrocarbons that exceeded the normal environmental background throughout the period of study. Concentrations varied from a minimum value of 14 milligrams (station II, August 1971) to a maximum value of 190 milligrams (station V, April 1970). These chemical analyses clearly refuted the unverified but frequently stated assumption that low boiling constituents of oil are rapidly lost through evaporation and dissolution. Blumer and Sass demonstrated that at the heavily polluted sites mentioned earlier the boiling point distribution of the oil continued to be very similar to the initially spilled oil with the minimal boiling range extending as low as C_{13} and C_{14}. In localities where the concentrations of spilled oil were intermediate (stations 7, 10, and 30) or low (station 20), hydrocarbons in the C_{13} and C_{14} range could still be detected two years after the spill.

Despite the fact that biodegradation of the straight-chain hydrocarbons was clearly evident in the less severely polluted sediments soon after the spill, low concentrations of n-alkanes persisted at all stations throughout the period of monitoring. Blumer and Sass pointed out that the "persistence after two years of even a fraction of the easily attacked normal paraffins throws some doubt on the expected effectiveness of bacterial seeding as means of reducing environmental oil residues in polluted sediments."

The chemical studies by Blumer and his colleagues were carried forward by Michael and others. As late as April 1973 at stations 9 and 10, and May 1974 (the last sampling date) at intertidal stations II, IV, and V, and subtidal station 31, they found that the boiling point range and the spread of the unresolved envelope of the oil at these stations closely approximated the Number 2 fuel spilled off West Falmouth by the *Florida*.

A third chemical investigation of the spill was undertaken by K. A. Burns and J. M. Teal, reported on in 1971. They centered their study on the Wild Harbor River Marsh, investigating its sediments, flora, and fauna. Taking all chemical analytical factors into account, they found that all the samples they analyzed yielded residues of the Number 2 oil. Each of the control samples from Sippewissett Marsh, with one exception, contained only hydrocarbons of biogenic origin.

These three independent chemical studies reinforced each other and, in totality,

showed the severe oiling of the inshore subtidal sediments, the intertidal flats, and the marsh by the Number 2 oil. They also documented the contamination of the flora and fauna.

Reaction of Species

Samples collected in our study showed an overwhelming numerical dominance by two capitellid polychaete species, *Capitella capitata* in the first year at intertidal stations II and IV and subtidal station 31, and *Mediomastus ambiseta* at the other subtidal stations during the second and third years. *Capitella* contributed 62.5 to 99.9 percent of the specimens present in 19 of the 25 samples obtained at stations II, IV, and 31 from September 1969 through August 1970. *Mediomastus* comprised 51.5 to 93.9 percent of the individuals in 26 of the 35 samples collected after July 1970 at stations 5, 9, 10, 20, and 35.

In response to the nearly total decimation of the benthic fauna in the area of maximum oil pollution immediately following the oil spill as exemplified by intertidal stations II and IV and subtidal station 31, there was an explosive increase in the opportunistic *Capitella*. Such an exponential numerical increase to densities of tens of thousands to more than 200,000 individuals per square meter composed almost entirely of this polychaete, and the persistence of these highly elevated capitellid densities through June 1970 demonstrated that from December 1969 to July 1970, the intertidal flats of the Wild Harbor River and the neighboring subtidal bottoms were converted into a remarkably dense unispecies culture of *Capitella*.

The intertidal Sippewissett control samples revealed considerably more stability regarding total density, species numbers, and faunal composition than did the samples collected from the Wild Harbor River stations II and IV. These findings support the interpretation that the differing temporal patterns evident at stations II and IV and at the Sippewissett station were a response to the oil-induced stress in the Wild Harbor estuary.

The pattern in the outer reaches of Wild Harbor in Buzzards Bay as documented by stations 9 and 10 showed a marked depression in animal numbers and species in the aftermath of the spill from September 1969 through July 1970. During this period, the habitat could be considered "biologically undersaturated." Within the brief period of a month (from July to August 1970), the benthic density increased more than 30- and 23-fold at stations 9 and 10, while the species numbers rose from 18 to 61 at station 9, and from 34 to 83 at station 10.

The fauna was composed almost entirely of very young individuals that had recently moved from the overlying water and settled onto the bottom. This phenomenon can be related to the fact that the majority of benthic species in this geographic region are summer breeders. These very high densities were immediately followed by a precipitous drop in numbers during the fall, winter, and spring of 1970-71 to the low density levels found in September and October 1969. Such extremely high mortality rates for the benthic invertebrates in the second year after the oil spill revealed that the benthic fauna had not recovered over this time period. The higher species numbers coupled with intermediate densities and less variation in the third year, particularly at station 10, were indicative of some recovery (Table 2).

The faunal density patterns at the more offshore stations — 5, 20, and 35 — differed considerably from the patterns evident at stations 9 and 10. Excluding *Mediomastus*, faunal densities averaged nearly an order of magnitude higher at stations 5 and 20 from September 1969 through July 1970 than did those at stations 9 and 10. The furthest offshore station (35) departed from the pattern found at stations 5 and 20 by its consistently lower densities, although the mean density from September 1969 through July 1970 remained well above the mean densities obtained at stations 9 and 10 for this same period. There was no obvious increase in faunal numbers in the August 1970 samples at stations 5, 20, and 35, when the densities increased 30- and 23-fold at stations 9 and 10. Unlike the precipitous drop in density found at stations 9 and 10 from August 1970 to at least the end of the year, densities at stations 5, 20, and 35 remained relatively constant during the same time interval.

A dominant species is arbitrarily defined as a species that numerically comprises at least 10 percent of a sample. The patterns of dominance at the intertidal stations II and IV

Table 2: The number of samples analyzed at a given station, the total number of animals collected at each station, the mean density at the stations and the time interval over which samples were collected at each of the stations.

	Total Density	Mean Density	No. Samples	Time Interval
Sta. II	5,375	448	12	Sept. 69-Oct. 71
IV	8,233	392	21	Sept. 69-May 72
Sippewissett Marsh	961	192	5	Sept. 69-Feb. 71
5	26,954	2,695	10	Sept. 69-Feb. 71
9	45,102	2,505	18	Sept. 69-March 72
10	50,084	2,636	19	Sept. 69-March 72
20	32,603	2,174	15	Sept. 69-Feb. 71
30	7,102	1,015	7	Sept. 69-Feb. 71
31	22,037	1,102	20	Sept. 69-Jan. 73
35	25,186	1,799	14	Sept. 69-Aug. 71
	Σ 223,637			
7	1,582	316	5	Sept. 69-Dec. 69
8	598	299	2	Sept. 69-Oct. 69
37	717	717	1	Nov. 69
80	3,281	1,094	3	June 70-June 71
90	78,314	9,789	8	Aug. 70-Aug. 71
	Σ 84,492			
		Amphipod density		
36	857	122	7	Nov. 69-Feb. 71
37	187	47	4	Nov. 69-March 70

clearly demonstrated that the fauna over the entire sampling period (from September 1969 through October 1971 at station II and from September 1969 through May 1972 at station IV) were highly unstable at these heavily oiled sites and in a state of changing composition. The density pattern and the dominant species pattern at severely oiled subtidal station 31 were similar to those found at intertidal stations II and IV. Despite the profound differences in sediment composition between station 31 and stations II and IV, eight of the eleven species that achieved dominant ranking at station 31 were also dominant species in the station II and IV samples. No species at station 31 was a constant numerical dominant, nor did any single species appear as a dominant in even half of the 20 samples. Because of the abrupt and often extreme changes in both densities and faunal composition, the presence of most numerically dominant species was highly erratic. The only exception to this erratic pattern occurred during the late fall, winter, spring, and early summer of 1969-70, when *Capitella* was present as a numerical dominant in seven sequentially collected samples obtained from November 1969 through August 1970, and *Polydora ligni*, in six, from December 1969 through August 1970. There was little faunal similarity between dominant species at station 31 and the other intensively sampled subtidal stations. Station 31 shared only two species with station 10, one with station 9, and none with stations 35, 5, and 20.

Intermediately oiled stations 9 and 10 shared 13 out of a total of 17 and 15 dominant species, respectively. These shared species at the two stations showed close temporal successional synchrony. Stations 9 and 10 had few dominant species in common with marginally oiled stations 35, 5, and 20. Only two were found to be the same in an atypical sample from station 5 that had a sediment composition similar to station 9.

Unlike the other stations, station 35 had a major amphipod constituency that included five of its 11 dominant species. Amphipod species were not present in proportions high enough to be called dominants at the other stations. Stations 5 and 20 were both minimally oiled, alike in terms of fauna, and had similar

coarse sandy sediments. More than at any of the other sampling sites, polychaetes, particularly syllids, overwhelmingly characterized the two stations. Six dominant species were shared between the nine dominants at station 20 and the eight dominants at station 5. The two species at station 5 that were not found as dominants at station 20 were collected from a single sample in somewhat finer-grained sediment than is normal for this station.

One of the most characteristic benthic elements found in the shallow waters of New England are various species of infaunal amphipod crustaceans belonging to the family *Ampeliscidae*. These crustaceans are typical components of the benthos in sandy and mixed bottoms. Both their high sensitivity to modest quantities of oil and their absence in oil-contaminated sediments make ampeliscid amphipods excellent oil pollution indicators.

Our study revealed that the impact on the ampeliscid amphipods off Wild Harbor followed temporal and spatial stress gradients induced by the concentration and relative degradation of the Number 2 oil. The effects were most severe and longer lasting at the more heavily oiled subtidal inshore stations and gradually became less intense and of shorter duration in the progressively less severely oiled stations further offshore.

An Overall View

It is not possible to cover all aspects of our study here. We have touched on only the highlights. It should be noted that the same hierarchial pattern emerged no matter what statistical criterion was used to measure the effects of the spill. During the course of our study, several statistical methodologies were employed to amass data. These also served as a cross-check on results. From the simple presence or absence of species data, the highest fidelity was found at the marginally oiled stations, lower fidelity at the intermediately oiled stations, and lowest fidelity at the severely oiled stations (Figure 2).

The Coefficient of Variation, which serves as a statistical index or measurement (standard deviation/mean) for determining variability, was used to assess faunal variability throughout the entire sampling period for each of the stations. Faunal variation remained very high at the severely and intermediately

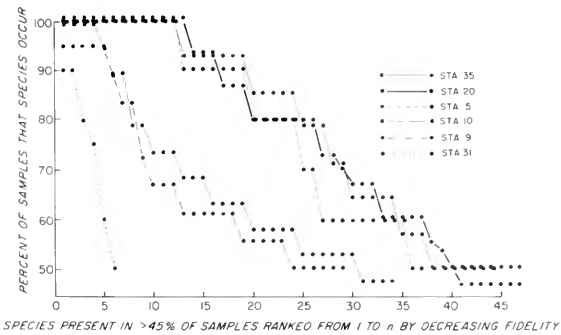


Figure 2. Fidelity patterns, determined on the basis of the absolute presence or absence of a species, at stations 31, 9, 10, 5, 20, and 35.

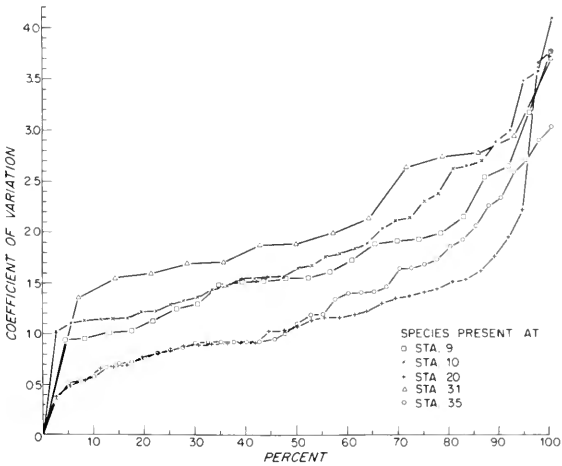


Figure 3. The Coefficient of Variation values (standard deviation/mean) at stations 9, 10, 20, 31, and 35. For a species to qualify, it must be present at a mean density ≥ 3.0 individuals at one or more of the five stations.

oiled stations and low at the marginally oiled sites (Figure 3).

A new statistical methodology, the Discrepancy Index, was developed to measure the average yearly difference in the benthic fauna at several of the stations (Figure 4). Very large and large differences were documented for the severely and intermediately oiled stations, but only small differences were found for the marginally oiled stations. Diversity (when corrected for obvious artifacts) was highest at the marginally oiled stations, lower at the intermediately oiled, and lowest at the severely oiled stations. Over time, increased diversity was found at some of the stations. This was primarily a response to species richness rather than greater equitability. Another methodology, cluster analysis, revealed profound temporal changes in the

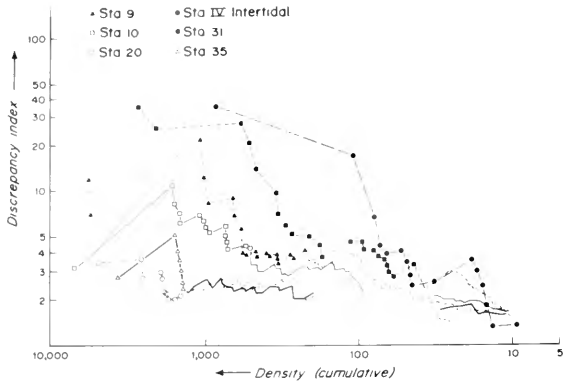


Figure 4. Discrepancy Indices for the whole fauna at stations 9, 10, 20, IV, 31, and 35 obtained by comparing the composition of the fauna in the first year of study with that in the second. The greater the departure from the baseline of 1.0 (exact identity) the greater the faunal difference between the two years.

fauna from samples collected at the severely and intermediately oiled stations but documented a much more homogenous pattern with only small seasonal changes from samples obtained at the marginally oiled stations.

From all these measurements we have gained our overall view. We can see that oil from the barge *Florida* moved along the seafloor so that previously unpolluted sediments became impregnated with the same oil weeks, months, and even years after the spill with resultant concomitant kills of bottom-dwelling organisms.

With some weathering of the oil, recovery was initiated first in the lightly oiled bottoms and progressively later at locations that were moderately and heavily oiled in the period immediately following the spill. At the intermediately oiled sites, there was only partial recovery when sampling was terminated after two and a half years. Recovery was even slower at those stations that were severely oiled initially, and the oil is still present in the sediments today, more than eight years after its spillage into Buzzards Bay. At least one station has not regained its normal complement of animal species. At others, although nominal recovery has taken place, the animals are not behaving normally.

My colleagues, Drs. John Stegeman and Denis Sabo, have demonstrated that a small fish, the Mummichog or Killifish, that lives in a shallow estuary that was oiled by the spill produces seven times as many lipids as do Mummichogs present in other nearby estuaries that were not polluted by oil.

Other scientists (C. T. Krebs and K. A. Burns, 1977) have shown from studies carried out five and six years after the spill that young larvae of fiddler crabs that settle onto the marshes do not survive if even very small concentrations of oil are present in the sediments.

The muscle tissue of a juvenile herring gull killed on the flats of the Wild Harbor River one month after the spill showed the entire range of fuel oil hydrocarbons (K. A. Burns and J. M. Teal, 1971). The chromatogram of the brain tissue demonstrated the presence of a large boiling point envelope that was identified as aromatics by ultraviolet spectroscopy. This is a concrete example of how an animal at a high level in the food chain was severely contaminated by the hydrocarbons from the Number 2 fuel.

Finally, the clam flats are still closed and the tissues of the edible clam are enfused with petroleum hydrocarbons. Thus a single influx of oil from a modest spill into the waters of Buzzards Bay has resulted in a sequence of pollution events that still has not run its full course.

Howard L. Sanders is a Senior Scientist in the Biology Department of the Woods Hole Oceanographic Institution.

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A Three-Year Study at Winsor Cove

Salt Marsh Grasses and #2 Fuel Oil

By George R. Hampson and Edwin T. Moul

The marsh grass community in a small cove in Massachusetts that was affected by spilled oil from a barge in October of 1974 has shown a progressive resistance to reestablish itself over the last three years. The sediments in some areas around the marsh grass roots contain high concentrations of petroleum hydrocarbons, which have impregnated the peat substrate. Erosion rates over the three-year period have been 24 times greater than those at a nearby control site.

These findings stem from a spill of undetermined amount that occurred on October 9, 1974. On that date, the barge *Bouchard No. 65,* loaded with 73,000 barrels of Number 2 fuel oil, hit a submerged object while traveling northeast into Buzzards Bay. She was then towed to the west entrance of the Cape Cod Canal, where she was anchored at the entrance to Hog Island Channel (Figure 1). By the day following the accident, an undetermined amount of oil had escaped from the 2.4-meter split in the *Bouchard's* hull, and strong southwest winds were driving the slick ashore on Bassett's Island and into Red Brook Harbor. This oil remained on the surface in this area for approximately 10 days.

The initial rough seas had made it impossible to contain the spill by use of a "boom." As is often the case, oil containment both at sea and on land is ineffective because of excessive wind conditions and lack of proper organization in the clean-up operation. In this case, much of the oil released from the barge escaped the confines of the boom.

Shortly after the oil came ashore, there were signs of massive kills of marine life — crabs, snails, soft- and hard-shell clams, and so on. A total of 4,360 invertebrates, comprising 110 species (2 of which were fish), were collected in eight separate samplings. This article, however, will not deal with this aspect of the spill, but will focus on the effect of the oil on the marsh grasses at Winsor Cove.

About three weeks after the spill, we noticed that the marsh plants in Winsor Cove — *Spartina, Salicornia, Limonium* — were exhibiting the same "browning" effect from Number 2 oil as seen in the West Falmouth spill of 1969 (see page 15). In contrast, a nearby

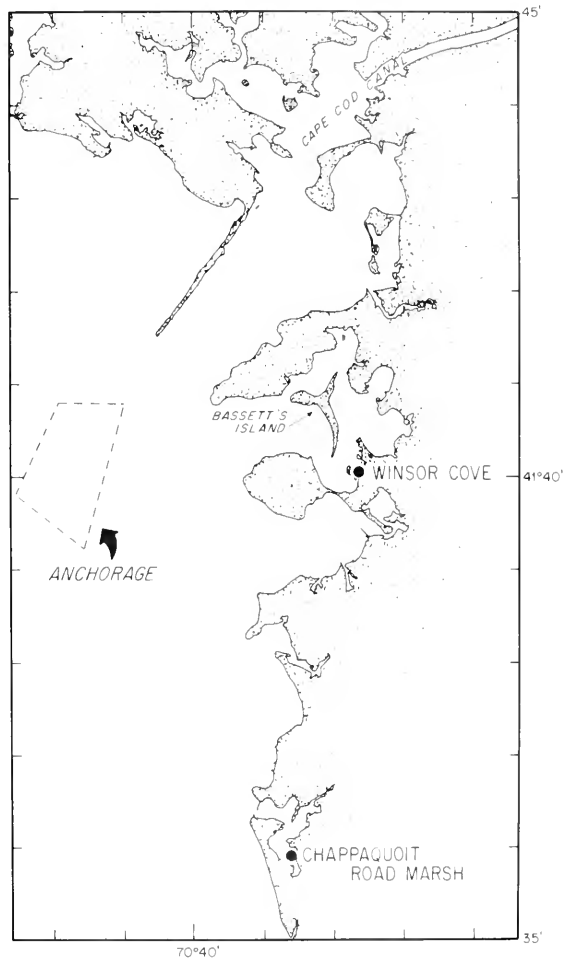


Figure 1. The Winsor Cove area on Buzzards Bay, Massachusetts.

marsh at Chappaquoit in West Falmouth Harbor showed no evidence of "browning" or discoloration, thus making it an obvious candidate for a "reference" station.

In Winsor Cove and off Chappaquoit Road a series of quadrats were established, running perpendicular from the low to the high waterline. An aluminum frame (41 x 35 centimeters) was used as a boundary marker, and the first quadrat was placed at the water's edge. The locations of the 18 successive quadrats were determined by a series of wooden stakes that were driven into the marsh. The species and individual stem counts

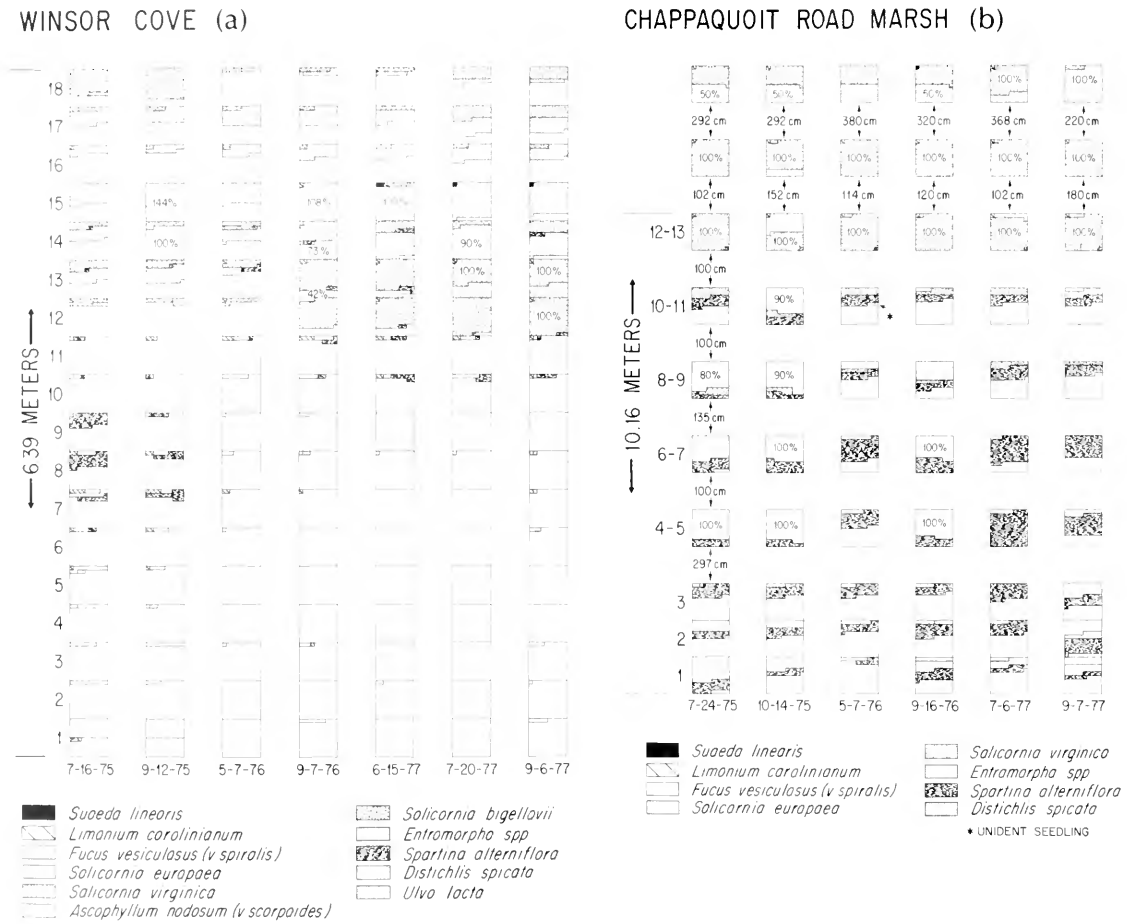


Figure 2. Quadrat species composition during sampling study. Winsor Cove (a); Chappaquoit (b).

of the marine grasses within each plot were recorded from July 15, 1975 to September 7, 1977. Figure 2a and b are comparative graphs for Winsor Cove and Chappaquoit, showing the quadrat species composition during each sampling period for the length of the study.

The Chappaquoit station was selected because of its similarity in flora, prevailing winds, and protection from wave erosion. The control transect was arranged differently in that all the quadrats were not adjacent, primarily due to a more gradual marsh slope. In some cases within a floral community, quadrats were spaced apart in order to reduce excessive repetition of data.

Precise photographic stations were established with permanent markers in Winsor Cove on October 23, 1974. The photographs accompanying this article document the growth of *Spartina alterniflora* and *Salicornia* before and after decomposition (Figures 3 and 4).

Since the *Bouchard* spill, the depauperate marsh grass community in Winsor Cove has not significantly reestablished itself either by reseeding or by rhizome growth. In the spring of each year, some species sparsely regenerate a few seedlings or stems (*Limonium* and *Fucus*), but by late summer, the majority of the new recruitments are either absent or remain seedlings or dwarfed specimens.

Spartina Growth Measurements

In September 1976 and 1977, a series of comparative random height measurements were made of *Spartina alterniflora* stems growing in Winsor Cove and at the control site in West Falmouth. The polluted marsh was roughly divided into an upper and lower marsh

as determined by the noticeable boundary between a highly stressed plant growth — the lower zone located within quadrats 1 to 11, and the somewhat more productive higher zone between 12 to 18. The control station also was divided into a comparative upper and lower marsh zone, and measurements were made at similar times.

Results over three years show that generally plants found growing on the upper slope were larger and more abundant than identical species measured in the lower zone. However, the reduced *mean stem counts* of *Spartina* recorded in the transect did not show any significant difference between the low and high marsh. The greatest dissimilarity between these two zones was found in *mean stem* heights, where a 2 to 4-fold difference was measured between the low and high marsh in Winsor Cove.

These variations in growth can be attributed to the fact that the substrate of the lower intertidal zone was more impregnated with fuel oil because of the absorptive ability of the peat and its proximity to the tide range. In this zone, exposure to initial oiling was more frequent than on the upper slope, which sometimes was beyond the reach of high tide. In addition, the substrate of the upper marsh was generally sandier and more susceptible to purging from tidal exchange. In the control site, data consistently showed a greater *Spartina* stem count in both high and low zones in comparison with the effected area, with the exception of the seepage area, which we will discuss next. Stem height in both zones was significantly greater than Winsor Cove in 1976. However, the values of the lower and upper marsh were similar by 1977.

Seepage Area

Water seepage continually passed over the sediments in the lower marsh during low tide at Winsor Cove. Therefore, the base of the plants was continually being flushed with a surface flow of water that prevented the plants and sediments from becoming heavily impregnated with oil. It is significant that the surface substrate in the seepage area was sandy mud mixed with coarse gravel. In this zone, *Spartina alterniflora* regeneration was only marginally affected by the spill, and growth exceeded that found elsewhere in the Winsor Cove area. This drainage area, in conjunction with the sand-gravel substrate, probably aided in flushing the initial oil from the *Spartina* roots, and served as an insulating factor from the chronic pollution thereafter. The usual strong odor of oil found in the sediments and in the peat at Winsor Cove was lacking in this area. Also, a source of nutrient enrichment might have been contained in the seepage water, thereby contributing to growth enhancement.

Burk's Study

A study by J. C. Burk (1977) includes a four-year analysis of vegetation polluted by a fuel oil spill in a freshwater marsh off Mill River in Northampton, Massachusetts. Data on long-term marsh destruction show similarities to results from the Winsor Cove study. Eighteen out of the 45 total plant species found before the spill were not present the following season. Perennial species were generally less affected than annuals. However, in Winsor Cove, a high mortality and persistent impairment of growth was evident in both perennials and annuals. As found in Winsor Cove, certain species in Mill River continued to decline in abundance during the second season. Vegetation in Mill River in the "high marsh" and "mid-marsh" zones had substantially recovered by the third and fourth years, and the "low marsh" was unaffected. In Winsor Cove, however, the low marsh is still acutely affected and the less impacted high marsh has begun to recover in terms of average stem heights. As previously mentioned, in Winsor Cove the mean stem number in both zones remained far below comparable numbers calculated from the control marsh.

In addition to the endemic species composition of a salt versus a freshwater flora, one of the major differences between these two studies was the influence of tidal amplitude and mixing through wave action. In the marine intertidal zone, a wider vertical area between low and high water was accessible to direct exposure to oil, whereas in the river, the oil was restricted to a smaller area due to the absence of tidal exchange.

Other Findings Assayed

J. M. Baker (1970) states that "oils vary in toxicity according to content of low boiling compounds, unsaturated compounds, aromatics and acids." Greatest acute damage

(A)

(B)

(C)

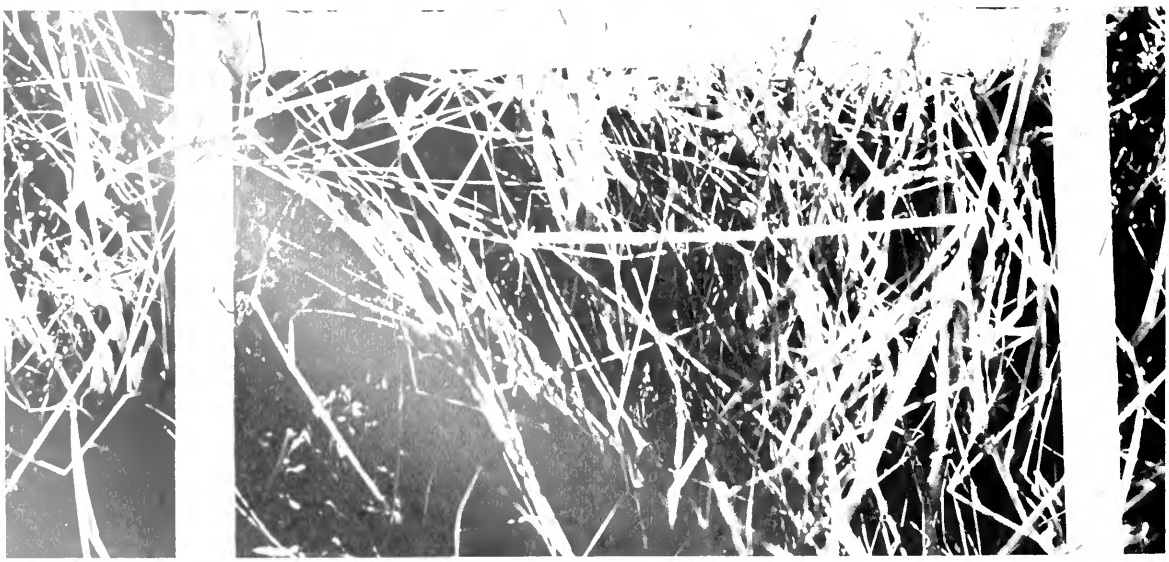
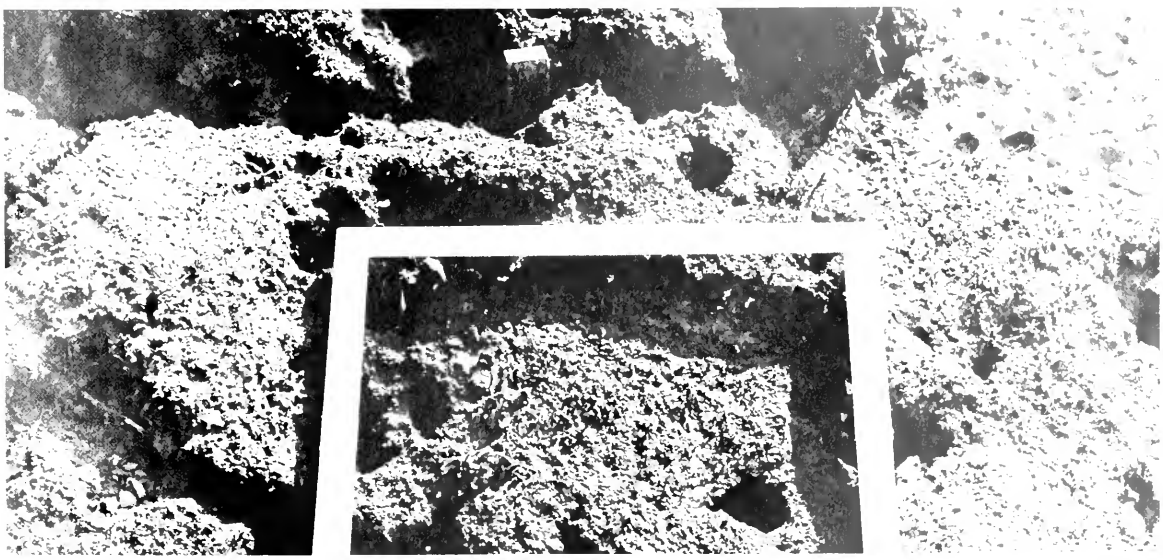


Figure 3. Photographic stations in Winsor Cove. Photographs A and B, taken in October of 1974, show an overview of the proposed site of the transect; C shows quadrat Number 1. These illustrate the density of marsh grasses existing

(D)

(E)



(F)

close to the water's edge prior to the marsh degeneration. Photographs D, E, and F are of the identical sites taken in September 1977, three years later. Note the total absence of the Spartina *stand in the lower marsh zone.*

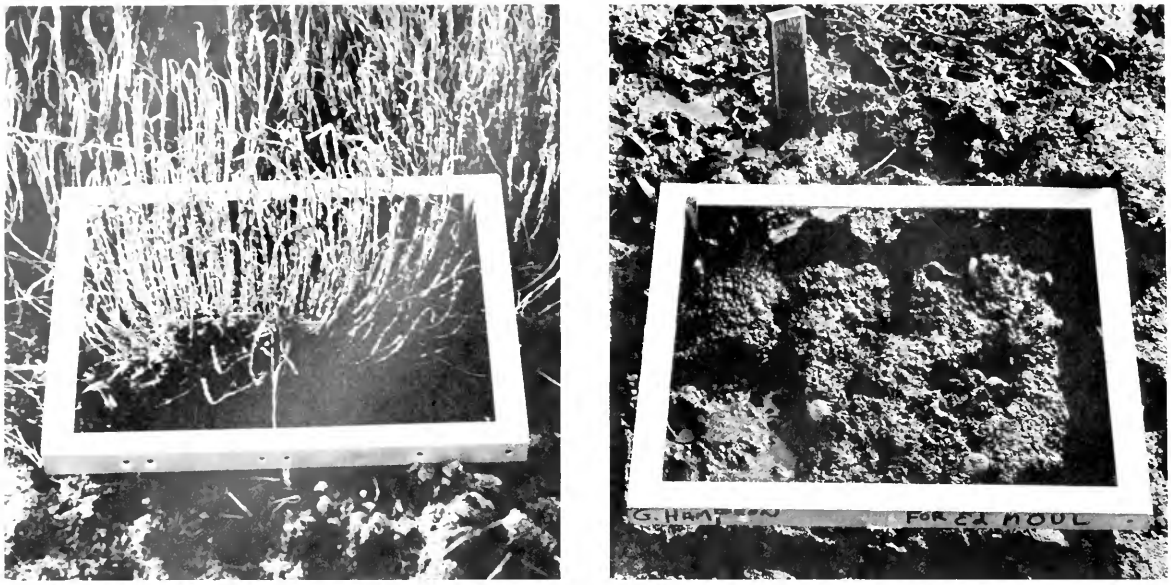


Figure 4. Salicornia *stand in October 1974 (G) and in September 1977 (H). As with the* Spartina *in Figure 3, the* Salicornia *plot shows little regeneration of high plant growth.*

generally is caused by the "very toxic oxidized oils and aromatics, which stop respiration and cause widespread injury and death"; the total severity being dependent on the constituents and amount of oil, the environmental conditions, and the species of plant involved.

A review on the effects of oil and its components on algae by P.Y. O'Brien and P.S. Dixon (1976) relate several studies that also show the relatively less harmful effects that weathered oil has on salt marsh plants.

C. H. Hershner (1977) and Baker (1971) mention that investigations seem to confirm that marshes are able to withstand or recover rather quickly from a "single dose" of oil. However, Winsor Cove, which could essentially be categorized as having a "single dose" type oil spill, actually involved a series of frequent, repetitive applications of oil that were the result of tidal oscillations and wind direction. Harbors, rivers, and embayments are very susceptible to this repetitive type of exposure.

During the initial spill, environmental conditions were such that the oil collected in the protected cove with the slick remaining a few days. The substrate of the Winsor Cove marsh, acting as a natural sink, became heavily impregnated with oil because of the marsh's porosity and interstitial absorption. In the absence of adequate oxygen and flushing, weathering of the impregnated oil was extremely limited. Slow, chronic discharge of buried oil contained toxic aromatics that leached to the surface substrate, causing a continuous stress on plant regeneration.

The Winsor Cove spill was not unique. The same results were evident in the West Falmouth oil spill study previously mentioned. Similarly, D. W. Mayo and others (1975) reported fresh oil leaching from saturated sediments up to 18 months following the initial detection of a spill involving JP5 jet fuel and Number 2 oil in Long Cove, Searsport, Maine. The Bunker C oil spill in Chedabucto Bay, Nova Scotia (see page 31), also revealed a slow release of petroleum hydrocarbons from saturated sediments and rooted eelgrass over at least five years.

George R. Hampson is a Research Associate in the Biology Department, Woods Hole Oceanographic Institution. Edwin T. Moul is Professor Emeritus of the Biology Department of Rutgers University and presently is doing research in the Gray Museum at the Marine Biological Laboratory, Woods Hole, Massachusetts.

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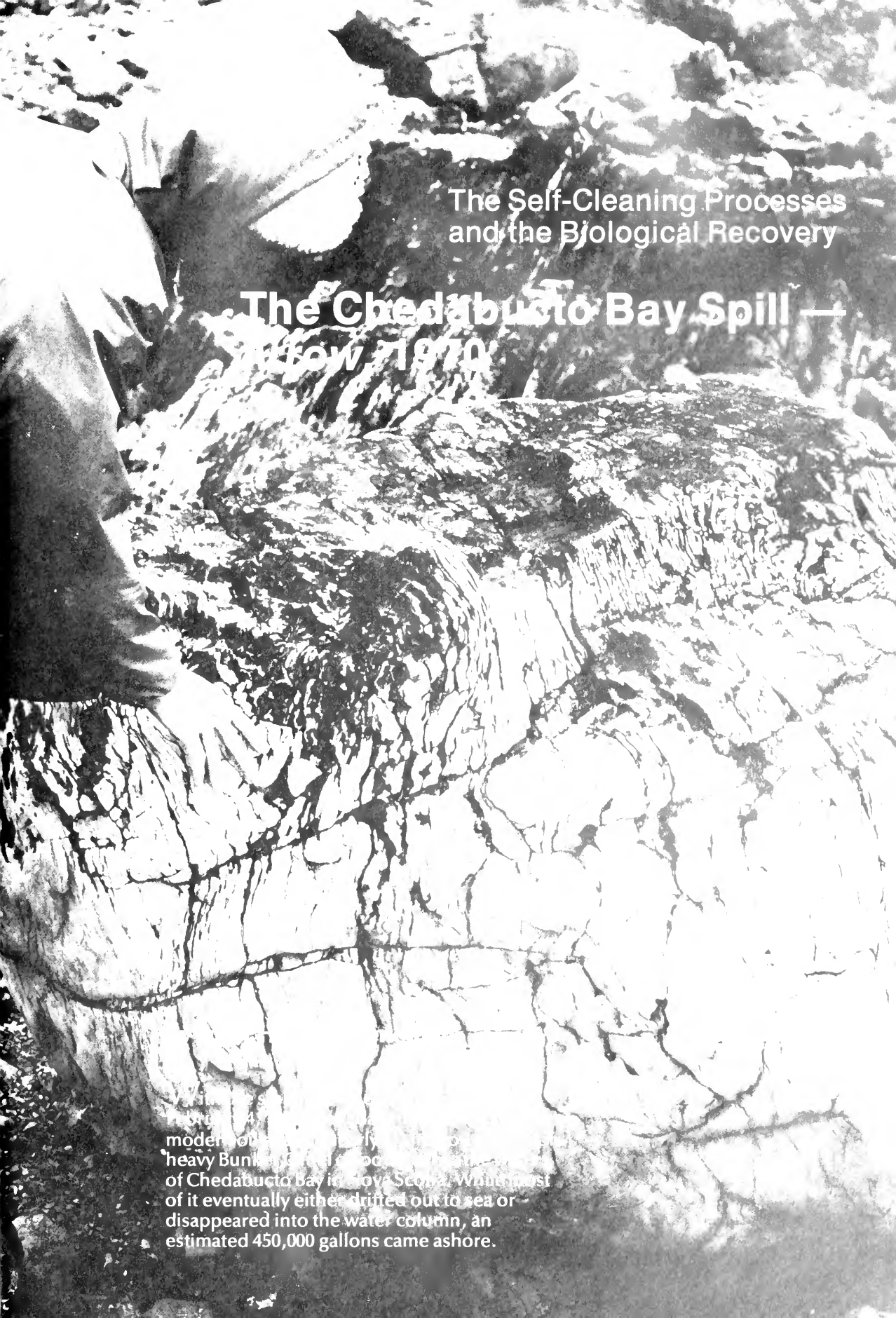

The Self-Cleaning Processes and the Biological Recovery

The Chedabucto Bay Spill — February 1970

moder[illegible]
heavy Bun[illegible]
of Chedabucto bay in Nova Scotia. While most
of it eventually either drifted out to sea or
disappeared into the water column, an
estimated 450,000 gallons came ashore.

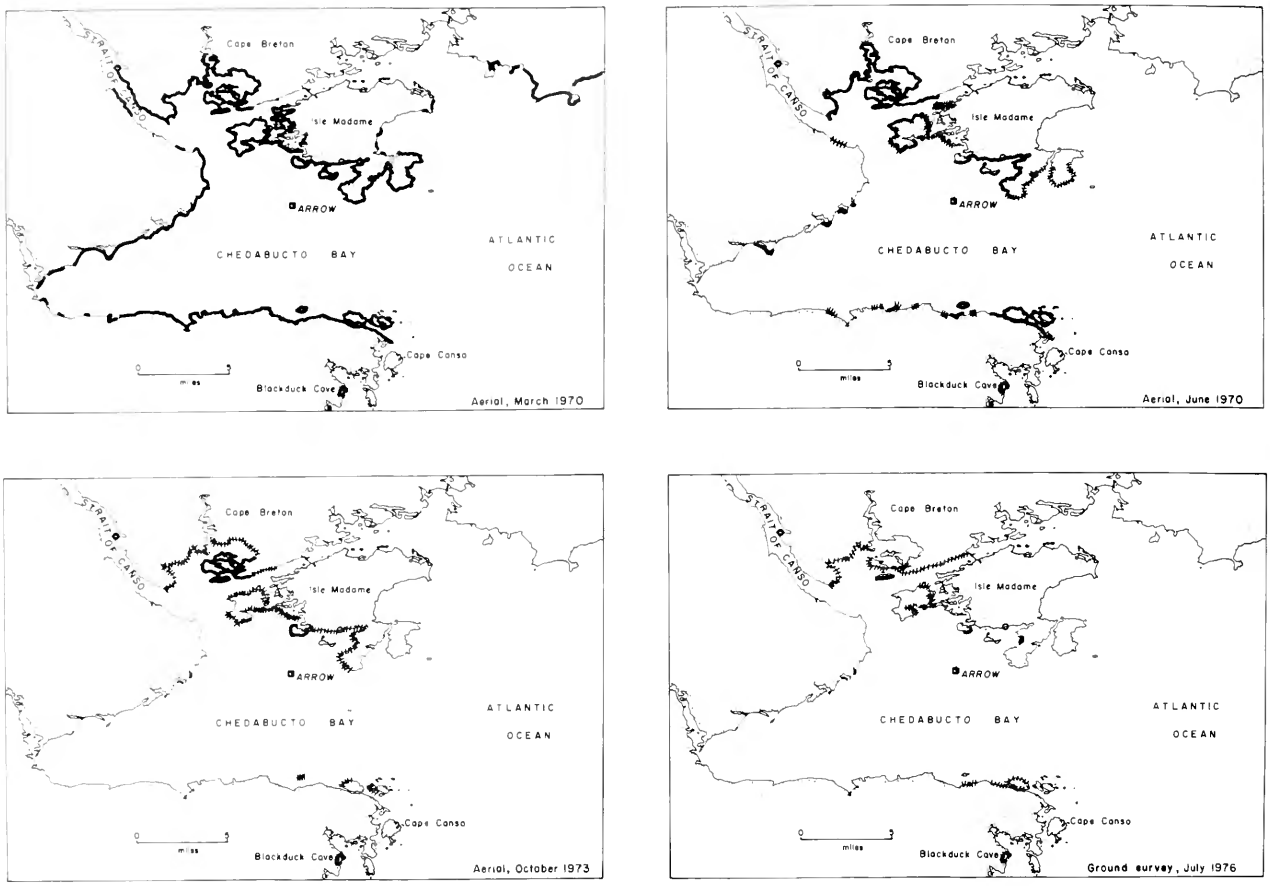

Figure 1. Distribution of oil residues in the shore zone of Chedabucto Bay, determined by aerial inspection in 1970 and 1973 (Owens and Rashid, 1976), and by ground survey in 1976.

Today, nearly eight years after the *Arrow* disaster and despite a massive Task Force clean-up effort by the Canadian government, there are still considerable amounts of the fuel oil in some isolated areas, while traces remain in others. These traces remain despite seven years of changing seasons and heavy weathering.

One of the most frequently asked questions about oil spills is: "Just what is the damage from a spill?" To the scientist, this question poses an enormous problem — one that is relatively new, having come to the fore only in the late 1960s. And with this new problem comes the attendant demand for new scientific techniques. The more we investigate oil pollution, the more complex it becomes.

A multi-faceted follow-up study of the *Arrow* spill was initiated about four years ago at the Bedford Institute of Oceanography in Canada, in collaboration with colleagues at the University of New Brunswick and at Bowdoin College in Maine. We measured and are still measuring not only the Bunker C petroleum hydrocarbons still resident on and in the shoreline sediments, but also the rates of hydrocarbon movement between water column and sediment, the degradation rates, and the tissue oil load and physiological responses of oiled organisms. Hopefully by analyzing the data in their entirety, we can arrive at a preliminary evaluation of the self-cleaning potential on an oiled marine environment. And by knowing rates or half-lives of oil erosion and biological recovery in oiled communities, we may then identify their more sensitive and vulnerable components.

Photograph preceding page shows that while the scum of spilled oil in Chedabucto Bay soon disappeared under the forces of wave action and scouring, traces of weathered and aged Bunker C fuel oil persisted for several years, especially when out of reach of the tide. (Photo R. Belanger, BIO)

Natural Erosion Patterns: 1970-1976

Oil, once stranded on shorelines, is vulnerable to erosion by various mechanisms — mechanical (wave action or bulldozer), evaporative, chemical (photodecomposition), or biological (bacteria).

Gross self-cleaning of the oiled Chedabucto Bay shorelines is shown in Figure 1. Of the 200 or so kilometers visibly oiled in

March of 1970, about a third were clear of obvious oil cover three months later, partly due to the Task Force clean-up efforts (concentrated mainly in urban or recreational areas) and partly due to natural cleaning by wave action. By June 1970, much of the exposed rocky high-wave energy shorelines of the south shore and of the northeast corner of the bay on and around Point Michaud were clear of visible stranded Bunker C oil.

By 1973, the oil cover was further reduced to a largely patchy distribution, restricted to the low-energy lagoons and estuaries of Isle Madame and Inhabitants Bay on the north shore of the bay. By 1976, six years after the spill, a shore survey found only traces of stranded oil. The high-energy rocky shorelines were largely cleansed of visible stranded oil, and only traces could be found in the low-energy areas of the north shore, on Isle Madame, and Janvrin Island. One exception, Blackduck Cove on the south shore of the bay, remains heavily oiled to this day. It was contaminated in 1970 by a single chance slick that broke off from the main body of oil that was heading out to sea. Today much of the shoreline cobble there remains covered in a heavy asphalt.

The general impression, however, is that most of the stranded oil has now disappeared (Figure 2). Self-cleaning occurred remarkably quickly during the first two years after the spill with 75 percent of the heavily oiled shoreline cleansed by 1973. Although 15 percent of the shoreline was still oiled in 1976, today less than 5 percent remains visibly oiled. An estimate of one and a half to two years for a self-cleaning or erosion half-life* of stranded Bunker C in this particular environment then seems reasonable, although this may be a conservative figure because the half-life of the remaining oil may be much higher.

Wave Energy Cleaning Study

A detailed study of the self-cleaning process of wave energy was carried out by Dr. Martin Thomas of the University of New Brunswick. Immediately after the *Arrow* spill he established his study sites on three heavily oiled beaches, revisiting them annually. These represented three different wave-energy

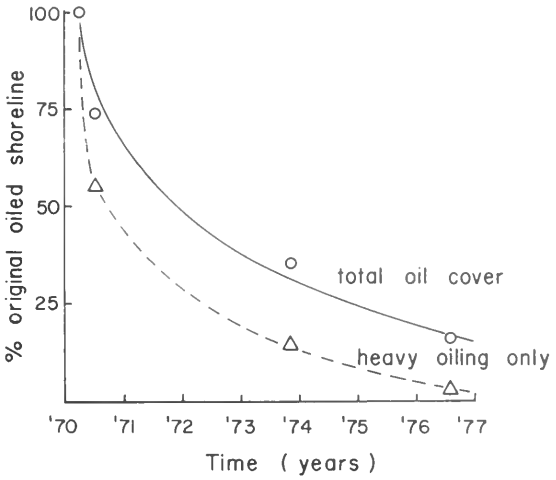

Figure 2. Erosion pattern of stranded Arrow Bunker C on Chedabucto Bay shorelines: 1970-1976.

situations — high energy (Crichton Island), medium energy (Arichat Church bluff), and low energy (Janvrin Lagoon).

His findings have shown that self-cleaning of stranded Bunker C can be directly related to the amount of wave energy impinging on the shoreline (Figure 3). Thus the rate of self-cleaning on high-energy Crichton Island (Exposure Index 200**) is significantly higher than on a low-energy shoreline, such as Janvrin Lagoon (E.I. = 0).

Thomas' observations also showed that the relative location of the stranded tar on the beach slope greatly affects its self-cleaning potential. Thus oil stranded halfway up the beach is moved off more rapidly than that lying along the top of the beach. In this respect, the high-water spray zone on high-energy beaches — that boulder and tide-pool area above the high-water line and just out of reach of the spent waves — behaves similarly to a low-energy lagoonal shore in terms of self-cleaning. Tar thrown up into these splash-and-spray zones, even along wave-washed high-energy shorelines, has potentially a long residence time, disappearing very slowly.

Thomas' plots also provide some much needed numbers on self-cleaning rates. In Chedabucto Bay, tar stranded along the mid-water line on high- and medium-energy beaches has a self-cleaning half-life of around

*The time required for half the hydrocarbon concentration to be degraded.

**An index of shoreline wave exposure, based on wave energy, tidal action, and shore topography (Thomas, 1977).

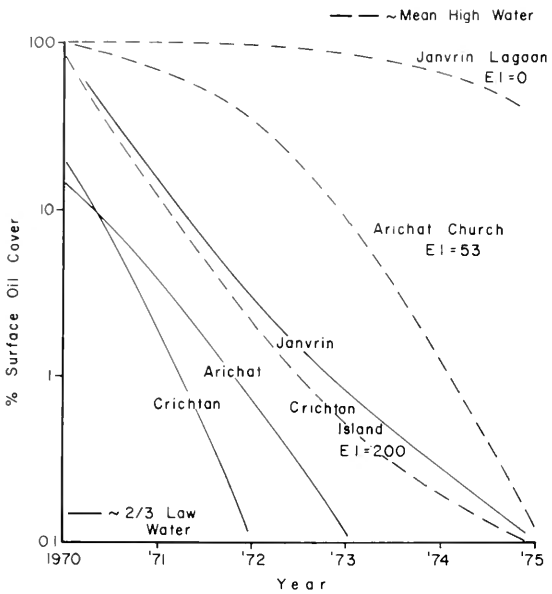

Figure 3. Rates of erosion of stranded Bunker C oil at two tidal levels under different wave-energy regimes. (E.I. is Exposure Index, based on wave energy, tidal flux, and shore topography.) (After Thomas, 1977).

one and a half to two years. However, this half-life is increased by a factor of at least 10 when the Exposure Index drops, such as with the oil stranded on low-energy shores of lagoons and estuaries.

Recovery of Fauna and Flora

The relationship between wave energy and surface oil cleaning is also reflected in the decimation and subsequent recovery of such associated organisms as the kelp *Fucus vesiculosus,* the salt-marsh cordgrass *Spartina alterniflora,* and the soft-shell clam *Mya arenaria.*

Unfortunately, there are no pre-spill data. This is a chief recurring problem in assessing post-spill damage. It is reasonable to assume, however, that the pre-spill populations were probably somewhat similar to those found today in adjacent non-oiled areas. The impact on *Fucus* was immediate and devastating. More than half of the kelp population was destroyed. Recovery did occur, however, but it was and is a relatively slow process. Today's *Fucus* population is not yet equal to the 1970 stock, but recovery is positive. A recovery half-life* estimate of four years is reasonable.

*The time required for a population to reach half its former, non-oiled numbers.

A similar reduction in abundance was observed for the cordgrass *Spartina,* although the recovery pattern differed from that of *Fucus.* Where *Fucus* experienced a gradual and continuous recovery, *Spartina* recovery was not seen until two years *after* the spill. (This underlines the need for caution in post-spill audits. Many effects are not evident until a year or more after the accident.) *Spartina* did recover, however. A reasonable estimate of its recovery half-life is about the three-year mark.

The third indicator organism, the burrowing clam *Mya arenaria,* showed a markedly different recovery pattern. Since 1970, *Mya* has shown a continued decline in abundance, so far with little apparent recovery in sight. Its recovery half-life then appears to be considerably longer than that of either the kelp or the cordgrass, and an estimate of 10 years seems valid.

Erosion Overview

These various observations — the oil cover erosion figures and the biological recovery half-life estimates — lead us to a preliminary model of the total clean-up and recovery potential of this marine ecosystem (Figure 4). We must emphasize here that this is only an approximation. We have left out some mechanisms and have made some guesses. We can, however, make two observations: (1) although stranded oil is a tenacious material, its self-cleaning potential is surprisingly high, with more than 50 percent disappearing by wave erosion in the first two years after the spill; but (2) assuming that about half of Chedabucto Bay shoreline is high-energy and the rest half medium- and half low-energy, then about one-sixth or around 15 percent of the original 450,000 gallons of Bunker C

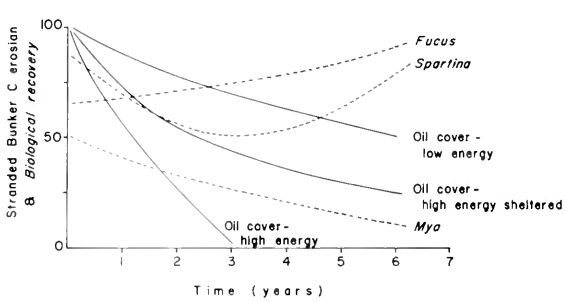

Figure 4. Summary of self-cleaning and biological recovery processes for Chedabucto Bay shore zone, 1970-1976.

washed ashore is still lying around on low-energy beaches and in sheltered pockets.

Our erosion and recovery half-life estimates, however, draw attention to the continued depression of *Mya arenaria* and the slow self-cleaning of oiled soft lagoonal sediments. Perhaps *Mya* is unusually sensitive, but the fact that it inhabits the soft inshore sediments identifies this clam/sediment system as a potential problem area in environmental recovery. It also makes us aware of the potential long-term impact of a spill, which is generally hidden from view within the sediments.

The Hidden Problem

The stranded Bunker C oil along the top of the low-energy shores is not static, but continually reenters the tidal environment. Only trace amounts, however, enter the tidal water column directly. Instead, the main route of reentry appears to be via the sediments and the interstitial water within the shoreline structure (Figure 5). Judging from flow studies with oiled sediments, the subsequent release of Bunker C hydrocarbons from those oiled sediments back into the overlying water column appears to occur very slowly, about as slowly as that dissolving into the water's edge directly from the stranded tar. The crucial point is that the sediments act as a large sink, and that oil entrapped within these sediments has an extremely high residence time.

Data from our flow studies suggest that, assuming linear loss, approximately 170 years would be required to completely flush out by water flow alone the tar contained in one of our experimental setups. Naturally, this is an over-estimate because we did not include other environmental erosion mechanisms, both physical and biological, but it does demonstrate that leaching of oil from sediments can occur very slowly indeed. For our preliminary model, the erosion half-life for total sediment-bound Bunker C is somewhere in excess of 25 years and possibly longer.

Just what is the composition of the sediment-bound Bunker C — or is it Bunker C? Sediment samples from a chronically oiled beach in a Chedabucto Bay lagoon, one with a tar layer along the top of the beach slope, were taken from the low-, mid-, and high-water line. They were obtained at three depths, 5, 10, and 15 centimeters below the surface, so that we would have an understanding of the changes in the oil's composition within the three-dimensional structure of the beach. The aliphatic or straight-portion chain of this sediment-bound Bunker C was found to be significantly reduced (Figure 6). The gas chromatography (GC)* spectra of all samples, regardless of depth or beach level, showed a marked erosion of the n-alkanes (n stands for normal or straight-chain) up to carbon-30 throughout the entire top 15 centimeters of the beach.

Six years after the Arrow *spill of 1970, tarry accretions of weathered Bunker C, pebbles, and beach debris still coat the shore of Blackduck Cove in Chedabucto Bay, Nova Scotia. (Photo R. Belanger, BIO)*

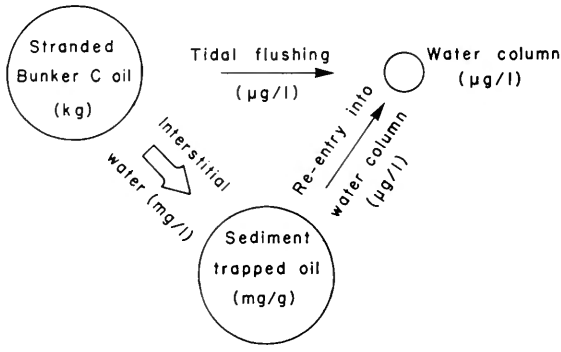

Figure 5. Summary of stranded Bunker C fuel oil reentry pattern into marine environment (Vandermeulen and Gordon, 1976).

*Gas chromatography is an analytical technique whereby individual compounds in a complex mixture can be separated and identified. Each peak in a GC spectrum represents a separate compound.

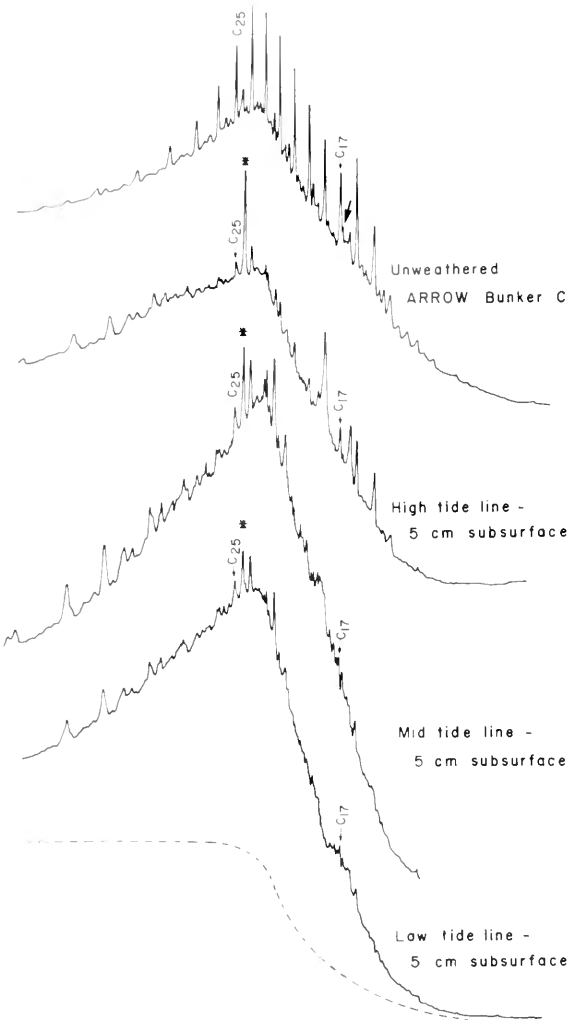

Figure 6. Gas chromatograms of oiled sediment samples (5-centimeter subsurface) from Moussiliers Passage, Chedabucto Bay, N.S. The peaks marked with an asterisk are contaminants, probably of organic or biological origin. The pristane peak is indicated by the large arrow.

The unresolved envelope,* however, suggests there is a considerable amount of undegraded material. Also, the aromatic or cyclic fraction does not appear to differ greatly from that of the *Arrow's* Bunker C, as indicated by the similarities of the fluorescence synchronous** spectra. Thus the aliphatic part of the stranded oil is being degraded preferentially (probably through microbial activity), while the aromatic and multi-ring components of the oil remain, resisting degradation.

This introduces the interesting notion of thinking of the beach and shoreline sediments as the n-alkane filter systems in oiled communities, with characteristic efficiencies and rates. The effectiveness of these "filters" can be estimated from data obtained from a salt marsh on the Quebec-New Brunswick border, oiled with Bunker C in 1974. Two years after this spill, the aliphatic part of the oil that had penetrated into the marsh sediments was significantly eroded, despite continuous replenishment from surface oil. However, as in the Chedabucto Bay beach system, the aromatic fraction remained, apparently unchanged. Thus an estimate of two years for the erosion half-life of n-alkanes in natural sediments does not seem excessive. The erosion half-life for the aromatic component, however, seems to be of much longer duration, possibly as much as 10 years. This brings us to the biologist's concern over the remaining aromatic petroleum hydrocarbons. The oil found in 1977 sediments in Chedabucto Bay, in fact, is *not* the same oil spilled there in February 1970. We are now dealing not with Bunker C, but with an aromatic derivative — one highly enriched with aromatic compounds, with a long half-life, with a long residence time, with a largely unknown composition, and with potential long-term biological implications.

The Biological Implications

Our recent work with Dr. E.S. Gilfillan of Bowdoin College, Maine, has shown that even six years after the *Arrow* spill clam populations in chronically oiled sediments are greatly reduced in numbers, have an altered age distribution, and in many cases show a curious break in the six-year age class, which coincides with the 1970 spill (Figure 7). Tissue growth rates of oiled clams were lower than those of non-oiled sediments. Also, shell growth (that is, the rate at which the growth rings were laid down) after 1970 was less than in those taken from non-oiled sediments (Table 1). Of particular interest was the observation that the clam's efficiency in utilizing food intake (that is, the balance between the amount of carbon

*The unresolved envelope is the large area under the "hump" of the GC spectrum. It represents a complex mixture of compounds not separated and identifiable as individual peaks by the techniques used.

**A plot of fluorescence emission intensity versus excitation wavelength, during which the excitation wavelength is scanned from 220 nanometers (nm) to 500 nm, while simultaneously scanning the emission wavelength, but always at 23 nm above the excitation wavelength. This technique was adapted from forensic analytical methods involving automobile oils and grease in criminal investigation.

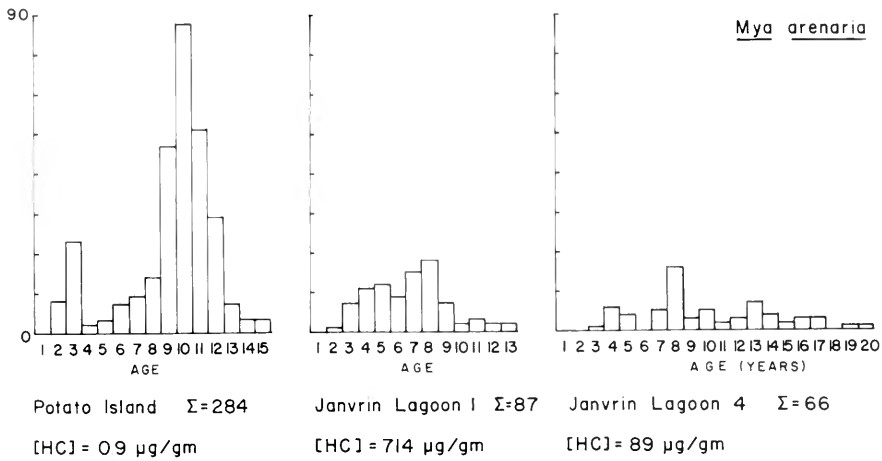

Figure 7. Abundance and population structure of the soft-shell clam Mya arenaria *from a non-oiled (Potato Island) and an oiled (Janvrin Lagoon) lagoon on Isle Madame, Chedabucto Bay, N.S. Abundance numbers are per 0.3 square meters sampling area. Sediment hydrocarbon concentrations were determined by fluorescence.*

taken in versus that amount assimilated and/or respired) differed sharply between oiled and non-oiled clams. In *Mya arenaria* from chronically oiled Janvrin Lagoon this efficiency was very much reduced, and in some batches the clams could be said to be barely holding their own, precariously balancing their carbon budget in their struggle for survival (Table 2).

Thus the *Mya arenaria* population in these chronically oiled sediments is under a great deal of stress. It is down in numbers, the physiology is upset, and the recruitment effort may be impaired.

Aryl Hydrocarbon Hydroxylase

Clams from oiled sediments invariably show petroleum hydrocarbons in their tissues, sometimes in surprisingly high concentrations. Presumably the hydrocarbons are taken up while feeding on sediment and

Table 1: Shell growth in *Mya arenaria* during the four-year post-spill period as against percentage of growth during four-year pre-spill period.*

Area	% Growth
Non-oiled:	
Control 1 + 2	69%
3	51
4	55
Chedabucto Bay:	
Janvrin Lagoon 1	43
2	42
3	36
4	58
5	33
6	34

*Shell growth determined as a millimeter per year on individual growth rings of 11- and 12-year-old clams.

Table 2: Carbon budget for *Mya arenaria* from a non-oiled lagoon (Potato Island) and a chronically oiled lagoon (Janvrin Lagoon). Data expressed as micrograms of carbon per hour per 100 milligrams of tissue.

Area	Net C*	Resp. C*	C Flux*
Potato Island	33.22	27.22	+ 6.00
Janvrin Lagoon–1	23.3	30.43	– 7.13
–2	14.33	26.1	–11.81
–3	6.37	30.95	–25.6
–4	7.66	24.80	–17.15
–5	2.27	23.03	–20.76
–6	2.74	44.6	–41.87

*Data relative, and based on 1,000 micrograms of carbon per liter algal food.

food particles and possibly also directly through the gill membranes. The mechanism of this uptake is not understood as yet. However, once into the tissues we become more concerned with how to rid them of these molecules, which are after all foreign molecules. The time pattern of this depuration or cleansing process in non-oiled seawater is shown in Figure 8. Surprisingly, when clams from oiled sediments were transferred to oil-free seawater, we found that even after 75 days some specimens retained as much as 40 percent of their initial hydrocarbon load within their tissues. In other words, with this slow a depuration rate in non-oiled seawater, the clam's cleansing effort is probably negligible when living in continuously oiled sediments.

Why such a slow depuration rate? In vertebrates, such as man and other mammals and in fishes, aromatic hydrocarbons are handled by a multi-functional enzyme system termed the aryl hydrocarbon hydroxylase

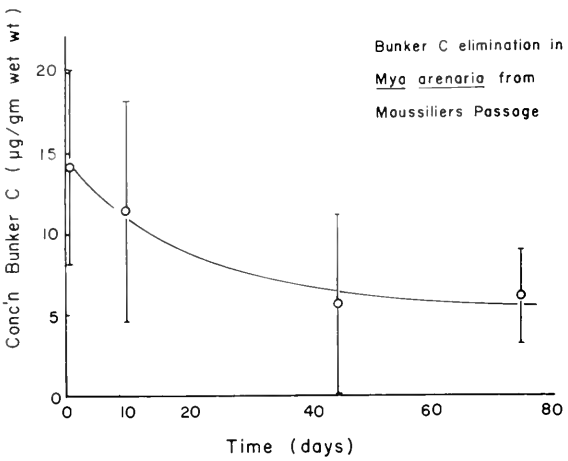

Figure 8. Depuration of Mya arenaria *from an oiled sediment in Chedabucto Bay, transferred to non-oiled seawater. Tissue hydrocarbons expressed as micrograms of Bunker C per gram wet weight of tissue.*

(AHH) system. Normally, this rids the body of unwanted steroids and other compounds naturally produced in the tissues, but when the body encounters a foreign molecule sufficiently similar to the steroids, then this enzyme will handle it as well. In fact, one can enhance the activity of this enzyme system by feeding it larger amounts of aromatic hydrocarbons. Indeed, trout taken from polluted waters show chronically enhanced activity levels of this enzyme.

In collaboration with Dr. W.R. Penrose of the Newfoundland Biological Station, we analyzed clams, mussels, and oysters for this AHH enzyme system. We then attempted to elicit enhancement or "induction" of this AHH activity by rearing the bivalves in experimentally oiled waters. Whereas trout under these conditions showed the necessary basal enzyme response, as well as the induced response, we were unable to detect any such enzyme system in the various bivalves (Table 3). More importantly, we were unable to find this system in clams and mussels taken from the six-year chronically oiled sediments in Chedabucto Bay.

The implication is that in the field the bivalves lack the enzyme mechanism necessary to deal with the long-term aromatic enrichment of the sediments. This is reflected by the slow and incomplete depuration of oiled bivalves when transferred to clean seawater. Indeed, the absence of this enzyme system, which in other organisms metabolizes the aromatic hydrocarbons, may well be the primary cause of all the population and physiological problems that the soft-shell clam experiences in these oiled lagoons.

The Short- and Long-Term Concerns

Self-cleaning of a Bunker C spill appears to be a two-stage process — one short-term, one long. The short-term stage has a half-life of about two years, and appears to be a direct function of wave energy.

The long-term stage has a half-life in excess of ten or twenty years. It is probably largely a function of microbial erosion and is associated with low-energy environments (lagoons and estuaries). Most importantly, this stage involves a compositional change from a Bunker C fuel oil to an aromatically enriched oil.

Biological recovery from shore spill damage is closely linked to the self-cleaning

Table 3: Aryl hydrocarbon hydroxylase (AHH) activity, as determined by benzo[a]pyrene hydroxylation in non-oiled, experimentally-oiled and chronically-oiled (Chedabucto Bay) bivalve molluscs. Activity expressed as fluorescence units per milligram of protein.

Test organism	Treatment	No.	AHH activity[1] x ±S.E.
Brook trout	control	5	0.23 ±0.23
	4-day, Kuwait crude	5	21.50 ±8.06
	4-day, Bunker C	5	54.28 ±41.37
Mya arenaria	control	5	0
	4-day, Kuwait crude	5	0
	4-day, Bunker C	5	0
	chronically-oiled	5	0
Mytilus edulis	control	5	0
	chronically-oiled	5	0
Ostrea edulis	control	5	0
	4-day, Kuwait crude	5	0
	4-day, Bunker C	5	0

[1]Nebert and Gelboin, 1968. *J.B.C.* 243(23): 6242-9.

Aged weathered Bunker C fuel oil literally paralyzed this boulder beach after the Arrow *disaster. Such immobilization severely reduces the shock-absorbing capacity of beaches during the winter season. (Photo R. Belanger, BIO)*

pattern. In areas of rapid cleaning, recovery follows with a half-life of around four years. In areas of slow self-cleaning, biological recovery of affected organisms is correspondingly slower, with a half-life in the decades, apparently tied to the change in oil composition toward aromatic enrichment.

Our long-term biological concern focuses on the long half-lives of aromatic hydrocarbon degradation and of biological recovery, and on the apparent inability of many benthic invertebrates to deal with these residual foreign molecules.

A further concern is that the absence of the aryl hydrocarbon hydroxylase enzyme system in bivalves may indicate a biological stage where accumulated aromatic hydrocarbons can slowly and continuously enter the food chain, or be carried through reproductive stages.

John H. Vandermeulen is a research scientist in environmental physiology at the Bedford Institute of Oceanography in Nova Scotia. He was general chairman of the OIL/ENVIRONMENT-1977 symposium held in October in Halifax, Canada.

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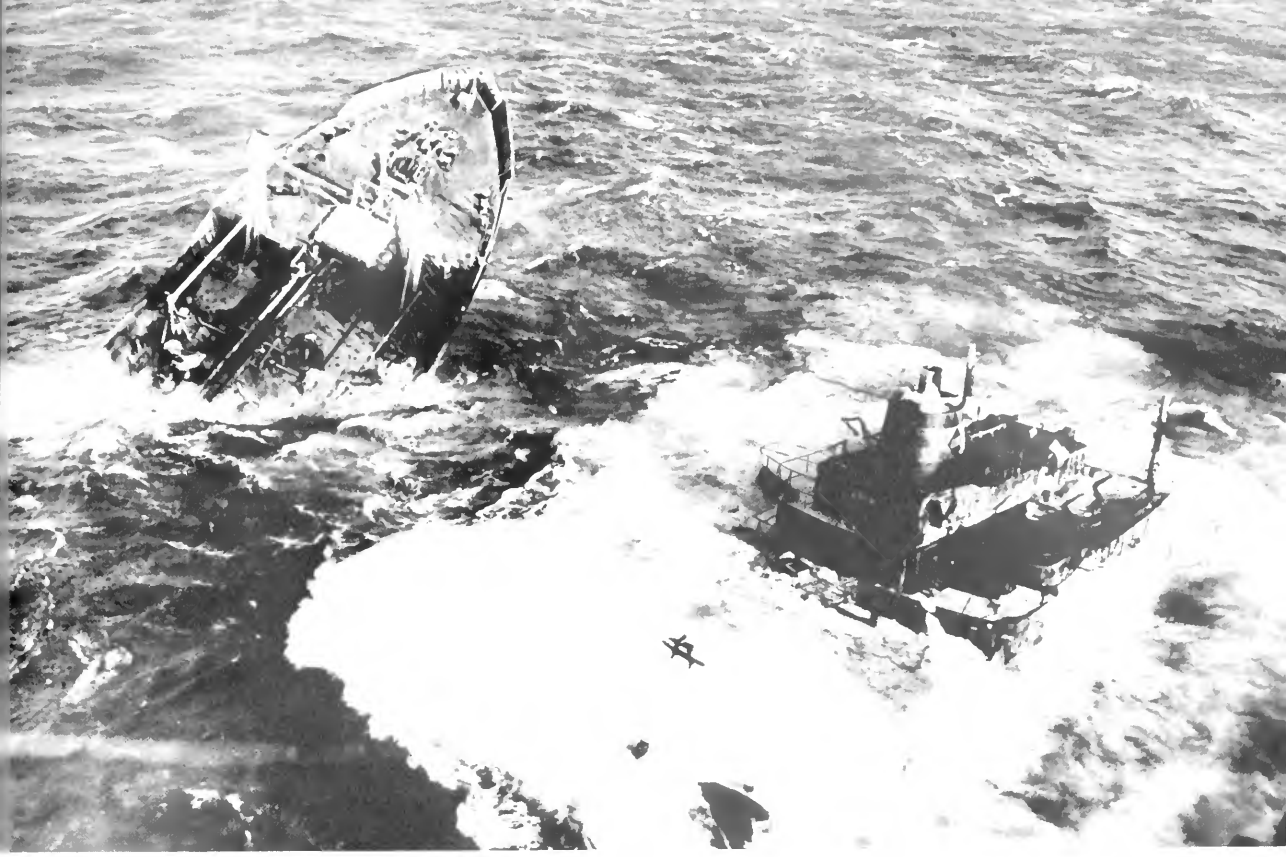
ARGO MERCHANT:

by John D. Milliman

Above, the Argo Merchant *spilling oil, with two oiled seagulls in vicinity. (Photos courtesy of NOAA) At right, vessel after she broke in half. (Photo courtesy U.S. Coast Guard)*

The seagoing lives of oceanographers are usually well-structured: they know how, when, and where they want to go, and what they want to accomplish. Insights into the scientific problems have to be gained long before the ship sails so that funding can be obtained to carry out the desired research. Cruises are often scheduled a year or more in advance. The proper equipment also needs to be on hand, along with the scientific expertise and assistance.

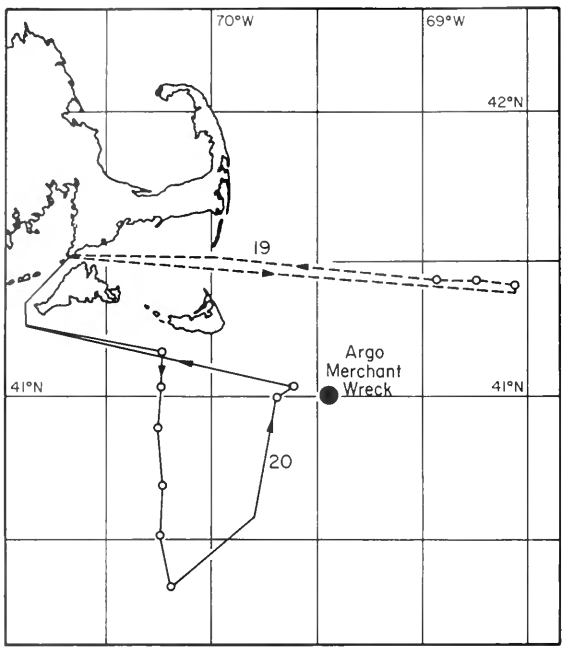
These standard procedures for conducting cruises stand in stark contrast to those needed for a disaster or an emergency. When response necessitates immediate action, the cruise must be arranged quickly, often before the specifics, or even direction of research can be defined. The shorter the interval between the disaster and the cruise (often corresponding directly to the intensity of the disaster), the less organized the efforts. On the other hand, oceanographers are capable of extemporizing programs and, when acting in tandem, can react to emergencies with both insight and foresight.



A Scientific Community's Response

On Tuesday, December 15, 1976, the *Argo Merchant,* a Liberian tanker carrying nearly 8 million gallons of Number 6 fuel oil, ran aground on Fishing Rip Shoals, about 25 miles southeast of Nantucket Island. By late afternoon, it became obvious that the ship could not free itself without help from the U.S. Coast Guard. If the weather had been calm, perhaps the ship could have been towed from the sand without major damage, but December was a particularly stormy month, even for New England waters. By Wednesday evening the 10- to 15-foot seas had not only kept ships away, but also had dug the 40-foot draft vessel deeper and deeper into the underlying sand. In the process, several major leaks in the hull had been opened. An emergency strike force team from the National Oceanic and Atmospheric Administration (NOAA) was flown in on Thursday, cooperating with the Coast Guard in monitoring the tanker's condition and the ever-increasing slick. No oceanographic ships, however, had been dispatched to the area, and thus no scientific measurements had been taken. By Friday, large amounts of oil had escaped into surrounding waters. At this point it was obvious that a major spill was imminent.

In Woods Hole, many scientists realized the need for an immediate response to the situation — but what, how, and when? On Friday morning, 40 interested scientists from the Marine Biological Laboratory, the U.S. Geological Survey (USGS), the National Marine Fisheries Service (NMFS), and the Woods Hole Oceanographic Institution (WHOI) met to discuss the situation. After going over personal interests, prejudices, and preferences, it became obvious that we had to obtain background data about the water and sediments in the areas near the slick that might be severely affected as the oil moved in the days and weeks ahead. Future sampling could delineate the degree of spill impact only if background levels of biological populations, hydrocarbons, and suspended particulates were obtained. Furthermore, measuring the currents in the area, a program already begun by the U.S. Geological Survey, would be vital to understanding the oceanographic regime.



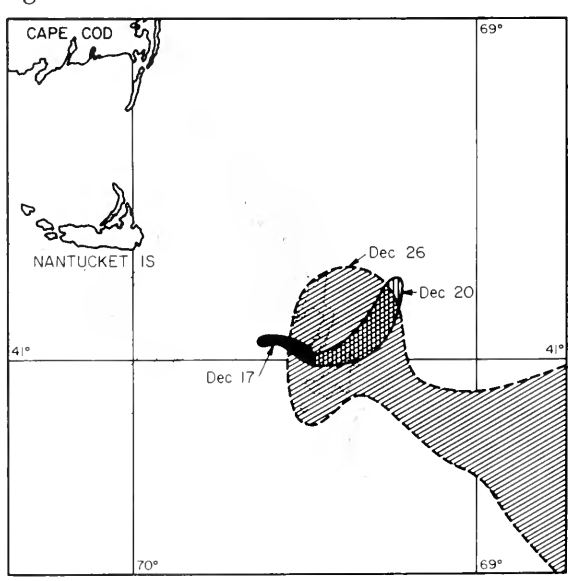
Tracks of Oceanus *cruises 19 and 20, late December 1976, showing the locations of samples collected. Rationale for picking these sites rested primarily on observed and predicted movement of the slick.*

An even greater question was the path that the oil itself might follow. If it continued to float, presumably it would follow the direction of the wind, generally toward the east in winter months. On the other hand, if it sank, it probably would move with subsurface currents in a westerly direction. If the oil did sink, how would it happen? Was some critical concentration of suspended particulates necessary, and if so, how much? Previous studies in Alaska have shown that oil sinks quickly in waters containing approximately 6 milligrams per liter of suspended sediment. Although concentrations of suspended particulates off New England generally are far lower, the oil in question and the sedimentary and oceanographic conditions were sufficiently different to complicate predictions.

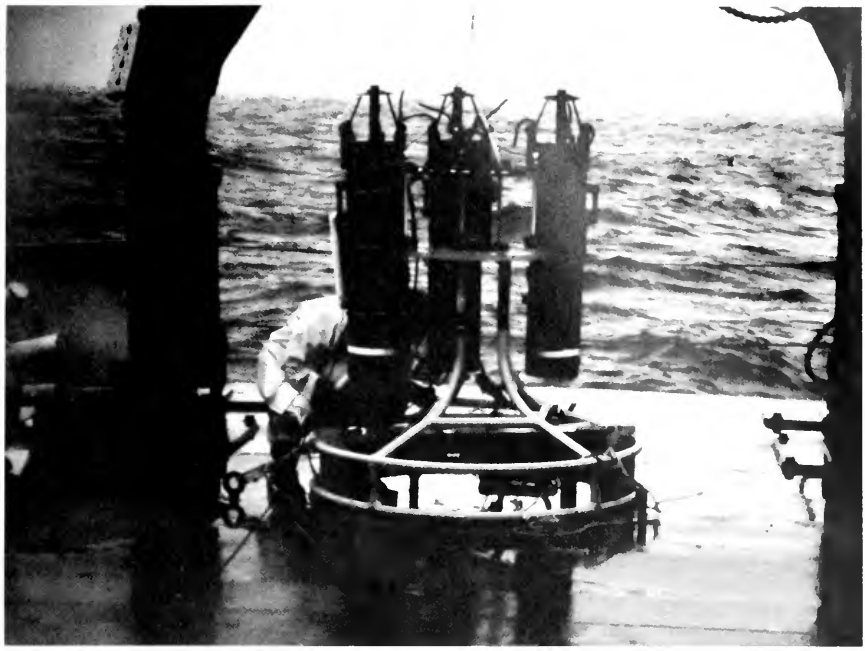
It may seem unusual that such background data were not available, particularly in an area so close to a major oceanographic community. It is only recently, however, that government agencies (primarily the U.S. Bureau of Land Management) have funded large-scale oceanographic research on the U.S. Continental Shelf, and a lot of the data either were incomplete, or had not been adequately synthesized. For instance, we could not be sure in which direction the oil would move because currents in the area were poorly defined.

As reasonable as these questions and objectives seemed, they necessitated getting near the foundering vessel in order to make the required measurements. Without an available oceanographic vessel (WHOI ships, at that moment, were scattered through the Atlantic and Indian Oceans) this could have proved to be a problem. Luckily, Dr. Holger Jannasch, Chief Scientist aboard the *R/V Oceanus*, 640 kilometers away, had been appraised of the situation and had begun steaming toward Woods Hole.

On Saturday evening, a group of 10 scientists met to arrange a crisis reaction cruise on *Oceanus*. The ship was to arrive in Woods Hole early Monday morning, and presumably could be offloaded, onloaded, and sail to the *Argo Merchant* the same day. Among the scientists on the cruise were Drs. Howard Sanders and John Teal (to study benthic organisms), John Farrington (hydrocarbons), the Coast Guard's Richard Jadamec, and myself (the particulate load in the water column). Eight other scientists and technicians agreed to sail with us.



At first, the oil escaping from the Argo Merchant *flowed west-northwest, but within a few days it changed to a northeast direction (December 20), and later to east-southeast. Except for brief shifts in the wind, (such as December 26, when the wind blew from the east), the surface slick flowed east-southeast until all traces were lost in mid-January.*



Rosette sampler is checked prior to lowering from R/V Oceanus *in area of* Argo Merchant *spill. Water samples were collected in 30-liter bottles at various depths within the water column. In addition, probes on the bottom of the instrument monitored the temperature, salinity, depth, and light transmission within the water column.*

Monday morning, December 20, arrived clear and quiet, although the forecast predicted gale conditions by the following day, giving us a narrow weather window for sampling. Preparing a ship for a cruise generally requires a full day; equipment used on the previous cruise must be offloaded, new equipment onloaded, and personnel and schedules organized. Not only did we have very few hours to arrange the cruise, but we had to organize and prepare equipment needed for a wide variety of observations and samples, and install them on the ship. Being wintertime, this equipment had to be lashed down securely to prevent it from crashing about in high seas. Nevertheless, by 3 that afternoon, the *Oceanus* was loaded and ready to steam to the area near the spill — but where exactly should we go?

Not knowing how long the oil would float, we assumed that it would remain near the surface and follow surface currents. Air flights monitoring the path of the oil spill showed it drifting toward the west, suggesting that our first area of interest should be directly west of the slick, the area of probable impact. Just before the *Oceanus* sailed, however, more recent aerial photographs showed that the slick was moving to the northeast, due to a shift in wind direction. Thus at the last moment, we changed our cruise track to an area northeast of the *Argo Merchant*.

By the time the *Oceanus* reached the first station, 25 miles north-northeast of the vessel, winds had increased and storm warnings had been issued. It was only a matter of hours before we would have to run back into Nantucket Sound for shelter. By working continuously, however, we were able to occupy 2½ stations. In addition to sampling the water column for particulate load, we took six bottom sediment samples at each station, three for invertebrate animals and three for hydrocarbon analysis, the replicate samples being necessary for statistical accuracy. By 5 a.m. Tuesday, conditions deteriorated to the point where we had to stop work and steam for the relative safety of Nantucket Sound. The three-day forecast predicted continued bad weather, so we returned to Woods Hole. Although we had gathered background data relatively near the stricken vessel, our cruise had been unsuccessful because we had collected an insufficient number of samples. Moreover, the shifting winds were forcing the slick east, necessitating further sampling.

Before a second cruise could be organized, another problem presented itself — Christmas. Emergency or not, Christmas holidays are a difficult time to be away from home, particularly for a ship's crew, who often spend 80 percent of their year at sea. Fortunately, a decision to remain in port was substantiated by continued heavy winds and cold weather, which made seagoing studies impossible. Oddly, the weather during Christmas Eve and Christmas Day was calm and relatively warm, but immediately afterward it worsened, preventing the ship from leaving Woods Hole.

The shipboard laboratory. Once collected, measured quantities of the water samples (stored in graduated cylinders on the overhead rack) were filtered onto filters (seen in their holders on the bench) with 0.45 micron openings, thus trapping most of the material in suspension. At the same time, other aliquots of the water samples were treated so as to remove both dissolved and suspended hydrocarbons.

Before the *Oceanus* could leave, changing winds again forced a reevaluation of cruise tactics. Over the weekend, the wind shifted to the southeast for a period of about 15 hours, during which time oil from the *Argo Merchant* began approaching the beaches of Nantucket Island. Clearly, if such winds had persisted, the oil could have reached not only Nantucket, but also the marshes that border the southern shore of Martha's Vineyard. This possibility forced us to restructure our tasks for the second cruise; background data were needed from the shelf and nearshore waters off these islands. Muds on the bottom of the middle and outer shelves of this area could provide a potentially long-term sink for the oil; its effects on such sediments would be far more severe than in sandy bottoms, where the oil could be oxidized, or washed away. In addition, we needed to set several oceanographic current-meter buoys nearby, that would supplement other USGS buoys that were being set at the same time from another ship. Finally, and perhaps most importantly, we needed to find out whether the oil was settling from suspension. To do this we had to take water and bottom samples directly west of the stricken vessel, an area that had received considerable oil spillage during the early days of the grounding. If we found little evidence of sinking, it could be assumed that the oil was remaining in suspension and would move primarily as a result of wind transport. Since winds in winter are primarily to the east, this would mean that the oil would move seaward, thus sparing the coastal environments. Also, since most spawning of marine fishes occurs in spring and summer, the oil might not have the impact upon commercial fisheries that it would have in warmer months (see page 46).

The time required for steaming to the area, occupying the stations, and installing two current-meter moorings totaled slightly more than 24 hours. If a window could be found in the generally stormy weather, we could accomplish the work and be back in port before the next storm. The weather forecast on Monday afternoon gave us some hope of finding the necessary time — winds were to moderate late that evening before increasing to near gale force early on Wednesday.

We left Woods Hole at midnight and by 3 a.m. on the 28th the weather began abating. Within a few hours, the winds were less than 10 knots, and we steamed for the first station. Although seas were by no means calm, we worked in relative comfort. The same measurements were taken as those on the first cruise. Since most of the crew was the same, the by now routine work went smoothly and quickly.

Twenty hours later, the work was complete. We ran for port with the storm on our stern. We had occupied a total of eight stations, six off Nantucket, and two near the *Argo Merchant,* and had taken more than a hundred various samples. We also had made numerous bird observations, but had seen no sign of larger sea life, such as marine mammals or sharks. Oil-coated birds were plentiful over the entire area, and patches of oil slick were common at the stations nearest the wreck.

U.S. Navy diver being questioned by partner aboard U.S. Coast Guard cutter Vigilant *after dive to film conditions under* Argo Merchant *main slick. (Photo courtesy U.S. Navy)*

However, there were no visible signs of oil in our samples, suggesting that if the oil was sinking, it was probably doing so quite slowly.

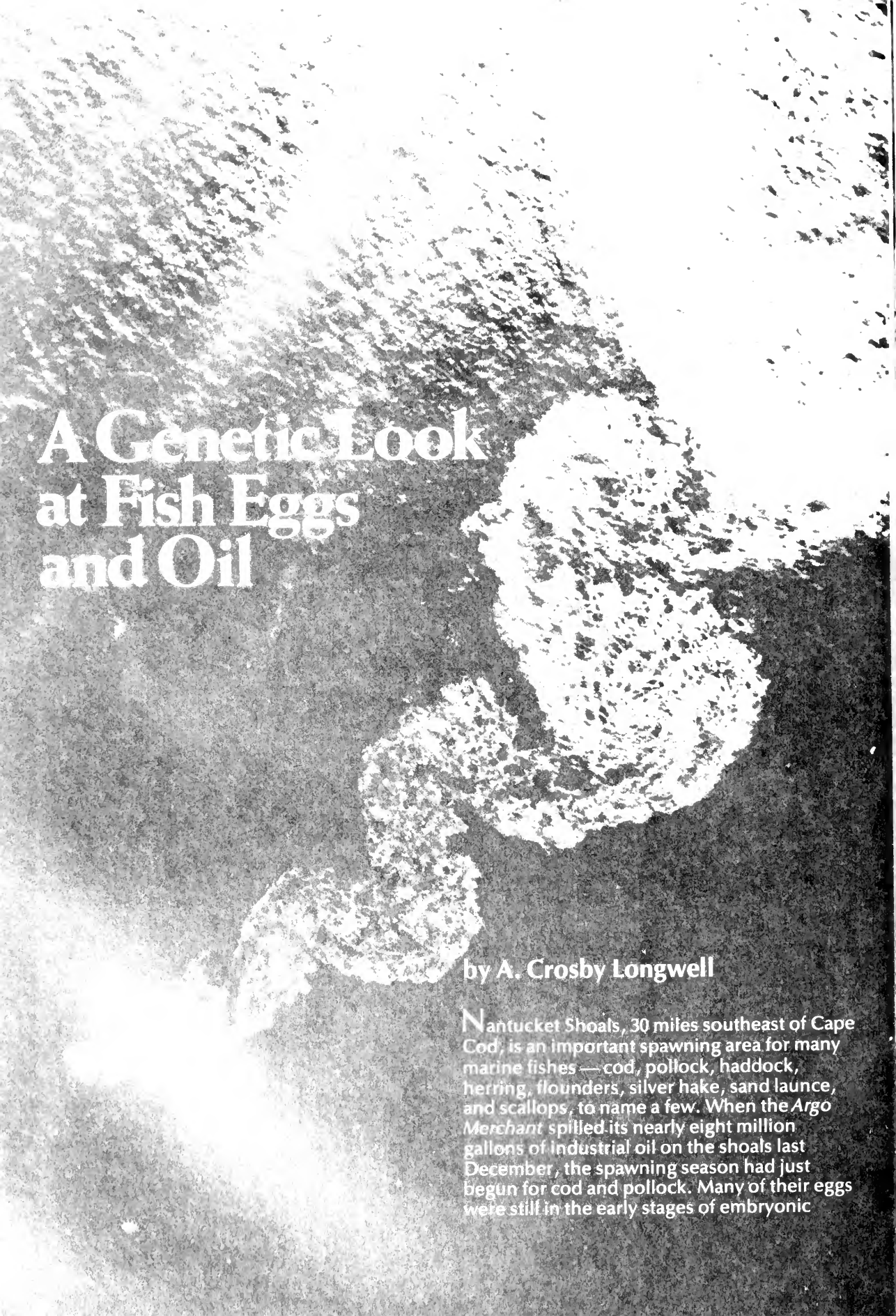
Within two weeks of the *Argo Merchant's* running aground, Woods Hole scientists had responded with two oceanographic cruises to assess the damage, as well as to monitor areas that might receive future impact. Since then cruises by the NMFS, USGS, and the University of Rhode Island have continued the observations and sampling. These original background samples, however, have proved most invaluable, since it is against these data that the impact of the spill must be measured. Of course, seaward movement of the oil lessened the immediate problem of the spill, but what if the winds had not been so kind? If they had been from the southeast, the oil could have reached shore within a day or two. Moreover, if the oil had sunk quickly, it could have moved westward with the bottom currents, resurfacing on beaches along the northeastern coastline of the United States.

What then was our lesson, and how can it be applied to future potential disasters? First, it must be remembered that disasters often do not move in predictable manners; at sea, they often occur during less than ideal weather conditions. One's options must be kept open, but if the time for sampling and observation is short, and the conditions adverse, one should monitor those areas in which the impact is potentially most adverse, particularly those waters closest to sites of human activity.

Second, the dearth of background data, concerning both the oceanography near the spill and how oil moves through the environment, clearly prevented a better response to the *Argo Merchant* spill. The types of data needed include insights into the following problems: How do various types of oil settle through the water column, and at what rates? What are the oceanographic/meteorologic regimes of the area (the relative importance of currents versus winds, relating to whether the oil remains at the surface or settles)? To what extent does oil volatilize and oxidize before reaching the bottom? What is the fate and effects of oil on bottom organisms and sediments? Of more practical importance, how can we sample in a potentially impacted area without almost hopelessly fouling the ship and sampling equipment with oil? How fast can we respond to the disaster (this ultimately depends on the availability of a ship and the weather conditions)?

None of these questions were totally answered during our cruise. However, if we could have more intelligently predicted the fate of oil in the water column and on the bottom, as well as the advective regime of the environment, our cruises could have gathered more detailed and meaningful information. With increased Federal and state supported research, such data might be available before the next disaster.

John D. Milliman is an Associate Scientist in the Department of Geology and Geophysics, Woods Hole Oceanographic Institution. He served as Chief Scientist on the Oceanus *cruises to the area of the* Argo Merchant *oil spill.*



A Genetic Look at Fish Eggs and Oil

by A. Crosby Longwell

Nantucket Shoals, 30 miles southeast of Cape Cod, is an important spawning area for many marine fishes—cod, pollock, haddock, herring, flounders, silver hake, sand launce, and scallops, to name a few. When the *Argo Merchant* spilled its nearly eight million gallons of industrial oil on the shoals last December, the spawning season had just begun for cod and pollock. Many of their eggs were still in the early stages of embryonic

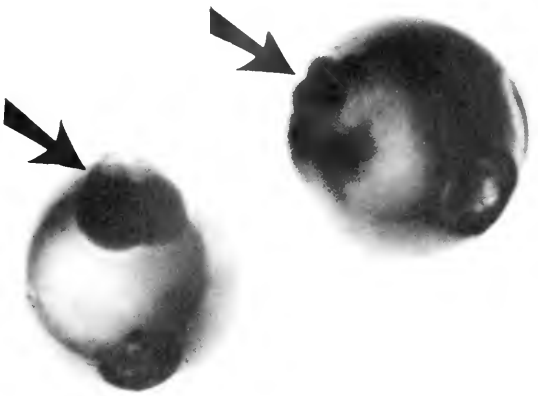


Figure 1. Pelagic Atlantic mackerel eggs as they occur in surface waters. Egg to left has completed its first cleavage division and has a 2-cell embryo. See arrow. Body to bottom of the egg is the oil globule characteristic of some species eggs. Egg to right has a 4-cell embryo at arrow. Actual egg size about 1 mm as viewed in low-power magnification under dissecting microscope.

development and some came into direct contact with the spreading oil. Soon after the cod and pollock spawned, their buoyant eggs, a fraction more than a millimeter in diameter, floated upward to the surface microlayer — the top millimeter of water — to remain until hatching, anywhere from a few days to weeks later, depending on the water temperature (Figure 1).

The *Argo Merchant* grounding attracted attention in part because it occurred on relatively clean, rich fishing grounds. The effect of the spill as it moved away from the wreck — into areas used by cod, pollock, and other species for winter and spring spawning — is not known. It should be noted, however, that in addition to spilled oil, the surface microlayer of the ocean is also subject to the direct assault of atmospheric pollution; it concentrates toxic heavy metals and retains long-lasting chlorinated hydrocarbons, such as DDT and the polychlorinated biphenyls. All told, chemicals have been polluting the surface of the sea at disquieting rates for the last 35 years or so. Among them are cytotoxins, specifically toxic to dividing cells, and mutagens, which provoke lethal chromosome changes.

The reproductive phase is by far the most sensitive stage in the life cycle of any species. In the early stages of development, this is true largely because the embryo needs a balanced set of chromosomes, which bear hereditary material essential to normal development. Fish eggs are genetically more sensitive than those of invertebrates, approaching those of mammals in this regard.

Cells undergoing meiotic divisions, which lead to the development of the male and female gametes in the gonads of fish, are particularly susceptible to errors of chromosome separation and to gene-level mutations. Early cleavage mitoses of the fertilized egg (zygote) are even more sensitive. Figure 2 shows this first cleavage mitosis of a healthy pelagic egg taken from a plankton sample. Chromosome errors are almost invariably lethal if they occur before the gastrula stage.* Unlike physiological effects,

Figure 2. Life cycle of a fish begins in surface waters. Just before the 2-cell embryo of Fig. 1 was formed, it underwent its first mitotic division, as seen in this photomicrograph. This embryo dissected off a planktonic mackerel egg is in mitotic telophase of its first chromosome division. It is this mitotic stage (telophase) that is used diagnostically in fish eggs to appraise chromosome breakage, irregular distribution of chromosomes, and other division irregularities. Phase-contrast 100x objective.

Overview of Argo Merchant *spill. The photograph at left was taken by a National Aeronautics and Space Administration aircraft on December 19, 1976, from an altitude of 1,675 meters. (Photo courtesy NASA)*

*The stage of embryonic development at the end of the cleavage period or blastula stage in which gastrulation movements carry those cells whose descendants will form the future internal organs from their largely superficial position in the blastula to approximately their definitive positions inside the embryo.

"Pancake" slick from the Argo Merchant *moving out to sea. (Photo courtesy NOAA)*

there can be no recovery. After gastrulation of the embryo, lethality depends on the number of affected cells, plus the destiny of their lineages in development. Mutations that occur during the period of major organogenesis lead to developmental abnormalities in systems that are not fully developed until the post-hatching period. When fish eggs are spawned, they are slightly more than halfway through the delicate meiotic divisions. Abnormalities in chromosome makeup at the early embryo stage are probably the most sensitive practical indicators of the sublethal effects of marine pollutants on reproduction in fish.

The Compounds in Oil

Crude and refined oils contain thousands of compounds with different physical and chemical properties. The low-boiling-point aromatic hydrocarbons are soluble in water. They also are highly soluble in lipid material, which is present in fish eggs. Benzene, the most abundant such chemical compound in crude oil, has proved mutagenic in a number of tests on different organisms. Polynuclear aromatic hydrocarbons can act as both carcinogens and mutagens. Most if not all carcinogens are mutagens. Tumors or malignant growths in molluscs and in macroalgae have been reported both in connection with spills of refined oil and with growth in marshes contaminated by industrial waste. Oil can act as either a stimulant to cell division in algae or, instead, retard or completely inhibit division.

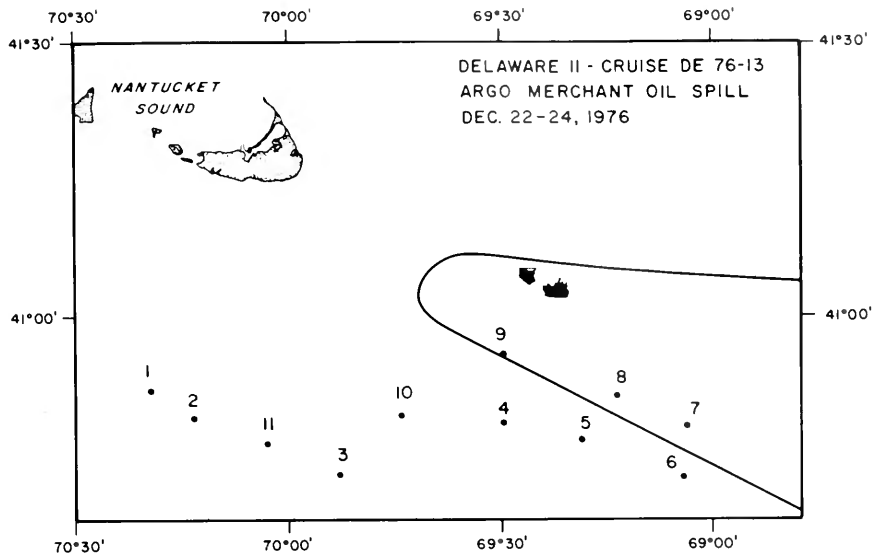
The membranes and the jelly coat of fish eggs afford a considerable measure of protection against pollutants. Such protection, though, is probably diminished temporarily when perivitelline fluid formation* takes place after fertilization and the pollutant enters the egg with imbibed water. A pollutant that damages or disorganizes an egg's membranes will also modify its permeability. Aromatic compounds of oil appear to alter the surface properties of cell membranes, whereas paraffin hydrocarbons do not.

The Fish Eggs on Nantucket Shoals

The *Argo Merchant* spill consisted of about 80 percent Number 6 fuel oil, which is so viscous at low temperatures that it is difficult to pump, and about 20 percent light distillate Number 2 fuel (a cutter stock to make the Number 6 more manageable). The Number 6 oil soon formed "pancakes" that stayed on the surface and increased in thickness as the oil aged. The persistence of this oil in clinging to the surface reduced the likelihood of serious damage to bottom-dwelling organisms, but may have increased the risk of toxicity to fish eggs and various other plankton. Apparently only the Number 2 stock — the more toxic of the two — penetrated the water column to any great degree. The highest concentrations, on the order of 250 parts per billion, were found 1.8 to 3.6 meters below the "pancake" slicks. This was at depths where pelagic fish eggs could be found. The surface water surrounding the "pancakes" was covered with a thin, greasy sheen that gave off a strong odor. This sheen probably was a source of egg contamination in itself.

In the rough weather that followed the *Argo Merchant* grounding, oil droplets must have been driven through the water column by breaking waves. Buoyant fish eggs would have been driven through the water column with the oil, eventually surfacing with it. Evaporation of the more toxic aromatics probably was limited by the extremely low temperatures (2 to 6 degrees Celsius) at the

*Fluid that forms between the fertilization membrane and the ovum after the entry of a sperm into the egg.



Station locations for Delaware II *cruise. The solid line indicates oiled area.*

surface, which in turn would have prolonged the eggs' exposure to these more toxic compounds. The concentration of the Number 2 fuel in the water column was diluted to background levels within a few days, but the surface contamination by the heavy oil remained.

Field Sampling of the Fish Eggs

Ichthyoplankton samples were taken in the area of the spill during the Northeast Fisheries Center's *Delaware II* cruise from December 22 to 24. A portion of the eggs in these samples was sent to the Milford (Connecticut) Laboratory of the National Marine Fisheries Service (NMFS) for microscopic study. Plankton were collected at cruise stations 4 to 9 with standard oblique bongo net tows of the water column and with neuston nets along the water surface. No surface oil was observed at stations 4, 5, or 6, and the samples of the water column were clean. Samples taken at the surface, however, contained specks of tar. Stations 7 and 8 were within the thick "pancake" slicks. The neuston nets here were saturated with oil. No fish eggs were collected at station 7. At station 9, located on the periphery of a thick slick, extremely high numbers of zooplankton and total biomass were observed.

Fish eggs were examined and identified at the Narragansett and Sandy Hook laboratories of the NMFS. Only cod *(Gadus morhua)* and pollock *(Pollachius virens)* eggs were present in the samples. Pollock eggs were most numerous within and adjacent to the thick floating slicks, whereas cod eggs existed mostly around the periphery of the spill area.

Oil Contamination of the Eggs

The eggs' outer membrane, the chorion, showed some contamination at all stations. Oil droplets and tar adhered to roughly half of all fish eggs examined (both species, all stations). Almost all the chorions of pollock eggs at station 9, just outside the "pancake" slicks, were fouled with tar-like oil (Figures 3, 4, and 5); in one estimate, this condition was found in

Neuston net fouled with oil being brought aboard Delaware II *during cruise to* Argo Merchant *area. (Photo Ronald E. Boisvert, NMFS, Woods Hole)*

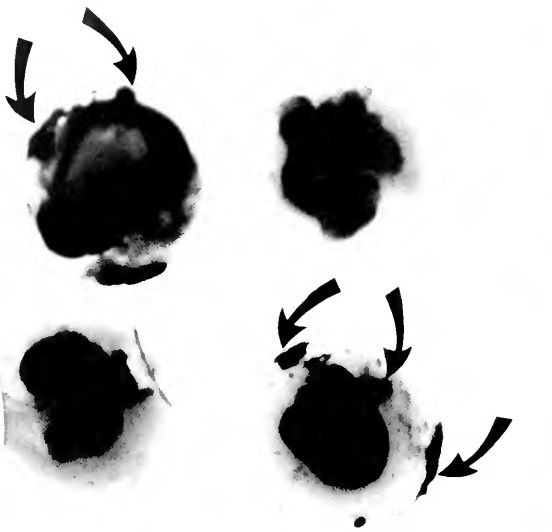


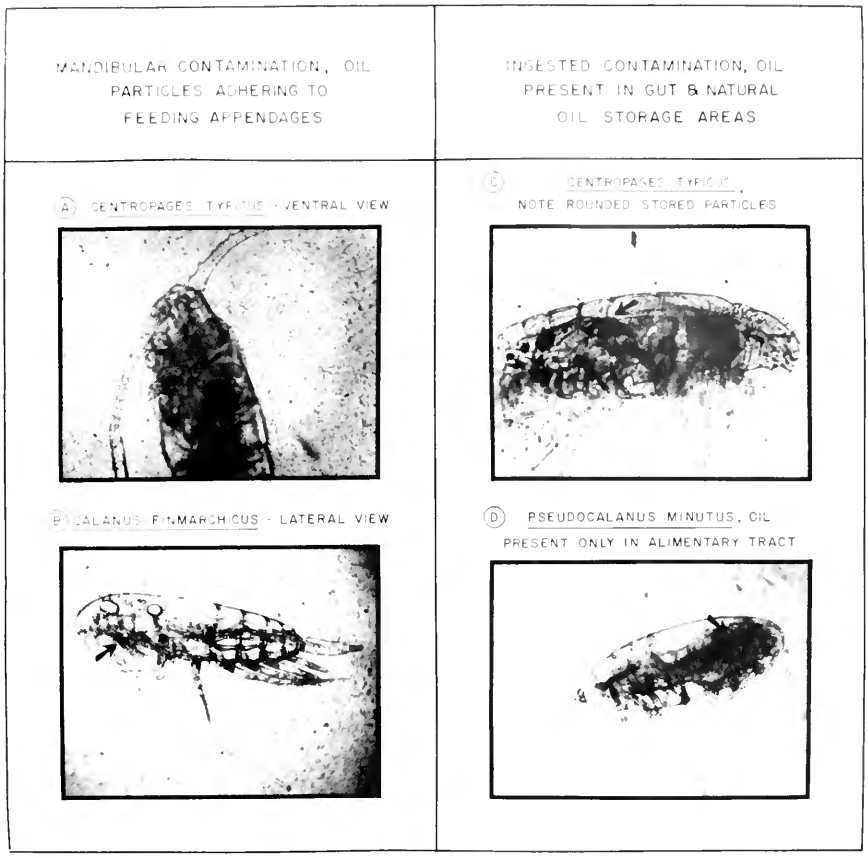
Figure 3. Pollock eggs sampled at edge of the Argo Merchant *oil slick. Tail-bud and tail-free embryo stages. Egg at upper left and egg at lower right have their outer membrane contaminated with a tar-like oil. Arrows point to some of the oil masses. The uncontaminated egg at upper right has a malformed embryo. The uncontaminated egg at lower left is collapsed and also has an abnormal embryo. Actual size of pollock eggs around 1 mm; of cod eggs around 1.5 mm.*

Figure 4. Surface of an oil-contaminated pollock egg from edge of the Argo Merchant *slick. Arrow at left points to one clump of oil. A clean portion of the outer egg membrane, its pores barely visible at this magnification, shows to the left, above and below this arrow. Arrow on right points to an antenna of a copepod stuck in a mass of the oil adhering to egg membrane. Copepods are other inhabitants of surface waters observed to be fouled with* Argo Merchant *oil. Scanning electron microscope. About 500x.*

Figure 5. Portion of surface of oil-contaminated pollock egg of Fig. 4 at greater magnification. Upper arrow points to one of many oil droplets. Lower arrow points to one of the membrane pores. Scanning electron microscope. About 5,000x.

94 percent of 49 pollock eggs. Quantitatively, these eggs were all more fouled than those at the other stations, whereas the particles of oil adhering to cod eggs at this station did not appear any larger than at the other sites. Generally, fewer cod eggs were fouled than pollock (60 percent of 60 in one estimate).

To our knowledge, this was the first report of oil droplets adhering to fish eggs, either from the vicinity of an oil spill, or in laboratory experimentation. (Crude oil has been reported to adhere to many species of coral, causing tissue death at points of contact.) Copepods sampled on Nantucket Shoals at the same stations where the cod and pollock eggs were fouled showed external mandibular contamination with the oil, as well as internal effects. This has been reported before. But over the last few years, no oil has adhered to any of the thousands of other planktonic fish eggs studied at the Milford Laboratory, with the recent exception of Atlantic mackerel eggs from one isolated station in the New York Bight sampled in May of 1977.



Copepods picked from samples taken on Delaware II *cruise.*

External fouling of the outer pelagic egg membrane obviously increases the risk of egg mortality. Although it is not probable, the oil could have adhered to the eggs (and copepod surfaces) during the sampling and preservation processes. Oil-fouled nets could have affected the eggs, but it is difficult to imagine that eggs that could be readily contaminated while being towed by nets, would not also be fouled, at least to some degree, by mixing with the oil in the water column. In fact, at one station a heavily contaminated net yielded samples that were less fouled than at another. Another possibility is that oil becomes attached to the chorion only at certain times. These possibilities and others will have to be explored further in the laboratory.

The greater membrane contamination of pollock eggs over the cod could be related to any different differential at which these fish spawn in the water column and to the rate at which their eggs rise to the surface. Of course, there is also the exposure time factor: the cod eggs were at an earlier stage of development than the pollock. Another factor might have been species variation in the chorion structure; scanning electron microscopy of the cod and pollock eggs revealed a different pore structure in the two species (Figures 6 and 7).

Examining the Dividing Chromosomes

Cytogenetics — the study of chromosomes and their divisions as they affect heredity —

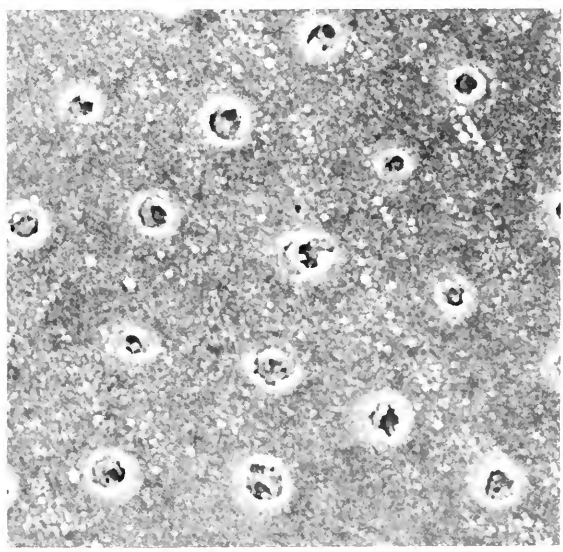


Figure 6. Still greater magnification of a portion of surface of a seemingly clean pollock egg from Argo Merchant *spill vicinity, showing pore pattern of outer egg membrane, the chorion. Scanning electron microscope. About 10,000x.*

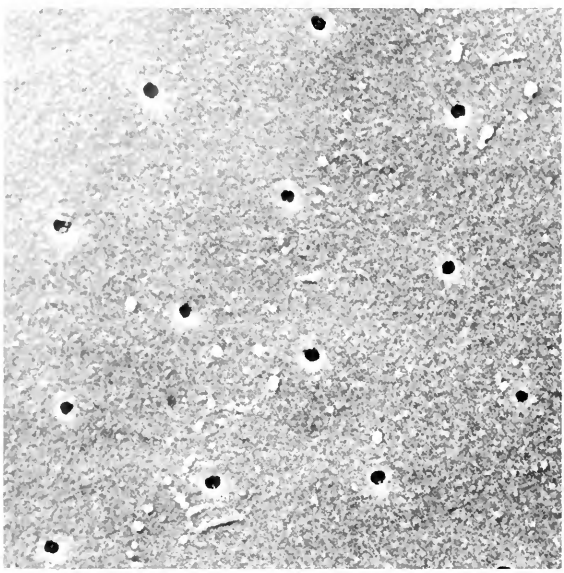


Figure 7. Portion of surface of a seemingly clean cod egg from Argo Merchant *spill vicinity, showing pore pattern of outer egg membrane, the chorion. Scanning electron microscope. About 10,000x.*

has been rarely applied in the past to fish. It is only recently that reliable methodology has been developed for conducting cytological and cytogenetic studies on fish eggs from plankton samples taken at sea. This methodology was applied in a limited manner to the small number of fish eggs sampled in the vicinity of the *Argo Merchant* spill.

Plankton sampling is a routine procedure on many biological research cruises. On the *Delaware II* cruise, samples were fixed in neutral formalin. Even if stored for decades, eggs in plankton samples can be studied cytologically and cytogenetically. The eggs are first identified as to species. They are then separated for processing according to their developmental stages (early stages, from cleavage to tail-free embryo, vary in their suitability for offering cytological and cytogenetic information). Under a low-power microscope, the embryo is dissected from the egg with a needle (Figures 8 and 9). After a post-fixation in acetic acid, the fragile embryo is stained and squashed into a monolayer of cells on a microscope slide (Figures 10 and 11). For cytogenetic work, the staining medium is the standard aceto-orcein to which proprionic acid is added. Cells and their dividing chromosomes are viewed under high-resolution, high-power, light microscope optics.

The first work of this nature began during a May 1974 cruise of the training vessel *Westward,* which sailed into the badly polluted New York Bight and collected Atlantic mackerel (*Scomber scombrus*) eggs. A report on the early results of the cruise appeared in a government technical memorandum (NOAA Technical Memorandum ERL-MESA-7, 1976). Since this report, which was based on a relatively small number of eggs from a few stations, a few thousand Atlantic mackerel eggs from more than 30 stations have been studied. These data are now being analyzed and the findings will be published in a NOAA technical memorandum and elsewhere.

At the most genetically sensitive stage of the newly formed zygote — early cleavage — mackerel eggs survived appreciably only at three stations in the northeast periphery of the Bight. At this and at later stages, intact embryos that exhibited no gross deterioration were often observed to be in an undisputable stage

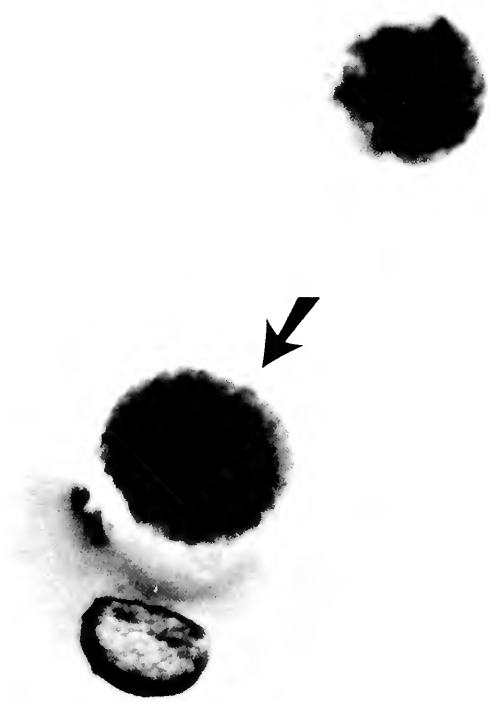


Figure 8. Planktonic Atlantic mackerel egg at very early morula stage of development, and embryo dissected off its egg. Arrow points to embryo still in the egg. Characteristic oil droplet is at bottom of the egg. Body to upper right is morula-stage embryo dissected off its egg in preparation for examination of its cells and chromosome divisions. Actual egg size about 1 mm as viewed in low-power magnification under a dissecting microscope.

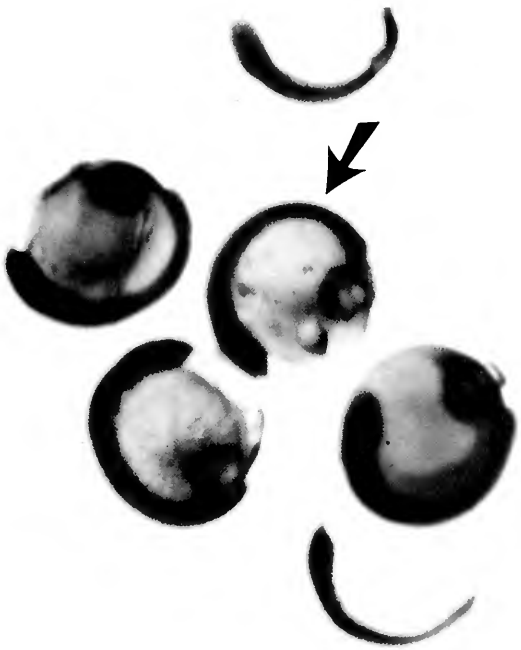


Figure 9. Planktonic Atlantic mackerel eggs at the later tail-free stage of embryo development — the stage of a large portion of the pollock eggs sampled at the time of the Argo Merchant *spill. Arrow points to a tail-free embryo partly encircling its egg. At top and at bottom of the photomicrograph are two such embryos dissected off their eggs. Actual egg size about 1 mm as viewed in low-power magnification under dissecting microscope.*

of deterioration at the cell level. Others had entirely ceased undergoing chromosome and cell divisions, prerequisites for embryo development. Although the next two embryo stages — morula and blastula — had greater viability than did the early cleavage stages, they often had many incidences of chromosome abnormalities, an arresting factor in embryo development (Figures 12 to 14). During and just after the gastrula stage, the incidences of chromosome abnormalities dropped dramatically, with the most severely abnormal embryos being unable to gastrulate.

Two indices of abnormalities in cell division and chromosome separation were chosen: (1) abnormalities in the movement of daughter chromosomes to opposite ends of the mitotic spindle during telophase*; and (2) the mitotic index — the total number of mitotic telophases per embryo in the blastula through the tail-free stages. Station-to-station variation in the mitotic index was very wide for mackerel eggs in the New York Bight. In general, one would expect a high number of mitotic telophases in normally developing embryos. Also, the low numbers would indicate a slowing or cessation of development.

The *Argo Merchant* Study

Using the same procedures described for mackerel, microscopic examinations were made of the dissected embryos of 79 cod and 162 pollock eggs taken from surface waters in the vicinity of the *Argo Merchant*. Seventy-five cod embryos from eggs of a laboratory spawning of aquarium-held fish were also examined.

This study was greatly limited by the small number of total eggs available. Cod and

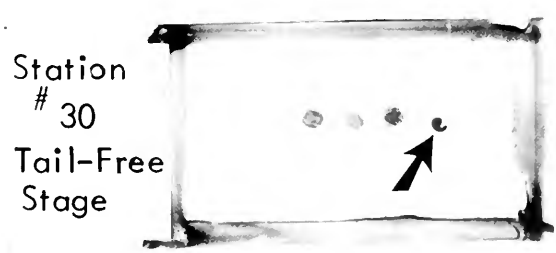


Figure 10. Four tail-free embryos dissected off planktonic fish eggs squashed onto microscope slide, stained, and ready for study of their cells and mitotic divisions. Near actual size.

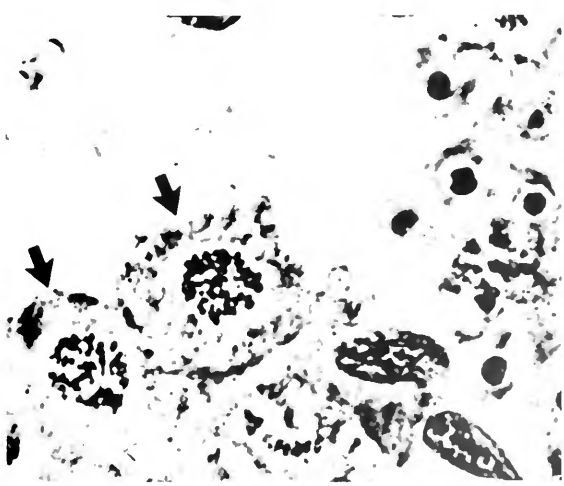


Figure 11. Monolayer of embryo cells prepared for cytological-cytogenetic study. Arrows point to two cells in prometaphase of mitosis. Low-power 15x phase-contrast objective.

*The terminal stage of mitosis, during which nuclei revert to resting-stage.

Figure 12. Normal mitotic telophase at gastrula stage in mackerel embryo from a planktonic egg. Arrow points to one of the two daughter groups of newly divided chromosomes. Light microscope, 100x objective.

pollock eggs were scarce at the cleaner stations (Table 1). Of the cod eggs, 63 percent were of phases earlier than the tail-bud stage, with the very earliest stages well represented. Pollock eggs were divided equally between the later tail-bud embryo and tail-free stages. This made precise station and species comparisons impossible, though some comparisons could be drawn, using the combined estimates of cytological mortality and cytogenetic moribundity.

All the cod and pollock eggs in the dead category showed a combination of cytological abnormality of the embryo's cells or nuclear configurations indicative of cellular death coupled with division arrest. Embryos that had ceased undergoing mitosis were categorized as moribund, and most of these also showed signs of early deterioration at the cellular level. The earlier-stage cod eggs generally showed far fewer abnormal chromosome divisions than did mackerel eggs at the most polluted stations studied in the Bight. For both cod and pollock eggs at the same developmental state, however, there was an extremely wide in-station variation in the embryo mitotic index (Table 2). There are no adequate baselines to interpret this variation. The possibility exists,

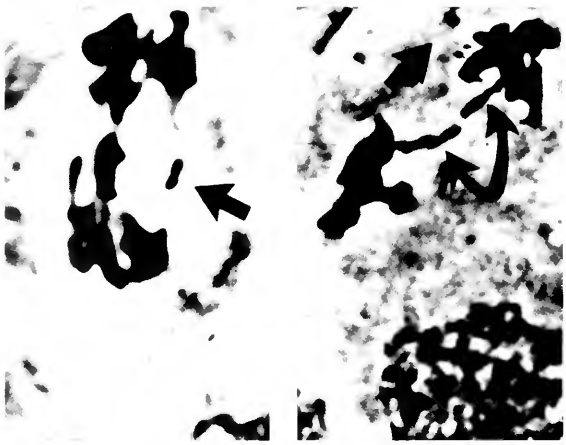


Figure 13. Two abnormal mitotic telophases at gastrula stage from planktonic mackerel eggs. Note chromosomes lagging between, and bridging the two groups of daughter chromosomes and to the back of one group. Such telophase irregularities are indicative of chromosome damage, and result in irregular distribution of chromosome material to daughter cells. Light microscope, 100x objective.

however, that many embryos that exhibited a low number of mitoses were headed for complete division arrest.

A higher mortality of pollock over cod was apparent. Because so many more of the cod eggs were at earlier developmental stages than were the pollock eggs, the mortality of cod was expected to be higher. Totaled over all the stations, about 20 percent of the collected cod eggs were dead or moribund, compared

Figure 14. Grossly abnormal mitotic telophase in mackerel embryo from a planktonic egg. Extremely abnormal stickiness of the chromosomes has caused them to lose their distinctness and prevents their completion of this mitotic division. Light microscope, 100x objective.

Table I: Cytological-cytogenetic assays of mortality and moribundity of cod and pollock eggs from the vicinity of the Argo Merchant oil spill.

Delaware II cruise DE 76-13 station numbers	Total number of eggs	Number of eggs viable	Number of eggs dead or moribund	Number of eggs with malformed embryos
Station 4				
Cod	14	13	1	0
Pollock	—	—	—	—
Station 5				
Cod	6	3	3	0
Pollock	11	0	11	0
Station 6				
Cod	3	3	0	0
Pollock	3	0	3	0
Station 8				
Cod	1	1	0	0
Pollock	105	86	19	19
Station 9				
Cod	55	43	12	0
Pollock	43	1	42	4
Laboratory spawning cod	75	72	3	0

Table 2: Total numbers of mitotic telophases in pollock embryos at stations 8 and 9.

Delaware II cruise DE 76-13 station numbers	Telophases (actual number or estimate)					
	0	3-14	15-25	±50	±75	-100 - +200
Station 8	6	7	8	27	8	28
Station 9	35	6	0	0	0	0

to 46 percent of the pollock eggs. As mentioned earlier, fewer cod eggs were fouled, and those that were, were less so than the pollock. Moreover, only 4 percent of the samples of cod eggs spawned in the laboratory (at about the same developmental stages as the samples from the spill) were dead or moribund. If this cod control is representative, then the cod were experiencing higher than usual mortality in the spill vicinity, but still less than the pollock.

At station 8, pollock embryos were also grossly malformed in 18 percent of the eggs (Figure 3). At station 9, gross malformations occurred in 9 percent of the eggs. None were observed at any of the stations more distant from the heavy slicks.

Pollock mortality was lower at station 8 than in the more membrane-contaminated eggs at station 9. Those embryos at station 9 (15 percent) that had not entirely ceased to undergo cell division had very few mitoses (Table 2). This station was probably in the "sheen" fed by the "pancake," which could have been more toxic than the waters just beneath the thick slick.

These non-dividing pollock eggs of station 9 were characterized by rather pycnotic nuclei.* The cells of these embryos had a clearly non-differentiated appearance, resembling more the cells of an earlier developmental stage. Differentiated

*Contracting into compact strongly staining masses as cells die.

embryonic cells are known from experimental work to react to various stress situations by undergoing de-differentiation. They become altered and disorganized, acquiring an appearance reminiscent of their earlier undifferentiated state. This appears to have been the case with the station 9 pollock eggs.

Along with the cod and pollock fish eggs sampled in the vicinity of the *Argo Merchant*, four other species of hatched fish larvae were sampled — sand launce, rockling, hake, and herring. (Though not a commercial species, sand launce are the basic food of cod, haddock, and silver hake, among others.) The abundance of the sand launce larvae decreased sharply at the two stations within the area of the thick slick. This decline and the paucity of other species' larvae may have been related to the spill.

Unfortunately, though now within the realm of the obtainable, there are still no baselines for cytological-cytogenetic mortality-moribundity of cod and pollock eggs at sea, or even in hatchery culture. Thus it is impossible to fully assess the significance of the cod and pollock findings from the *Argo Merchant* vicinity without additional samples. For sizeable oil-induced mortalities to have an effect on these fisheries, a large number of eggs would have to be concentrated in the spill area. Oil components also would have had to be present in toxic concentrations for the bulk of the period in which the eggs and larvae were in the pelagic stage. Given the frequency of oil spills and the variety of commercial species of different life habits, these conditions would be met in a few, but certainly not all spills. Species that spawn in the open ocean over wide areas would be the least likely to suffer substantial mortalities.

Cod and pollock spawn from December to May off New Jersey along the coast as far north as Greenland. The extent of their spawning area and the length of their spawning period would minimize the impact of a localized phenomenon, such as the *Argo Merchant* spill. On the other hand, Nantucket Shoals is one of the important spawning areas for both cod and pollock. The oil slicks from the *Argo Merchant* remained on the shoals for a month, more or less. Depending on the temperature, the incubation time of pollock is 6 to 9 days and for cod 10 to 40 days, after which the yolk-sac larvae are hatched. Thus the slicks persisted on the shoals for the incubation periods of these eggs and during what should have been the peak spawning time of these fish. Yet, the slicks did not remain the entire length of the spawning period there. If fish actively avoid oil spills, and there is some evidence they do, they may or may not spawn in areas that afford less chance of survival for their hatched larvae. Of course, a free-floating egg spawned elsewhere could be swept into the spill area. In addition, complications of real impact assessment on the fisheries stem from the possibility that different spawning grounds vary considerably in what they contribute to any particular year-class recruitment of juveniles, depending on variable weather, predation, availability of larval foods, and so forth.

Effects of Oil on Gametes

Effects of oil on the chromosome divisions of developing fish embryos have not been studied in the laboratory. The genetics group at the Milford Laboratory, however, will be collaborating with Dr. W. Kühnhold of the University of Kiel, West Germany, in a study of the toxicity of oil on cod eggs in hatchery culture, one facet of which will be cytogenetic.

Kühnhold (1972) has conducted experiments in laboratory culture systems on the effects of extracts of Venezuelan, Iranian, and Libyan crude oils on cod eggs. These eggs were most sensitive during the first few hours after fertilization. After 10 hours of exposure, mortalities were significant. The oil retarded development and, in some cases, hatching was delayed or did not occur. Most of the larvae that did hatch were abnormally developed or had abnormal swimming movements, dying after a few days. Lethal concentrations at which 50 percent of the larvae were dead by 48 and by 96 hours were on the order of 1 to 12 parts per million.

In a test conducted jointly at Narragansett, R.I., by the Northeast Fisheries Center and the Environmental Protection Agency in an effort to obtain some information on the toxicity of Number 6 fuel oil, cod eggs were exposed to the water-soluble fraction of this oil in static systems. Estimates of mortality were then made from live cultures. The greatest effect measured was at 500 parts per billion (ppb) on the 2-cell stage. Ten ppb did not appear to increase embryo mortality or

alter the hatching rate. Full results have not yet been reported. Prior to dying, eggs dropped to the bottom of the culture beakers, presumably because of faulty osmoregulation of their membranes. Accordingly, mortality estimates of surface-sampled fish eggs in the field after a spill may be biased toward too low estimates even with cytological examination of dissected embryos.

O.G. Mironov (1968, 1969, 1972) has shown that eggs of the turbot *(Rhombus maeoticus)*, plaice *(Pleuronectes platessa)*, anchovy, scorpion fish, and sea parrot are adversely affected by concentrations of oil in water of around 1 part per million, or even lower. As in Kühnhold's work on cod, there were gross abnormalities and abnormal swimming of the turbot larvae.

Struhsaker and others (1974) found development of abnormal embryos to be the principal effect of benzene, a water soluble component of crude oil, on eggs of the Pacific herring *(Clupea pallasi)* and anchovy *(Engraulis mordax)*. This effect of oil on early embryo stages leading to abnormal development of the fish larvae seems to be observed to some degree by workers exposing early egg stages. It has been reported that 50 to 90 percent of the pilchard (*Sardina pilchardus*) eggs were dead and juvenile forms scarce or abnormal in the vicinity of the *Torrey Canyon* spill. This could have been due to the toxic effects of the emulsifier used to disperse the spill, or to the oil itself, or to other unknown factors.

These reports of abnormality and increased mortality on exposure of early-stage fish eggs to oil or oil fractions probably to some degree reflect damage to the zygote at the chromosome and cellular levels, but before the present study conducted on eggs from the *Argo Merchant* spill area, chromosomes had not been examined.

Recovery of Impacted Populations

With mounting evidence that oil is toxic to the eggs and larvae of fish, especially during the early spawning period, it is clear that serious damage from a spill need not show up immediately or in a manner obvious to the naked eye. Should serious damage be done to the spawn affecting recruitment into a new-year class, the number of breeding generations occurring each year would greatly influence the length of the population recovery time. Also affecting recovery time are fecundity of the females, their fertility, and the quality of their eggs.

Greatly fecund species, which includes most fishes and marine invertebrates, are more resilient than less fecund ones. (A pollock female spawns about 225,000 eggs each season; cod 1,000,000 or more.) There is even a good possibility that natural genetic selection would result in populations with resistance against particular pollutants. Yet resiliency can be exhausted. An exploited species of fish might be expected to be less resilient to damage than a whole ecosystem. In the same manner, a commercial fishery would be less flexible than a natural population.

Furthermore, immature eggs in development in the fish gonads (on which population recovery would ultimately depend) are affected by the same genetically toxic chemicals that adversely affect the mature, spawned, fertilized egg and its developing embryo. Germ-line primordial cells are also susceptible to damage. Even though mutations can be transmitted by the male, contaminant uptake is particularly serious in the female spawners. This is due largely to the exposure the zygote and embryo may receive at their most sensitive developmental stages from maternal contaminant loads carried in the egg yolk.

Some marine contaminants are present in ovarian tissues at levels where they are liable to damage the genetic-sensitive meiotic stages, which occur prior to spawning. It appears that levels of the pesticide DDT transmitted from the parent during oogenesis* are sufficient to affect the survival potential of some fish eggs. Concentrations of 2 to 4 parts per million DDT are often found in the gonads of cod from the North and Baltic seas.

Appraisal of Pollution Impacts on Fish Eggs

It is difficult to apply laboratory data on the toxicity of oil to fish eggs and embryos to field conditions where the oil itself is affected by the environment, and the environment influences the exposure the eggs receive. However, such laboratory data and also good field samples from uncontaminated areas are required to obtain control values for the cytogenetic indices, as used in this study. Both field and laboratory controls are needed because ideal

*Formation of the ova.

conditions for such estimates cannot be reasonably met for most commercial fish in either the laboratory or field alone. For example, it is important to find out what percentage of spawned pollock eggs, developed in clean water, do not develop, or show inherent chromosome aberrations, so that the values can be compared with those obtained in field studies of contaminated areas. Appraisal of any long-term effects of oil spills, or of any particular pollutant on the fisheries, involves both laboratory and field studies. Any harmful effects of marine contaminants, whether measured on fish eggs or on other components of the ecosystem, must be further viewed as superimposed on whatever other combinations of natural factors limit a population. These factors, of course, extend to other segments of the ecosystem. (Recall, for example, the previous statements on the spawning habits of cod and pollock, and the variable importance of different spawning grounds.)

Another problem of appraisal is the limited number of ways an organism can respond to stress, whether it be a pollutant or the weather. For example, adverse temperature, sub-optimal salinity, and the toxic mutagenic heavy metal cadmium can lead to teratogenetic effects under certain circumstances, increasing incidences of abnormal fish larvae.

An additional complication is that various stresses generally increase the effectiveness of a mutagen or alter the physiological cytotoxicity of a chemical. The same contaminant level under different environmental conditions could cause greater or lesser mortality of fish embryos.

Generally, little is known about the factors in nature that control the mortality of fish eggs and larvae, particularly in the early stages. The problem of gametic wastage in fish has not yet been addressed in genetic terms. As indicated throughout this article, classic genetics offers some explanations on the mortality of fish eggs. It also can serve as a means of monitoring this most fragile link in the life cycle of fishes in their natural habitat. A greater knowledge of the effects of marine pollution on the reproductive cycle of fish populations depends heavily on a fuller understanding of the natural mortality processes of fish eggs and larvae.

A. Crosby Longwell is a biologist and geneticist at the Milford Laboratory, NEFC, Milford, Connecticut.

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Fate and Effects of Oil in Marine Animals

by John J. Stegeman

The occurrence of an oil spill, such as the *Argo Merchant,* inevitably results in extensive question, comment, and prediction regarding the effects of such an event on the marine environment. Just as inevitably, the pro and con positions often exceed both reason and available fact. For a realistic appraisal one must explore the middle ground between the Pollyannas and the Doomsayers. However, this is the more difficult approach. It requires attention to all the available knowledge concerning fate and effects of hydrocarbons in the marine environment, while recognizing that some of the information will not always hold true.

Marine waters generally contain rather low, yet not inconsequential, levels of biogenic and nonbiogenic hydrocarbons, the latter often derived from petroleum. In the vicinity of spills, and in many bays, harbors, and estuaries near urban areas, there may be rather substantial amounts of nonbiogenic hydrocarbons, many of which are clearly foreign to most life forms. The importance of these hydrocarbons in the marine environment may often be considered together with other xenobiotics (foreign compounds), such as pesticides and PCBs. In this article, what applies to petroleum hydrocarbons may often hold for these compounds as well.

The significance of petroleum, or other xenobiotics, introduced into marine waters rests ultimately with how it may affect mankind. There is potential for this effect to occur through 1) an immediate loss of food or material resources by destruction or reduced marketability; 2) an ultimate loss of such resources, resulting from altered species composition or productivity over time; or 3) a toxicological hazard to human health, resulting from consumption of contaminated produce. In addition, and more recently recognized, a knowledge of how petroleum behaves in the marine environment may provide model systems to aid both in understanding certain oceanic geochemical processes, and in understanding the mechanisms by which xenobiotic compounds exert biological effects.

It is the first and second of these items that are principally concerned with effects on marine organisms *per se.* In the first instance, where there is an immediate loss of resources, this alteration concerns the lethal toxicity to members of the current standing stock in a given population, and also to the severe tainting of resource organisms, both of which may accompany the sudden introduction of substantial amounts of oil into a restricted area. Concern over an ultimate resource loss is related to an imperiled abundance, survival, or marketability of species through succeeding generations. Ultimate resource loss might be the result of the persistent presence of low levels of hydrocarbons from whatever source, of a brief exposure to higher levels of oil, or of catastrophic events. Effects on resource organism populations and community structure through time will be determined by the summated chronic and sublethal effects of xenobiotics, such as petroleum hydrocarbons and their metabolites, on primary production and species at the base of food chains, as well as on higher organisms.

Uptake and Distribution of Hydrocarbons

Usually, though not always, a given xenobiotic compound must make its way into an organism for an effect to be realized, and must possess a potential for altering some biological activity. In this regard, the absorption, distribution, and metabolism of hydrocarbons and other xenobiotics are important factors that

determine the biological fate and effects of these compounds.

It has been established that the uptake of petroleum hydrocarbons by marine organisms — absorption from the environment into the tissues — is a general phenomenon. Members of all classes of hydrocarbons, from short chain n-alkanes to polycyclic aromatics, have been implicated in such uptake. Based on present data, it is safe to speculate that virtually all marine species possess the capacity to take up nonbiogenic hydrocarbons from the environment, given appropriate conditions and availability, and there are few if any restrictions on the type of hydrocarbon that may be involved.

Any mechanisms by which exogenous hydrocarbons enter the body of an aquatic animal require transport through membranes and across an epithelial cell layer, be it gill, gut, or integumentary. Evidence from a number of sources confirms that the various suspected internal and external routes of assimilation — for example, from food and through the gills — are utilized, but present thought is that gill uptake is the more rapid route in many animals. The movement of compounds such as hydrocarbons across biological membranes, and the physical-chemical properties influencing such movement, have not been absolutely characterized, although in many cases partition coefficients, based on relative affinities for water and lipid, may be of paramount importance. However, whether the initial transport is unmediated or accomplished by some form of cellular activity is moot, although both are likely depending on the physical state of the hydrocarbon and the tissue involved.

Once absorbed, both aliphatic and aromatic hydrocarbons will accumulate or concentrate in tissues of a wide range of marine animals, whether under experimental conditions or in the environment (Table 1). Accumulation of both whole oils and individual compounds from the water has in some cases been shown to bear a direct relationship to the concentration in the water. This is particularly true for initial periods of exposure and for real concentrations certainly less than 1,000 micrograms per liter, or 1 part per million. In any event, with present knowledge it should come as no surprise when animals in the vicinity of an oil spill are shown to contain that oil in their tissues. Rather, it should come as a surprise if they do not.

To understand the extent of hydrocarbon accumulation by marine organisms, the process must be considered in conjunction with an animal's ability to dispose of these compounds. As with uptake, the ability to clear nonbiogenic hydrocarbons from the body is now recognized as a general attribute of marine organisms and again, this extends to virtually all classes of hydrocarbons. The disappearance of accumulated hydrocarbons commences immediately upon transfer of fish, crustaceans, or molluscs from contaminated to uncontaminated water. The details of such

Table 1: Examples of hydrocarbon content of uncontaminated and contaminated marine animals.*

		Hydrocarbon content (ppm)		
Source of sample	Type of hydrocarbon	Oyster (*Crassostrea virginica*)	Lobster (*Homarus americanus*)	Flounder (*Pseudopleuronectes americanus*)
clean environment	biogenic	1-2	4-57	0-21
contaminated environment	petroleum	11-236	1-230	-
experimental exposure	petroleum	25-334	33-2,840	7-622

*The values are ranges resulting from analyses of several groups of animals, several tissues, or several exposure periods. The concentrations indicated may in some cases represent only a portion of the total hydrocarbon content, depending upon the method of analysis. Taken from data cited in Anderson, *et al.*, 1974.

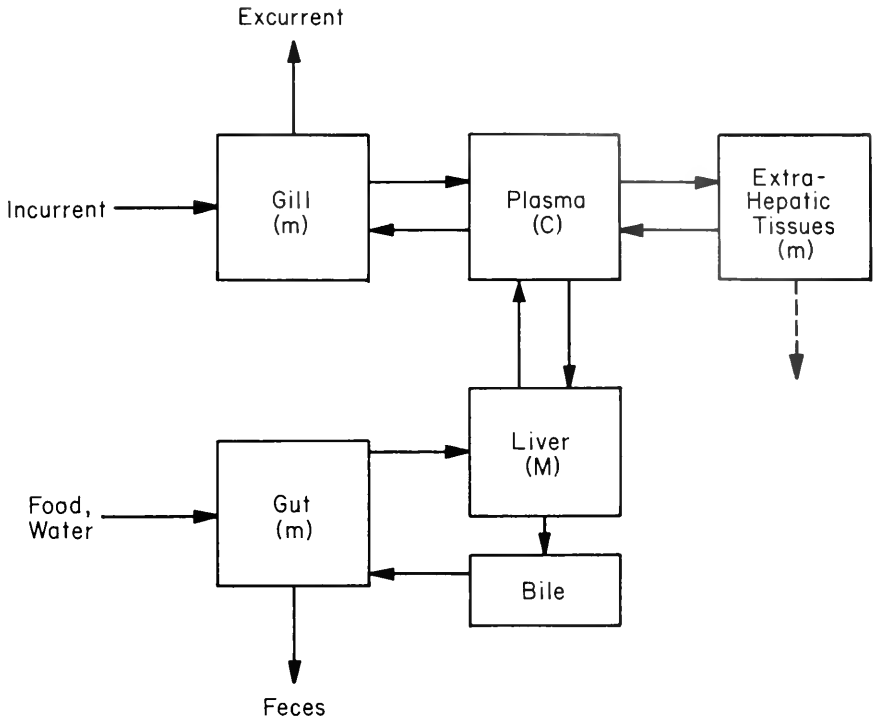

Figure 1. Model of principal routes of uptake, distribution, and disposition of hydrocarbons in a fish. "M" and "m" refer to metabolism in the liver and possibly in certain extrahepatic tissues such as gill, gut, and kidney. "C" refers to the presence of "carriers" such as serum albumin, in the plasma. Rates of transport between the various compartments have been estimated in only a very few cases.

depuration (or cleansing) appear to differ in the three groups, however, as well as to vary with experimental or environmental conditions. Although there may be near universality in the types of hydrocarbons assimilated and depurated, there can exist large differences in the relative rates of these activities for different types of compounds. A complete disappearance of the hydrocarbons does not necessarily occur in a short period, if at all.

The distribution of accumulated hydrocarbons in various tissues is also a process related to partitioning of specific compounds between aqueous media and various types of lipids. Figure 1 presents a model for distribution of organic xenobiotics entering an animal, such as a fish. As indicated in Figure 1, a principal mechanism by which disposal of foreign organic compounds can be mediated in fish is metabolism, accompanied by biliary and, to a lesser extent, renal excretion. Metabolism appears to be an option available to crustaceans as well. Bivalve molluscs, however, are apparently not capable of metabolizing hydrocarbons. These animals seem to rely exclusively on alternative mechanisms, such as transport across the gills in a "reverse" direction. This possible alternative may also be employed, in concert with metabolism, by both fish and crustaceans. It is well established that other compounds with at least a moderate affinity for lipids (lipophilic character), can readily move across fish gills in either direction, although direct proof that this applies to hydrocarbons as well is lacking.

The rate constants determining pharmacokinetics (the accumulation, distribution and disposition) of a compound may be influenced by a large number of factors. Differences in the lipid quantity and quality of various tissues, the degree of association with "carriers" in the plasma, the route of entry, and the extent of xenobiotic metabolism in the various tissues may significantly modify the patterns of distribution for a given compound and its metabolites. For example, metabolism of hydrocarbons in the gut mucosa, or by the gut flora, may influence distribution of compounds assimilated by this route differently than might metabolism during uptake through the gills. Similarly, absorption in the gut may be followed immediately by passage through the liver, where metabolism could substantially influence what is made available to other tissues. Defining distribution patterns and rates even for single compounds is quite difficult, however, let alone doing so for complex mixtures, although if we were to use all of the available information for fish, as well as extrapolate from mammalian studies, we might be able to achieve a fair impression of the pharmacokinetic characteristics of hydrocarbons in fish.

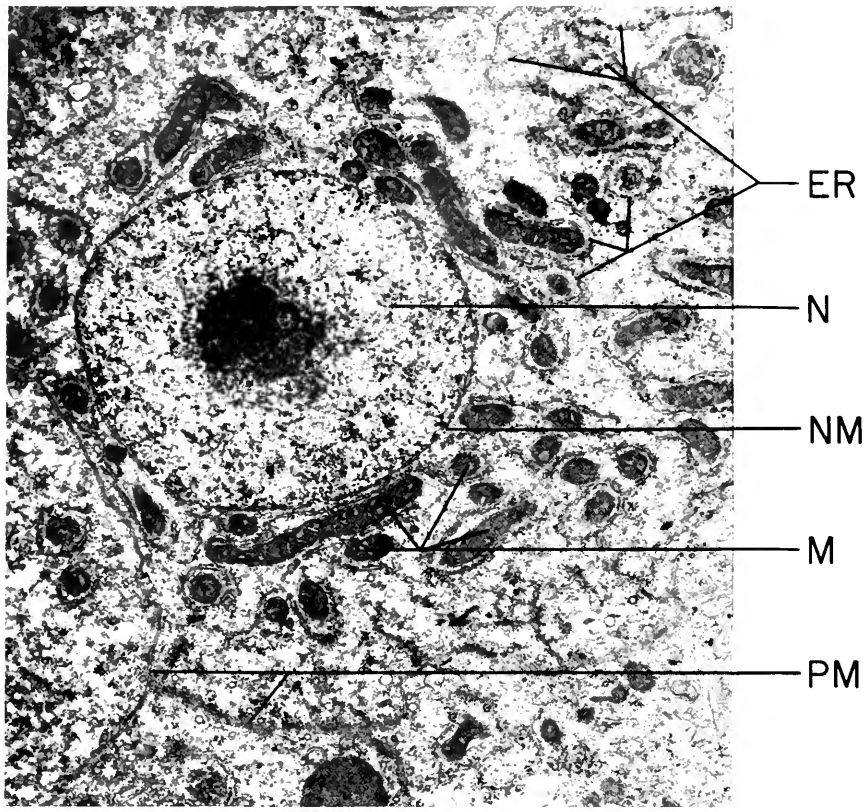

Figure 2. An electron micrograph of scup (Stenotomus versicolor) *liver cells. The micrograph shows portions of four different cells. ER–endoplasmic reticulum; N–nucleus; NM–nuclear membrane; M–mitochondria; PM–plasma membrane or cell surface membrane.*

Effects of Hydrocarbons

Once the movement of hydrocarbons into an organism has been accomplished, the effect obtained will depend on the toxic potential of the compound or mixture of compounds, as well as the cell type and the site of the hydrocarbon within the cell.

The relative toxicity of various crude oils and refined products are known to differ from one another, and in general the lighter crude and refined oils, such as Number 2 fuel oil, have been found more toxic than oils with a higher boiling range. This is often true only insofar as they contain a greater proportion of more soluble compounds. The toxicity of waste oils is often extremely high, although in some cases this has been attributed to the presence of very high concentrations of heavy metals in the oil, while the low immediate toxicity of most weathered oils is clearly a result of such processes as evaporation and photooxidation of many toxic components.

In a comparison of water soluble fractions of four different oils, J. Anderson and others (1975) determined that toxicity to several species was related to the concentration of di- and triaromatic hydrocarbons in the oils. These are among the compounds that are accumulated more rapidly and also retained more readily, indicating that availability may be a critical factor governing evident toxicity. Comparative studies also have demonstrated that naphthalene is more toxic than benzene and that methylation of both of these compounds is accompanied by substantial increases in toxicity with each methyl group added, perhaps due to increased solubility or availability.

The exact mechanisms by which toxicity or other effects may be mediated are in most cases still unknown, although some trends are evident. As indicated previously, lipophilic xenobiotics, such as hydrocarbons, preferentially associate with lipoidal structures and in most cell types these are predominantly membranes, including the plasma membrane, mitochondrial membranes, the nuclear envelope, and the endoplasmic reticulum, as well as other organelle membranes (Figure 2). There also may be binding to cellular proteins and other macromolecules. Accordingly, any resultant biological effect will necessarily be determined by the nature and extent of disruption of normal membrane or molecular shape and function caused by these foreign compounds, and in different cell and tissue types the biological results will vary according to the normal function of that cell or tissue.

In liver, for example, disturbances of either the plasma or mitochondrial membrane may possibly result in alteration of normal

intermediary metabolism; in olfactory mucosa, there may be similar membrane lesions, affecting ability to perceive the normal chemical environment; in the gonads, the effect of hydrocarbons may not appear until the next generation. In other tissues, molecular disruption may have different results, and hydrocarbons in different tissues possibly may produce effects that appear similar on the organismic level.

Any effects will of course vary with concentration and exposure duration. Very high concentrations of hydrocarbons in the central nervous system, for example, may lead to complete arrest of vital functions, and death. As concentrations decrease, obvious stress responses may disappear and there will be, and are, greater difficulties in distinguishing between physiological alterations that represent some dysfunction capable ultimately of affecting reproductive potential, and those which merely represent adaptation to change in another environmental parameter.

Hydrocarbon Biotransformation

Most of the sublethal effects of hydrocarbons, known or postulated, will be determined by the tissue and plasma levels of a given compound. Hence, any factor influencing the half-life of that compound is of key importance. As mentioned earlier, metabolism and excretion may be among these factors. Several of the more interesting scientific questions regarding sublethal effects concern the metabolism of hydrocarbons, and some of these will be addressed here, with particular reference to fish.

An enzyme "system" known variously as the mixed-function oxidase, mixed-function oxygenase, or drug-metabolizing system is responsible for initiating metabolism both of a wide variety of foreign organic compounds, and also a number of endogenous compounds, such as steroid hormones. The term "biotransformation" rather than metabolism may better describe the action of the mixed-function oxygenase system on xenobiotics in vertebrates, as most of these are not metabolized as a source of energy, but rather are merely transformed into products generally more polar and available for excretion. While true in some cases, this process, however, does not necessarily constitute detoxification of foreign compounds.

The mixed-function oxygenase system in fish is present in various tissues and, as in mammals, the greatest activities are found in liver. The system is localized in membrane structures of the cell, principally, although not exclusively, in the "microsomal" (endoplasmic reticulum) portion. In its simplest form, the component parts of the mixed-function oxygenase system include a flavoprotein that acts as a cytochrome reductase, a phospholipid, and a heme protein termed cytochrome P-450. Together, these components perform as an electron transport system when combined with a source of reducing power (NADPH), molecular O_2 and an appropriate substrate such as a hydrocarbon, with the resultant incorporation of one-half O_2 into water and one-half O_2 into the substrate (Figure 3). The active site, where

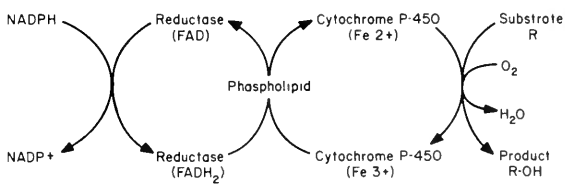

Figure 3. Scheme representing mixed-function oxygenase reaction, showing components of the system and its electron transport nature. Substrate R may be any of a vast number of compounds.

the catalytic function occurs, is associated with the iron-containing heme group of cytochrome P-450. The characterization of this heme protein in fish is therefore of interest, particularly as compared to terrestrial mammals, because there is a wealth of information concerning mixed-function oxygenases in those animals.

Heme proteins bound with carbon monoxide generally exhibit peaks of absorption in a particular region of the visible spectrum, and the absorption maximum exhibited by reduced, CO-bound cytochrome P-450 is at or near 450 nanometers wavelength (Figure 4). By virtue of the iron, the heme group can also be analyzed by electron paramagnetic resonance spectroscopy, a technique that can yield information about molecular structure. The magnetic and optical properties of fish cytochrome P-450 are similar to those from mammalian species. The range

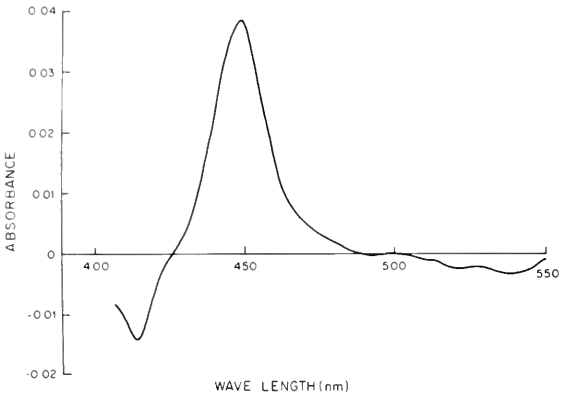

Figure 4. Difference spectrum of reduced, carbon monoxide bound cytochrome P-450 in liver microsomes prepared from scup (Stenotomus versicolor). *(From Stegeman and Sabo, 1976.)*

of catalytic reactions and the number of compounds serving as substrates further point out the similarities between the fish and mammalian mixed-function oxygenase systems. There also appears to be a multiplicity of cytochromes P-450 in fish, each perhaps possessing different catalytic efficiencies with various substrates.

The polycyclic aromatic hydrocarbon benzo[a]pyrene, a potent carcinogen, is the most commonly employed hydrocarbon substrate for studies of mixed-function oxygenases. This is due partly to the ease with which the particular mixed-function oxygenase reaction, referred to as benzo[a]pyrene hydroxylase, can be studied. Although benzo[a]pyrene is present in petroleum products in very small amounts (if at all), it is often formed during combustive processes and is a dominant polycyclic hydrocarbon pollutant in marine systems. Thus knowledge of its biotransformation in fish is important. Furthermore, studies with benzo[a]pyrene may be useful in providing models for studying the biotransformation of other hydrocarbons in fish.

The rate at which benzo[a]pyrene is biotransformed allows us to at least approximate how rapidly some hydrocarbons are metabolized. This is of concern because of the potential induction, or increased rates, of hydrocarbon metabolism caused by the presence of organic pollutants. An increase in benzo[a]pyrene hydroxylase activity in fish treated with the polycyclic aromatic hydrocarbon 3-methylcholanthrene has been clearly demonstrated experimentally (Table 2). Environmental contamination of fish populations by petroleum also has been associated with elevated levels of mixed-function oxygenase activities, including benzo[a]pyrene hydroxylase.

Although there may be several possible explanations for observed population differences, it nevertheless appears that environmental contamination may in certain cases cause increased rates of hydrocarbon metabolism in some species. In addition to possibly enhancing the potential for hydrocarbon elimination, the induction of benzo[a]pyrene and other hydroxylases by organic pollutants may eventually prove useful as an indicator of organic pollution levels sufficient to elicit a biochemical response. There remain, however, many significant questions about petroleum and such induction. These concern dose-response relationships, the fractions of petroleum that may be involved in any induction, and how induction by petroleum may affect metabolism of other substrates, including endogenous compounds such as steroid hormones.

In considering the effects of hydrocarbons on marine organisms, one must be concerned not only with hydrocarbons *per se* but also their metabolites, which in most instances are equally as foreign to living systems as are the parent compounds. In mammals, the biotransformation of several aromatic hydrocarbons, such as benzo[a]pyrene, proceeds by way of one or more epoxide intermediates. There is evidence that the same is true in fish. As indicated in Figure 5, epoxide intermediates may be rearranged to phenols or quinones, or hydrated by the microsomal enzyme epoxide hydrase to dihydrodiols. Many of these varied

Table 2: Induction of hepatic microsomal benzo[a]pyrene hydroxylase in scup (*Stenotomus versicolor*).

Treatment	Benzo[a]pyrene hydroxylase activity
Control (6)	126 units/mg protein
3-methylcholanthrene injected (3)	219 units/mg protein

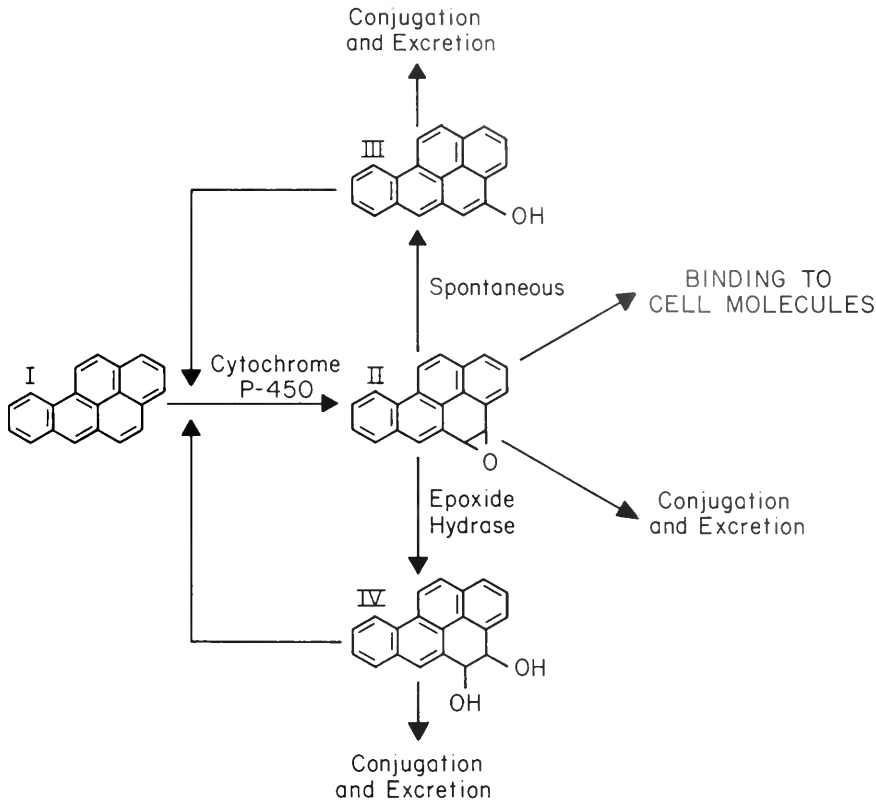

Figure 5. Possible scheme for metabolism of benzo[a]pyrene by fish. Benzo[a]pyrene (I) is metabolized by cytochrome P-450 to an epoxide (II), which may rearrange to a phenol (III), or be hydrated to a diol (IV). Epoxidation may occur at any of several sites on the molecule, and compounds III and IV may again serve as substrates. (Adapted from Lu, et al., *1976.)*

products may be excreted, with and without conjugation with glutathione or glucuronic acid, or they may again serve as substrates for mixed-function oxygenases, resulting in the formation of products such as phenol-epoxides and diol-epoxides.

Many of the metabolites of benzo[a]pyrene are far more toxic to living cells than is the parent compound. The biotransformation that results in the formation of these products is thus a "bioactivation" to more toxic compounds, or a "toxification," rather than a detoxification. Furthermore, studies carried out at several laboratories have elegantly demonstrated that certain of the epoxides and diol-epoxides, which are very electrophilic, bind readily to cellular macromolecules, including DNA, and are in all probability the ultimate mutagenic and carcinogenic forms of benzo[a]pyrene (Sims and Grover, 1974; Levin *et al.*, 1977). Thus, metabolism of certain hydrocarbon pollutants, which in themselves may be relatively inert, can result in the production of highly toxic, mutagenic, and carcinogenic derivatives.

While similar details of benzo[a]pyrene transformation have not been absolutely demonstrated for fish, all of the requisite enzymes have been identified (e.g., Bend *et al.*, 1977). Furthermore, limited data on metabolites of benzo[a]pyrene formed by fish indicate such a process is likely. The metabolism of benzo[a]pyrene by fish mixed-function oxygenases does result in formation of metabolites that are more toxic and mutagenic than the parent compound. This has been demonstrated by adding a particular strain of the bacteria *Salmonella typhimurium* to a reaction mixture containing benzo[a]pyrene and fish liver mixed-function oxygenases. After a suitable incubation, there appeared a reduced number of bacterial survivors and an increased number of bacterial mutants (Table 3), indicating that toxic and mutagenic compounds had been produced.

Although fish are capable of activating selected hydrocarbons to toxic, mutagenic, and possibly carcinogenic derivatives, at least *in vitro,* it is not known whether similar derivatives produced *in vivo* might have sufficient opportunity to interact with the appropriate cellular macromolecules, such as DNA, and exert their mutagenic or carcinogenic potential. Nevertheless, there are instances where fish from contaminated environments have exhibited a much higher incidence of neoplastic lesions than those in cleaner waters (for example, Brown and others, 1973). The results of mutagenic or teratogenic events also have been observed in larval and juvenile fishes from contaminated regions. There is, however, only very limited

Table 3: Bioactivation of benzo[a]pyrene to toxic and mutagenic derivatives by scup *(Stenotomus versicolor)* liver mixed-function oxygenases.*

Incubation Conditions	Bacterial Survivors ($\times 10^{7}$)	Mutant Fraction ($\times 10^{-8}$)
Complete (12.5 μg B[a]P/ml)	53	47.2
minus B[a]P	1088	0.55
minus NADPH	945	0.21

*Incubation of *Salmonella typhimurium* strain TA-98 with scup liver microsomes and appropriate cofactors. Mutant Fraction refers to the number of His^{+} revertants per number of survivors. Acknowledgement is given to W. G. Thilly, Massachusetts Institute of Technology, for use of facilities. (Unpublished information.)

information concerning which, if any, of the myriad organic xenobiotics present in the marine environment, including those from petroleum, may be bioactivated by fish in a scheme similar to that for benzo[a]pyrene. We also are ignorant of how the many hydrocarbons present in oils may interact with each other, or with other common organic pollutants, in influencing xenobiotic metabolism and effects.

Future Directions

Toxicological information of the type already mentioned represents a vastly improved knowledge of fate and effects of petroleum in fish, although gains made in understanding the impact of organic pollutants in the marine environment, including petroleum, still do not permit accurate prediction of the effects of a given oil spill. The type of oil and the location and season of the spill may greatly influence the effects and recovery that can be observed. Yet while each spill must still be considered unique, we are nevertheless approaching the point where generalizations may have some validity. Nature, however, has not exhausted her storehouse of surprises. If investigation of these problems were to be curtailed, the prospect of extremely unpleasant surprises would have to be considered.

Increased understanding, particularly of chronic effects, will not come easily, stemming in part from the difficulties in generalizing from results of both field and laboratory studies on the biological effects of petroleum. These difficulties are linked to the inherent complexity of living systems, their great diversity, the added features of temporal and spatial variability in a given animal or species, and often the influence of a changing environment. Added to this is the chemical complexity and variability that exists in different crude, refined, waste, and weathered oils, plus the potential influence of factors such as concentration, photoactivation, and synergism. In this context, we can thus better appreciate the many areas of controversy concerning the biological effects of petroleum. Further studies of the metabolism and disposition of foreign compounds, such as petroleum hydrocarbons, may help dispel some of the controversy by expanding our understanding of their effects on marine organisms, as well as by increasing our knowledge of the disposition of potentially toxic materials in food organisms from the sea.

John J. Stegeman is an Associate Scientist in the Biology Department of the Woods Hole Oceanographic Institution.

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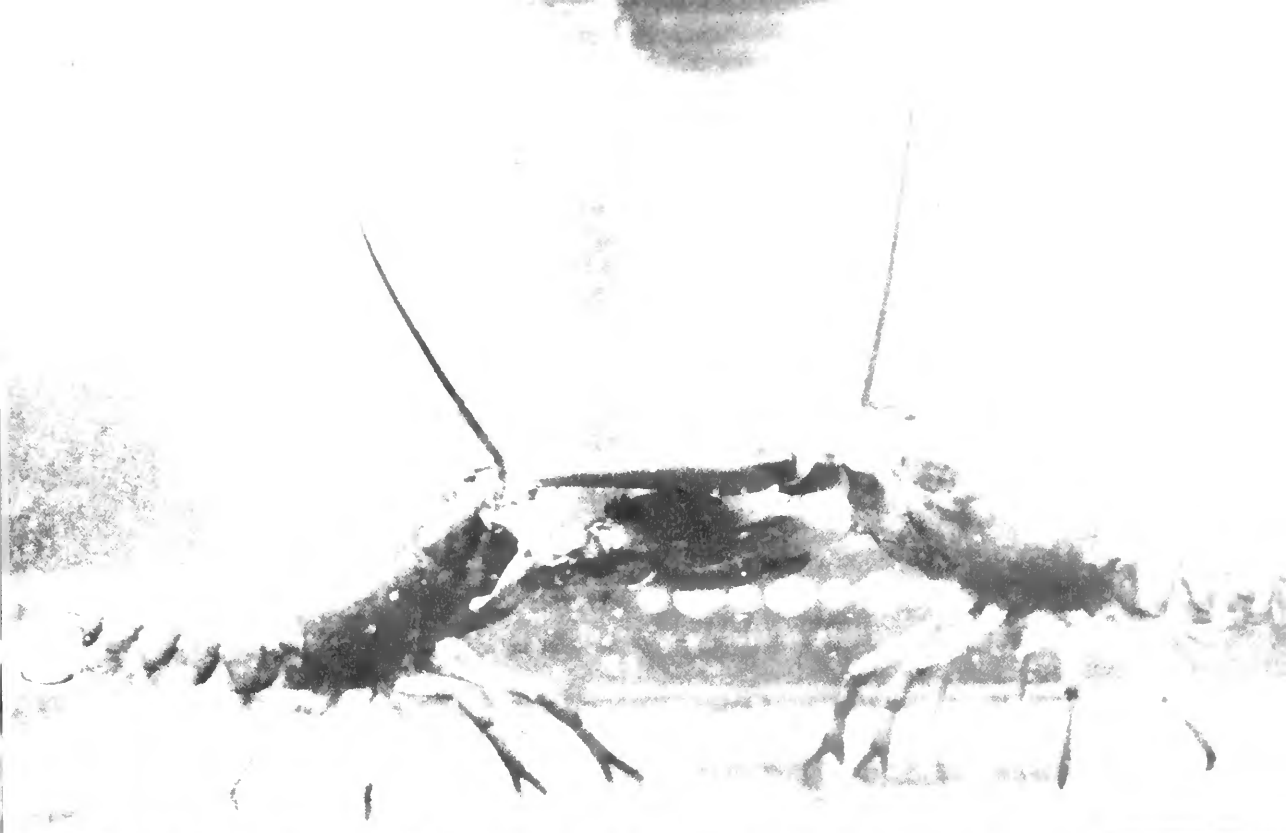
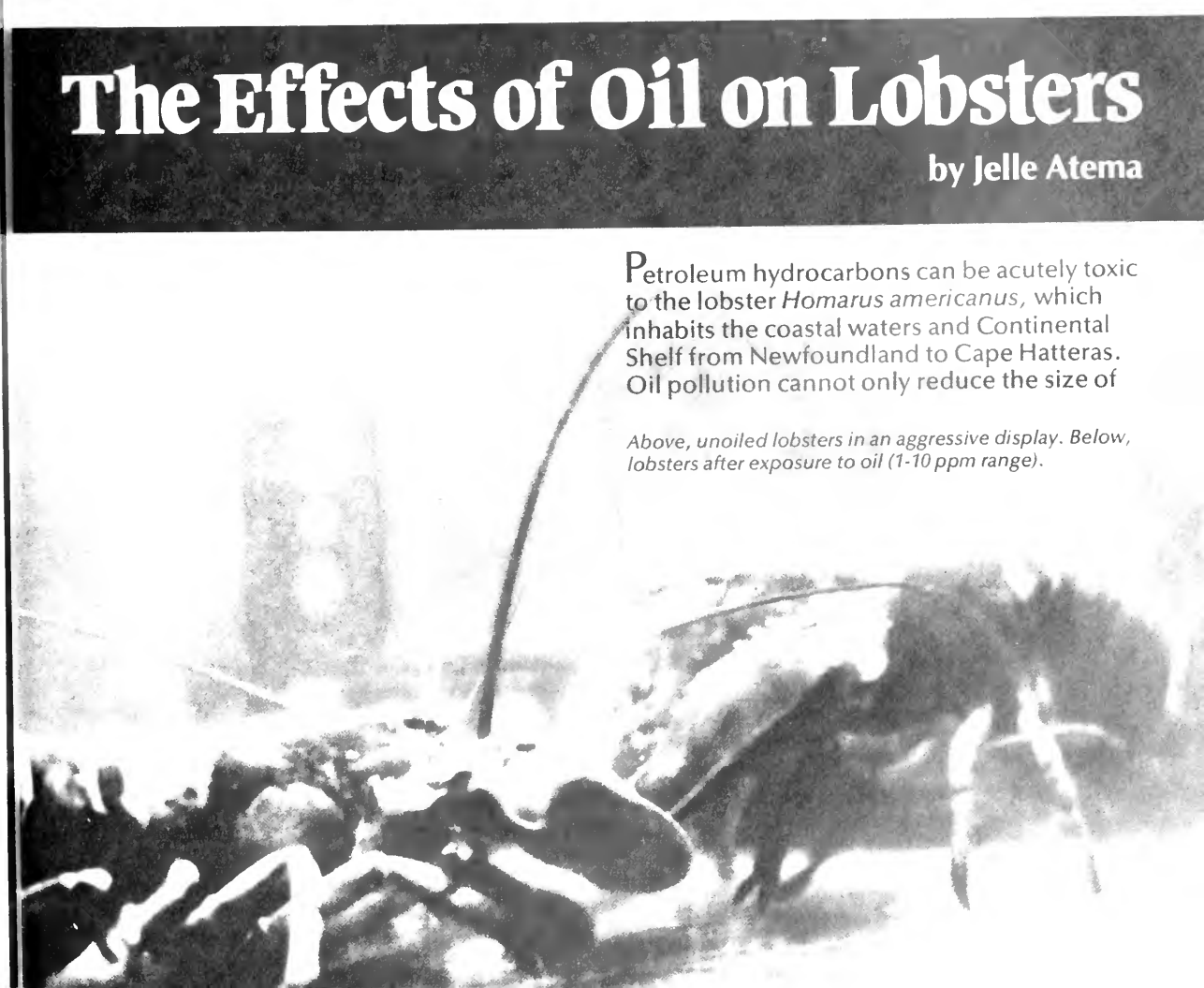


The Effects of Oil on Lobsters

by Jelle Atema

Petroleum hydrocarbons can be acutely toxic to the lobster *Homarus americanus*, which inhabits the coastal waters and Continental Shelf from Newfoundland to Cape Hatteras. Oil pollution cannot only reduce the size of

Above, unoiled lobsters in an aggressive display. Below, lobsters after exposure to oil (1-10 ppm range).



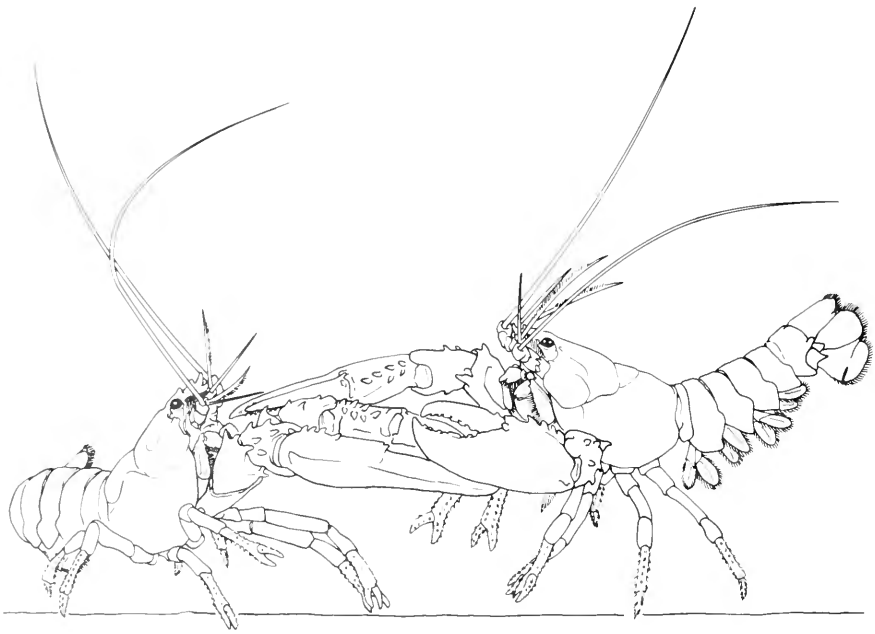


Figure 1. Normal interaction between uncontaminated lobsters when first placed in a small enclosure. Under these conditions, lobsters display aggressive behavior: they attack each other with thrusts and jabs of their claws and often lock claws in a push-pull test of strength. Under conditions of ample space — as in nature — such fights rarely occur because smaller animals simply avoid approaching superiors.

the lobster population, it can contaminate those marketed for human consumption. Recent tests on lobsters, whose main predator as an adult is man, have shown that they react in a variety of abnormal ways when exposed to different concentrations of these hydrocarbons — ranging from death throes and spastic-like behavior to critical delays in feeding responses.

The goal of our research at the Marine Biological Laboratory, Woods Hole, is to understand the principal mechanisms by which specific groups of petroleum hydrocarbons interact with the chemical communication signals of living organisms. We chose behavioral studies because behavior is an important factor in determining the organism's fitness in the ecosystem. Also, the techniques of behavioral analysis make it possible to quickly detect the effects of low oil exposure levels. A dramatic example is shown in Figures 1 and 2.

It has been often suggested that man's input of oil to the marine environment can cause interference with the chemical signals that are vital to the lives of the animals that live there. These signals — the subject of present research — are used for feeding (both for prey

Figure 2. When the same two lobsters are placed together in a small enclosure after exposure to oil (1-10 ppm range), they totally ignore each other just as they ignore food in feeding experiments. In this illustration, two typical "oiled" postures are shown. One lobster lies listlessly flat with stretched claws and limp legs, occasionally twitching its legs or body. The other stands in a spider-like position, tail closely tucked and high on his legs, claws held close to the body, repeatedly attacking imaginary objects or running into walls. Both animals would be defenseless against attack or predation.

detection and scavenging), mating, habitat selection, migration, and for emergency and escape situations. There also is mounting evidence that the mechanism by which sperm cells (both in plants and in animals) are attracted to the egg is based on chemical signals from the egg. Interference with these chemical communication systems undoubtedly has important consequences, which may not be immediately obvious. Animals may not show clearly visible signs of locomotor difficulties, but yet may have problems in feeding, finding mating partners, and in escaping from predators. To explore these subtle but potentially far-ranging effects of oil pollution, we are presently combining behavioral analyses with neurophysiological analyses of chemoreceptors. Experiments have been conducted on both lobsters and mud snails *(Nassarius obsoletus)*, although we will only discuss the former here. These animals were chosen because of the background data available, the relevance to the ecosystem, availability, laboratory adaptability, and so on.

In an oil polluted environment, different petroleum compounds are in solution or emulsion in the water column, while the heavier fractions become part of the benthic sediments for many years (see page 15). Thus one can speculate that these chemicals continually interfere with the normal biological signals that the lobster receives. These "false" signals could cause lobsters and other animals to look for imaginary food or mates, or to avoid danger when there is none. Along the same lines, the signals that a lobster receives may be so "masked" by "false" signals that they miss opportunities to feed, mate, or escape.

Another possibility is that the animals become subjected to two competing signals (Atema and Stein, 1974) — for example, an attractant signal from food and a repellent signal from oil. In such cases, chemoreception would be perfectly normal, but the animal could not decide whether to feed or hide. Even a slight delay in responding to food can put an individual at a significant disadvantage when competing with an unimpaired rival, or while escaping from predators.

We can see then that interference with the chemoreception of lobsters and other animals may represent one of the lowest detectable effects of oil pollution; the more immediately obvious neuromuscular abnormalities have been demonstrated at higher levels of oil exposure.

Kerosene-Soaked Bricks

In some fishing areas, lobstermen use kerosene-soaked bricks as bait in their traps, indicating that kerosene attracts the animals in the field. Our early experiments investigated the effects of this practice from both a practical and theoretical point of view.

Small groups of from three to five mature and submature lobsters were kept at 20 degrees Celsius in slowly running seawater in several 400-liter aquaria, where large windows permitted clear observation of their behavior. They were given shelters and food (pieces of mussel and fish). Testing began when social stability was observed, usually somewhere between one to two weeks. Kerosene fractions on asbestos strips were then introduced into the tanks and the lobsters' behavior toward these strips recorded. Asbestos was chosen because it is an inert, absorbent material that can be chemically cleaned to avoid contamination from other materials. In a series of trials, both blank control strips and strips with 20 microliters of kerosene fractions were used. The fractions included: 1) whole kerosene, 2) branched and cyclic fractions, 3) polar aromatics, 4) straight-chain aliphatics. A summary of the test results follows:

Control: occasional approach, no feeding behavior.

Whole kerosene: searching, feeding, and ingestion.

Branched-cyclic: searching, feeding, and ingestion.

Polar aromatic: searching, repulsion when near, grooming, no feeding.

Straight-chain aliphatic: similar to control.

It was concluded that kerosene contains inert (aliphatic), attractive (branched-cyclic, and to some extent, polar aromatic), and repellent (polar aromatic) fractions. The feeding response to whole kerosene was less than to the branched-cyclic fraction alone, perhaps due to the presence of the polar aromatics in the former.

In a similar series of tests, lobsters were exposed to kerosene fractions (in the

microliter range) soaked into pieces of brick, which were placed upstream from their shelter. Tests were conducted with single mature lobsters at night under low-intensity red lights. In comparison with the previous study, the following differences were noted:

Control: lobsters often manipulate foreign objects in their range — control pieces of clean brick were no exception; no abnormal behavior observed.

Whole kerosene: depressed activity, followed by some attraction and feedings attempts; food ingestion ceased for three to seven days after kerosene-feeding attempts.

Branched-cyclic: ambivalent behavior, aggressive postures toward brick, simultaneous feeding (by the maxillipeds) and rejection (by the pereiopods, or walking legs); followed by alarm and defensive postures, and reduced activity.

Polar aromatic: increased activity, spastic-like behavior, approaches and fast rejection of brick; food ingestion afterward faster than normal.

Straight-chain aliphatic: depressed activity, prolonged attempts at feeding; food ingestion ceased for three to four days after feeding attempts on this fraction.

While these two studies were indicative of the different effects of petroleum fractions on lobsters, they were qualitative as to levels of exposure and exact behavioral measurements. They did, however, serve to point us in the direction of our present research — into the mechanisms of interference of specific hydrocarbon fractions. But before we embarked on this path we undertook a study to establish a quantitative methodology for the investigations of oil effects on lobster behavior. In the first of these experiments we simulated a single spill of La Rosa crude oil; in the second series, we exposed the lobsters to a number of constant levels of Number 2 fuel oil.

Effects of La Rosa Crude

Mature lobsters (about 9 centimeters carapace length) were kept in individual 100-liter aquaria at 22 degrees Celsius, with standing water and aeration. They were kept for two weeks without food prior to the experiments, which were conducted under dim, ambient light. During the experiment, they were fed a half a mussel once a day. This food was carefully lowered on a string in the corner of the aquarium farthest away from the lobster so that the animal responded only to the chemical stimuli of the food.

Behavior measurements were taken for 10 days; the first five without oil, and the second five under exposure of 1 milliliter of La Rosa crude oil, which was carefully placed on top of the water in each tank. Aeration stirred the slick, which practically disappeared over the course of the five days. Each lobster was observed for 10 minutes prior to the introduction of the day's food. The feeding behavior was then timed in seconds from introduction to first alert (Alert), from alert to first movement of the whole animal (Wait), and from movement to first touching of the food (Search). The experiments were made on eight individual lobsters, while four others served as the control (they did not receive any oil over the 10-day period). In addition, a second group of eight lobsters were subjected to the soluble fraction of the same amount of crude oil for the last five days. Aliquots of water from the lobster tanks were taken on the fifth, sixth, seventh, eighth, and tenth day for chemical analysis of the petroleum hydrocarbons.

The exposure of the first group of lobsters to an initial oil-to-water ratio of 10 parts per million (ppm) whole crude oil had clearly measurable effects. The waiting period of the feeding behavior doubled, and the movements of some chemosensory related appendages changed significantly. The overall result was an increase in the time it took hungry lobsters to find food, which would put them at a selective disadvantage with competitors in nature. No effects were found in the feeding and general behavior of those lobsters exposed to the soluble fraction. Chemical analysis showed that about 10 parts per billion (ppb) of hydrocarbons were recovered from the seawater in these later tests.

From the results of all the tests we have advanced the hypothesis that 1) specific hydrocarbon fractions are responsible for distinct behavioral changes; and 2) the changes in behavior are general enough to affect a large number of marine invertebrates in a similar manner. Since we know that these fractions are present in varying quantities in different oils, we may be able to predict the toxicity of different oils for various marine organisms.

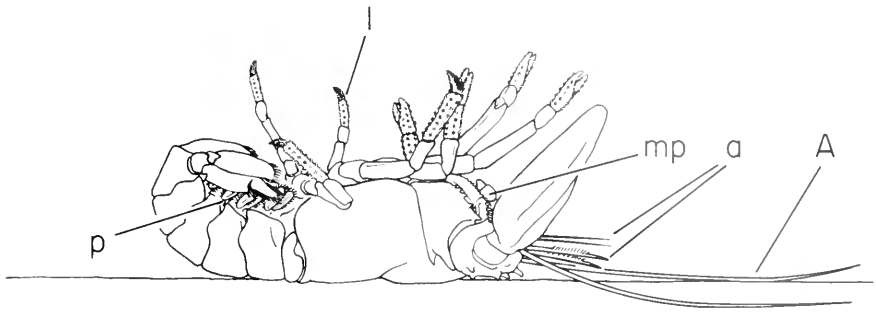


Figure 3. Worst effect of exposure to 1.5 ppm Number 2 fuel oil for one day. The lobster lies on his back, slowly moving and twitching his legs, unresponsive to outside stimuli. Recovery from this state is very slow (more than 5 days) and we believe that continued exposure would surely kill them. A = antennae; a = antennules; mp = maxillipeds; l = walking legs; p = pleiopods or swimmerets.

Effects of Number 2 Fuel Oil

At the present time, we are experimenting to determine *how* Number 2 fuel oil affects the feeding behavior of lobsters, specifically focusing on the narrow range of exposure levels that trigger chemically stimulated behavior without causing neuromuscular defects.

The lobster uses two chemoreceptor systems. The antennules (Figure 3) represent their sense of smell, probably functioning to detect distant chemical signals in low concentrations. The walking legs and maxillipeds (Figure 3) are the equivalent of a taste sense, being essential in picking up food and bringing it into the mouth while testing its palatability for ingestion. In our present studies, we have been mainly concerned with the antennules (Figure 4).

We have observed the behavior of three male and three female lobsters that were put into individual tanks with a flow-through oil-dosing system. Such a system can keep a constant level of oil in the water column, partly dissolved, partly in very fine emulsion. Over a period of five days in four separate experiments, the lobsters (different sets were used in each experiment) were subjected to Number 2 fuel oil inputs, ranging from 0.08 to 1.5 parts per million. Two males and two females in another set of tanks served as controls. It is not possible here to go into detail on the materials and methods used in these experiments, other than to note that the oil was introduced at a predetermined flow rate via a syringe pump, and that oil levels in the water column were measured daily to determine actual exposure levels.

In the first and second experiments, the measured oil levels in the water were 0.08 and 0.15 ppm, respectively. At these levels, very minor effects on the lobsters were observed. In general, they were slower to become alert to the presence of food and to obtain it. Some animals showed defensive postures and occasional frantic and erratic movements. Recovery, after the removal of the oil, was immediate in both experiments.

In the third series of tests (at the 0.3 ppm level), generally no feeding occurred. The behavior of the animals was similar to that in the first and second experiments. Complete recovery took two days, although most feeding resumed immediately (but at a slower than normal rate) after removal of the oil.

In the final experiment (at 1.5 ppm), we observed three types of behavior, ranging from minor abnormalities to very extreme ones. These reactions appeared to be neuromuscular in origin, not merely interferences with the animals' chemoreception systems. Therefore, the oil inflow was stopped after 30 hours, but observations on the recovery continued for five days. At this highest exposure level there were great differences in the ways in which the lobsters were afflicted. We grouped the effects in three categories from mild to severe. Even the mild effects were more serious than those found in 0.3 ppm exposures.

In instances where a mild effect was noticed, the lobsters often remained in their burrows, but were high on their walking legs and shaking. They displayed sporadic alerts, which did not seem to be necessarily related to food. There was no search carried out during the oiling. During recovery, there were slow, hesitant approaches to food after two days, sometimes interrupted by tail-flip escape responses.

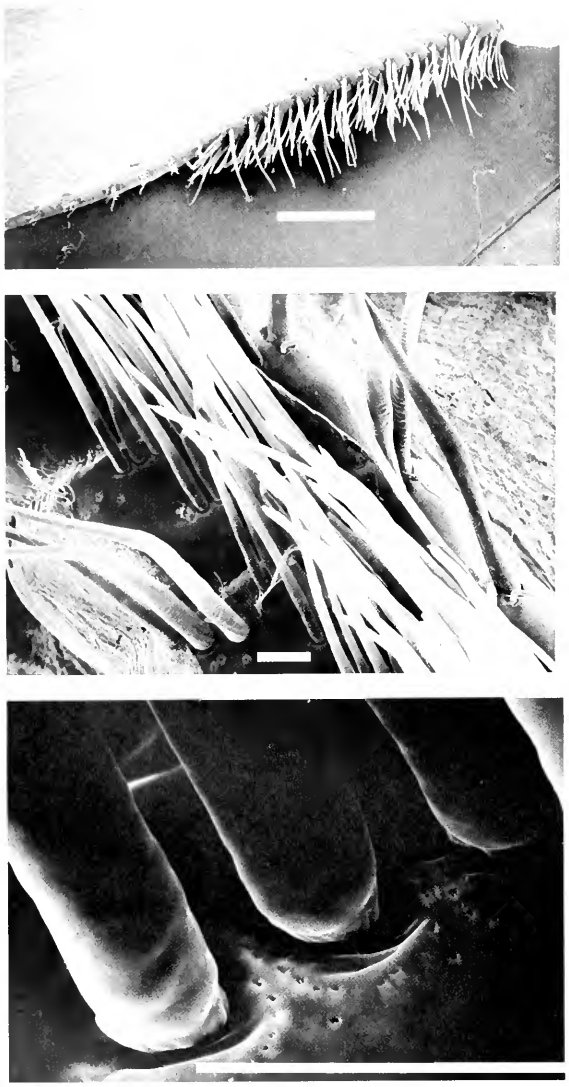


Figure 4. a = Antennule with olfactory sense hairs (magnified 18x in scanning electron microscope); b = higher magnification (100x), showing sturdy guard hairs and rows of delicate olfactory hairs, called aesthetasc hairs, which contain about 400 chemoreceptor cells each. Together these act as the equivalent of the lobster's nose; c = base of aesthetasc hairs with mysterious pores (1,000x). White bar is micron scale.

In the more severe effect state, the lobsters were generally out of their burrows, antennae folded back against the body, antennules bursting sporadically, high on legs, tail either tightly curled, or straight out high above the substrate with pleiopods fanning. The claws were held high near the body, opening and closing often; one leg often lifted to the side (as seen in molting, when the lobster falls onto its side). The lobsters alternately took two main stances. In one, the tail and head were down, the antennae folded back, the antennules low, and the animals were low on the walking legs (Figure 2). In the other, the tail and head would arch up, the claws open, the antennae and antennules would be held straight up and together, with the lobster high on the walking legs, often displaying tail flips. There appeared to be no coordination in their jerky movements. There were many aggressive displays with an open, raised seizer claw, or jabs with both claws at no obvious target (Figure 2). The lobsters were apparently unaware of the presence of food, and at times would walk right over it without responding. If they did pick up food, they continued to wander aimlessly around the tank with the food clutched tightly in their maxillipeds.

In the most extreme behavioral state, the lobsters were found out of their burrows, lying on their backs, pleiopods twitching or not moving, tail half curled, walking legs twitching, antennae and antennules limp, gill bailers moving slightly (Figure 3). Occasionally, the back and tail were arched, and then curled. At times, they appeared to make attempts to right themselves. Their bodies jerked after food entered the tank, but this did not appear to be a definite reaction to the food. The lobsters that showed these responses did not recover in the five-day observation period following the oiling. The fact that severe oil stress caused the lobsters to leave their burrows may have significant implications for lobsters in the field, because good shelter is their main defense against predators.

The Task Ahead

Neurophysiological experiments on the lobsters' antennules have shown thus far that these chemoreceptors indeed perceive oil as a chemical stimulus and that oil added to a natural mussel juice causes nerve firing patterns different from those of mussel juice alone. These results were obtained from nonexposed lobsters. When we used antennules from oil-exposed lobsters that were showing behavioral effects, we frequently found abnormal bursting patterns (compare Figure 5a, normal, with 5d, oil exposed). We concluded that exposure to

Figure 5. Neurophysiological recordings of chemoreceptor activity. When the electrical messages of the chemoreceptor cells inside the olfactory hairs are intercepted on their way to the brain, we can observe differences caused by exposure to oil. a = response to mussel juice, b = response to oil itself (10 ppm), c = response to mussel juice and oil mixed, d = response of oil-exposed lobster to mussel juice. From such experiments, we have learned that oil causes changes in normal chemoreceptor messages that may be involved in feeding and other behavior. Each trace is about 12 seconds in duration. The signal peaks are about 0.1 millivolts.

Number 2 fuel oil in the 0.1 to 1.0 ppm range does affect chemoreceptor performance. At present, we are trying to correlate the observed effects on chemoreception with the observed effects on behavior.

It is hoped these experiments on the nature of oil interference with behavior and chemoreception processes will provide us with a general understanding of the more subtle long-term effects of oil pollution. The processes of chemoreception — still largely unknown — are probably similar in many marine animals. Therefore, the results obtained on lobsters may apply to other animals as well.

Jelle Atema is an Associate Professor in the Boston University Marine Program, Marine Biological Laboratory, Woods Hole, Massachusetts.

Drawings by Bob Golder

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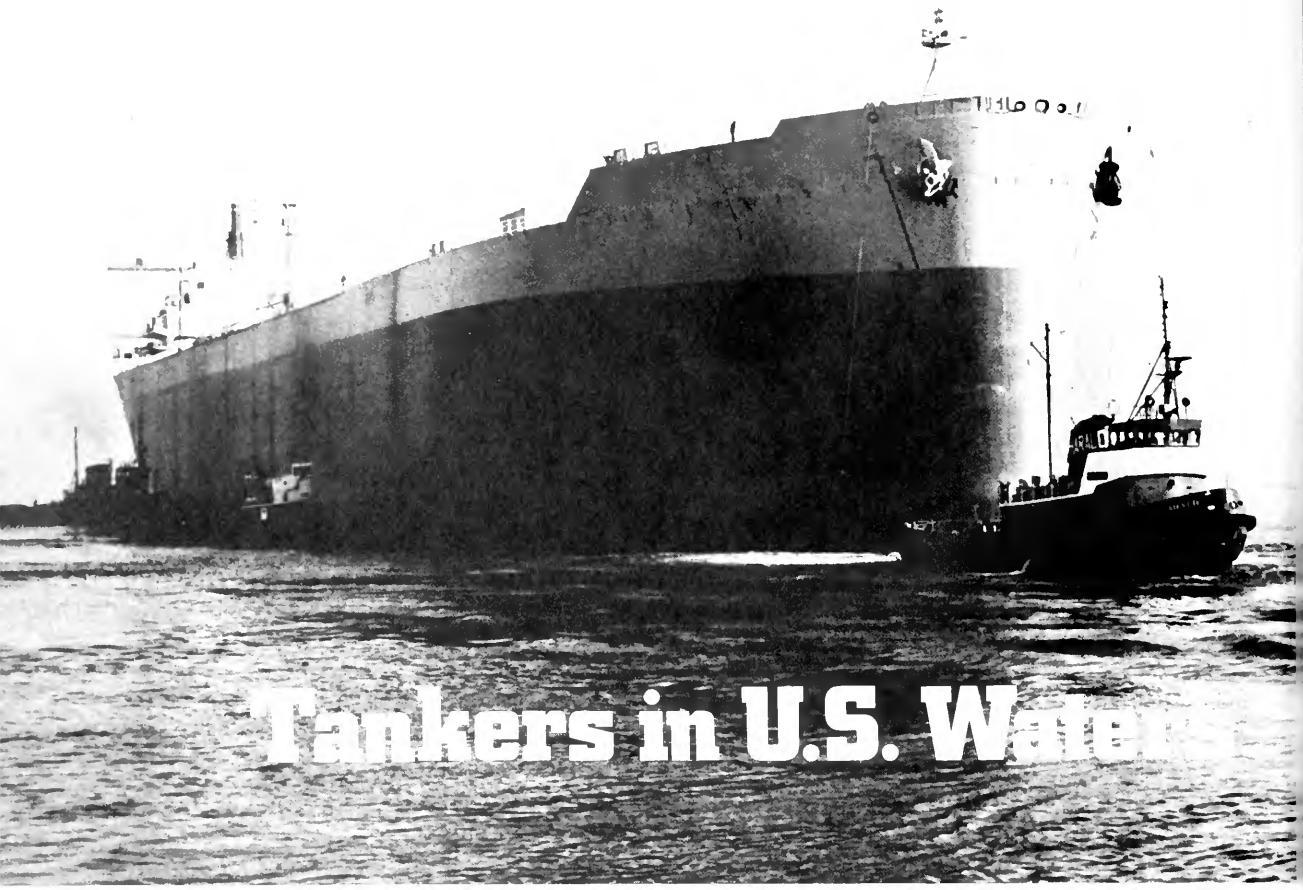


Tankers in U.S. Waters

by Robert J. Stewart

It is fashionable these days to agonize over the transport of oil by tanker. Unfortunately, this problem is not easily defined. Is it the rare enormous spill, or the more common small spill? Is it the oiling of fauna, or the oiling of recreational beaches? Is it the small size of the U.S. tanker fleet, or the increase in the size of tankers? The list seems endless.

Because the problem is as obscure as it is large, it serves as a ready vehicle for special interest groups. The technique is to state the problem so that the obvious solution incorporates one or more program elements desired by the definer of the problem. It is axiomatic that the simpler the assertion, the more compelling the solution. As a result, the popular conception of the problem consists of a collage of vivid but superficial images — shriveled, penurious tanker owners manipulating world oil supplies from Riviera hideaways aided by loutish, underpaid skippers driving rusty, gigantic, thin skinned, underpowered tankers through oceans that are both increasingly crowded with similar vessels and covered with tar balls. These visions reflect anxieties about the increasing reliance of the U.S. economy on foreign economies; a Club-of-Rome and Sierra-Club fostered sense of the finiteness of our resources; a union supported view of the superiority of American seamen over foreign crews; and a government and industry sponsored view of the inadequacies of foreign tanker design.

With the exception of the view that the oceans are not a limitless dumping ground, none of these conceptions are a suitable basis in themselves for responsible decision making. For example, on closer examination, the shriveled, penurious foreign tanker owner is liable to be a Liberian corporation formed by American citizens living in New York. The

loutish skipper might well be an urbane Britisher with 20 or 30 years experience.

To focus on a small portion of the problem, let us examine oil spillage in recent years from American and foreign tankers in U.S. waters. The results and analysis presented here were taken from oil spill studies that the author has collaborated on since 1972, when the Sea Grant program of the Massachusetts Institute of Technology undertook an analysis of the impact of developing oil resources on Georges Bank. The principal source of spillage information is the U.S. Coast Guard's Pollution Incident Reports System (PIRS) for the years 1973-1975. These data do not include the Christmastime spills of 1976 that were responsible for the current interest in tankers. These spills — the *Argo Merchant* (7.5 million gallons), the *Olympic Games* (134,000 gallons), and the *Sansinena* explosion (11 people killed) are not atypical of accidents that beset tankers. However, the conjunction of these events both in time and in U.S. waters was unlikely, as we will see.

This article deals strictly with tanker accidents and accidental spills. Operational discharges of oil in ballast and bilge water are not included. At present, these discharges are estimated to be about 1.2 million tons of oil a year worldwide.

Thinking About Oil Spills

In tankers spillage studies, there is a tendency to use the simplest of tools in grappling with enormous problems. An example is the common spill parameterization, barrels spilled per barrels handled. A typical result might be "Tankers spill .0144 percent of all oil handled." Never mind that you can look at 9,999 tankers and none will have a spill and then the next will be lost with full cargo. Never mind that if a million barrels of oil were handled, the chance of seeing exactly one spill in the range 10-1,000 barrels would be exceedingly remote. Such considerations are apparently viewed as needless impediments to the simplification and "solution" of the problem.

In contrast to this approach, we will keep the problem here in a sufficiently complex form so that it at least resembles the real situation. This involves thinking about the number of spills that might occur with tanker transport, and then thinking about the volume of oil that might be spilled in one incident. Both the number and the volume are random, so that estimating techniques must assign probabilities to all the possible outcomes, ranging from no spills at all, to many spills, each of large volume. A second objective is to establish techniques for assessing whether a

The Liberian-registered tankship SS Sansinea, *after she was torn apart by an explosion on December 17, 1976, at Union Oil Terminal, San Pedro, California. The ship's 34 cargo tanks had been unloaded prior to the blast, which occurred during ballasting operations. An estimated 20,000 gallons of bunker oil spilled into the harbor, most of which stayed on the surface and was later cleaned up through the use of containment booms. (Photo courtesy U.S. Coast Guard)*

particular group of tankers has either more spills or volume spilled per incident than another. This requires data on ship characteristics and usage, as well as facts on spill incidents.

One of the advantages of breaking the spillage problem into number and volume subproblems is that the former is well behaved. Each year we see a fairly constant number of spills, but the volume fluctuates greatly from year to year on a random basis.

The degree of variation in oil spill volume statistics is not generally appreciated, and such statistics are quite often misused in drawing comparisons. This variability stems from the enormous range in oil spill sizes: most spills are very small, but most of the oil spilled comes from the rarer large spill. In our everyday experiences, we usually do not run across such phenomena. However, one commonly observed parameter with similar variability is the weight of animals, ranging, for example, from fleas to elephants. If they were collected in a net with no distinction as to size or weight, then 100 or even 1,000 of them would hardly be enough to establish the average weight, and the total weight would vary radically from one collection to the next. One sample might yield 100 fleas, 400 mosquitoes, 450 flies, 40 birds, 7 cats, and 3 dogs. The next sample might yield 2 elephants and a rhinoceros, plus a miscellaneous assortment of lesser creatures. An average based on either sample is liable to be greatly in error.

In the same way, the volume of oil spilled in the United States in any given year varies, depending on the size of the five or ten largest spills. One year the largest spill might be only 1 or 2 million gallons, the next 10 million gallons. Since the number of oil spills is more or less constant from year to year, this random variation could lead to calculations of an average spill that differed by a factor of five or ten. This variability makes comparisons based on volume extremely unreliable.

U.S. Data Sources

Even though tankers presently supply several Federal agencies with information on their activities, it is very difficult to make a detailed accounting of foreign and American tanker traffic in United States waters. Tankers on foreign trade routes supply the Census Bureau with information on their journey via several U.S. Customs forms. Concerns operating tankers on domestic trade routes supply the Army Corps of Engineers with confidential summaries of their monthly activities. These reports and the Customs data are summarized and published annually in the Corps' five-volume *Waterborne Commerce of the United States,* in which both the Census Bureau's interest in the flow of goods between American and foreign markets, and the Corps' interest in channel usage are reflected. Translating channel usage information into cogent traffic flow patterns is generally difficult, and identifying the flag-specific tanker component of this flow is impossible. Thus it is not possible at present to know how many days are spent by Liberian tankers in Gulf Coast harbors or in American harbors as a whole.*

In contrast to the difficulty in obtaining detailed exposure data, spillage data are readily available through the Coast Guard's PIRS. These data contain information on the time, date, location, type of oil spilled, volume spilled, environmental conditions, recovery operations, and numerous other items. While the system has flaws, it is not a barrier to analysis provided that one is careful in interpreting these data. There are errors both in the coding of spill incidents and in the coding language. About 7 percent of all tanker incident records, for example, are erroneously coded, showing tank barges as the source. Conversely, about 60 percent of all indicated U.S. tanker spills are due to vessels other than tankers (principally tank barges). These errors can be found and corrected only by obtaining characteristics based on the vessel's identification — its radio call sign, or U.S. registration number. Neither code is readily available. To interpret these data, one must use American Bureau of Shipping (ABS) or other private information sources, such as Martingale's Master Vessel File (MVF).

In the PIRS coding language, the erroneous classification of incidents is caused by ambiguities in the language and outright non sequiturs. For example, a tanker can be underway and cause a spill by pumping its

*The increased emphasis on tanker spillage makes it unlikely that this situation will persist. The Maritime Administration, for example, is developing a computer system based on the above mentioned data sources that will make such information available for the years 1975 onward. This, however, will not be operating until 1978.

bilges. The coding choices for describing this event include two descriptions — "Underway" and "Pumping Bilges." The coder must choose one or the other. How can one unambiguously interpret such information after it has been coded? As an example of the second type of fault, the coding manual identifies general categories of spill cause. Two of these are "Personnel Errors" and "Equipment Failures." A closer examination of the detailed causes within the categories makes it clear that better names for these groupings would be "Faulty Operational Procedures" and "Faulty Equipment," since personnel errors and equipment failures are provided for in both groupings.

Because of these problems and others of a lesser nature, one cannot rely too heavily on summaries prepared by the Coast Guard; reliable figures can only be obtained through detailed editing and correcting of the data, coupled with a knowledge that statistics in some of the fields should be disregarded due to ambiguities.

The Use of Petroleum in the U.S.

Before we can properly understand tanker spillage and accident problems, it is necessary to consider the use of petroleum in the United States. Not all oils are alike. There are three basic categories — crude, distilled, and residual. Crude oil exhibits the greatest variability within this classification system. It is the raw material from which various products are made. Its properties range from a heavy sludge-like composition to very light oils that vaporize like gasoline when exposed to air.

Crudes are classified by their density, according to a rather unusual formula that gives low-density liquids large values and high density liquids low values. Most crudes exhibit specific gravities in the range of .8 to .92. The viscosities of crudes in the .92 range are 30 to 100 times the viscosities of crudes in the .8 range. The differences in the properties of various crudes are attributable to variation in the crudes' molecular composition. The hydrocarbons that tend to be of low density also tend to vaporize readily and have low viscosities. A low-density crude is composed primarily of these light chemical compounds, although small fractions of heavier compounds may also be present.

Because crude oils vary, they are unsuitable for direct application as fuels or lubricants. Refining is the process whereby products having specified rheological (flow) and vapor-point characteristics are derived from the crude oil. These refined products vary in order of increasing density from gasoline to kerosene to Number 2 heating oil (similar to diesel oil) to Number 4 heating oil. Originally, these products were obtained through a simple fractional distillation process. However, the high value of the low boiling fractions, such as gasoline, compared to the higher boiling fractions, makes it desirable to chemically convert the structure of the higher boiling compounds into low boiling compounds. This is done with catalytic converters, allowing the refiner to produce more gasoline from a specified crude than its original composition would allow.

There are still some very high boiling compounds left after the refiner has produced as much of the higher valued refined product as it is economical for him to do. These comprise residual oils that are used to fuel ships and power plants. These grades are of such a composition that they might not behave like liquids at ambient temperatures. This complicates pumping; thus the oils are "cut" with less viscous, lower boiling fractions and heated to enhance handling properties.

An essential point to remember is that crude oil and its products cannot be substituted. New England, for example, needs a lot of Number 2 heating oil, gasoline, and residual oil. These are all obtained from refineries, not from oil fields. A discovery of crude oil in New England, therefore, would not change the existing traffic of products, unless a refinery was built there. Even in this case, there might still be considerable importation of those products that could not be economically produced from the local crude. Residual oils, for instance, are presently obtained in large quantities from Europe, where the demand for gasoline is insufficient to warrant the extensive converting done in refineries built for the U.S. market.

Tanker Traffic in U.S. Waters

Despite the problems outlined previously, it is possible to make some rough estimates of tanker traffic in U.S. waters. Table 1 shows the percentage by flag of the crude oil and

Table 1: Tanker carriage of U.S. imports/exports of crude and petroleum products by registry.

	1973 (%)	1974 (%)	1975 (%)
U.S.	6.34	4.44	6.89
Liberia	39.77	43.50	40.22
Greece	10.79	11.16	10.06
Panama	9.82	7.59	10.29
Norway	8.63	5.94	6.69
Britain	6.84	5.29	5.98
Other	17.81	21.98	19.87

Source: *Office of Subsidy Administration,* Maritime Administration, Department of Commerce.

petroleum products carried in the U.S. import and export trade. These figures were obtained from the Maritime Administration (MarAd). Notice that U.S. flag tankers carry only about 6 percent of all U.S. imports and exports for 1973 through 1975. This is a result of the extra cost of using U.S. tankers compared to the various foreign flag alternatives.

Table 2 summarizes the tonnage of U.S. import, export, and domestic coastal petroleum traffic for the same three years. The distinction between domestic coastwise commerce and import/export commerce is an important one. By law, only U.S. flag tankers may carry petroleum between American ports, so all domestic coastwise trade is in U.S. bottoms. Therefore U.S. tankers carry the sum of the domestic coastwise category, plus about 6 percent of the import/export trade.

From these figures, we can make estimates of the number of trips made by foreign and U.S. tankers. In 1973, the average American tanker, including petroleum and asphalt carriers, was 35,000 deadweight tons (DWT); in 1974, it was 37,000 DWT; and in 1975,

Table 2: Summary of U.S. petroleum traffic in tons of 2,000 pounds.

	1973	1974	1975
Foreign imports	3.284×10^8	3.228×10^8	3.295×10^8
Foreign exports	0.049×10^8	0.027×10^8	0.026×10^8
Total	3.333×10^8	3.255×10^8	3.321×10^8
Domestic coastwise	2.099×10^8	1.727×10^8	1.806×10^8

Source: *Waterborne Commerce of the United States,* Army Corps of Engineers, 1973, 1974, 1975.

39,000 DWT.* This annual trend reflects the increased size of the vessels now being built and brought into service. Equivalent figures for the average size of foreign vessels plying U.S. waters are not available. The average Liberian tanker in 1975 was about 93,000 DWT. However, because of draft limitations, none of the larger Liberian vessels can trade with continental U.S. ports. With this limitation in mind, a generally accepted approximation for the size of foreign vessels trading with U.S. ports is about 40,000 DWT. Using these figures, the number of trips made by U.S. and foreign vessels is obtained by dividing the dead weight tonnage (conventionally measured in long tons) into the tonnage carried by these two groups. Table 3 shows the results of this calculation.

Table 3: Estimated number of trips by tankers engaged in the carriage of crude and petroleum products.

Flag of Registry	1973	1974	1975
U.S.	5,894	4,918	4,658
Foreign	6,968	6,941	6,902
Total	12,862	11,859	11,560

Assumption: Average foreign tanker size = 40,000 DWT

The simplest tanker trip is that involving only one port call at the point of delivery. Most crude oil deliveries are of this type. Tankers carrying petroleum products, however, might conceivably make two or three port calls in the process of discharging their cargo. Under these circumstances, it is difficult to determine the actual number of port calls made by these vessels. A simple approximation is made by ignoring this difficulty and assuming one U.S. port call for vessels in the import/export trade and two U.S. port calls for vessels in the domestic coastwise trade. From this assumption, the number of port calls can be estimated (Table 4). Since tankers usually only spend one or two days discharging or loading, these values also may serve as the basis for estimates of the number of days spent by U.S. and foreign tankers in U.S. ports.

These figures can be checked by comparing them with numbers from one of the several ports where accurate traffic figures are available. For our comparison, we used data

*MarAd, *Merchant Fleets of the World,* 1976.

Table 4: Estimated port calls by U.S. and foreign flag tankers.

	1973	1974	1975
U.S.	11,248	9,085	8,793
Foreign	6,968	6,941	6,902

acquired in 1975 from the Boston Port Authority. Table 5 shows the number of port calls made by U.S. and foreign flag tankers based on these data. Also shown are figures depicting the makeup of the world fleet by draft category based on Martingale's Master Vessel File. The ratio of U.S. to foreign tanker port calls in Table 4 is 56/44; the Boston data in Table 5 suggest a ratio of 66/34. This is a reasonable comparison, considering the number of assumptions made and the peculiarities of the Port of Boston.*

Despite the fact that the U.S. tanker fleet is an inconsequential fraction of the total world fleet (for example, 9.5 percent by number and 3.1 percent by capacity), the U.S. flag is thus by far the most common flag seen in U.S. waters.

Assuming that the number of port calls is proportional to the volume carried, the next most common flag is that of Liberia (based on MarAd's data in Table 1). This seems reasonable since the Liberian fleet is the largest in the world, although the relative proportion is somewhat in excess of what we might expect. For example, if we consider the fraction of the free world fleet with a draft less than 42 feet under Liberian registry, we find it is only 17.7 percent (Table 5). Yet Liberian tankers carry some 40 percent of the U.S. petroleum imports and exports (Table 1). A value closer to 20 percent would be more in keeping with their fraction of the world fleet.

This observation may be related to the strong American flavor evident in typical Liberian tanker names. *Seatrader, Shenandoah, Statue of Liberty, Ogden Exporter, Corona Beach,* and the *Union Glory* are all of Liberian registry. By comparison, a few typical Greek tanker names are *Iamatikos, John Colocotronis, Thermopylai,* and *Appollonian Glory.* We might speculate that

*In Boston, the ratio of Liberian port calls to other foreign flag port calls is about 1:2, whereas it is more like 3:4 over the U.S. as a whole.

Table 5: Tanker port calls by flag in the Port of Boston, 1975.

Flag	No. Port Calls	% Port Calls	% of World Tanker Fleet by Number with Draft Less than 42'	% of World Tanker Fleet by Number with No Draft Criteria[a]
U.S.	373	65.6	10.4	8.5
Liberia	66	11.6	17.7	21.3
Panama	37	6.5	6.3	5.4
Greece	35	6.2	8.6	7.9
Norway	12	2.1	4.6	6.1
Britain	10	1.8	9.4	10.0
Italy	10	1.8	5.8	5.2
West Germany	5	.9	1.2	1.5
France	5	.9	1.8	2.5
Finland	4	.7	NC	NC
Netherlands	3	.5	1.5	1.6
Sweden	3	.5	NC	NC
Bermuda	2	.4	NC	NC
Cyprus	1	.2	NC	NC
Denmark	1	.2	NC	NC
Soviet Union	1	.2	NC	NC
Rumania	1	.2	NC	NC
Total	569			

NC: Not calculated.

[a]Based on Martingale Master Vessel File for September 1975.

Liberian vessels are preferentially in the U.S. import/export trade because of their owners' nationality.

The number of port calls shown in Table 4 may seem excessively large to some. They correspond to a port call by both a U.S. and a foreign flag tanker once every hour. In 1975, however, the U.S. fleet comprised some 235 tankers over 1,000 Gross Registered Tons (GRT). These tankers were generally on one-way trade routes of 1,000 to 2,000 miles. This corresponds to a steaming time at 15 knots of three to six days. Adding two days for discharging or loading, a one-way trip time is around eight days. Allowing an additional two days per one-way trip for periodic maintenance and hauling, this works out to an average 10-day one-way trip, or a 20-day round trip. One port call per tanker per every 10 days equals about one port call per hour for the whole U.S. fleet. This coincides with our previous estimates.

On the basis of Tables 1 and 2, it appears that about 200 U.S. tankers are to be found plying routes between U.S. ports. The remaining 30 or 40 are thus on routes between the U.S. and its trading partners. In this trade, which is largely imports, U.S. flag tankers are supplemented by 600 to 700 foreign tankers, 300 to 400 of which are of Liberian registry. The registry of the remaining ships probably roughly corresponds to the volume percentages shown in Table 1.

Tanker Spills in the U.S.

The conventional technique for reporting spill incidence rates is to normalize the number of spills by the number of port calls. On this basis for the years 1963 through 1971, the Port of Milford Haven (in northern Wales, Britain) could report a spillage rate of .021, or 481 spills in 22,456 tanker calls. This port is modern and closely supervised, serving a number of refineries in Pembrokeshire. Because it is relatively new (1961) and fairly free of natural hazards, such as fog, it frequently serves as a standard in spill incidence analyses. Thus having one spill in 50 port calls may be considered a good record.

Based on the estimated port calls of Table 4 and the corrected Coast Guard PIRS data, equivalent spill incidence rates by flag for 1973 through 1975 have been calculated (Table 6). We have aggregated all spills in U.S. waters for these figures. In addition to the assumptions underlying Table 4, these values also rest on the assumption that vessel port calls are distributed among flags in proportion to the tonnage ratios of Table 1.

These numbers seem to tell a rather interesting tale. They show, for example, that U.S. ships have about half as many spills per port call as Liberian tankers, and about a third to a fifth as many spills per port call as foreign tankers as a whole. Does this mean that if U.S. tankers replaced all foreign tankers we would have fewer spills? If we hypothesize that spills result from a Bernoulli process* in which each port call involves some fixed probability of a spill, then the answer would be yes.

A model based on Bernoulli trials has many attractive features, such as plausibility and analytical tractability. For these reasons, it is widely accepted in the literature. Unfortunately, the usual arguments in favor of the port call hypothesis rest on the favorable linear regressions that appear when the number of spills for a region is plotted against the corresponding number of port calls. Such regression results may be likened to comparing the number of cancer cases to the number of supermarket visits in several towns. We would expect that larger towns would have larger numbers of both cancer cases and supermarket visits. Thus such a regression should be a good one. It does not demonstrate, however, that cancer and visits to supermarkets are linked, except through ancillary variables. In the same way, good regressions between regional port calls and oil spill numbers establish neither a causative linkage, nor the applicability of the binomial model.

To establish the validity of the binomial model it would be necessary to categorize tankers based on existing trade patterns, attempting to form two or three reasonably representative groups, each group having a characteristic range of port calls. This would require specific knowledge of both port call activity and the other parameters of interest.

*A common example of this process is the flipping of a coin to see who picks up the bar bill. The odds are even, but more generally the probabilities of the two outcomes may be different. A Bernoulli process generating tanker spills based on port calls, where the probability of having a spill is 1/36 in any given port call, could be modeled by casting dice for each port call and counting a spill each time "snake eyes" come up.

Table 6: Estimated spill incidence rates for the six most common flags in U.S. waters from 1973 to 1975.

(Number of Spills per Port Call)

Year	U.S.	Liberia	Greece	Panama	Norway	Britain
1973	.011	.031	.043	.029	.061	.052
1974	.014	.042	.083	.046	.094	.077
1975	.010	.031	.073	.022	.051	.062

Unfortunately, data on port call activity for individual tankers are not available, although considerable data are available from MVF on the other parameters. However, even if such information were available, there is still a good possibility that we would be unable to form equivalent groups, since there is likely to be a strong correlation between tanker size and the number of port calls, and because tanker size is linked by tanker age to various other characteristics. Table 7 shows the average age of the U.S. fleet by Gross Registered Tonnage. Notice that old tankers are small tankers. Small tankers, because of their much higher ton-mile costs, are extremely unsuitable for long trips compared to larger ships. The market will respond to this difference by allocating the smaller vessels to those routes requiring many port calls. Thus any collection of ships that annually makes more than the average number of port calls also is likely to be older and smaller than the average. Separating the effects of age or any other colinear measure from that of port call activity would in this event be problematic.

For all of these reasons, it is unlikely that we will soon have conclusive evidence that port calls are related to spill incidence. More perplexing, there is mounting evidence that ships are prone to have a rather constant number of spills per year irrespective of variations in port call exposure. Not only is this behavior implicitly suggested by the 1973-1975 U.S. tanker spillage histories, but similar observations have been made from Milford Haven data. This means that Table 6 may not provide a useful comparison of U.S. versus foreign spill performance.

Table 7: Average age of U.S. tanker fleet by Gross Registered Tonnage (GRT) as of September 1975.

GRT	Average Age (years)
0–10,000	34.3
10,001–30,000	27.3
30,001–50,000	7.1
50,001–100,000	4.2
more than 100,000	2.5

An alternative approach is to calculate an annual spill incidence rate based on the idea that ship time is the exposure parameter. This is readily done for U.S. tankers using the PIRS data and MarAd's tanker activity figures. These data show that such a model compares well with actual U.S. tanker spill histories. One difficulty with the model is that it requires a large number of assumptions for tankers in the import-export trade since we only have records of their spills in U.S. waters. Because these are mostly foreign tankers, we cannot be overly confident of comparisons between U.S. and foreign flags. However, this way of parameterizing spill incidence (Table 8) seems at least as valid as the port call technique. Notice that U.S. tankers have the best record, but their margin is now a factor of 2 to 3 instead of 3 to 6. Notice also that the two principal Flag of Convenience fleets (Liberian and Panamanian) have lower rates than the other three fleets included.

The volume of oil spilled by U.S. and foreign tankers is readily obtained from the PIRS data. Figure 1 is a cumulative histogram of oil spill volume. The three curves correspond to the histograms of U.S. tankers, tankers from other Western Developed Countries, and Flag of Convenience tankers. The vertical axis is the fraction of spills less than the volume corresponding to the point on the horizontal axis lying beneath the curve. Thus 76 percent of all U.S. tanker spills were less than 100 gallons, while 65 percent of all Flag of Convenience spills were under 100 gallons. Cumulative histograms of this type are usually shown as a series of steps. For clarity of presentation we have drawn a smooth curve through these steps. In this process, we smoothed out a number of peculiar bumps in the curves. The U.S. and Flag of Convenience histograms indicated there was interpretive round off in the 10 and 100 gallons regions,

Table 8: Estimated spill incidence rates based on the ship year model.

(Year)	(Number of Spills per Year) U.S.*	Liberia	Greece	Panama	Norway	Britain
1973	.627	.7	1.0	.7	1.4	1.2
1974	.587	1.0	1.9	1.1	2.2	1.8
1975	.417	.7	1.7	.5	1.2	1.4

*U.S. values reflect actual observations. Other values are based upon a large number of assumptions and do not have the same reliability.

while Western Developed Countries histograms showed these effects at 4, 42, and 84 gallons, corresponding to convenient multipliers of one barrel. The distinction between U.S. and Flag of Convenience spills as shown in these curves is probably significant. That is, if nothing changes with time, as we add more and more samples to the curves they will be unlikely to change positions relative to one another. The difference between the Western Developed Countries curve and either the U.S. or the Flag of Convenience curve is not sufficient to rule out the possibility that its position relative to others is due to random chance, and thus might change with a larger, more representative sample.

Although it is somewhat speculative to conclude that foreign tankers have more spills than U.S. tankers, we can be fairly certain from Figure 1, that once a spill has occurred, most likely the U.S. tanker one is smaller than that from the Flag of Convenience, and perhaps the Western Developed Countries. It is also worth a second look at Figure 1 to emphasize the generally small volume of these spills, whether they are from U.S. or foreign tankers. When we calculate that the U.S. fleet will have about 100 spills in a year, these are by no means all blockbusters — most will be fairly small.

Tanker Losses in U.S. Waters

Between 1964 and the beginning of this year, 199 tankers larger than 6,000 DWT were lost worldwide due to a combination of explosions, strandings, collisions, and miscellaneous other causes. In the last four years, fires, explosions, and strandings accounted for 44 of 68 losses. In this four-year period, 480 men were killed, 322 injured, and 443,458 tons of oil were spilled. Many of the explosions occurred while the vessel was in ballast, or virtually empty of oil. These incidents usually resulted in a large number of fatalities, but relatively minor oil spills. Usually, large spills were found in those incidents where a fully loaded tanker was stranded and subsequently lost at an exposed, remote site, or where a vessel foundered on the high seas under severe storm conditions. The *Torrey Canyon, Metula,* and the *Argo Merchant* are examples of strandings. Unlike the other two vessels, the *Metula* was

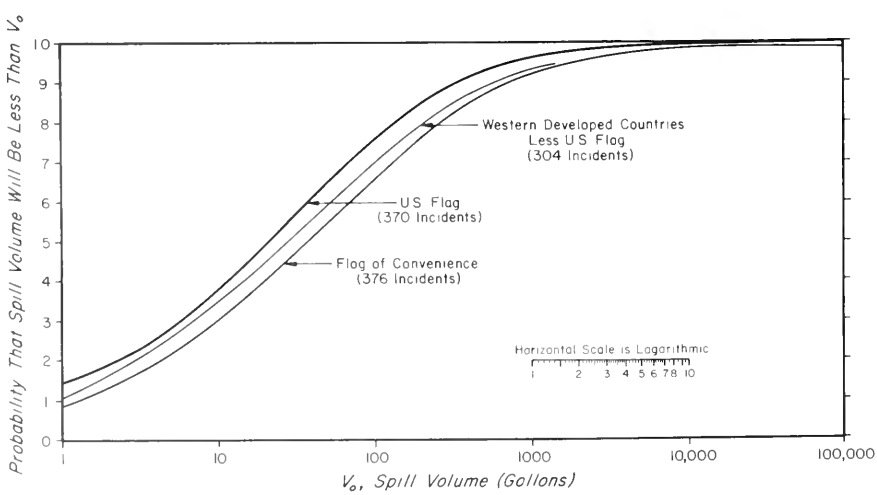


Figure 1. Historical estimate of the probability that a spill from a tanker will be less than V_o gallons based on U.S. Coast Guard PIRS data, 1973-1975.

A tug assists the listing tanker Metula, *aground on Satellite Bank off Barranca Point in the Strait of Magellan, Chile, August 9, 1974. In insert, members of the U.S. Coast Guard National Pollution Strike Force operate an ADAPTS oil pump rig aboard the grounded vessel. The Chilean government requested assistance from the United States when some 300,000 barrels of oil leaked from the* Metula *and contaminated 40 miles of coastline. (Photos Courtesy U.S. Coast Guard)*

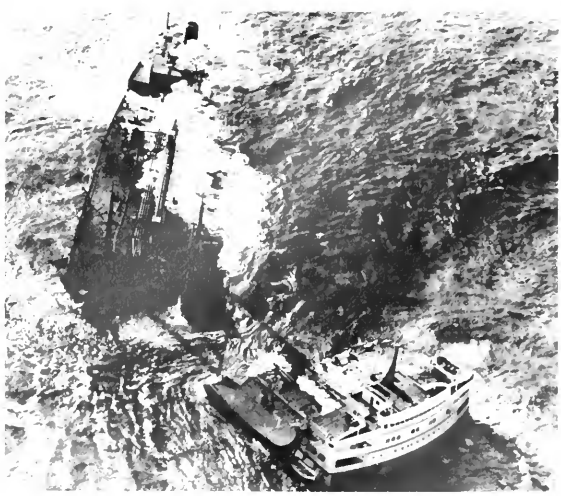
salvaged, but she had already spilled 53,500 tons of crude oil and Bunker C into the Strait of Magellan. In 1974, this event accounted for about 75 percent of all the oil spilled from tankers over 6,000 DWT. In 1975 and 1976, tankers over 6,000 DWT spilled 188,041 tons and 204,235 tons, respectively. In 1976 the *Argo Merchant* spill, involving some 27,000 tons, was responsible for 13 percent of the year's total.

While collisions are rather rare (accounting for only 5 of 68 losses) compared to these other causes, an incident occurred in 1971 in San Francisco Bay involving two tankers. In dense fog, the *Arizona Standard* and the *Oregon Standard* collided, spilling 3,000 tons of Bunker C. Neither ship was lost.

It might seem that these events are too sporadic to predict. If we look at the number of ships lost in terms of their fraction of the total world fleet, however, we find that this fraction has remained between .0030 and .0057 since 1964 (Figure 2). If we hypothesize that tanker losses are caused by a simple binomial process with a constant probability of loss of about .0043 per year per ship (the long-term average), then the observed values are not inconsistent with such a hypothesis.

Numerous studies of tanker losses suggest that this probability is not a constant between fleets. The Liberian fleet, for example, lost 68 vessels over the period 1964-1976.* Based on the Martingale MVF, the Liberian tanker fleet had an average size of about 700 vessels over this 13-year period. This works out to a loss rate of .0075. Equivalent data for the U.S. fleet suggest a loss rate of .0035. Some, like the Japanese fleet, had rates as low as .0018.

Based on these observations, we can construct a crude, but useful model for predicting the number of tanker losses incurred in U.S. waters in one year. Assume



The American-owned Liberian tanker Torrey Canyon *after she split in half on March 27, 1967, on Seven Stones Reef 15 miles off Land's End, England. All told, the tanker spilled 117,000 tons of Kuwait crude oil into the sea, after striking the reef on March 18. Despite large-scale efforts to disperse the oil using mixtures of solvent and emulsifying chemicals (some of which are toxic to marine organisms), some 18,000 tons came ashore, much of it onto Cornish beaches. (Wide World Photo)*

*Based on Table D of the Tanker Advisory Center Newsletter of March 26, 1976.

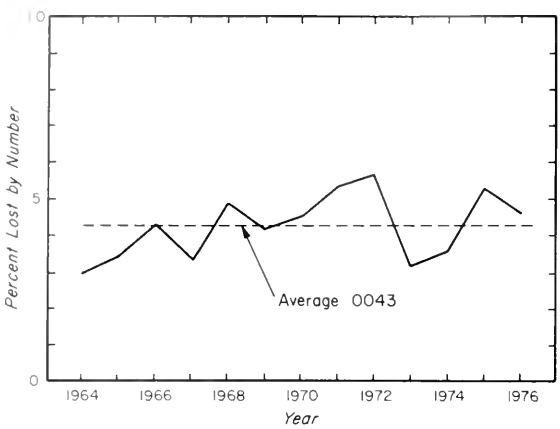


Figure 2. Percentage of world tanker fleet lost annually based on number of vessels. Tankers less than 6,000 DWT not included.

that all American tankers spend all their time in U.S. waters, which means an exposure of about 235 ship years each year. Assume that foreign vessels spend a total of six days in or near to U.S. waters per port call. Based on Table 4, this corresponds to about 130 foreign tanker years of exposure each year. Both assumptions are probably a bit too generous. Now assume that U.S. vessels have a probability of loss of .0035 and that all foreign ships have a probability of loss of .0055. On this basis, we can estimate the probabilities of 0, 1, 2, or more losses. Table 9 suggests that 1, 2, or even 3 tanker losses in a year in or near United States waters should not be considered uncommon. In fact, the probability that there will be no tanker losses in a one-year period is only about 0.22.

Based on the distribution of worldwide tanker incidents, about half of these losses could be expected to occur in conditions favorable to a spill in coastal waters. These include losses due to strandings on coastal shoals, collisions and groundings in harbors, and rammings. The remaining half could be expected to involve foundering on the high seas (near to the United States), and fires and explosions. The latter two might not involve oil spills. All three, however, would be expected to cause considerable crew casualties.

There are many things this model does not address. We do not have enough space to mention them here. However, despite its limitations, the results of the model still appear to be very close to the mark. For example, excluding the *Argo Merchant*, three tankers have been lost in the region between Nantucket Shoals and Cape Hatteras within the last eight years. They are the *Keo* (1969), the *Texaco Oklahoma* (1971), and the *Spartan Lady* (1975). I do not know whether they were all destined for U.S. ports but, assuming they were, they were all within one or two days steaming, and so fall within the envelope of the six-day assumption. Further, in the spring of this year, a small U.S. tanker foundered off Gloucester and the *Grand Zenith* disappeared northeast of Georges Bank, within several days of port. Add the *Sansinena* and the *Globtik Sun*, which rammed a platform in the Gulf of Mexico and burned, and perhaps one or two others, and one has a set of outcomes quite compatible with the model.

Assuming the model results are reasonably accurate, the chance of two or more tanker losses occurring in a one-month period can also be calculated. It is .012, or about 1 chance in 80. On this basis, the odds are about 50/50 that over the next five years we will not have another month like December 1976 in which two tankers were lost. For those who prefer to think of their cup as being half empty, it can also be said that there is a 50/50 chance that we will have at least one month in the next five years in which two or more tankers are lost in U.S. waters.

Future Trends

In any given year, the U.S. tanker fleet of 235 vessels over 1,000 GRT can be expected to have about 100 spills in U.S. waters. In the same period, foreign flag tankers will contribute approximately 250 spills. There is, however, some evidence in the figures for 1973 to 1975 of a trend toward fewer spills (Table 8), in which case these figures may be on the high side.

Using other statistical techniques, it is possible to estimate that about half the time

Table 9: Estimated probabilities of M_o tanker losses in U.S. waters in a one-year period.

M_o	U.S. Tankers	Foreign Tankers
0	.44	.49
1	.36	.35
2	.15	.12
3	.04	.03
4	.01	.01

Assumptions: U.S. tanker loss rate = .0035 (Ships/Ship year)
Foreign Tanker loss rate = .0055 (Ships/Ship year)
Exposure Estimate Based on Table 4

the largest U.S. tanker spill during a one-year period will be less than 5,000 gallons. The median volume for the largest spill from foreign tankers will be closer to 50,000 or 100,000 gallons. These values reflect the different tail behavior of the cumulative histograms of Figure 1.

Accompanying these oil spill incidents will be serious accidents resulting in tanker loss. In any given year, one or two such events should be anticipated. Some of these will occur on the high seas, where the only possible response will be search and rescue efforts for the survivors. Losses occurring in coastal waters and harbors will occasion intensive clean-up and salvage efforts.

In protected waters, our clean-up and salvage capabilities are fairly good. In the period 1973-1975, for example, 24.5, 23.3, 21.9 percent, respectively, of all oil spilled from tankers and tank barges in harbors and other protected waters was recovered. The most difficult spills in these areas are those that occur under conditions of strong tidal or river currents. Strong currents tend to complicate the logistical problems associated with delivering clean-up equipment to threatened sites. They also tend to impose technological limitations on clean-up equipment effectiveness. In contrast to the protected waters case and as evidenced by the *Argo Merchant* spill, our abilities to deal with spilled oil at exposed coastal sites is not nearly so good.

It is clear from these numbers that accidental spillage from tankers warrants continued attention. Especially important are the problems of tanker losses and spill cleanup at exposed sites. However, we should recall that *these numbers do not account* for the intentional discharge of oil from tankers. Under the current U.S. system, no oil may be discharged out to 12 nautical miles, but beyond this boundary any amount of oil can be discharged, although cargo oil may only be discharged for safety purposes and legal penalties may result if the oil drifts to within 12 miles. There are very few reliable figures on the quantity of oil so discharged off the U.S. coast, but it might well be of comparable magnitude with that of accidental spills. While the imposition of new legal sanctions on such practices would not necessarily result in a halt of intentional discharges, the present code seems to be a remarkable anachronism, especially in view of the intense interest in accidental oil spills.

Robert J. Stewart is an Oceanographer at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory in Seattle, Washington. Much of the material presented here was developed while he worked as a consultant to Martingale, Inc., Cambridge, Massachusetts.

Correction

In Henry Lyman's article on "The New England Regional Fishery Management Council" in the Summer issue, the wrong figures were given for the overall landings of all species at eight New England ports. The sentence in the first paragraph in column one on page 8 should have read: "According to National Marine Fisheries Services (NMFS) figures, the overall landings at eight New England ports between January and July increased by 15 million pounds over the 202 million pounds taken in 1976."

Technology and Policy:

The Cleanup of Oil Spills from Unprotected Waters

by Jerome Milgram

Should a major offshore oil spill occur tomorrow, it would be impossible to clean up the largest portion of the spill. In fact, there has never been a major spill in unprotected waters in which more than a few percent of the oil has been cleaned up. This situation exists despite the fact that over the last 10 years, much of the technology has been developed to clean up such a spill, and we have learned how to develop the rest. The total spill clean-up systems that are needed have not been implemented. While there is some question of whether preparedness for dealing with such spills would be worth the cost, there is no question that the issue should be aired on a national basis and a conscious public decision rendered as to whether we should pay the price and be prepared, or save the money and accept the risk.

When oil comes ashore anywhere, it results in major damage. Frequently the impacted area cannot be used for its regular purpose. Many forms of beach life are often killed with several years required for natural replenishment. The same applies to marshes, shellfish beds, and other near-shore life.

While no long-term major damage has been conclusively demonstrated from an oil spill that has moved offshore, there is evidence of the toxic effects of such oil on various forms of aquatic life inhabiting unprotected waters, including spawning fish and birds (see page 46). The long-term effects of such spilled oil are the subject of current research. We can thus state at this point in time that the adverse effects of spilled oil coming ashore are much more severe, as far as the general public is concerned, than those from oil spills that move offshore.

Most oil spills can be divided into three categories:

(1) Chronic oil spills at oil-handling depots, such as refineries and ports; characterized by frequent discharges of small amounts of oil.

(2) Intermediate-sized spills in protected waters. Generally, these are spills ranging in size from a few hundred gallons to many thousands of gallons and are caused by accidental opening of valves during oil transfer operations, and the grounding or ramming of vessels in harbors. Because of the proximity of these accidents to shore installations, leaks can usually be stopped and damaged vessels can be offloaded before extremely large amounts of oil are released into the water.

(3) Major spills in unprotected waters; they usually occur because of ships grounding on shoals, or as a result of blowouts from offshore wells.

Oil spills in the first two categories are far more frequent and much easier (and therefore cheaper) to clean up than those in the third category. Much technology has been developed for the smaller spills and that technology is being continuously improved. There is little question about the advisability of developing and using this technology. More questions exist about what should be done about large spills in unprotected waters.

Cleanup of Spills in Offshore Waters

Some offshore oil spills are very large — that is, millions of gallons. Cleaning up such spills requires the ability to contain and collect enormous quantities of oil. Spilled oil moves away from its source through the combined

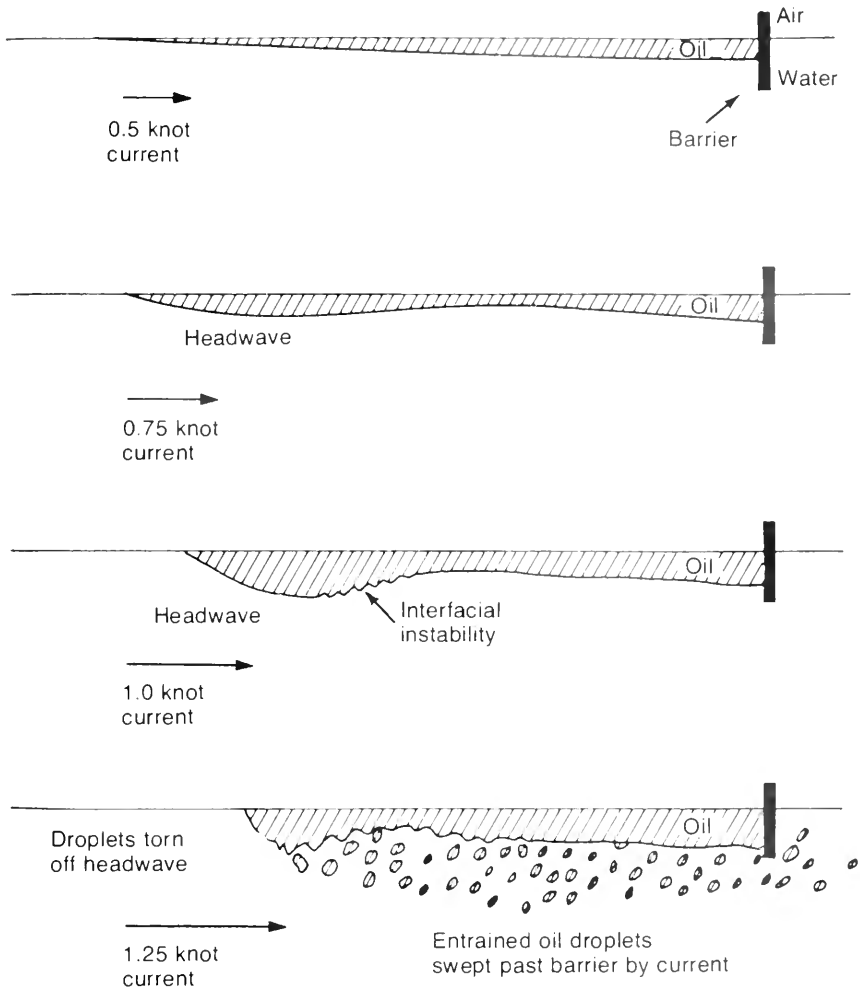


Figure 1. A simple oil boom or floating fence (black bar in chart). If the boom is towed slowly, with a speed relative to the water and oil of 0.5 knots, the oil is held against the boom as shown at the top; in the absence of ocean waves, the oil pool is relatively smooth. At a higher relative speed of about 0.75 knots, the oil pool forms a headwave near its leading edge, as shown in the second drawing. At a still higher relative speed of about 1 knot, the size of the headwave is substantially increased and there is instability in its lee; and at an even higher speed (about 1.25 knots), oil droplets are torn off the headwave by the water stream and may be carried below and past the collection device.

effects of spreading and mass transport by winds, currents, and waves. The combined speed of these forces is usually in the range of 0.5 to 2.0 knots. Oil does not usually spread in the form of a single pool of nearly constant thickness, but rather in relatively thick pools with an approximate diameter in the range of 0.5 to 10.0 meters and a thickness of 0.05 to 1.0 centimeters. These pools, in turn, are situated in a very thin oil layer with a thickness of 0.001 to 0.1 centimeters. Generally, it is oil in this form that must be removed if cleanup is to be achieved.

Any clean-up device must have some relative velocity between the oil (and the underlying water) and itself. Most clean-up devices slow down the oil, which results in an oil pool buildup in front of the device. When a pool of oil is held in a relatively stationary position above flowing water, there are hydrodynamic limitations on the relative velocity between the fluid and the device (Figure 1). This is precisely the situation that exists when oil is contained by a barrier in a relative current (Figure 2). During skimming, when oil is slowly withdrawn from the pool, the change in velocity is insignificant. Thus we can understand the speed limitations on both the containment and skimming phases by examining the containment situation alone.

As shown in Figure 1, when a relatively motionless pool of oil is held against a barrier by slowly moving water, the thickness of the oil is a slowly varying function of distance from the leading edge of the slick. At very low water speeds (less than 0.4 knots), the dominant force on the oil is the shear force of the water on the bottom of the slick. Figure 3a shows a side view of oil held against a barrier by slowly moving water in a free surface water channel.

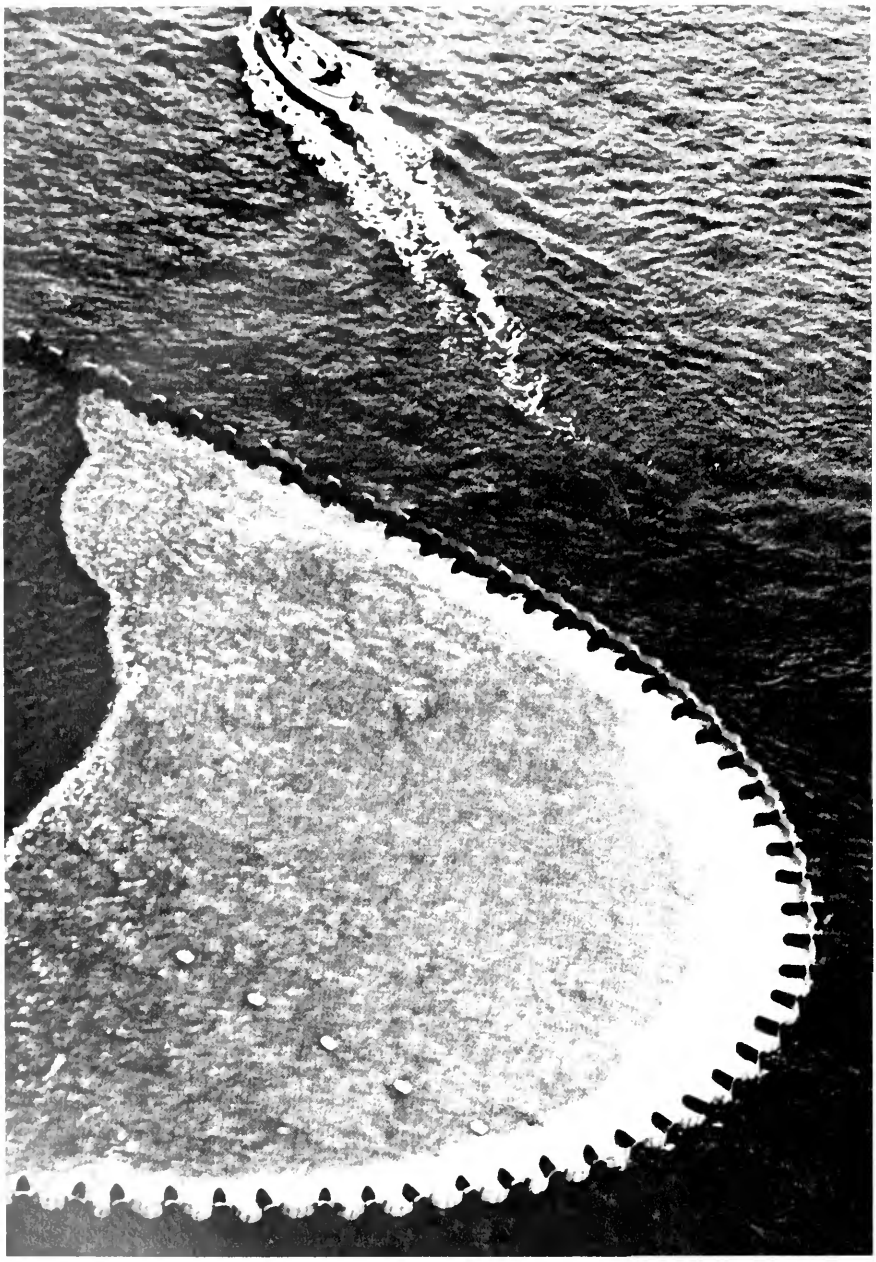


Figure 2. An oil boom holding oil. The boom is being towed by two tow vessels off the picture to the left. The tow speed through the water is about 1 knot.

As the water speed is slowly increased, a critical speed is reached above which the oil-water interface is unstable with respect to Kelvin-Helmholtz waves.* These waves make the surface near the leading edge of the slick very rough, as shown in Figure 3b. Separation of the basic flow behind the wavelets results in a vastly increased "effective skin friction" that drives the oil toward the barrier and causes the pool to thicken. Directly behind this thickened region, called the headwave, the basic flow is partially separated so that the local skin friction is very small. Further downstream, the skin friction slowly grows to a typical value of the skin friction coefficient of 0.01. In Figure 3b, it can be seen that the oil-water interface has fairly long waves behind the region locally

*Created by an instability in motion caused by a coupling between the pressure field and the motion itself.

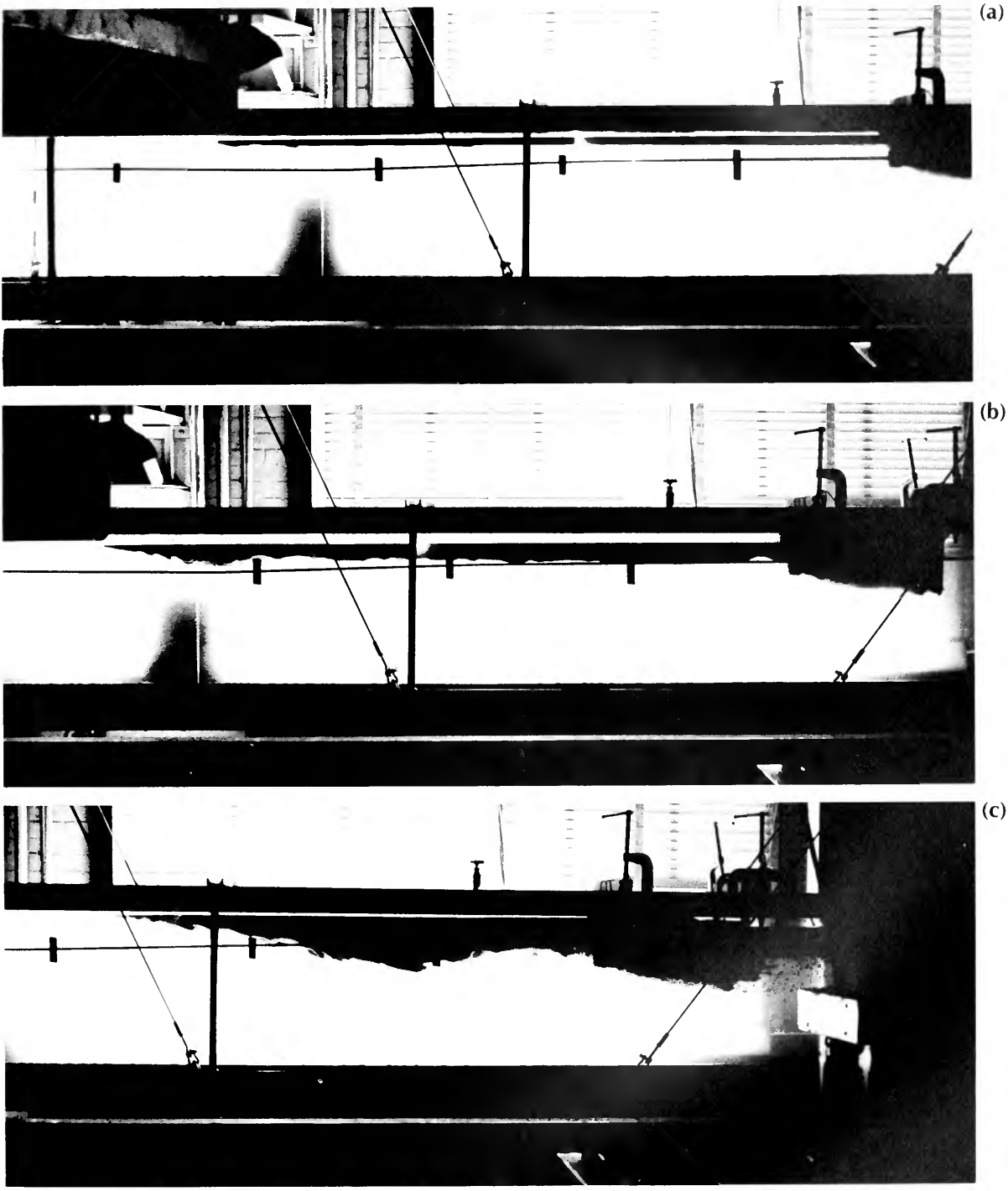


Figure 3. Oil held against a barrier by a current under laboratory conditions. The current is running from left to right. In (a) the current speed is 0.23 meters per second or 0.45 knots; (b) current speed =0.30 m/sec. (0.59 knots); (c) current speed =0.46 m/sec. (0.89 knots). The barrier consists of an undershot weir behind a pad of rubberized horsehair. The pad is needed to diffuse the vorticity generated in the flume sidewall boundary layers, which otherwise would form concentrated vorticities in the corners between the walls and the weir that would in turn draw the oil beneath the weir. Physical properties of the oil: specific gravity =0.880; viscosity =150 cp; oil-water interfacial tension =37.0 dynes/cm.; oil-air surface tension =30.8 dynes/cm.

thickened by the "skin friction" effects on the region of the Kelvin-Helmholtz waves. For still higher velocities, the combination of the Kelvin-Helmholtz waves and the unsteady boundary layer flow in the water beneath them results in oil droplets tearing off from the bottom of the slick, which then pass beneath the containment or collection device.

The loss of oil droplets by this process is known as entrainment loss. For most types of oil, this loss is small at speeds below 1.0 knot and large at higher speeds. Therefore, for a large oil spill, 1.0 knot is a practical upper limit of the relative velocity between a collection or containment device and the fluid.

For smaller spills, collection devices, such as belts moving across the water surface or devices that can actually slow down the water in front of the slick, can extend the upper limit of relative speed to about 2 or 2.5 knots. However, the relationship between the physical size of such devices and their oil-collection capability makes them impractical for the cleanup of large spills at sea. Such devices are generally limited to oil collection rates on the order of 50 gallons per minute, whereas devices for the cleanup of major spills must collect at least 500 gallons per minute. Therefore, the 1-knot speed limit exists for the cleanup of large offshore spills.

A typical average combined oil thickness over the thick and thin regions is 0.05 centimeters. At a relative encounter speed of 1 knot, achieving a 500-gallon-per-minute collection capability requires that the width of the clean-up device be approximately 125 meters. For thinner layers of oil or higher collection rates, a greater width is needed. Because of this requirement, a single collection vessel is an inappropriate device for the cleanup of most offshore spills.

To achieve the large gap width, an oil barrier (boom) must be used. Essentially, this is a floating fence that maintains a skirt beneath the surface of the water and a sail above it to prevent the passage of oil over or under the barrier. At relative water speeds below 1 knot, effective containment and concentration (local thickening of the oil pool in the barrier) of an oil slick can be achieved by a barrier.

The largest environmental difference between spill cleanup in protected waters and that in unprotected waters is the presence of much larger waves in unprotected waters. Clean-up equipment for offshore spills must be effective in the presence of different sea states. Generally speaking, an effective clean-up device must follow the vertical up and down motion of waves with high precision so that the portion of the device that is designed to collect oil remains in the oil most of the time, not in the air or the water. Devices with this capability for long, gentle waves of any height and steep seas up to 2 meters high have been developed and constructed.

There is considerable evidence that in short, steep waves more than 2 meters high, the frequent breaking of the waves entrains so much oil into the water column beneath the surface that cleanup from the surface may not be feasible. When such rough conditions subside, much of the entrained oil rises to the surface and can be cleaned up from the surface at that time. This influences two aspects of spill clean-up equipment and procedures. One, the need for surface clean-up equipment to work in waves much higher than 2 meters may not exist, although the equipment must remain undamaged in rougher seas so it is available for use when conditions improve. Secondly, the need for carefully planned logistics is apparent. Clean-up operations need to take place in the regions where oil rises after conditions subside. Thus predicting what the distribution of oil will be after it rises is an important aspect of the problem. This is affected by how the oil droplets at various depths are transported by tidal currents and those induced by wind stress and by waves, as well as the way in which the droplets rise. Considerable knowledge in each of these areas exists, and research is ongoing in those areas where present knowledge is deemed insufficient.

One way to collect oil is to build collection devices into a barrier in such a way that they do not impede the wave-following ability of the structure. The devices can then deliver the collected oil to storage vessels through flexible hoses (Figure 4). An alternative would be to install small lightweight skimming devices inside the U-shaped configuration of a towed barrier designed to be able to follow the vertical up and down motion of the liquid. Again, oil could be delivered to a storage vessel through hoses (Figure 5).

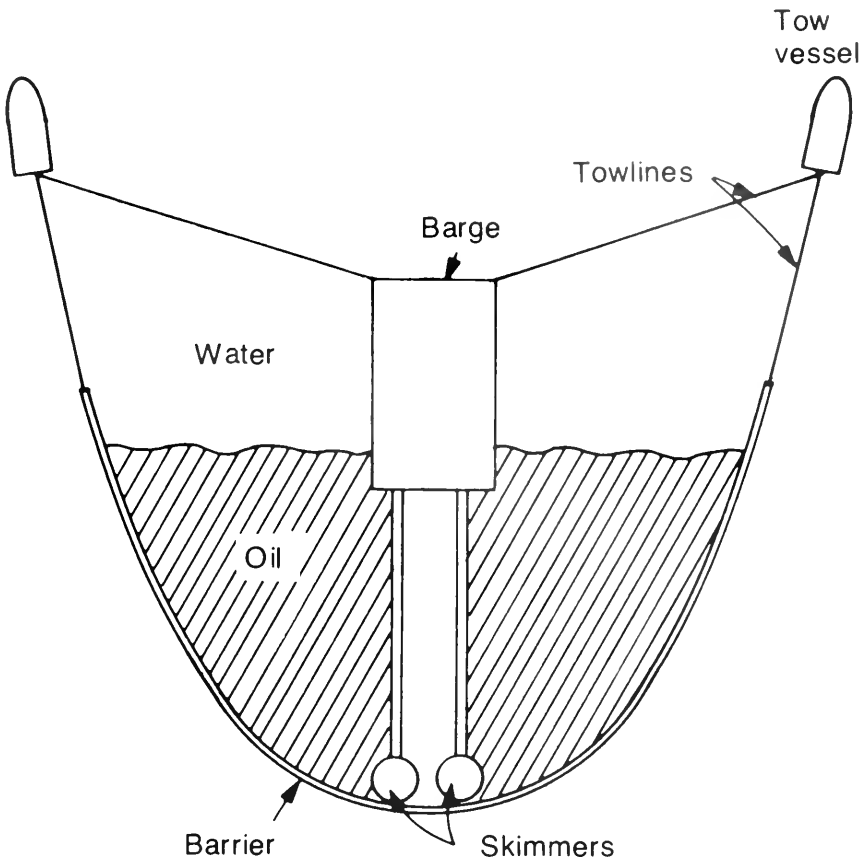


Figure 4. Device for high-volume collection of oil spilled offshore with skimmers inside U-configuration of towed barrier. The barrier provides a high oil encounter rate and a thick pool of oil in which the skimmers can operate efficiently. The tow vessels must not tow faster than 1 knot through the water. The oil shown in the sketch is the thick pool. Generally, a thin pool is encountered ahead of the tow vessels.

The preceding discussion indicates four of the five crucial items needed in a total spill clean-up system:

(1) A basic wave-following oil barrier that can provide the needed sweeping width and serve as an oil thickness concentrator. When towed at a speed of 1 knot through an oil slick, the pool that builds up at the center of the U-shaped configuration can be relatively thick. For example, for a total barrier length of 300 meters, designed with a draft of about 0.8 meters, an oil depth of 0.4 meters at the barrier can be achieved. It is far easier to design oil collection devices that can achieve a high oil/water collection ratio for such depths than it is to design such devices to work in much thinner oil layers.

(2) Oil collection devices (skimmers) to actually collect the oil from the pool contained by the barrier.

(3) An oil storage vessel into which the collected oil can be pumped and then stored.

(4) Towing vessels that can maneuver the arrangement of barrier, skimmer, and storage vessel through an oil slick at a sweeping speed of 1.0 knot. Most existing tow vessels cannot move at such a slow speed and still maintain good steering control. However, the knowledge exists to design such vessels or to refit existing ones.

The final element that needs to be added is highly trained personnel. To do the job effectively, it would require a rapid response so that the oil did not spread too far before cleanup began, plus efficient procedures throughout the entire process. This could only be achieved by personnel who were thoroughly trained in the work, who were always ready to respond to such a crisis, and who would participate in frequent practice sessions.

So five crucial items have been listed: barriers, skimmers, storage vessels, towing vessels, and trained personnel. If a single one of these items is absent, no oil can be cleaned up. The solution to the problem thus is one that requires a total system. It should be

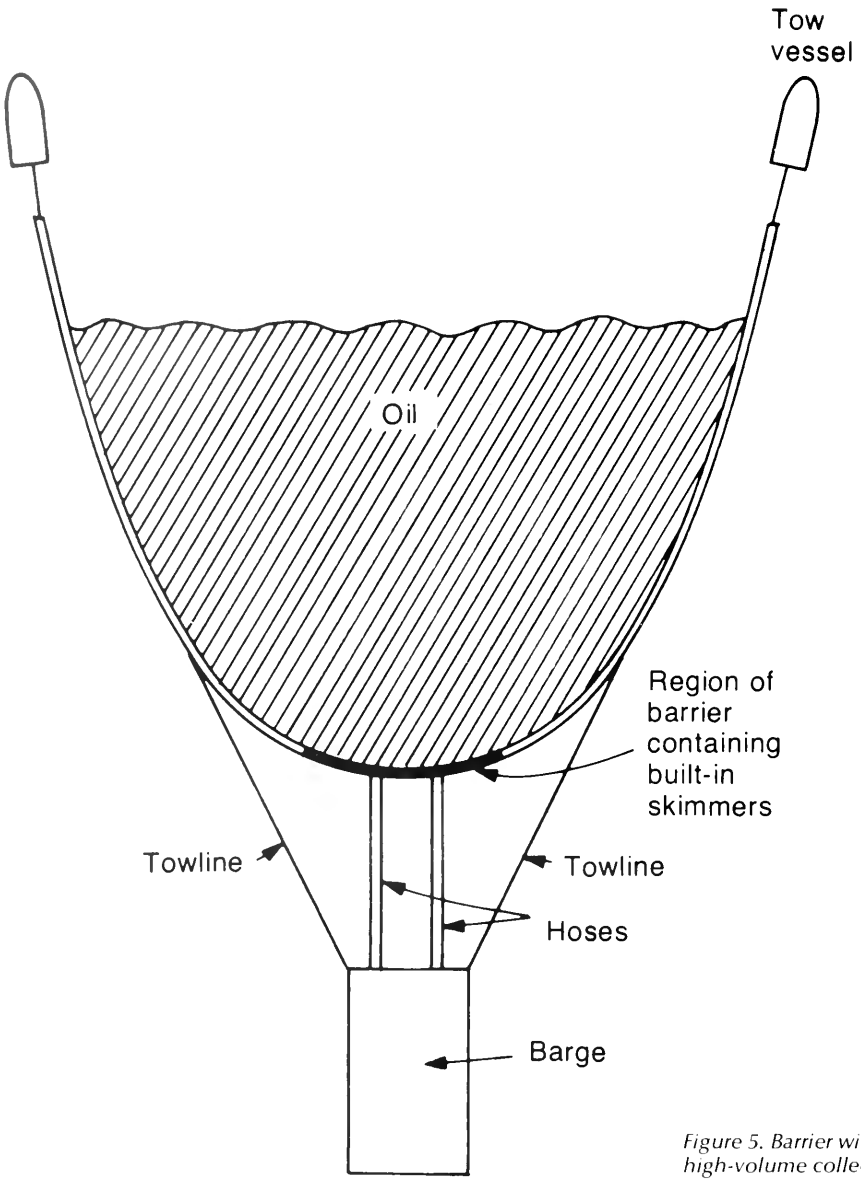


Figure 5. Barrier with built-in skimmers that affords high-volume collection of oil spilled offshore.

pointed out that these items are those needed for actual clean-up operations. In addition, supporting equipment and facilities for the five items is needed to deliver, launch, and later recover barriers and skimmers. Shoreside facilities are needed to rapidly offload and later process or dispose of recovered oil contaminated with seawater. No such facilities presently exist, although we do know how to build them. Thus we see that preparedness for cleaning up large oil spills requires a multi-faceted and thoroughly coordinated effort.

Even with a total system, not all of the region containing spilled oil could be swept. And some oil would leak past the system. We thus would never be able to clean up all of the oil spilled in an accident. This leaves us with the question of what should be done about the oil that is not cleaned up.

The weight of the available evidence is that nothing should be done about oil that is not cleaned up and which is moving away from shorelines, if the expectation is that it will be evaporated, dissolved, dispersed or biodegraded to relatively safe concentrations

before it reaches land. Generally, such processes take up to a few weeks, although longer periods may be required in very cold water. For oil that is moving toward shore, the possibility should be considered of speeding a reduction in oil concentration by the use of dispersants.

Much research has taken place on the use and effects of dispersants on oil spills. Unfortunately, none has included controlled tests on the use of different types of dispersants on quantities of oil as large as could be expected from a large spill at sea, even after most of the oil was physically removed. At the present time, it is somewhat difficult to make an objective judgment about the benefits to be gained by the use of dispersants. According to Environmental Protection Agency (EPA) regulations, dispersants should almost never be used. The oil industry, on the other hand, takes the position that dispersants should almost always be used. Neither position is particularly constructive.

Under certain conditions dispersants would probably be beneficial; under others, they would not. All dispersants are, to some extent, poisonous so that a net gain would only be achieved when the benefits of their use outweighed the toxicity effects. What is needed is a rational study, including field trials with large amounts of oil, to determine the conditions under which use of dispersants would be appropriate and those where such use is best avoided.

The Need for Policy Decisions

Since clean-up equipment for unprotected waters is both large and heavy, its delivery from a storage location to the site of an oil spill is limited to moderate waterborne speeds — 12 to 15 knots. Because a rapid response (say, 6 to 8 hours) is essential in successfully cleaning up an oil spill, and since we would like to respond to spills up to 50 miles from shore, the limited delivery speed means that equipment at a fixed storage location is only appropriate for a stretch of coastline about 100 miles long. The equipment is expensive. A total spill clean-up system that collects 500 gallons per minute has a daily collection rate of 2,000 tons. A super tanker holds several hundred thousand tons. Effective protection would require that each equipment storage area have about 10 total spill clean-up systems — each costing roughly $2 million. In any stretch of coastline 100 miles long, the possibility of a major offshore oil spill occurring during a 5-year period is remote. Providing protection from a major spill would require an initial capital investment of about $20 million for each 100 miles of coastline, plus an annual maintenance cost of about $2 million.

Such remote eventualities make it economically impractical for oil spill clean-up contractors to make such expenditures. Protection against the damage of major oil spills, therefore, will only be provided if required by Federal or state legislation, or if the protection is provided by the government. We need to address the issue of whether or not the protection is worth the cost.

The cost would be approximately $250 million for the entire United States. Although such protection could clean up more than half the spilled oil, some would still be left. The alternative is to save the money and accept the increased risk of damage from offshore oil spills. A conscious decision is needed now as to which policy should be adopted.

During the last 10 years, a number of individuals and organizations have participated in research and equipment development for the cleanup of oil spills in unprotected waters. They now see that the results of their efforts are not being used to provide environmental protection. For this reason, many have left the field. It can be expected that more will follow unless a policy of protection is adopted. If the decision is put off for 5 or 10 years, the implementation would be far more expensive than if begun now.

The question of the benefits of the use of dispersants on volumes of oil of about 1 million gallons needs to be addressed whether or not the implementation of total spill clean-up systems takes place. Typically, the volume of dispersant required to disperse oil is about 10 percent of the volume of the oil. This makes the required dispersant volume for dispersing an entire large spill impractically large. However, if dispersants can provide benefits, some protection of especially vulnerable shoreline areas could be provided by dispersing the oil that would be likely to come ashore in these areas. Naturally, if most of the oil was physically removed from the water, the amount of dispersant needed would be reduced.

At the present time, EPA regulations prevent the needed tests of dispersants on large quantities of oil. Those regulations need to be changed so that we can find out when, if ever, dispersants should be used.

In summary, a national decision needs to be made first as to whether or not the implementation of total spill clean-up systems should take place. We know enough about the five crucial items needed for total spill cleanup to be able to provide effective systems. Research is presently taking place on ways to improve these systems. If they are to be provided, this research should definitely continue. If the decision should be to save the money and accept the risk, there would be little sense in continuing the research. Without the stimulation of the actual implementation of the systems, the most capable people in the field will probably leave. More research of dispersants is needed, including field trials with large amounts of oil. As a result of these tests, a realistic approach to dispersants, different from that of the EPA and the oil industries, could be developed.

Jerome Milgram is Professor of Naval Architecture in the Department of Ocean Engineering at the Massachusetts Institute of Technology. He was one of two scientists aboard the Argo Merchant *before it broke in half.*

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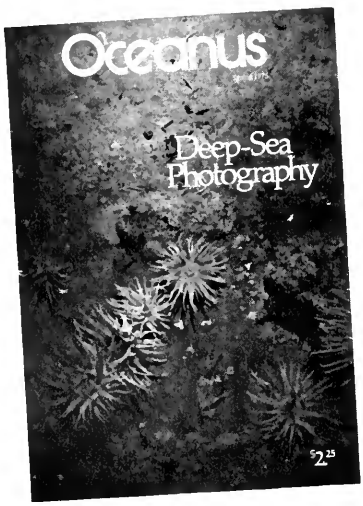

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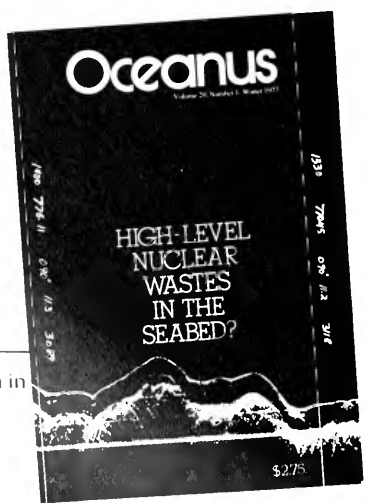

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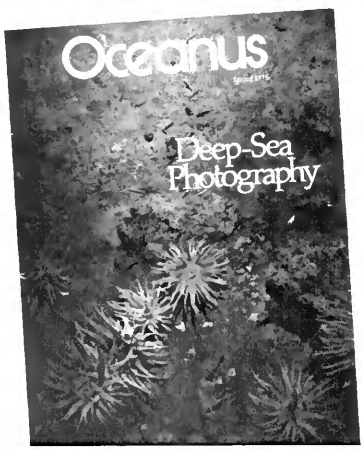

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