Oil Pollution:

A Decade of Research and Monitoring

by John W. Farrington

Few technological disasters ignite the public's imagination so much as a major oil spill. The site of a broken ship or an out-of-control well is matched with heart-rending visions of struggling seabirds and blackened beaches. Surely, the typical observer speculates, this is one arena in which stricter regulations and enforcement could prevent damage to the environment.

But the problem of oil pollution in the ocean is much more complex than such striking images might lead one to believe. The vast majority of oil pollution comes not from highly visible accidents, but from much more ordinary sources, such as sewer outfalls, ships' bilges, and normal oil tanker operations. Furthermore, oil is an amalgam of thousands of chemicals, each affecting the marine environment and marine organisms in different ways.

The effect of any given chemical is far from certain. Wind, waves, and currents, all of which vary in intensity from location to location, act to disperse the oil. As a result, a given oil spill may be diluted rapidly or may remain concentrated in a small area. Sunlight and microorganisms may modify the composition of the oil. Some oil may dissolve in seawater or become attached to suspended particles of solid matter that later settle to the ocean bottom. Finally, the ultimate effects of oil pollution depend on the uptake of the various petroleum chemicals by fish, crabs, lobsters, and other marine organisms.

Unfortunately, understanding these obstacles to evaluating the effects of oil pollution is of no help in making pressing policy and regulatory decisions. As with decisions to limit the use of pesticides or to stop disposal of sewage sludge at sea, a decision to reduce the input of petroleum to the environment would involve significant costs to society—costs that must be balanced against the detrimental environmental effects of not acting. As a result, such decisions require more quantitative information than is available in many cases. Decision-making on such complex issues relies heavily on periodic, thorough reviews of present knowledge by groups of scientists.

In 1975, the National Research Council (NRC) published just such a thorough review, entitled *Petroleum in the Marine Environment*. It provided guidance for policy, monitoring, and regulatory activities related to oil pollution in the United States and elsewhere. In addition, the report stimulated much research during the last decade. New knowledge resulting from this research, coupled with expanding exploration for and production of oil in several valuable fishing areas, prompted a request from U.S. government agencies for an update of the 1975 report. The urgency of this request was augmented by questions about the long-term impacts of visually spectacular oil spills, such as the *Amoco Cadiz* tanker spill on the coast of France in 1978 and the IXTOC-I oil-well blowout in the Gulf of Mexico in 1979.

The process of updating, begun in 1980, was completed this April with the publication of the 1985 report, entitled *Oil in the Sea: Inputs, Fates, and Effects*. More than 100 scientists contributed to the report [see box page 9]. Despite my attempt to portray their findings accurately, it is inevitable that a summary cannot possibly convey all the details present in the 601 pages of the report.*

In updating the report, two key questions had to be answered. What happens to oil in the marine environment during the course of years and decades? What are the effects of oil on marine

* Interested readers may obtain a copy of the report for $39.50 from the National Academy Press; 2101 Constitution Avenue, N.W.; Washington, D. C. 20418.

organisms at all levels of complexity, again considering time scales ranging up to decades?

Sources and Characteristics

A major problem in evaluating the fate and effects of petroleum in the ocean is the complexity of the mixture of chemicals we call petroleum. Thousands of compounds are found in most crude oils. During refining, crude oils are processed to yield "fractions" for different uses. These fractions are, in fact, just that—groupings by molecular weight or type of chemicals isolated from crude oil. But even one of these fractions, such as home heating oil or jet fuel, can contain more than 100 chemicals.

The chemicals in petroleum are of many types. Hydrocarbons—compounds made up of only hydrogen and carbon—are the most abundant. Hydrocarbons can be subdivided into alkanes and aromatic hydrocarbons. Alkanes are formed of linear chains of carbon with hydrogen atoms coming off the sides much like the hairs on a caterpillar. Aromatic compounds feature a ring of carbon atoms, and several are used in making polyester, DDT, mothballs, and vanillin (an artificial flavoring used in perfumes and ice cream). Other compounds found in petroleum in smaller quantities include the N, S, O heteroatom compounds, in which nitrogen (N), sulfur (S), or oxygen (O) atoms replace a carbon atom. Sulfur and traces of metals such as vanadium, nickel, and iron also may occur in petroleum.

Unfortunately for those of us who try to examine the effects of petroleum on marine systems, petroleum is not the only source of such compounds. Organisms synthesize alkanes, and simple transformations of other organic compounds can yield small amounts of certain alkanes and aromatic hydrocarbons. Thus, there are normal biological processes already contributing hydrocarbons to the environment. However, petroleum contains more aromatic hydrocarbons and N, S, O, heteroatom compounds than normally are present. This may be particularly significant because aromatic compounds seem to be more harmful to marine organisms than other hydrocarbons. Another complicating factor is that incomplete combustion of fossil fuels (coal, oil, gas) and wood yields aromatic hydrocarbons of the same types as those found in petroleum. The origin of a given aromatic hydrocarbon can be determined only through detailed chemical analyses.

Table 1 presents the best estimates available for sources of petroleum hydrocarbon inputs to the marine environment. There are several very important messages contained in this table, but three important qualifiers need to be emphasized. *First,* these estimates are averaged in time and space. At any given location or any given time interval the relative importance of each source of input can vary substantially. For example, oil-tanker-related inputs will occur where there are oil tankers (Figure 1). *Second,* the estimates have a wide range of uncertainty—more so for some categories than others—because accurate measurements or means of estimation for global inputs are rare. *Third,* the estimates are for total petroleum hydrocarbons; the data base does not permit accurate input estimates for those portions of petroleum, such as the aromatic hydrocarbons, known or suspected to cause adverse biological effects.

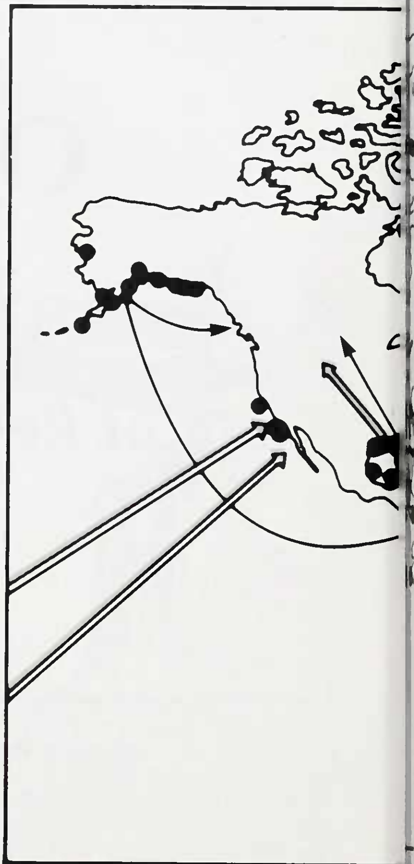


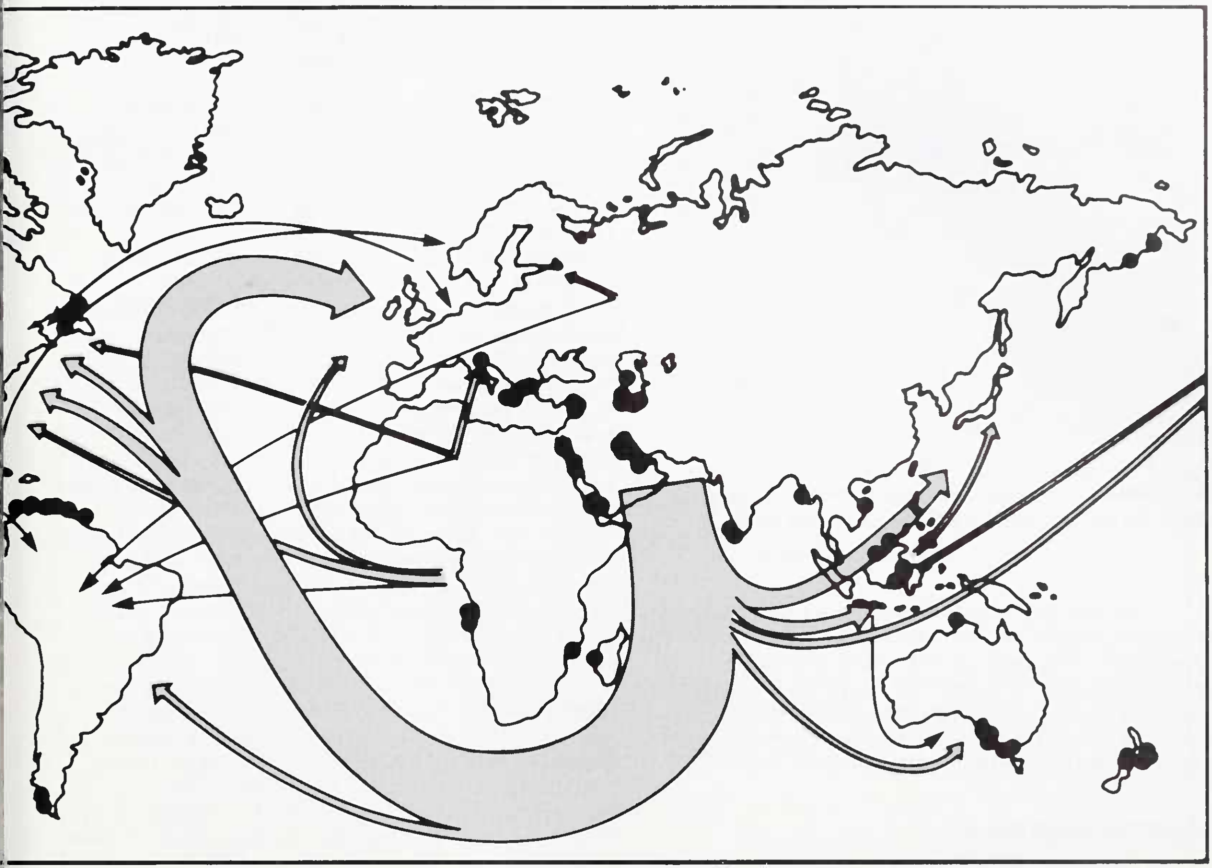
Figure 1. International oil transport routes (arrows) and the location of natural petroleum seeps (dots).

The world's oceans have received inputs of petroleum for a long time—probably for at least 100,000 years. The sources of these inputs are seepage of oil from natural reservoirs near the Earth's surface and erosion of sediments, such as shales, that contain petroleum-like hydrocarbons. Approximately 0.25 million tons of petroleum per year, mostly from seeps, enter the oceans from natural sources (Figure 1). Thus, low levels of petroleum contamination have existed since well before human use of petroleum began. I do not mean that human inputs of petroleum to the ocean are harmless; rather I want to point out that the world's oceans were not pristine with respect to petroleum—especially in seep areas.

The 1985 NRC report also reaffirms two important findings of the 1975 report:

- *Accidental inputs are a small fraction of the total inputs.*

- *Land based sources—industrial effluents, municipal sewer effluents, marine tanker terminal and dry dock operations, and urban*



runoff—account for more than a third of the total input (Table 1).

Table 1. Input of petroleum hydrocarbons into the marine environment in million tons per year.

Source	Probable Range	Best Estimate*
Natural sources		
Marine seeps	0.02–2.0	0.2
Sediment erosion	0.005–0.5	0.05
Total natural sources	0.025–2.5	0.25
Offshore production	0.04–0.06	0.05
Transportation		
Tanker operations	0.4–1.5	0.7
Dry-docking	0.02–0.05	0.03
Marine terminals	0.01–0.03	0.02
Bilge and fuel oils	0.2–0.6	0.3
Tanker accidents	0.3–0.4	0.4
Nontanker accidents	0.02–0.04	0.02
Total transportation	0.95–2.62	1.47
Atmosphere	0.05–0.5	0.3
Municipal and industrial wastes and runoff		
Municipal wastes	0.4–1.5	0.7
Refineries	0.06–0.6	0.1
Nonrefining industrial wastes	0.1–0.3	0.2
Urban runoff	0.01–0.2	0.12
River runoff	0.01–0.5	0.04
Ocean dumping	0.005–0.02	0.02
Total wastes and runoff	0.585–3.12	1.18
TOTAL	1.7–8.8	3.2

The chronic dribbling of petroleum from sloppy use by modern society is responsible for a large fraction of the input to the world's oceans. This fact usually is greeted with surprise by a general public that associates oil pollution with tanker spills and offshore oil-well blowouts (Figure 2). Accidental oil spills are important in the local areas or regions of the ocean where they occur, but are a small percentage of total inputs over the course of several years.

A major source of uncertainty about the sources of contamination is petroleum or petroleum-like hydrocarbon input from incomplete combustion of fossil fuels and wood. These compounds may be transported to the ocean by wind. Little more can be said about the relative magnitude of such inputs than was said in 1975—that this is one of the major sources of hydrocarbon inputs to the ocean. Very little progress has been made since 1975 in obtaining actual measurements of fossil fuel compounds in the atmosphere over the ocean or in rain collected at sea.

*** The total best estimate, 3.2 million tons per year, is a sum of the individual best estimates. A value of 0.3 was used for the atmospheric inputs to obtain the total, although the author realizes that this best estimate is only a center point between the range limits and cannot be supported rigorously by data and calculations.**
Source: 1985 NRC report.

Figure 2. The IXTOC-I oil-well blowout. To the left of the well, flames, barely visible, rise some 30 meters. The larger ship in the background is more than 250 meters long.

Another problem is the existence of extensive geographical gaps in data, especially for the southern hemisphere. This requires estimating global petroleum inputs by using data on inputs from a few countries and extrapolating these data to other countries where patterns of petroleum use and release to the environment may be quite different.

Fate of Petroleum Inputs

Once petroleum enters the oceans, it begins to be acted on by a wide variety of processes (Figure 3). One of the first is contact with sea water. The old adage "oil and water do not mix" is true for the bulk of accidentally spilled oil—for short periods of time. But over a period of hours to months some mixing will occur. Furthermore, the adage does not apply to petroleum compounds entering the ocean already dissolved in water or widely dispersed in another medium, such as urban runoff, waste effluents, or the atmosphere. Some compounds in petroleum, while not as soluble as other organic chemicals such as sugar, are somewhat soluble in seawater. Other compounds enter the water column as dispersed droplets and water-in-oil emulsions (resembling a freshly shaken bottle of salad dressing) mixed together by wind, waves, and currents. The more volatile portions of petroleum are generally lost to the atmosphere by evaporation from slicks or, if they entered the water via a subsurface effluent, by sea-air gas exchange.

Some oil becomes attached to solid particles suspended in the water through the twin processes of adsorption (clinging to the surface of a solid) and absorption (being soaked up by a solid, as by a sponge). These particles may later sink to the bottom, carrying the oil with them, resulting in incorporation of petroleum compounds into sediments. Oil also may reach sediments in shallow waters by turbulent mixing throughout the water column down to the sediment-water boundary. This is an important phenomenon because once incorporated into sediments the compounds may have a long-term impact on bottom-dwelling organisms that are key components of coastal ecosystems.

An impressive amount of new knowledge about bacterial degradation of oil in the oceans has been obtained during the last decade. Numerous strains of bacteria have been isolated that are capable of metabolizing one or more classes of petroleum compounds. Field studies have demonstrated quite clearly that these bacteria are present at spill sites and chronic release sites in much greater numbers than at oil-free sites. These studies also have demonstrated that the mere presence of oil-metabolizing bacteria is not sufficient to guarantee that oil compounds will be destroyed. Sufficient nutrients and oxygen must be present—and oil, nutrients, and oxygen must be mixed together in the correct manner—to attain significant metabolism. If good mixtures are achieved, bacterial metabolism can be quite rapid for certain classes of compounds. If conditions for growth are poor, rates of metabolism are significantly slower. In addition, the type of oil involved has a major effect on microbial degradation. Although 90 percent of some crude oils may be biodegradable, as little as 11 percent of others may be so broken down.

Since the 1975 report was written, marine photochemistry has emerged as a subdiscipline of marine chemistry. Concomitantly, photochemical processes acting on petroleum in the oceans are now being investigated in more detail. The pioneering work of a few scientists in the mid- to late 1970s alerted researchers to the importance of these reactions. For example, some experiments have shown that certain oils subjected to photochemical alteration are more toxic to some marine organisms than the unaltered oil.

In such bacterial and photochemical processes, oxygen is added to hydrocarbon molecules. This changes them from electrically neutral compounds to more polar compounds, with positively and negatively charged sections. As a result, they are able to mix more readily with the water molecules, which are also polar. The presence of these polar compounds in spilled oil may promote or assist in the formation of water-in-oil emulsions, which greatly alter the fate and effects of spilled oil. The water-in-oil emulsions are often referred to as "mousse" because they resemble chocolate mousse. In some cases, the mousse accumulates in large patches at oil spill sites. Studies at the IXTOC-I oil spill demonstrated that mousse "rafts" could float across the Gulf of Mexico and deliver relatively fresh oil (that is, oil not extensively altered by evaporation, dissolution, or microbial metabolism) to shorelines a thousand kilometers from the spill.

A wide variety of marine organisms will take up petroleum compounds from water, sediments, or food. Some of these organisms—such as bivalve molluscs, worms, crabs, lobsters, and fish—can release petroleum compounds back to the environment after the petroleum contamination is reduced or removed. The rate of uptake and the final concentration attained in a given organism's tissues depend on the chemistry of the compounds,

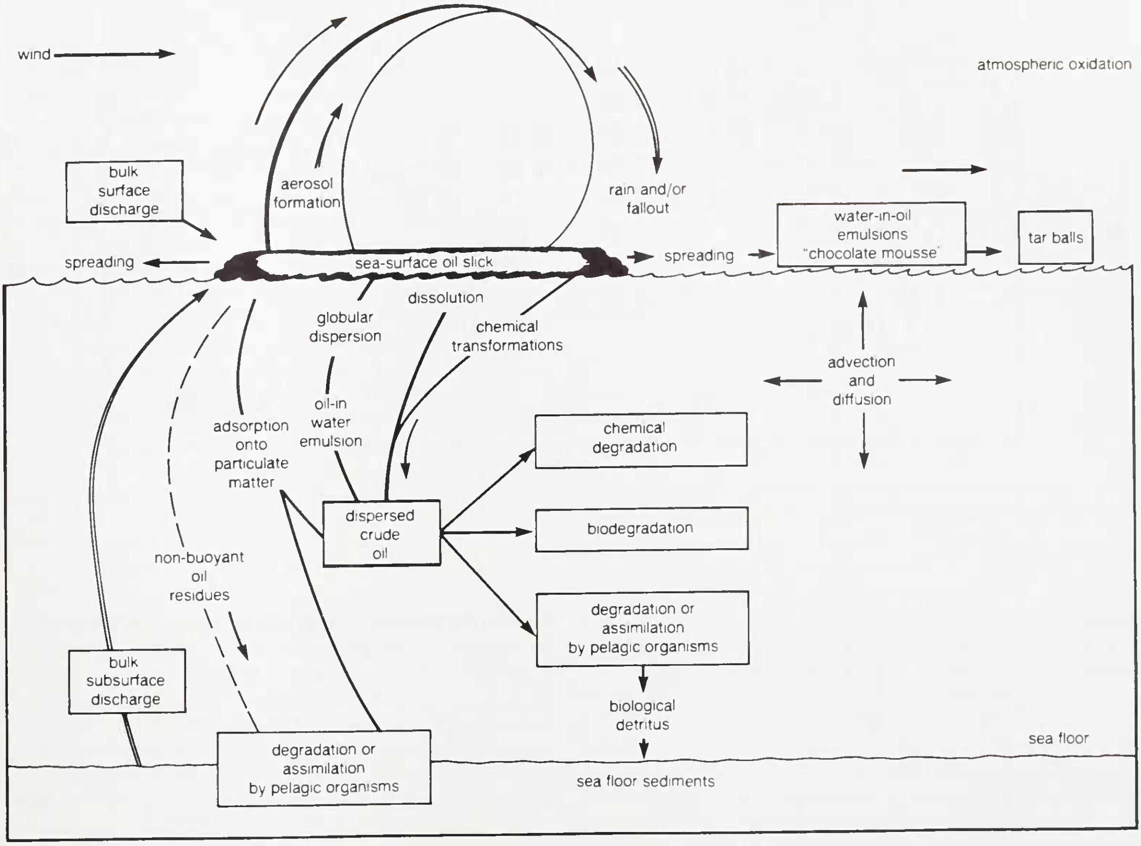


Figure 3. Some of the processes affecting oil once it enters the marine environment.

the form of exposure, and the concentration and duration of exposure. Release back to the environment is dependent on similar parameters. Shellfish transplanted from contaminated urban harbor areas to relatively clean waters require at least several months to reduce concentrations of petroleum in their tissues to levels found in the same species residing naturally in the clean areas.

In addition to releasing compounds, several species of fish, crustaceans, birds, marine mammals, and worms can metabolize aromatic hydrocarbons and excrete the resulting products. Thus, these marine organisms have a means of reducing their burden of toxic compounds. But the metabolism process can be a two-edged sword. Metabolites of some higher molecular weight aromatic hydrocarbons may be mutagenic or carcinogenic. The extent to which this is a problem for the organism that produces them is being investigated.

Overall, despite impressive progress, it is not yet possible to measure the rates of the major processes acting on petroleum inputs so as to make a mathematical model for the fate of petroleum from a given source. Only for some well-studied oil spills, such as the *Amoco Cadiz* spill (Table 2), is the fate of the bulk of the oil known.

Petroleum Pollution Today

Scientists researching ocean pollution are often asked "How badly polluted are the oceans with petroleum?" It is a difficult question to answer. Most data on the subject come from coastal areas. There are, however, three types of observations available from the open ocean—slicks on the surface recorded by ships of opportunity, floating tar in surface waters, and rough measurements of dissolved or dispersed hydrocarbons. Since natural slicks from organic matter released by plankton are not differentiated from petroleum slicks by the seamen who observe them, and since the

Table 2. Mass balance accounting of oil spilled by the tanker *Amoco Cadiz*.

	Tons	Percentage
Total Spilled	223,000	
Incorporated into subtidal sediments	18,000	8
Onshore (beaches, marshes, rocky areas)	62,000	28
In or on Water	30,000	13.5
Biodegraded (mainly by bacteria)	10,000	4.5
Evaporated	67,000	30
Unaccounted for	46,000	20.5

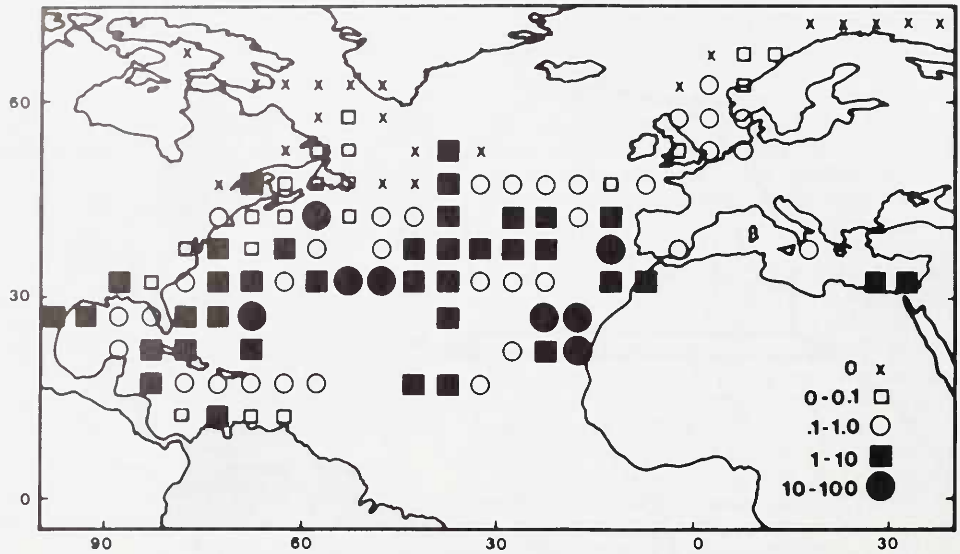


Figure 4. Concentrations of tar balls (in milligrams per square meter) for the North Atlantic. The zero data points indicate that an area was sampled but no tar found.

observations are subjective, not much can be gleaned from the slick observations except that large portions of the world's oceans are free of readily discernible petroleum slicks.

Floating tar is the residue remaining after oil has been acted on by the various processes described previously. This tar comes ashore in many places in the world, and becomes a nuisance to recreational boaters and swimmers. I still possess a bottle of "Tar Away" cleanser sold to bathers on Bermuda in the mid-1970s. Higher concentrations of floating tar are associated with shipping routes, seep areas, and mid-ocean gyres*, such as the Sargasso Sea (Figure 4).

It is possible that the introduction of new, more efficient oil tankers and new procedures for reducing oil inputs from ballast operations at sea have prevented increases in floating tar residues despite increased oil transport at sea. Overall, there is no statistically significant evidence of increase or decrease in levels of floating tar for the ocean as a whole, but this may be due to insufficient data rather than to constant levels of floating tar.

Concentrations of dissolved or dispersed hydrocarbons in open ocean waters have been measured by the most discriminating techniques for only a few samples. Many more samples have been analyzed by less discriminating survey techniques. More of the better-type measurements have been made in coastal waters. In general, concentrations in the open ocean appear to be in the range of 0.1 to 100 parts per billion. The higher concentrations are usually associated with urban harbor areas or areas near other probable inputs. Of course, higher concentrations of dissolved or dispersed oil have been reported in the immediate vicinity of oil spill sites. For example, near the IXTOC-I oil-well blowout concentrations of 500 to 10,000 parts per billion were measured. The majority of the oil, however, was not in dissolved form but present as dispersed droplets of oil. As the oil was transported away from the well site by currents, much of it rose to the surface, and the concentration of that remaining mixed with the water was reduced by dilution as cleaner water mixed with the oil-polluted water.

Marine sediments also may be used as a rough indicator of oil contamination. Measurements of petroleum hydrocarbons in sediments have revealed the not too surprising fact that higher concentrations are found near sources of input. The rate at which concentrations decrease with increasing distance from the source of pollution depends on the type of input and the physical characteristics of the area in question.

Effects of Oil

Oil in the oceans has a number of undesirable effects. There is the obvious aesthetic effect associated with spilled oil and floating tar. This translates into an economic impact in tourist and recreational industries. Fouled fishing gear is also a problem with some types of oil spills. Some petroleum compounds also impart an offensive taint or taste to seafood, under certain conditions rendering the seafood unmarketable. Not all people agree. I have dined with a scientist who claimed, with a straight face, that some U.S. Gulf Coast oysters had a better taste because of oil contamination.

The main concerns and controversies surrounding the effects of petroleum focus on two

* Mid-ocean gyres are enormous, generally tranquil eddies in the middle of the ocean.

Iterations on a Slick Theme

The 1975 National Research Council (NRC) report, Petroleum in the Marine Environment, has proven to be an extremely important document. It has been used as a primary source by individuals and groups ranging from scientific investigators to concerned laymen. However, in mid-1980, it became clear that an update of the 1975 report was necessary. Much of the published material used as a basis for the earlier report predates a workshop held in 1973 that provided most of the background for the 1975 report. Since then, significant new data and information have been published. Thus, the U.S. Coast Guard requested that the Ocean Sciences Board (OSB)—now the Board on Ocean Science and Policy—undertake a new examination of this subject. The OSB appointed a steering committee consisting of cochairpersons Gordon A. Riley, Halifax, Nova Scotia, and William M. Sackett, University of South Florida, along with Rita R. Colwell, University of Maryland; John W. Farrington, Woods Hole Oceanographic Institution; C. Bruce Koons, Exxon Production Research Company; and John H. Vandermeulen, Bedford Institute of Oceanography. Later, the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, the Bureau of Land Management (now the Minerals Management Service), Mobil, Exxon, and the Andrew W. Mellon Foundation joined the U.S. Coast Guard in providing financial support for the project.

The steering committee took the following major steps:

1. A public meeting was held on November 13, 1980, at which representatives from oil industry, university, government, and environmental groups were invited to make presentations on important topics for consideration by the steering committee.

2. In February 1981, 46 expert contributors were invited to prepare summary papers on all aspects of petroleum in the oceans. These were reviewed and commented on by other experts selected by the steering committee.

3. An international workshop was held November 9–13, 1981, at which contributors, reviewers, and other invited scientists came together to discuss the main issues brought out from the previous two steps and to make recommendations concerning future research needs. Approximately 90 of the participants came from U.S. university, governmental, and industrial organizations. Another 22 came from Canada, the United Kingdom, France, Germany, Norway, Israel, and Sweden, providing a strong expert background and a wide range of institutional and foreign governmental expertise to this new report.

4. In February 1982 the steering committee began the task of preparing the new report, based on the input, ideas, and comments obtained by the previous steps. The writing process involved several review steps. Drafts from these iterations were carefully reviewed at several meetings of the entire steering committee. The review process was completed in November 1984.

From the 1985 NRC Report

general issues: human health and effects on valuable living resources. These were major concerns for the 1975 NRC report, but the information available to address them was inadequate to resolve many of the controversies—particularly the issues of duration of adverse biological effects at oil spill sites and effects of chronic inputs of petroleum compounds in sewage effluents, releases from production platforms, and dredge spoils. These issues have been more thoroughly addressed in the 1985 report.

The concerns in the area of human health focus on petroleum-contaminated seafood. There are several chemicals in petroleum, particularly certain polynuclear aromatic hydrocarbons,* which are known or suspected of being mutagens or carcinogens when taken up and metabolized by humans. Evaluating the seriousness of this problem is hindered by the input to the environment of the same or similar compounds from other activities. Such compounds may enter the environment as soot from the combustion of fossil fuels or leakage from wood pilings impregnated with creosote. Foods other than seafood also may be so contaminated. Other routes of human exposure to such compounds also exist (Table 3).

This discussion does not indicate that the NRC advocates continued inputs of such large aromatic hydrocarbons into the environment, but rather that the problem of such inputs from petroleum should be considered within the perspective of other sources.

To avoid any misunderstandings, I quote directly from the NRC report (p. 482):

> *Thus, at present there is no demonstrated relationship that chronic exposures through eating petroleum-derived [polynuclear aromatic hydrocarbon] contaminated seafood are related to the incidence of cancer or other diseases in humans.*

* Polynuclear aromatic hydrocarbons contain two or more aromatic rings that share at least two carbon atoms.

Table 3. Estimated human exposure to benzo(a)pyrene [B(a)P] through respiratory and gastrointestinal intake.

Source	Daily Consumption	Estimated Annual Intake of B(a)P (micrograms)
Respiratory intake[a]		
Air		0.05–500
Cigarette smoking	20 cigarettes	15–900
Gastrointestinal intake		
Drinking water	2.5 liters	6–70
Food		
Normal diet	1.5 kilograms[b]	250–500
Smoked food diet	1.5 kilograms[c]	550–3000
Potential seafood contribution	100 grams[d]	36.5–1825
Contaminated seafood burden	24–48 grams	263–920

[a] Respiratory intake is assumed to be 5,000 cubic meters per person per year.
[b] For 0.5 micrograms B(a)P per kilogram of food.
[c] Assumed to be contaminated with 1 to 5 micrograms B(a)P per kilogram.
[d] Assumed B(a)P levels from 1 to 50 micrograms per kilogram.

Corrected for error from Table 5-17 of 1985 NRC report.

> *Exceptions to these conclusions may arise in localized areas, as in the case of isolated fishing villages where seafood constitutes a major portion of the animal diet. No data are available, however, for these cases.*

With respect to effects of oil spills on valuable living resources, by the time of the 1975 NRC report there was a consensus that the fate and effects of spilled oil varied enormously depending on such factors as the composition of the oil, temperature, wind, waves, currents, type of ecosystem, and the clean-up measures used to "minimize" the impact of the oil. For example, bulldozing oil-contaminated sediments out of a marsh could have as much, if not more, impact on the long-term viability of the marsh ecosystem as the oil. Fortunately only a few harsh lessons were needed to illustrate that certain "cures" for cleaning up spilled oil were worse than, or as bad as, the "disease."

Studies of accidental oil spills and their effects have provided important general information about what types of environments are most susceptible to damage from spilled oil. Several stretches of coast in areas likely to experience accidental oil spills are now classified as to susceptibility. Low-energy coastal environments (such as intertidal mud flats, marshes, and subtidal areas) appear to be particularly vulnerable to impacts of oil. In these environments, remnants of spilled oil can persist for up to a decade. This is important information for on-scene clean up directors (usually U.S. Coast Guard personnel in the United States) who must decide how best to deploy protective booms and oil clean-up measures as a spill approaches or occurs in a coastal area. Fortunately, oil slick trajectory forecasting has improved; through the use of such information it is possible to minimize the environmental impact of accidental oil spills.

There are substantial regional differences in environmental response to oil pollution. Most research on, and monitoring and assessment of, oil pollution has occurred in northern temperate zones. During the last few years research in polar (Arctic) regions has begun to fill the gap for that climatic regime. Nevertheless, the potential impact of oil inputs on polar ecosystems can be estimated with even less confidence than the uncertain estimates for ecosystems effects in temperate regions.

The Report's Conclusions

In summarizing the effects of oil inputs on the environment, the 1985 NRC report offered a mix of cautious optimism and gaps in scientific knowledge. For example, it pointed out that "where oil has had an effect, subsequent monitoring has shown biological recovery taking place." Furthermore, the report noted that "most living organisms can co-exist with hydrocarbons when concentrations are very low (less than 0.1 [milligrams per liter]) and when the oil is weathered." On the other hand, although it notes that there is little evidence of reduction of commercially important fish stocks by oil pollution, the report emphasized that "present census techniques remain too crude to provide clear knowledge of standing fish stocks, while natural variabilities in the stocks probably mask such impact from petroleum as may exist." Furthermore, the report pointed out a major scientific problem: "The fragmented evidence on the effects of petroleum on some larval fish and fish eggs from a few laboratory and field studies indicates that [adverse] impact is possible, although it has not been rigorously examined. This inability to transfer information obtained from laboratory studies to field conditions has been an intractable problem throughout this report."

Such gaps between laboratory knowledge and field data are evident throughout the conclusion of the report. For example, in examining the carcinogenic and mutagenic potential of petroleum, the report stated that "some petroleum compounds are carcinogens and/or mutagens and can bind to nucleic acids. Metabolic products of petroleum degradation also can be potentially hazardous. However, the data are not available to indicate that such a hazard has occurred in populations [of marine organisms] in affected environments."

Finally, the report expressed great concern about the impacts of oil pollution in coastal and tropical waters. "The greatest impact due to oiling clearly occurs in coastal areas, especially those with shallow water, and in areas where local current systems tend to contain . . . the contaminant. Of special concern are situations of local chronic oiling where there is low level [less than 1 part per million] but continuous exposure, as in waters near industrialized or heavily populated coastal regions. There is a clear need to continue research on these local situations, not only because of the intrinsic toxicity of petroleum, but also because of its poorly understood but suspected synergistic impact with other contaminants."

With respect to tropical areas, the report

Between the Lab and the Ocean: The Role of Mesocosms

In their efforts to determine the effects of oil on the marine environment, scientists have recently turned to a new tool—the mesocosm. Mesocosms are enclosed tanks large enough to incorporate several interacting segments of marine ecosystems. They are helping to fill a crucial gap in scientific knowledge, providing a bridge between the laboratory and the real world.

There is a widespread assumption that oil pollution is extremely harmful to marine organisms. Indeed, laboratory experiments on many different species have shown a wide range of effects, both lethal and sublethal, from exposure to petroleum. In such experiments, effects have been documented at all physiological levels—from individual cells to the whole organism. The problem lies in extrapolating from particular laboratory experiments to the wide range of conditions found in the field.

The types and intensity of effects produced by petroleum and the concentrations at which such effects occur vary widely from species to species. Most laboratory studies have been conducted at much higher concentrations than are found at oil spill sites or chronic input sites, and cannot be strictly extrapolated to lower concentrations.

Field studies do not necessarily clarify the situation. Studies at major sources of chronic inputs (such as urban harbors) often face the problem of distinguishing between petroleum hydrocarbon effects; effects from other pollutants, such as chlorinated pesticides, industrial petrochemicals (PCBs and their relatives), and trace metals; viral and bacterial diseases; reduced oxygen in the water; and the combined effects of all of such stresses. The combined effect may be much greater than the effects of the individual components—a phenomenon referred to as synergism. It also is possible that some pollutants reduce or cancel effects of other pollutants—a phenomenon referred to as antagonism.

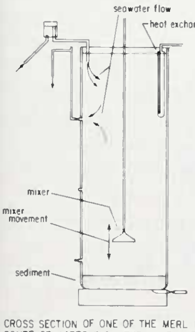
Field studies of accidental oil spills are difficult because of the lack of predictability and the subsequent mad dash to gain valuable initial information. Good marine biologists do not sit around waiting for an oil spill. Furthermore, properly conducted studies of the biological effects of large oil spills are enormously complicated, time consuming, and expensive efforts.

Frustrations with unravelling the complicated interactions in the field have caused researchers to turn to mesocosm experiments. One such experiment, at the Marine Ecosystems Research Laboratory (MERL) at the University of Rhode Island, consists of tanks approximately 2 meters in diameter, 5.5 meters tall, and containing about 13 cubic meters of water, as well as 30 centimeters of sediment along the bottom. The sediments contain typical organisms from the sediments of Narragansett Bay, and the water contains planktonic organisms typical of Bay waters. Simultaneous operation of several mesocosms allows comparison of controls to experimental tanks in which oil is added.

The results from mesocosm experiments demonstrate quite clearly that concentrations of petroleum present around urban harbors, spill sites, and other input sources can alter interactions between organisms in coastal marine ecosystems. Extrapolation of these results to long time periods in entire ecosystems is not possible within the strictures of science and our present knowledge. But the fact that low concentrations did show the adverse impacts in the mesocosms gives us cause for concern. In particular, because they depended on interacting effects among several species, some effects could not be predicted from laboratory toxicity studies on individual species. Further mesocosm studies are in progress and should provide additional insights.

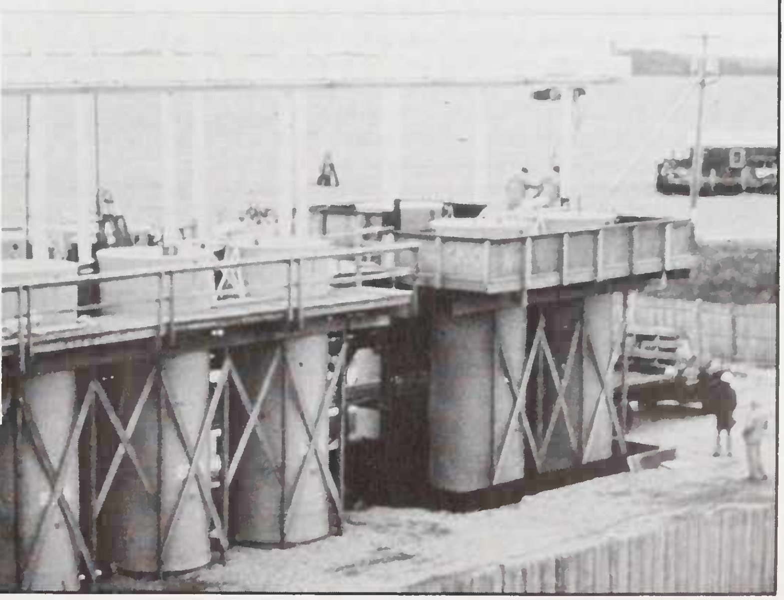
—JWF

MERL MICROCOSM TANK



TANKS	
INTERIOR DIAMETER	1 83 m
INTERIOR HEIGHT	5 49 m
WATER	
DEPTH	5 00 m
AREA	2 63 m^2
VOLUME	13 10 m^3
MASS	13 40 tons
SEDIMENT	
AREA	2 52 m^2
DEPTH	0 30 m
VOLUME	0 76 m^3
MASS (wet)	1 10 tons
(dry)	0 57 tons

CROSS SECTION OF ONE OF THE MERL MICROCOSM TANKS, SHOWING THE ROUTE OF WATER FLOW, THE MIXER, SEDIMENT CONTAINER & HEAT EXCHANGER



stressed the potential impact of oil on mangrove systems and coral reefs. "These represent a major part of the coastline in tropical and subtropical regions and are highly significant in terms of fisheries and other resources. They have unique physical and biological characteristics that make them highly vulnerable to the effect of oiling. Unfortunately, the research effort on these ecosystems has been confined to comparatively few studies."

Personal Comments

There is a strong need for further research on oil in the marine environment, to allow intelligent political, social, and economic choices. Several of the questions regarding oil pollution asked in the late 1960s and early 1970s have been answered by research conducted during the last decade. We now know that biological effects from oil spills do not last more than a decade or two; but such effects can last as long as a decade, not always the year or two that some predicted. Furthermore, areas of the coast can be classified as to degree of susceptibility to long-term effects and plans made to protect these areas during spills. The technology of oil-spill containment and clean up is progressing. Thus, there is the probability that technology coupled with knowledge of oil spill behavior may be used to further minimize adverse impacts of accidental oil spills.

Progress in understanding the toxicity of petroleum to marine organisms has been excellent. The fractions and in some cases specific compounds that are responsible for most of the immediate toxicity in several oils have been identified through the coupling of advanced analytical chemistry techniques with biological effects studies. A concern identified in the 1985 NRC report is that such toxic compounds make up a larger portion of oils derived from shale and coal (synfuels) than of petroleum currently in use. Attention should be given to these environmental concerns early in any planning for a substantial switch to synfuel usage.

The increased knowledge about the uptake and release of compounds and metabolism by marine organisms has yet to be adequately linked with knowledge of sources of inputs. We cannot assume that all sources of input have equal potential for biological uptake. For example, atmospheric inputs of polynuclear aromatic hydrocarbons may not be readily available for biological uptake because of strong binding to atmospheric particulate matter. In contrast, oil entering the marine environment dissolved or dispersed in urban runoff may be readily available. Thus, the physical form of the inputs could control uptake and toxicity. This is an important problem that should be researched prior to taking regulatory and management action to reduce inputs from a given source simply because of the volume of inputs from that source.

Concerns with long-term impacts of petroleum on ecosystems and on fish and shellfish resources cannot be separated from two important factors. *First,* much of the chronic input in continental shelf and coastal waters occurs in areas where inputs of other chemical contaminants and bacteria and viruses also occur. Separating effects of the various inputs or understanding the effects of the combinations are research challenges made more difficult by the *second* factor: knowledge of short-term (years) and long-term (decades) natural fluctuations in populations of organisms is incomplete. Major progress in understanding the effects of chronic petroleum inputs will depend on a better understanding of natural population fluctuations.

The major problem with undertaking these research efforts is ensuring funding. Even once agreement is reached as to which federal agency has the responsibility for such research, a long-term program commitment is still needed. This is a difficult task in science research leadership and management because the duration of the program must be longer than the terms of those elected and appointed to political office. Furthermore, if we are to obtain substance rather than rhetoric, the level of funding must be significant.

One of the most important features of the 1985 NRC report was its emphasis on the dirth of knowledge about oil pollution in tropical areas. Rapid development is proceeding in coastal areas of many developing countries, many of which are in tropical and subtropical areas. Such development often includes offshore production of oil and gas, build up of refining and petrochemical industries, and urbanization in coastal areas. Although some lessons can be translated from oil-pollution research in temperate climates and developed countries, it would be a serious mistake to proceed with development in subtropical and tropical areas without increased research and monitoring efforts.

In summary, research and monitoring focused on oil pollution has shown that the worst fears of the late 1960s and early 1970s have not been realized. Large areas of the world's oceans have not been killed by oil pollution. That these predictions were wrong is in part a function of increased understanding of how the marine environment copes with oil inputs. In part, it may be attributable to reductions in inputs of certain types of oil, such as oil from tanker ballasting operations and in effluent releases from offshore platforms. On the other hand, we cannot be complacent. The effects of many compounds and fractions of petroleum on a myriad of biological processes in the marine environment are not known.

Oil pollution is one of several natural and man-made stresses affecting marine ecosystems. The 1985 NRC report has assessed current knowledge and made recommendations for further research. The next step is to incorporate the report's conclusions and recommendations into an overall strategy for marine environmental quality protection that assesses the relative importance of oil pollution vis-à-vis other types of pollution.

John W. Farrington is a Senior Scientist in the Chemistry Department and Director of the Coastal Research Center at the Woods Hole Oceanographic Institution.