

ALASKA LEGISLATURE SPECIAL COMMITTEE/SUBJECT FILE 8672  
1999 SCOMM 77: SENATE SPEC. COMM. EXXON VALDEZ OIL SPILL. 1991

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TABLE 7  
Recovery of Littoral Benthos

| Shore Type            | Location                             | Oil                                                                                                               | Observations on Recovery                                                                                                                                                                                                  | Reference                                         |
|-----------------------|--------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|
| Rock reef             | Godrevy Point, Cornwall, SW England  | Kuwait mousse from the <i>Torrey Canyon</i> spill, 1967 (no direct dispersant use on this moderately oiled shore) | Good recovery after 2 years.                                                                                                                                                                                              | Southward and Southward (1978)                    |
| Rock shelf            | NW coast of the State of Washington  | Navy Special fuel oil from <i>General MC Meigs</i> spill, 1972                                                    | Effects on urchins and algae for at least 1 year. No marked long-term effects on community balance. Hydrocarbon residues present in mussels after 5 years; attributed to recontamination by winter discharges from wreck. | Clark <i>et al.</i> (1978)                        |
| Rock/boulders/cobbles | Sullom Voe, Shetland                 | Heavy fuel oil from the <i>Esso Bernicia</i> spill, 1978                                                          | 9 years after, 5 km of shore still showed successional changes (resulting mainly from use of bulldozers in cleanup).                                                                                                      | Westwood <i>et al.</i> (1989)                     |
| Rock/boulders/cobbles | Sullom Voe, Shetland                 | <i>Esso Bernicia</i> oil and subsequent inputs                                                                    | Winkles <i>Littorina littorea</i> collected 1981 had significant enzyme changes indicating lysosomal destabilization.                                                                                                     | Moore <i>et al.</i> (1982)                        |
| Exposed rock          | Hurlstone Point, N Somerset, England | Experimental applications of Forties crude, 1979                                                                  | Reductions in limpets and small littorinid winkles during the year following treatment.                                                                                                                                   | Crothers (1983)<br><br>Baker <i>et al.</i> (1984) |
| Exposed rock          | Hurlstone Point, N Somerset, England | Experimental applications of Flotta residue and mousse, 1981                                                      | Only significant change after 6 months was an increase of colonisation by barnacle larvae in oiled plots.                                                                                                                 | Baker <i>et al.</i> (1984)                        |
| Rock platform         | Watchet, N Somerset, England, 1979   | Experimental applications of Forties crude                                                                        | Main change in all plots including controls was increase of furoid algae, interpreted as a continuation of a long-term trend.                                                                                             | Baker <i>et al.</i> (1984)                        |

TABLE 7 Continued

| Shore Type                         | Location                                | Oil                                                                             | Observations on Recovery                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Reference                                                                          |
|------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Rocky shores                       | Swedish archipelago, Baltic Sea         | No. 5 fuel oil and some bunker oil from the <i>Tsesis</i> spill, 1977           | Dominant alga <i>Fucus vesiculosus</i> not affected. Funal density within algal zone was 8-10% of previous level 2 weeks after spill. Recovery began within 2 months, with normal densities after 1 year at some sites. Recovery varied depending on severity of oiling and species involved. After 1 year hydrocarbon concentrations in mussels approached normal conditions except at the most heavily oiled sites, though there were still elevated levels of substituted naphthalenes. | Notini (1980)<br><br>Linden <i>et al.</i> (1979)<br><br>Boehm <i>et al.</i> (1982) |
| Rocky shores                       | Åland, Finland, Baltic Sea              | Crude oil from the Soviet tanker <i>Antonio Gramsci</i> , 1979                  | By 4 months after spill there was new settlement of barnacles and mussels close to remaining oil on rocks. Little difference between oiled and non-oiled areas in <i>Cladophora</i> belt; in <i>Fucus</i> belt there was some decline in mussels and mobile crustaceans.                                                                                                                                                                                                                   | Bonsdorff (1981)                                                                   |
| Rocky, moderately exposed shore    | W coast of Norway                       | Iranian crude oil from 1976 spill                                               | 13 months after spill, significant amounts of hydrocarbons remained in winkles <i>Littorina littorea</i> . No detectable effects on fertilization, but hatching success significantly less in oiled population.                                                                                                                                                                                                                                                                            | Staveland (1979)                                                                   |
| Beaches with sand, stones and rock | Gastviken Bay, Musko Island, Baltic Sea | Medium and heavy fuel oil from the <i>Irini</i> spill, 1970; mechanical cleanup | No oil-associated effects on <i>Fucus vesiculosus</i> ; severe initial depletion of fauna. Recolonisation by most species occurred within 1 year, but low population densities during the 2nd year. After 4 years, no significant evidence of lasting detrimental effects, when natural annual variations taken into account.                                                                                                                                                              | Notini (1978)                                                                      |

TABLE 7 Continued

| Shore Type                       | Location                    | Oil                                                              | Observations on Recovery                                                                                                                                                                                                                                                                                                   | Reference                                                      |
|----------------------------------|-----------------------------|------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| Variety of shores in bay         | Chedabucto Bay, Nova Scotia | Bunker C fuel oil from the Arrow spill, 1970                     | 6 years after, lower diversity, lower biomass of flora, smaller clams ( <i>Mya</i> ) and larger winkles ( <i>Littorina</i> ) at oiled sites compared with controls. Abundant lugworms (with elevated hydrocarbon concentrations) in oiled sediments.                                                                       | Thomas (1978)<br><br>Gordon <i>et al.</i> (1978)               |
| Variety of shores in bay lagoons | Chedabucto Bay, Nova Scotia | Bunker C fuel oil from the Arrow spill, 1970                     | <i>Mya</i> remained under continued stress in oiled lagoons 6 years after spill.                                                                                                                                                                                                                                           | Gilfillan and Vandermeulen (1978)                              |
| Variety of shores                | Straits of Magellan         | Light Arabian oil/mousse from the <i>Metula</i> spill, 1974      | 1977 data suggested continuing impact in areas still heavily oiled, and recovery of invertebrates in areas which had lost oil.                                                                                                                                                                                             | Straughan (1978)                                               |
| Variety of shores                | Straits of Magellan         | Light Arabian oil/mousse from the <i>Metula</i> spill, 1974      | Asphalt pavement recolonised by algae and (more slowly, from lower intertidal levels) animals, mainly mussels and the gastropod <i>Siphonaria lateralis</i> . 5 years after spill, community still relatively simple in composition.                                                                                       | Guzman and Campodonico (1981)                                  |
| Variety of shores                | Straits of Magellan         | Light Arabian oil/mousse from the <i>Metula</i> spill, 1974      | Persistent effects on flora and insect fauna of heavily oiled salt marsh.                                                                                                                                                                                                                                                  | Guzman and Campodonico (1981)                                  |
| Variety of shores                | Brittany                    | Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978 | Marshes severely affected, with no recovery in 2 years at the most heavily oiled sites. 5 years after, Cantel marsh which was oiled but had no cleanup was essentially restored by natural processes. 8 years after, the Ile Grande marsh which had heavy cleanup was well recovered, facilitated by artificial plantings. | Gundlach <i>et al.</i> (1981)<br><br>Baca <i>et al.</i> (1987) |

TABLE 7 Continued

| Shore Type                      | Location                    | Oil                                                              | Observations on Recovery                                                                                                                                                                                                             | Reference                         |
|---------------------------------|-----------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| Variety of shores               | Brittany                    | Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978 | 9 months after, hydrocarbons from the spill identified in limpets from rocky shores and <i>Mya</i> from mud flats. Heavier molecular weight aromatics present in <i>Mya</i> , not in limpets.                                        | Vandermeulen <i>et al.</i> (1981) |
| Variety of shores               | Brittany                    | Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978 | Japanese oysters taken from the oiled Aber Wrach in 1979 had reached a steady state with respect to environmental exposure to weathered oil; they were able to reach background levels during a 96-day depuration period (in Maine). | Page <i>et al.</i> (1987)         |
| Variety of shores               | Brittany                    | Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978 | Delayed effects: declines in populations of clams <i>Tellina</i> and nematodes reported 1 year after spill at St. Eflam and Bay of Morlaix, respectively.                                                                            | Conan (1982)                      |
| Sediments in experimental trays | Sequim Bay, Washington      | Experimental application of Prudhoe Bay crude, 1976              | Initial concentrations of oil in sediments upon field emplacement were up to 5000–6000 ppm; no substantial inhibition of recruitment by benthic organisms.                                                                           | Anderson <i>et al.</i> (1978)     |
| Salt marsh                      | Buzzards Bay, Massachusetts | No. 2 fuel oil from the <i>Florida</i> spill, 1969               | Recovery of fiddler crab population was correlated with the disappearance of naphthalene in sediments; not complete after 7 years.                                                                                                   | Krebs and Burns (1978)            |
| Stonework jetty                 | Buzzards Bay, Massachusetts | No. 2 fuel oil from the <i>Florida</i> spill, 1969               | Reasonably functioning population of oyster drill <i>Urosalpinx cinerea</i> re-established at Wild Harbour by 1975, but with greater year-to-year variation in genetic structure than at reference site.                             | Cole (1978)                       |
| Salt marsh                      | Steart, Somerset, England   | Experimental applications of Forties crude, 1979                 | No detectable retention of experimental oil in sediment samples of May 1981, but flora did not recover to control levels during 1981 growing season.                                                                                 | Baker <i>et al.</i> (1984)        |

TABLE 7 Continued

| Shore Type                | Location                        | Oil                                                                         | Observations on Recovery                                                                                                                                                        | Reference                   |
|---------------------------|---------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Salt marsh                | Stear, Somerset, England        | Experimental applications of Forties crude, Flotta residue and mousse, 1981 | Recovery of all treated plots started during 1982, but <i>Spartina</i> density remained low in the Forties crude plot throughout 1982.                                          | Baker <i>et al.</i> (1984)  |
| Intertidal sea grass beds | Angle Bay, Milford Haven, Wales | Experimental applications of Nigerian crude                                 | No visual effects on sea-grass following tidal removal of oil, but no increase in cover during growing season following treatment (compared with increase of cover in control). | Howard <i>et al.</i> (1989) |

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## APPENDIX A

### COLD WATER ECOSYSTEMS

*Marine cold water ecosystems are characterised by high seasonal temperature fluctuations relative to tropical and sub-tropical waters. As a result, the diversity of the fauna and flora is generally lower than at lower latitudes. Because of the better mixing of the water layers in cold water areas, productivity is still relatively high. Fauna of cold water ecosystems also tend to adopt reproductive strategies that involve a higher degree of brood protection and thus are believed to recover more slowly from major ecological damage.*

### PHYSICAL CONDITIONS

Cold water ecosystems, in the context of the marine biospheres, include those marine habitats found in temperate, boreal/antiboreal, subpolar and polar seas. Circumglobal cold water habitats also exist in the deep sea; however, since this review is primarily concerned with the natural recovery of coastal littoral and sublittoral environments, discussion of the deep sea environment is excluded.

The extent of the cold water habitats in the world's oceans is shown in Figure 8. In the southern hemisphere, the boundaries between the regions are relatively uncomplicated, with the transition between the polar/subpolar, antiboreal and temperate zones following latitudinal parallels across the oceans in the southern hemisphere. The boundaries between the temperate and tropical zones are displaced south on the western boundaries of the Indian and Atlantic Oceans and north on the eastern boundaries as a result of the interaction between the continental masses of South America and Africa and the main global oceanic currents (Bogdanov, 1963).

In the northern hemisphere, the boundaries between the temperate, boreal and polar seas are more complicated, since there is no direct latitudinal interconnection between the oceans. The displacement of the boundaries is most marked in the northern Atlantic Ocean, where the Gulf Stream pushes the boreal/subpolar boundary 30° further north on the eastern margin of the ocean. A consequence of the greater preponderance of land masses in the northern hemisphere and the greater displacement of zonal boundaries is that there is a much greater cold water coastline in the north than the south. For example, antiboreal coastline is represented only by the southern tip of South America and a few southern ocean islands (see Figure 8).

Cold water ecosystems range in annual mean temperature from around 18°C in the temperate zones to 5°C at the edge of the cool or boreal/antiboreal zones. At higher latitudes (polar and subpolar), surface temperatures are below 5°C. Probably of more ecological significance is the difference in annual temperature range between the different zones. In tropical regions, surface water temperatures show an annual variation of no more than 2°C

(Ekman, 1967), whereas in temperate to subpolar waters this may reach up to 10°C (see table below). Temperature changes are seasonal in cold water ecosystems and are thus important in controlling cyclical biological events such as reproduction. As a result of thermally induced mixing of water layers, seasonal temperature changes are an important factor in enhanced productivity in these regions (Koblentz-Mishke *et al.*, 1970).

In addition, temperate to subpolar regions correspond to a band of greater atmospheric turbulence and experience many storms, especially during winter, with gales and heavy precipitation (Gross, 1987). This turbulence also aids water mixing and hence nutrient dispersion, resulting in a greater likelihood of high-energy shores on coastlines in this region.

#### Mean Surface Temperatures in the Coldest and Warmest Months and the Annual Mean at the Boundaries of the Atlantic Boreal Region

|                                              | Temperature, °C |        |             |
|----------------------------------------------|-----------------|--------|-------------|
|                                              | February        | August | Annual Mean |
| Murman coast, Kola peninsula                 | 1               | 9-10   | 4           |
| Northern Iceland                             | 0-1             | 8-10   | 3-4         |
| Bear Island (between Spitzbergen and Norway) | 0-1             | 5      | 2-3         |
| Southern tip of Greenland                    | 1               | 5      | 3           |
| English Channel, southwestern entrance       | 9               | 17     | 12-13       |

(from Ekman, 1967)

#### FAUNA AND FLORA

The cold water environment embraces a range of temperature regimes and other climatic factors that place stress on the plant and animal communities. These stresses are manifested principally in a reduction of coastal species diversity that broadly forms a gradient from low to high latitudes (Sanders, 1968). Another consequence of the more stressful conditions is greater instability in the communities, which can vary both in species composition and abundance from year to year, relying heavily on successful recruitment of short-lived organisms each season. Such reproductive strategies theoretically favour rapid recovery after environmental impact. However, reproductive strategies, particularly of the fauna, also relate to the severity of the environment. Marine fauna may reproduce either by viviparity (the bearing of live young), direct development (directly from egg to miniature adult), or by larviparity (the egg develops into a larval form that spends some time in the water column before settling and metamorphosing into a miniature adult). In the latter case the larvae may be planktotrophic, in which case they feed on other organisms in the plankton, or lecithotrophic where they are nourished by a yolk supplied by the parent.

Planktotrophic larvae hatch from small eggs, since they do not carry food reserves, whereas other reproductive strategies are characterised by large egg production to accommodate nourishment for the developing embryos (Thorson, 1957). Because the energy available to a parent for egg production is limited, the larger the egg the smaller is

the number of eggs produced. Thus, the potential for a population of non-pelagic breeders to recover quickly from a mass mortality is considerably less than for one producing large numbers of planktotrophic larvae.

In the higher latitudes, where the summers are short and the plankton production curtailed, there is a tendency for fewer animals to reproduce with planktotrophic larvae and a preponderance of species with viviparous or direct development (Thorson, 1950) or a brooding habit (Wells and Percy, 1985). This is illustrated for marine snails in Figure A1.

The implication is that communities from higher latitudes (subpolar and polar) may recover more slowly from environmental damage than those from farther south, where planktotrophic reproductive strategies predominate (Dunbar, 1968; Clarke, 1983).

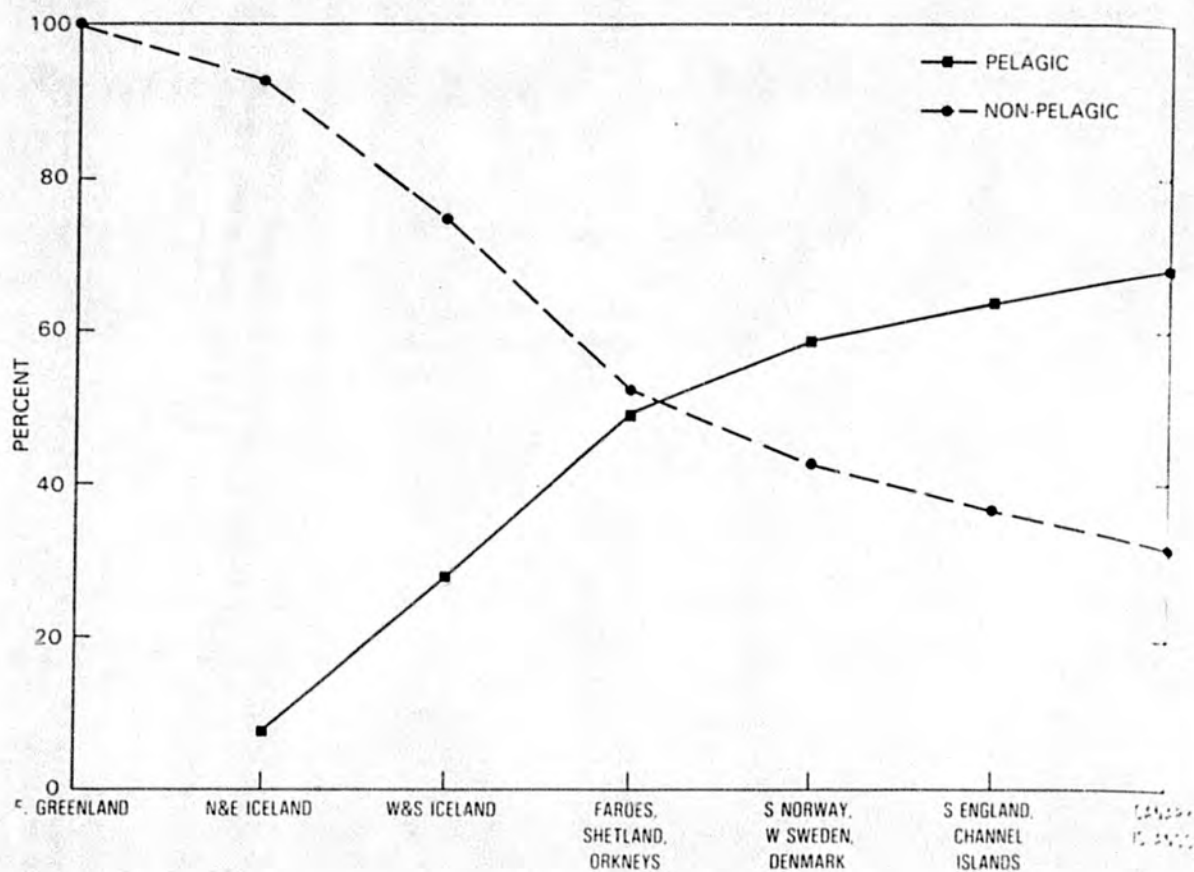


Figure A1: The relations between a pelagic/non-pelagic larval development in prosobranchs throughout the North Atlantic (Thorson, 1950).

## APPENDIX B

### PHYSICAL AND CHEMICAL BEHAVIOUR OF SPILLED OIL

#### BEHAVIOUR AT SEA

The marine environment may be divided into the open water or pelagic division and the seabed or benthic division. The benthic division extends from the top of the shore to the deepest part of the ocean. These divisions form various ecological zones (Figure B1) and broadly follow a scheme first proposed by Hedgpeth (1957).

In oceanic waters, impact from oil spills is likely to be minimal and confined more or less to the surface and near-surface water layers. The greatest impact is usually in coastal waters and on shores (littoral zones).

The shoreline, where land, air and sea meet, is the most dynamic part of the ocean (Gross, 1987). Its nature is determined by tides, winds, waves. The most obvious of the factors are waves which, together with offshore currents, are most influential in determining the type of intertidal substratum. Where the shore is sheltered from rigorous wave action (so-called low-energy shores), sedimentary beaches will form. These may range from highly sheltered or estuarine mud flats, through sand beaches, to gravel or boulder shores where wave and current action is strong enough to wash fine particles away faster than they are brought in. Rocky shores exist where the effect of waves on the coastline is mainly erosive, wearing down the softer materials and carrying them away, leaving the hardest rocks exposed. Rocky shores are biologically zoned, with the zones varying in extent depending upon the slope of the rock surfaces, the tidal range, and exposure to wave action. Thus for a given tidal range and shore gradient, the range of the littoral zone increases with increasing wave exposure (see Figure B2).

When crude oil and petroleum products are released at sea, they are subject immediately to a series of complex interactions of physical, chemical and biological processes (Koons, 1987). These processes are collectively called 'weathering' and include

- Spreading
- Evaporation
- Sinking
- Dissolution
- Natural dispersion into the water column
- Emulsification
- Biodegradation and photolysis

The time-frame following an oil spill over which the above processes occur is illustrated in Figure B3.

The significance of these natural processes in determining the fate of spilled oil is determined by a number of factors, such as the type of oil spilled and the oceanographic and meteorological conditions. A brief discussion of the above processes follows.

## Spreading

*Spilled oil initially spreads over the sea surface to form a relatively thin slick. Under the influence of 'weathering' and winds, thicker layers of oil/mousse may be formed.*

Under the influence of gravity and the difference in density between oil and water, the spilled oil will spread over the surface of the sea. Amongst the mathematical models which describe this process, the best known are those of Blokner (1964) and Fay (1969).

Several models are available to predict the movement or drift of the surface slick under the influence of winds, surface currents, and waves. There is a tendency, with time, for the oil slick to become non-homogeneous in thickness, and to form lenses of thicker portions of oil which align themselves along the direction of the wind to form 'windrows'. The formation of thicker lenses of oil becomes more significant as the viscosity of the oil increases due to 'weathering'. Hollinger and Mennella (1973) have reported that as much as 90 percent of the oil in the slick (after evaporation) may be associated with these thick patches, although the major area of a slick is composed of a relatively thin sheen.

Observations made at the Ixtoc 1 oil well blowout (Atwood *et al.*, 1980) indicated that near the blowout, the oil slick thickness ranged from 1 to 4 mm. However, at a more distant location, long lines of thicker material were observed surrounded by thin films of oil. At times, the winds rolled the portions of the slick upon itself, and rafts of agglomerated material up to 1 m thick were seen 5 to 15 nautical miles from the spill site.

## Evaporation

*Most of the toxic components in crude oil rapidly evaporate after spillage, and disperse into the atmosphere to background levels. Evaporation is a major process for the removal of oil from the sea surface for lighter crudes.*

When oil is released, the volatile components rapidly evaporate. For example, estimates from major incidents such as the Ekofisk Bravo, Amoco Cadiz, and Ixtoc 1 indicated that 30 to 50 percent of the spilled oil evaporated within the first few hours or days. This process is especially dominant in the initial phase following a spill and is a major process that removes oil from the sea surface—particularly for light crudes.

The rate of evaporation is dependent upon

- Spreading (the increase in surface area of the oil will facilitate evaporation)
- Temperature

- Wind speed
- Sea state conditions
- Oil composition

Spills of light petroleum products such as liquefied petroleum gas (LPG) and gasoline will evaporate very quickly, leaving virtually no residual surface slick.

The volatile components in crude oils which evaporate include the toxic hydrocarbons benzene and the mono-nuclear aromatics. After evaporation, these organics disperse into the atmosphere and are rapidly diluted to 'background' levels. Payne *et al.* (1980) found that air samples taken immediately above the surface slick of freshly spilled oil at the Ixtoc 1 oil spill had concentrations of benzene below the level for detection (1 ppb) by selected ion monitoring.

For spills of relatively non-volatile materials such as heavy fuel oils and Bunker C, the evaporation losses from the slick would be much lower. Studies following the *Potomac* spill of Bunker C oil in Melville Bay, Greenland (Petersen, 1978), attributed additional factors such as light winds, low water temperatures, thick oil slicks, and the oil composition to the low evaporation rates experienced.

## Sinking

*Most crude oils have little tendency to sink to the seabed even after extensive weathering and associated density increases. Oil concentrations in the water column measured below the surface slicks at sea trials and oil spill incidents have been very low. Similarly, samples of the seabed taken at offshore oil spill sites have been only lightly oiled. Some oil may reach the seabed associated with particulates. This process is unlikely to be significant for spills offshore unless the seawater is highly turbid. Spills of very dense oils (e.g., heavy fuel oil) may weather to form slicks of sufficient density to sink to the seabed.*

Wilson *et al.* (1985) conclude that most crude oils have little tendency to sink to the seabed even after extensive weathering and the density increases associated with emulsion formation. They attribute reports of oil sinking to the ability of heavy oil slicks to adopt a position just below the sea surface and so become undetectable by remote sensing systems such as IR.

Sea trials carried out with Ekofisk crude oil (Cormack *et al.*, 1978) showed a rapid decrease in oil concentration, falling to 0.02 to 0.08 ppm at 10 to 15 m below the oil slick. Measurements taken approximately 50 hr after the well had been capped indicated oil concentrations as low as 0.055 to 0.118 ppm at a 1-m depth below oil sheens (Cormack and Nicholls, 1978).

Maximum subsurface concentrations of oil measured at major spills are 0.30 ppm for Ekofisk Bravo (Grahl-Nielsen, 1978), 0.35 ppm for *Amoco Cadiz* (Calder *et al.*, 1978), and 0.45 ppm for *Argo Merchant* (Grose and Mattson, 1977).

At the Ixtoc 1 oil well blowout, the hydrocarbons were released subsea which resulted in relatively high concentrations (10.6 ppm) of oil droplets measured in the top 20 m of the water column near the spill site (Fiest and Boehm, 1980). Boehm and Fiest (1980) concluded that only 1 to 3 percent of the oil spilled partitioned into the sediments. However, the area experienced a hurricane before the samples were taken. This might have significantly affected the contamination levels of the sediments.

The sediments sampled from the seabed in the area of the Ekofisk Bravo blowout, had relatively low concentrations of oil immediately after the blowout and fell to background levels 4 to 6 weeks after the well had been capped (Johnson *et al.*, 1978). Studies of the biological populations in the sediments (Addy *et al.*, 1978) were not able to attribute any specific changes to the blowout.

Significant levels of oil contamination of sediments are most likely to occur in the nearshore environments, where substantial quantities of sediments are suspended in the water column by the wave energy (see later section entitled Behaviour Near Shores).

Petersen (1978) studied the spill of Bunker C heavy fuel oil in Melville Bay, Greenland, when a combination of low water temperatures (3 to 4°C), light winds (0 to 7 knots) and calm seas resulted in relatively slow evaporation, biodegradation and dispersion rates. However, because of the special conditions described above, this can be viewed as an exceptional situation. Pancakes of spongy material ranging from 8 to 15 cm in diameter arranged in windrows on the sea surface were observed 15 days after the spill. It was estimated that most of the residues eventually sank in less than 50 days.

## Dissolution

*Less than 1 percent of spilled oil is likely to be dissolved into the seawater. Although the water-soluble constituents of oils are relatively toxic, they are rapidly diluted to very low concentrations in the water column.*

The components of oil which dissolve in the seawater are the volatile, low molecular weight compounds which are relatively toxic. However, on physico-chemical grounds it is expected that the evaporation rates of such compounds would be two orders of magnitude greater than rates of solution (Cormack, 1983). Furthermore, a substantial proportion of these dissolved hydrocarbons are likely to be evaporated from the water column.

Because of their toxicity, the dissolved components pose a potential threat to marine life. However, this toxic effect is short-lived because the soluble components are quickly dissolved from the fresh oil and rapidly diluted in the water column to very low concentrations. Measured concentrations of dissolved hydrocarbons underneath slicks were less than 0.1 ppm (McAuliffe, 1986). Payne *et al.* (1980) measured up to 0.1 ppm of

benzene, toluenes, xylenes and other low molecular weight aliphatic and aromatic hydrocarbons in seawater samples taken immediately beneath the surface slick near to the Ixtoc 1 oil well blowout.

It has been estimated (Mackay and McAuliffe, 1989) that less than 1 percent of the crude oil spilled would be likely to dissolve into the seawater.

### Natural Dispersion Into Water Column

*Natural dispersion is generally recognised to be a major process for the removal of oil from a surface slick by the formation of small droplets. The process is favoured by high wave energy conditions and for low-viscosity oils.*

Natural dispersion is the process whereby small oil droplets (0.01 to 0.1 mm) are generated from an oil slick by wave energy. Because of their small size, the droplets disperse speedily into the body of water, resulting in ever-decreasing concentrations.

Natural dispersion is generally recognised to be a major process for the removal of oil from the sea surface. This is particularly the case for low-viscosity, lighter oils which do not form highly viscous weathered materials. Studies carried out following the Ekofisk Bravo blowout (Cormack, 1983) indicated that only about 1 percent of the initial quantity of oil spilled would remain as a surface slick after about 80 hours. Sea trials with the Ekofisk crude oil indicated that even in moderate sea conditions, natural dispersion represented a major process which contributed to the complete removal of oil from the sea surface.

The rate of dispersion of oil is enhanced by high wave energy conditions and is inhibited with increased viscosity of the oil slick. Evaporation of the volatile components leads to an increase in viscosity of the remaining slick, but the most significant increases can result from the formation of water-in-oil emulsions (discussed below). Slicks of highly viscous oils/emulsions are relatively persistent due to their cohesiveness (Mackay and McAuliffe, 1989). Floating slicks of viscous emulsions are slowly broken up into smaller rafts or pancakes of material, then finally form tarballs. When this material reaches the nearshore, where sediments are suspended in the water column, the sediments can become enmeshed into the residual oil to form asphaltic deposits or pavements. Floating tarballs on the sea surface are relatively innocuous to marine life, but may persist for many months or years.

### Emulsification

*The formation of water-in-oil emulsions (mousses), which commonly occurs following marine oil spills, can have a very significant effect on the fate and behaviour of spilled oil. Some crude oils rapidly form stable emulsions of very high viscosity and form slicks which are relatively persistent.*

The formation of water-in-oil emulsions (mousses) can have a significant effect on the fate and behaviour of spilled oil. Some crude oils and fuel oils have been shown to form very stable emulsions that contain 20 to 80 percent seawater. These emulsions have densities approaching that of seawater and viscosities exceeding 100,000 cP (EEC, 1986). Slicks of highly viscous material are relatively persistent (*i.e.*, resistant to natural dispersion).

The key compositional factors in the oil which favour the formation of stable/viscous emulsion are not known, but are believed to include asphaltenes, waxes, natural surfactants and surfactants formed by photolysis. Emulsification is also enhanced by low temperatures and by high-energy conditions.

The formation of mousse is a very common feature of marine oil spills. The emulsification process leads to an increase in the quantity of material in the slick, its density, its viscosity and, hence, its persistence on the sea surface. Light refined petroleum products such as gasoline usually do not form water-in-oil emulsions.

### Biodegradation and Photolysis

*Biodegradation is regarded as the ultimate fate of much of the dissolved and dispersed oil, but the process generally has a long time scale. The rate is controlled by oxygen and nutrient availability, temperature, chemical composition, and the surface area of the oil. Photolytic oxidation of some oil components occurs under the action of ultraviolet radiation (in sunlight). The oxidation products from both biodegradation and photolysis may be relatively toxic, but are biodegradable, water-soluble and rapidly dilute to very low concentrations in the sea.*

Naturally occurring populations of bacteria, yeast and fungi which are present in seawater (and in other environments) are capable of degrading petroleum hydrocarbons to oxidation products. Biodegradation is regarded as the ultimate fate of much of the dissolved and dispersed oil, but the process takes place over a long time scale. The rate of biodegradation is controlled by temperature, oil composition, surface/volume ratio of the oil, and the supply of oxygen and of nutrients such as nitrogen and phosphorus. Bacteria preferentially attack the low molecular weight components in the oils and the normal paraffins.

Water samples taken at the mouth of Aber Wrach following the *Amoco Cadiz* spill indicate a large reduction in nC-17/pristane and nC-18/phytane ratios and an increase in the content of branched, cyclic and aromatic hydrocarbons compared with samples taken near the spill site (Calder and Boehm, 1981). From this, the authors conclude that biodegradation was occurring at a faster rate than evaporation or dissolution.

The biodegradation of the mousse formed from the Ixtoc-1 blowout was found to be extremely slow (Atlas *et al.*, 1980), and the supply of nutrients was suggested as the limiting factor. Higher rates of biodegradation of mousses and of stranded tarballs when they are associated with decaying plant material have been observed (Boehm and Fiest,

1980; Blumer *et al.*, 1973), presumably due to nutrients. The biodegradation of oil in sediments is discussed later in the report.

Under the action of ultraviolet radiation (in sunlight) and the presence of air, some components present in oil are oxidised by photolysis. These oxidation products include phenolic and acidic compounds that are water-soluble and biodegradable. The oxidation products derived from photolytical reactions of spilled oils are relatively soluble. However, their rates of generation at the surface of spilled oil are slow because they are controlled by diffusion. Consequently, if these products are leached from the surface of the oil and enter the water column, they are rapidly diluted. Although the effects on marine life due to the formation of these oxidation products have not been quantitatively assessed, they are unlikely to have significant ecological impact.

### BEHAVIOUR IN ICE

*Oil may be entrained within a developing ice field under freezing conditions. This process would significantly reduce or even stop evaporation, dissolution, biodegradation and dispersion of the oil.*

From a series of field experiments, Wilson and Mackay (1986) concluded that significant quantities of oil may be entrained within a developing ice field under freezing conditions. The extent of oil incorporation was enhanced by

- A high oil density and/or viscosity occurring naturally or induced by weathering
- The presence of sufficient turbulence to disperse the surface oil and to induce mixing within the ice field
- The formation of emulsions of seawater and/or ice in oil
- The formation of small oil droplets
- The formation of coalesced ice particles measuring about 5 mm in diameter

The authors also concluded that the densest oils would be released relatively slowly from a frozen pancake during thawing. Once the oil begins to collect on the surface of the ice, solar radiation will tend to hasten the thawing process.

From a series of experiments in flow-through tanks, Payne *et al.* (1987) observed that extremely rapid formation of stable water-in-oil emulsions occurred under ice-forming conditions. Emulsions of Prudhoe Bay crude oil were formed within four hours of initiating waves in the presence of grease ice and breaking or rotting ice floes. They attributed this rapid emulsion formation to the low water temperatures and to the micro-scale turbulence created by the grinding of the grease ice crystals, which injected small water droplets into the viscous oil. On thawing, these emulsions were sufficiently dense to cause them to reside immediately below the grease ice. With continued agitation and melting, the emulsions eventually surfaced into patches of open water between the individual ice floes.

When oil is trapped into ice, weathering processes such as evaporation, dissolution, biodegradation and dispersion are significantly retarded or even stopped. Hence when released after thawing, the oil will be relatively 'fresh'.

In addition to being rapidly formed, emulsions formed in the presence of developing ice have significantly higher viscosities than those formed under ice-free conditions.

## BEHAVIOUR NEAR SHORES

*The coastline exposure and geomorphology are very important factors which influence the retention and dispersal of oil in the nearshore areas. The churning action of waves in shallow waters may result in the oil being incorporated into sediments. Beached oil may be washed off and may also become incorporated into subtidal sediments. Alternatively, the oil on the beach may be refloated and transported to impact other stretches of the coastline, or dispersed into the water column as fine droplets. Oiled sediments on beaches could be buried under fresh deposits of sand. However, oil transported from beaches is usually weathered and less toxic than fresh oil. High-energy rocky shores tend not to accumulate oil and, if impacted, are rapidly cleaned by wave action.*

Because of the turbulence in shallow inshore waters and the churning action of waves, the relatively high sediment burden of these waters can result in oil being incorporated into the bottom sediments to a greater extent than in the offshore environment.

The oil stranded on the intertidal coastal areas may be partially removed by subsequent tides and transported to unimpacted stretches of the coastline. During the first two weeks following the *Amoco Cadiz* oil spill, a total of 72 km of coastline was heavily impacted (Hayes *et al.*, 1979). One month after the incident, 84 percent of the stranded oil was estimated to have been naturally removed from the shoreline. But the impacted area had increased to 213 km of lightly oiled and 107 km of heavily oiled beaches.

Hayes *et al.* (1979) also report that the geomorphology in the coastal zone was very important in the dispersal and accumulation of oil once it came onshore. Exposed rocky coastlines did not accumulate significant quantities of oil. Mousse and oil stranded on fine-grained sandy beaches or sediments did not usually penetrate far below the surface.

Sandy beaches may undergo cycles of erosion and deposition in response to changing wave conditions. Hence, high-energy beaches may rapidly self-clean or, alternatively, the oiled sediments may become buried under fresh deposits of sand, dependent upon the phase of the beach cycle.

Local entrapment of oil was found to occur between rock crevasses, in marsh pools and in scour pits around boulders. Penetration of oil into coarse-grained sandy beaches, mixed sand and gravel beaches, and gravel beaches may occur rapidly.

Oiled sediments washed from the beaches can be a major contributor to oiling of subtidal sediments. This is not an important process for high-energy, rocky coastlines.

Harper *et al.* (1985) studied the retention and residence times of oil in low-wave-exposure, tidal flat environments. Their main conclusions were that

- Retention of oil in the sediments was proportional to the loading thickness, up to a limit beyond which the retention increased very little. This limiting thickness for oil loading was thought to be a function of the sediment size.
- The retention was proportional to the sediment emergence time. Intertidal sediments which are exposed longer have greater oil retention times.
- The retention was inversely proportional to the mud content of the sediments. Even small amounts of mud may significantly reduce oil retention in sediments.
- Sediment size and composition were thought to be the most important factors which influence oil retention.

Mechanical removal of bulk oil from beaches is beneficial (1) by reducing a potential source of oiling of the subtidal sediments and other stretches of the coastline and (2) by enhancing the self-cleaning of intertidal sediments.

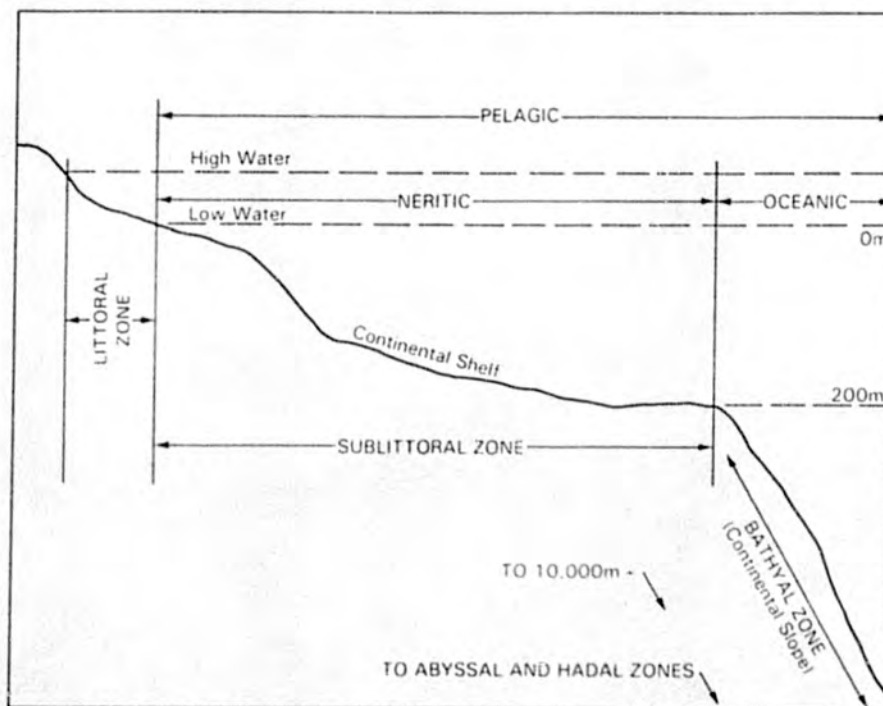


Figure B1: Divisions of the marine environment (modified after Hedgpeth, 1957).

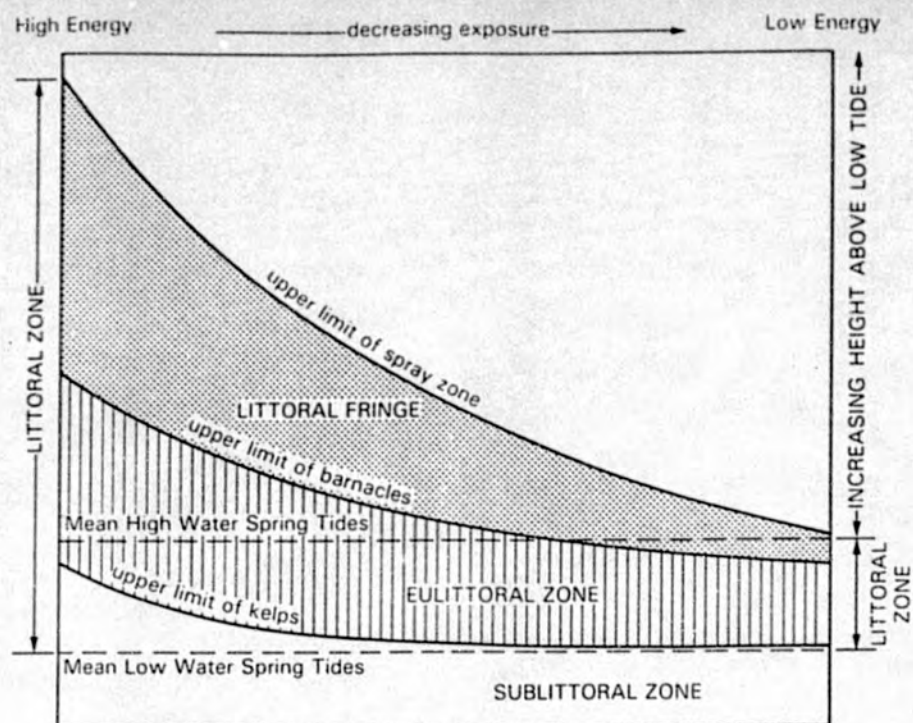
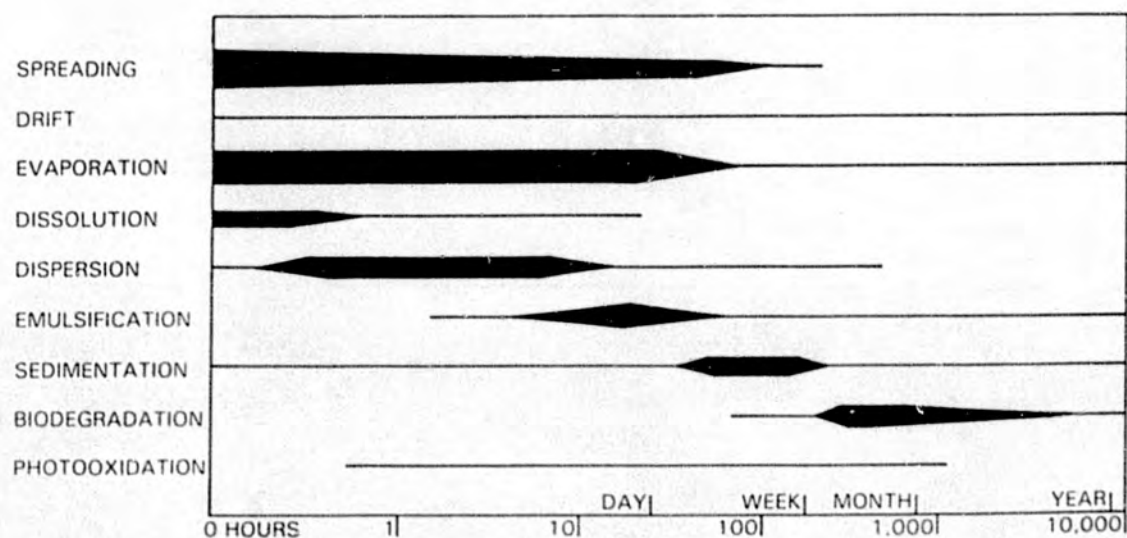


Figure B2: Effect of exposure on the width of the littoral zone of a rocky shore (modified after Lewis, 1964).



LINE LENGTH - probable time span of any process.

LINE WIDTH - relative magnitude of the process both through time and in relation to other contemporary processes.

Figure B3: Time span and relative magnitude of processes acting on spilled oil (modified after Whittle *et al.*, 1982).

## APPENDIX C

### EFFECTS OF OIL ON BIRDS

The most serious effect of oil is on the bird's plumage. Oil mats the feathers and destroys their water-repellant properties. For aquatic birds, this results in water displacing the air normally trapped under the plumage. This air layer provides buoyancy and thermal insulation. Birds with a water-logged plumage may sink and drown, but will certainly suffer rapid loss of body heat; fat reserves are used to counter this, but within a short time these are exhausted and the birds succumb to hypothermia, pneumonia, or related diseases. It may be anticipated that birds are more likely to die after oiling in cold climates (Brown, 1982) or after prolonged stormy weather has prevented feeding and energy reserves are low (NERC, 1971).

Lightly-oiled birds are able to clean themselves by preening within about 2 weeks (Birkhead *et al.*, 1973), but in doing so swallow oil. Depending on the age and toxic properties of the oil, this may cause gastric disorders (Croxall, 1977) and may reduce egg-laying or decrease the fertility of eggs that are laid (Grau *et al.*, 1977). While these factors may result in additional deaths or depress reproduction for a time, they are insignificant compared with the direct mortality from oiling.

If oil is transferred from the plumage to incubating eggs, the developing embryo may be killed and breeding success reduced (Brown, 1982), although there is no evidence that this happens on a large or widespread scale.

#### Birds at Risk

The casualties of oil pollution (*e.g.*, bilge water, dirty ballast water, *etc.*, as well as oil spills) are overwhelmingly aquatic birds, though in exceptional circumstances shore birds or even land birds may be affected. The following birds are most at risk.

#### Alcids (auks)

These include murre, guillemots, razorbills, puffins, *etc.* They are weak fliers and spend virtually all their time on the surface of the sea, returning to land only for breeding. They hunt their food (small fish) under water and are very gregarious at all times of the year. Because of their habits, auks are more likely than most birds to encounter oil slicks and, since they dive rather than fly up when disturbed, may surface through the oil slick and become coated with oil. Because they occur in large, dense flocks on the water, casualties from an oil spill are likely to be high.

### **Diving Sea Ducks**

Many species of sea duck disperse to land or fresh water for breeding, but occur in very large flocks in coastal waters during the fall and winter. Some species dive for their food in a similar manner to auks and are vulnerable to oil slicks in the same way. But for all species, casualties may be very high if oil impacts winter flocks in coastal waters.

### **Grebes and Loons**

These, like auks, are divers and weak fliers. They breed in fresh waters but spend the winter in ice-free coastal waters. They are likely to become oiled if they encounter an oil slick, but since they occur in only small groups, casualties are usually small. However, because the world population of these birds is small, even low casualties may be significant.

### **Pelican, Gannet, Tern**

These birds dive from the air into the sea to catch fish. If, as sometimes happens, they dive through an oil slick, they become coated with oil. Pelican and gannet casualties have been reported, though not in large numbers. Terns appear to avoid this hazard.

### **Other Birds**

Almost any seabird or shore bird may encounter floating or stranded oil and suffer some oiling of the plumage, the extent of which is usually slight, and casualties are small.

## BIOGRAPHICAL SKETCHES OF THE AUTHORS

### DR. JENIFER M. BAKER

Dr. Baker is a biological consultant specialising in environmental impact assessment and oil spill response. Her doctoral studies at the University of Wales involved research on the effects of oil on and cleaning methods for salt marshes, and she has subsequently worked on oil pollution problems in many parts of the world. She was formerly Research Director of the UK Field Studies Council, and is presently a fellow of the Institute of Biology and of the Institute of Petroleum. Dr. Baker has published numerous papers in the scientific literature on the subject of the recovery of impacted shoreline ecosystems.

### DR. ROBERT B. CLARK

Dr. Clark is currently Professor Emeritus of Zoology at the University of Newcastle upon Tyne. He received his Ph.D. from the University of Glasgow and a D.Sc. from the University of London. He has served as Honorary Director of the Seabird Research Unit of the British Advisory Committee on Oil Pollution of the Sea (1969-75), and as Director of the Natural Environmental Research Council (NERC) Research Unit on Rocky Shore Surveillance (1980-87). Dr. Clark also worked with numerous national and international bodies, including the United Nations group of experts on the Scientific Aspects of Marine Pollution, and the Royal Commission (UK) on Environmental Pollution. His extensive publications include the textbook *Marine Pollution*. He is founder (1969) and Editor of the *Marine Pollution Bulletin*.

### DR. ROWLEY H. JENKINS

Dr. Jenkins became Deputy Director, in 1986, of the Institute of Offshore Engineering at Heriot-Watt University in Edinburgh, Scotland. He had earlier served 28 years in the petrochemical and oil industry in research and environmental areas. His current focus in oil spill research includes emulsification and weathering, as well as modelling and fingerprinting by GC/MS analysis. Part of his environmental experience involved a two-year secondment to Woodside Petroleum as Environmental Coordinator for the North West Shelf Gas Project in Western Australia. In his post as Oil Spills Divisional Manager for British Petroleum (BP), Dr. Jenkins provided the BP group worldwide with a wide range of services — e.g., emergency response from the Southampton Oil Spill Response Base, equipment testing and appraisal, and oil spill response training. He was active in both CONCAWE and IPIECA as the BP representative.

### DR. PAUL F. KINGSTON

Dr. Kingston obtained his doctorate from the University of London and, after a three-year post-doctoral research fellowship at the University of Newcastle upon Tyne, joined the staff at Heriot-Watt University in 1975 as lecturer in marine biology. He is currently the

Assistant Director of the Institute of Offshore Engineering. Earlier, he had acted as Consultant to the Institute on all offshore, inshore, and coastal environmental projects, and served as part-time Assistant Director with responsibility for biological studies. Dr. Kingston has had considerable experience in assessing the environmental impact of the offshore oil industry and has worked on most major North Sea developments. His research interests centre on the structure and dynamics of seabed communities. He has published extensively and currently serves as News Editor of the *Marine Pollution Bulletin*.

## GLOSSARY

|                        |                                                                                                                                                                       |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| aerobic bacteria       | Bacteria that can live only in the presence of free oxygen.                                                                                                           |
| aliphatic hydrocarbons | Saturated straight-chain or branched-chain hydrocarbons.                                                                                                              |
| anaerobic bacteria     | Bacteria that can live in the absence of free oxygen.                                                                                                                 |
| antiboreal             | Cool or cold-temperate regions in the southern hemisphere (see Figure 8).                                                                                             |
| aromatic hydrocarbons  | Hydrocarbons containing one or more benzene rings in their molecular structure.                                                                                       |
| asphaltenes            | High boiling point constituents of crude oils that are soluble in polar solvents such as benzene or methylene chloride but are not soluble in paraffin naphthas.      |
| bacterial mat          | A carpet of filamentous bacteria which can form over the surface layer of organically enriched sediments.                                                             |
| benthic fauna          | Animals inhabiting the seabed.                                                                                                                                        |
| benthos                | Those forms of marine life that are bottom-dwelling; also, the ocean bottom itself. Certain fish that are closely associated with the benthos may be included (AGI).* |
| biodegradation         | Breaking down of substances by bacteria.                                                                                                                              |
| biogenic               | Originating from living matter.                                                                                                                                       |
| biomass                | The amount of living material in a particular area, stated in terms of the weight or volume of organisms per unit area or of the volume of the environment (AGI).     |
| biota                  | All living organisms of an area; the flora and fauna considered as a unit (AGI).                                                                                      |
| bivalves               | Molluscs having a shell in the form of two plates, e.g., clams.                                                                                                       |
| boreal                 | Cool or cold-temperate regions in the northern hemisphere (see Figure 8).                                                                                             |

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\* American Geological Institute, *Glossary of Geology*, Third Edition

|                    |                                                                                                                                                                                                                                                                                                                                                               |
|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| copepod            | A subclass of <i>Crustacea</i> , generally of small size. These crustaceans are important members of the zooplankton and meiofauna.                                                                                                                                                                                                                           |
| crustaceans        | A class of <i>Arthropoda</i> , mostly of aquatic habitat, which includes shrimps, prawns, barnacles, crabs, and lobsters.                                                                                                                                                                                                                                     |
| depurate           | To rid of contaminants, especially with relation to shellfish.                                                                                                                                                                                                                                                                                                |
| diatom             | A microscopic, single-celled plant which grows in both marine and fresh water.                                                                                                                                                                                                                                                                                |
| dispersants        | Chemical mixtures containing surface-active agents which enhance the dispersal of oil in water.                                                                                                                                                                                                                                                               |
| ecosystem          | Any area of nature which includes living organisms and non-living substances interacting to produce an exchange of materials between the living and non-living parts, <i>e.g.</i> , the sea, a pond, lake, or forest. It comprises four constituents: abiotic substances, producers, consumers, and decomposers, and is the basic functional unit in ecology. |
| emulsification     | A colloidal suspension of one liquid in another, <i>e.g.</i> , mousse.                                                                                                                                                                                                                                                                                        |
| epifauna           | Fauna living upon rather than below the surface of the seafloor (AGI).                                                                                                                                                                                                                                                                                        |
| eutrophication     | Depletion of oxygen in the water column in response to an increase in nutrients and associated elevation in primary production.                                                                                                                                                                                                                               |
| fauna              | A collective term denoting the animals occurring in a particular region or period.                                                                                                                                                                                                                                                                            |
| fucoid algae       | Brown seaweed belonging to the family <i>Fucaceae</i> .                                                                                                                                                                                                                                                                                                       |
| gas chromatography | An analytical technique for the separation of components in a mixture on the basis of boiling point. The use of very sensitive detectors enables this form of chromatography to be applied to microgram quantities.                                                                                                                                           |
| gasoline           | A distillate of crude oil (boiling temperature less than 190°C), having a carbon number distribution between C5 and C10, that is used as a liquid fuel.                                                                                                                                                                                                       |
| herbivore          | An organism that feeds on plants.                                                                                                                                                                                                                                                                                                                             |

|                       |                                                                                                                                                   |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| infauna               | Those aquatic animals that live within rather than on the bottom sediment (AGI).                                                                  |
| intertidal            | The benthic ocean environment between high- and low-tide water levels (see Figure B1). Syn. <i>littoral</i> .                                     |
| lecithotropic         | A form of larval development whereby the eggs are dispersed in the water column and contain an independent food source for the developing larvae. |
| lipids                | Generic terms for fats, waxes, and related products in living tissues.                                                                            |
| littoral              | See <i>intertidal</i> (see Figure B1).                                                                                                            |
| lysosomal             | Cellular particles intermediate in size between mitochondria and microsomes and which contain hydrolytic enzymes.                                 |
| macrofauna            | Animals large enough to be seen with the naked eye.                                                                                               |
| meiofauna             | Organisms in the size range of 0.1 to 1.0 mm that live within sediments.                                                                          |
| metabolic             | The chemical and physical changes constantly taking place in living matter.                                                                       |
| mousse                | A viscous water-in-oil emulsion which is often brown in color (also: chocolate mousse).                                                           |
| n-alkanes             | Normal alkanes; straight-chain aliphatic hydrocarbons; paraffins.                                                                                 |
| nematodes             | A phylum of unsegmented worms with an elongate rounded body pointed at both ends. Included are round worms, thread worms, and eel worms.          |
| neritic               | That portion of the seafloor lying between low-water mark and the edge of the continental shelf, at a water depth of about 180 m (see Figure B1). |
| oleophilic            | Having a strong affinity or preference for oil.                                                                                                   |
| opportunistic species | Species which are able to quickly colonise and exploit environmentally disturbed areas.                                                           |
| paraffins             | A whole series of saturated aliphatic hydrocarbons of the general formula $C_nH_{2n+2}$ .                                                         |
| pelagic               | Living in the middle depth and surface of waters of the sea.                                                                                      |

|                        |                                                                                                                                                                                                     |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| petrogenic             | Derived from rocks.                                                                                                                                                                                 |
| petroleum hydrocarbons | Liquids that are generated through the action of time and temperature on organic matter buried below the earth's surface. They consist of saturated and unsaturated structural groups.              |
| phenolic compounds     | Compounds containing a hydroxyl function (OH <sup>-</sup> ) substituted on a benzene ring.                                                                                                          |
| photolysis             | The decomposition or dissociation of a molecule as the result of the absorption of light.                                                                                                           |
| phytane                | A branched-chain saturated hydrocarbon containing 20 carbon atoms.                                                                                                                                  |
| phytoplankton          | Plant members of the plankton.                                                                                                                                                                      |
| plankton               | Animals and plants floating in the water of seas, rivers, ponds, and lakes, as distinct from animals which are attached to, or crawl upon, the bottom; especially minute organisms and forms.       |
| planktotrophic         | A form of larval development whereby the eggs are dispersed pelagically and the larvae then spend time as temporary members of the plankton where they feed and grow before settlement.             |
| polar compounds        | Molecules in which the electrical charge distribution is dipolar (like a bar magnet); commonly used to refer to components of crude oil containing the elements N, S, and O in addition to H and C. |
| polychaete             | A type of segmented marine worm, <i>e.g.</i> , bristle worm.                                                                                                                                        |
| polynuclear aromatic   | Aromatic hydrocarbons containing two or more benzene rings.                                                                                                                                         |
| pristane               | A branched-chain saturated hydrocarbon containing 19 carbon atoms.                                                                                                                                  |
| recruitment            | Addition by immigration or reproduction of new individuals to a population.                                                                                                                         |
| saturated hydrocarbon  | A general term including straight-chain, branched-chain, and ring structures in which all carbon-carbon bonds are covalent. Syn. <i>alkanes</i> , <i>paraffins</i> .                                |

|                    |                                                                                                                                                                                                                                                                              |
|--------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| shingle            | Coarse, loose, well-rounded, water-worn detritus, especially beach gravel, composed of smooth and spheroidal or flattened pebbles, cobbles, and sometimes small boulders, generally measuring 20-200 mm in diameter; it occurs typically on the high parts of a beach (AGI). |
| sublethal toxicity | The toxicity of a substance which is shown to cause deleterious effects in plants and animals, but not death.                                                                                                                                                                |
| substrata          | Non-living materials to which a plant is attached and from which it obtains substances used in its nutrition.                                                                                                                                                                |
| subtidal           | The benthic ocean environment below low tide which is always covered by water (see Figure B1). Syn. <i>sublittoral</i> .                                                                                                                                                     |
| tarballs           | Water-insoluble, buoyant agglomerates formed in water from weathered crude; consist largely of the non-hydrocarbon fractions.                                                                                                                                                |
| toxins             | Poisonous substances of plant or animal origin.                                                                                                                                                                                                                              |
| zooplankton        | Animal life that floats or drifts in water.                                                                                                                                                                                                                                  |

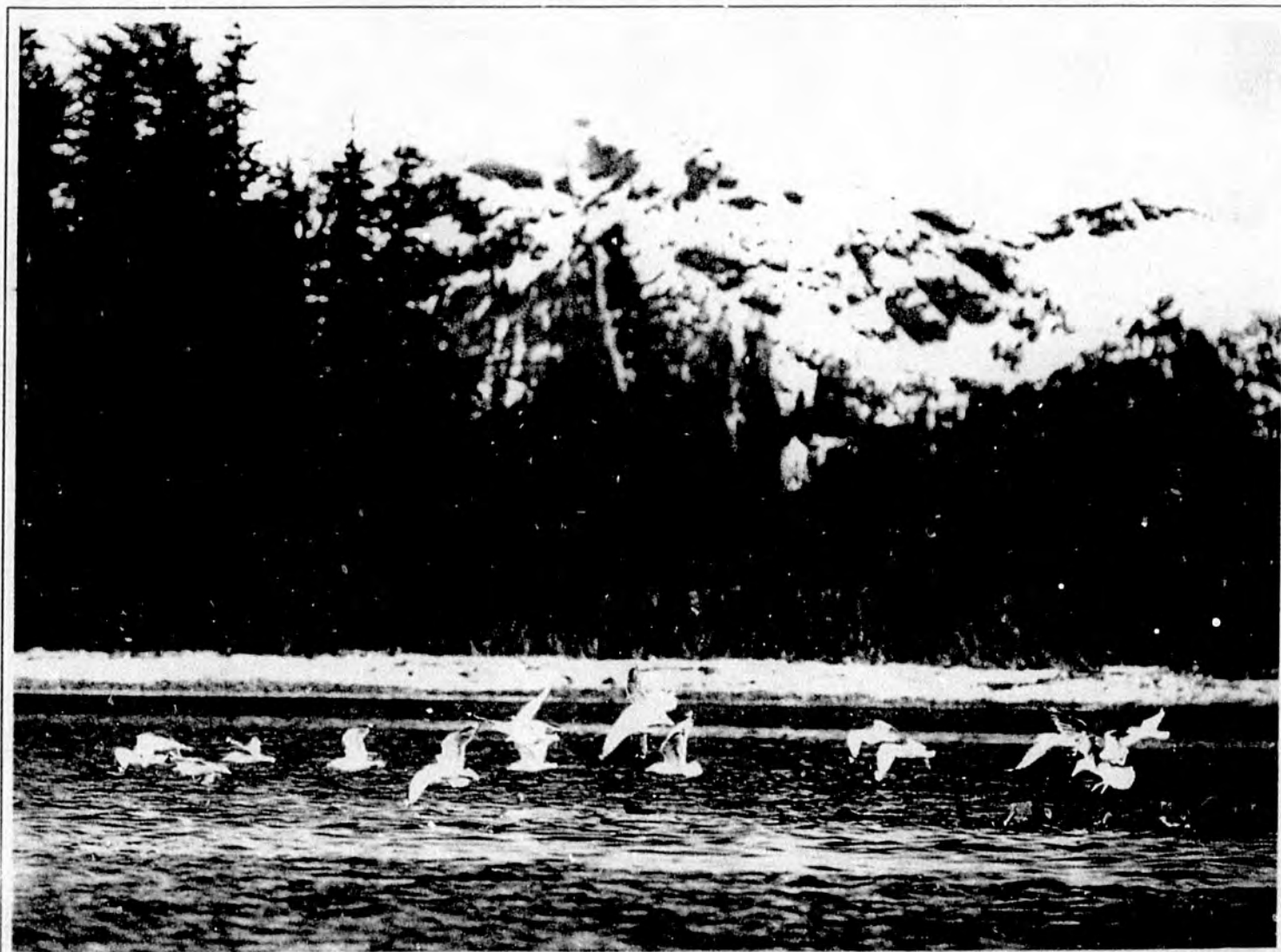
# ENVIRONMENTAL RECOVERY IN PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

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## Field Observations of:

Jenifer M. Baker, Ph.D  
Robert B. Clark, Ph.D  
and Paul F. Kingston, Ph.D

A supplement to the authors' scientific review:  
"Natural Recovery of Cold Water Marine Environments After an Oil Spill"



June 1990

## INTRODUCTION

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This report is based on work commissioned by Exxon as part of a programme of analyzing the ecosystem recovery process in Prince William Sound and the Gulf of Alaska following the oil spill of March 1989.

Written by three distinguished scientists, it supplements a comprehensive study they and a fourth researcher prepared on the subject of "Natural Recovery of Cold Water Marine Environments after an Oil Spill." This scientific review was presented at the 13th Arctic and Marine Oilspill Program Technical Seminar sponsored by the Canadian Government in Edmonton, Alberta, on June 6, 1990.

As a followup to this study, the scientists spent two weeks in April 1990 gathering insight into the Prince William Sound and Gulf of Alaska environment as a whole and examining plant and animal life in the area. They compared their Alaska findings to their knowledge gained from studying the recovery process from other oil spills in cold waters of the world.

The scientists, all from the United Kingdom, are:

**Dr. Jenifer M. Baker**, a biological consultant who works on oil-pollution problems for conservation organizations, corporations and government agencies throughout the world.

**Dr. Robert B. Clark**, zoology professor emeritus at the University of Newcastle upon Tyne, author of the textbook *Marine Pollution* and editor of the international journal *Marine Pollution Bulletin*.

**Dr. Paul F. Kingston**, a marine biologist and assistant director of the Institute of Offshore Engineering in Edinburgh, Scotland.

The following pages contain a summary of their conclusions and answers to questions they have encountered since their inspection tour in Alaska. Also, excerpts from their review of previous spills are provided in the back of this report.



Researchers closely examine a worm from a sedimentary shore. From left, Dr. Kingston, Dr. Baker, and Dr. Clark.

## OVERVIEW

In April 1990, we toured Prince William Sound and the Gulf of Alaska for two weeks to obtain a perspective on the total area relative to the affected region, and to conduct field observations on the environmental impacts of the Valdez oil spill. Because the Sound and Gulf comprise an immense region with thousands of miles of coastline, most of which was not oiled by the spill, we obtained an overview with extensive low-altitude flights of the area. In addition we conducted shoreline investigations on numerous beaches, including some of the most heavily impacted areas. The map on this page indicates the broad geographical scope of our investigation.

Prior to our field investigation, we were familiar with the considerable body of scientific research focused on the biological implications of previous oil spills. Since the wreck of the tanker Torrey Canyon created a major oil spill off the southwest coast of England in 1967, the scientific community has been investigating how areas affected by an oil spill recover through natural processes. As specialists in this field

of study, we were aware of the conclusions reached through this research and therefore what one might expect to find in Alaska.

Our examination of plant and animal life in the many unoiled and previously oiled areas was designed to provide an overall perspective of environmental conditions in Prince William Sound and Gulf of Alaska. From this field analysis, we derived impressions on how the natural recovery was proceeding in Prince William Sound and the Gulf of Alaska. What follows is a brief summary of our field observations and impressions.

### General findings

Our experience in Prince William Sound, one year after the oil spill, held few surprises.

Only a portion of the shoreline had been oiled, and, as with most other oil spills, the bulk of the damage had disappeared during the first year. The area has retained its natural beauty; there are abundant signs of



## OVERVIEW

plant and animal life, and recovery is well under way on even the most severely impacted beaches.

Since there are few sheltered areas with extensive mudflats, which elsewhere have sometimes taken a long time to recover, the overall impact of the oil spill on the environment in Prince William Sound and Gulf of Alaska is likely to be short-lived.

### The search for oil

Prince William Sound and the Gulf of Alaska are vast, mainly inaccessible areas, and the spilled oil only impacted a small portion of the total shoreline. On our visit one year after the spill, most of the shoreline of the Sound and the Gulf did not have an oily appearance. The main reasons for this generally favourable impression were: most of the shoreline was not oiled or was only slightly oiled by the spill; bulk oil had been removed by the extensive cleanup programme during the summer following the spill; the natural cleaning process has been effective, and this process includes wave action, winter storms and breakdown by bacteria.

Despite the generally favourable appearance from



Rock covered with black lichen, which can look like oil at a distance.

Most of the Prince William Sound had a generally favourable appearance.



## OVERVIEW

the air, dark patches on the rocks and dark zones on the upper shore invited further investigation. On the ground, we found that many of these dark patches were formed by a black lichen, not by oil. Other noticeable dark patches were beds of algae or mussels, although some were caused by oil or oil stains.

### The remaining oil

Overall rocky shores generally appeared clean from the air, and this was confirmed by ground observations. However, residues of weathered oil were present and had a varied distribution depending upon exposure to wave action and height on the shore. Most of the residual oil was found in sheltered inner bays or on upper shores.

We dug into several sedimentary shores and found oil that had penetrated below the surface. Even in the sediment bays that were heavily oiled, a variety of plants and animals were present, some of them abundant. This was consistent with recovery processes noted in other oil spills. In some areas, small oil sheens (microscopically thin films) emerged from these disturbed sediments. On some shores, there are recent deposits of fine sediment on top of oil residues, and these could help reduce any remaining surface stickiness.



Beach cleaned by strong wave action, oil stains remaining on sheltered area in the background.



Otter observed in previously oiled waters of Prince William Sound.

### Sea otters

Sea otters were affected by the spill and attracted a great deal of media attention. We were therefore particularly interested to see otters in many parts of Prince William Sound and the Gulf of Alaska, including previously oiled waters. The frequency with which we saw the otters suggests that they are reasonably common throughout the Sound and Gulf.

### Seals and Sea lions

Large numbers of sea lions, with at least 100 in each group, were basking on the rocks at several locations in the region. In addition, many seals were observed swimming in the open waters. Although we did not undertake a detailed study of the seals and sea lions, large numbers of them appear to exist in areas affected by the spill.

### Sea birds

The dominant seabirds in the area were auks (murre) and gulls. These birds, which do not start breeding until late May or June, were primarily distributed in small feeding groups throughout Prince William Sound and the Gulf of Alaska, although large numbers were already congregating around some of the breeding colonies.

Migrant birds were only just beginning to return from their winter quarters. Small groups of mallard and other ducks were seen, in addition to a pair of swans, a group of black-bellied plover and other wading birds. Cormorants were often seen flying around

## OVERVIEW



Starfish found in the tidal region of a previously oiled shore.

Prince William Sound and the Gulf of Alaska.

The most conspicuous casualties of cold-water oil spills are seabirds such as auks, which often congregate in dense flocks on the sea, making it possible for large numbers to be killed by a single oil slick. Despite this, previous research cited in the scientific review on natural recovery has shown that seabird breeding populations rebound rapidly because any losses are replaced from a large reservoir of previously non-breeding adults. Also, we would expect no further casualties since the water now appears clear of oil with only a minor sheen presence.



Fresh grass shoots sprouting from sediment containing residual oil.

### Bald eagles

Bald eagles were seen perching at the top of lookout trees at regular intervals along the entire coastal area. It is not a rare bird in the area. Bald eagles obtain much of their food by foraging on the shoreline and may have been affected by oil in this way. As with other large birds of prey, bald eagles do not start breeding until the age of 3 or 4. There is therefore a substantial reserve of young adults ready to fill gaps in the breeding population as nesting territory becomes available.

### Shoreline creatures

The creatures we saw most commonly on the rocky shores were barnacles, periwinkles (sea snails), mussels and limpets. They were abundant at widespread



Rock overturned in an oiled area, exposing a variety of shoreline creatures.

locations in Prince William Sound and the Gulf of Alaska, including areas which had been heavily oiled. We found egg clusters of a variety of molluscs at sites which had been oiled. Worms and shellfish were living in the sediments of the more sheltered shores, including areas which had been oiled and some of which still contained oil. Numerous worms and other creatures living in the sediment promote aeration, helping the bacterial breakdown of oil.

Sighting of numerous young barnacles on the rocks implies that environmental quality has been good enough to support these animals through the sensitive stages of the life cycle, both at sea and on shore. It is likely that shore oiling killed many barnacles, but we saw many that had survived the spill, some with oil still visible on their shells. Some young barnacles have settled next to oil crusts on the rock, indicating that

## OVERVIEW



Young fucus (rockweed) growth on a previously oiled rock.



Bald eagle atop lookout tree, a common sight.

the residual oil has a very low toxicity. Periwinkles also were active on oiled rocks.

### Plant life

In all marshes or upper-shore grass zones, we saw new grass shoots of normal appearance emerging from the sediment. We were particularly interested in the presence of marsh grasses at sites which were reported as heavily oiled. Many of the plants making new growth were rooted in sediments which retained visible oil residues, indicating low toxicity of the residues and the existence of a robust system of underground stems and roots.

Algae were seen throughout Prince William Sound and the Gulf of Alaska, including young rockweed plants which had established themselves after the spill. Filamentous green algae were noticeable on many shores.

We found sea or eel grass on shores which had been oiled and compared it with the grass growing on an unoiled shore. Most of the grass on all these shores looked green and healthy.

We saw numerous kelp beds with plants of normal colour along the more exposed shores of the Kenai Peninsula and the mouth of Prince William Sound.

### Fish

While it was not possible to make observations of fish during our field analyses, extensive research referenced in the scientific review has shown that oil spills have little impact on fish, and, indeed, the herring fishery opened successfully while we were in the area.

## CONCLUSION

Our examination of the spill area confirmed our expectations, based on knowledge gained from previous accidents, that natural recovery is proceeding in Prince William Sound and the Gulf of Alaska. We expect the recovery to continue and to be relatively rapid.

Although isolated patches of weathered oil may still be found, nearly all of the beaches in Prince William Sound and the Gulf of Alaska are of clean appearance. Some small and isolated portions of the shoreline may retain oil for several years, but our investigations of previous oil spills indicate that the long-term impact on plants and animals should be minimal.

The recovery process is well under way. Once started, if it is allowed to proceed without interruption, it will continue and be robust, as it has been following other spills throughout the world.

**What follows are answers to questions  
perceived to be of general public interest.**

## COMMONLY ASKED QUESTIONS

The following are responses given by the authors to questions they have been asked following their examination of Prince William Sound and the Gulf of Alaska.

### **Were you surprised with what you found in Alaska?**

What we saw in Prince William Sound, from the point of view of biologists, confirms what the research on previous spills had told us we might expect to find. Over the past 25 years, there has been extensive research on oil spills around the world, at least 30 of them larger than the Valdez spill. That helped prepare us for what we found. What did surprise us was a smaller amount of oil on the beaches than we expected. We were impressed with how extensive the cleanup effort had been, as well as the combined effectiveness of the strong natural cleansing processes and the cleanup operation.

### **What is the overall impact of the spill on the ecology of Prince William Sound?**

For the parts of the Sound that were affected, it was a shock. However, it was more like a rash on a human body that will heal itself, rather than a crippling or terminal disease. After the initial shock, the natural recovery process began. Animals and plants are thriving, and the environment is healing.

### **What is the scientific evidence on the effects of major oil spills on water quality or on Prince William Sound?**



Investigators dig into the sediment to find worms and other creatures.

Indications of the good water quality in Prince William Sound are provided by biological evidence. We saw on the shoreline abundant evidence of life that has survived or has newly settled on shores that were previously heavily oiled. For example, young barnacles and seaweeds are abundant on most shores. These organisms, in their most sensitive stages, float in the water until settling. Furthermore, they are quite fussy about where they settle, and they must find suitable rock surfaces to settle upon.

### **Will the oil that remains in shoreline sediments pose a danger to plant and animal life?**

There are abundant signs of life such as worms, shellfish and grasses thriving on many sedimentary shorelines. This indicates that sediments either do not contain toxic residues or, if they do, the level of toxicity is not high enough to affect the survival or activity of these creatures. Their presence indicates that recovery is in progress. Once started and allowed to proceed without interruption, we believe it will continue and will be robust, as it has been following other oil spills throughout the world.

### **Is oil a toxic compound that will persist for decades?**

No, oil is not a persistent toxic compound like PCBs, mercury and many pesticides. The toxicity in oil diminishes very rapidly as it is exposed to the air and water. Most of the oil released in PWS was afloat for at least four days before it reached the shoreline, and in that time would have lost much of its toxicity. Therefore the damage it did to wildlife was not so much because of its toxicity as because of its smothering effect. It follows it is unlikely that much of the oil that remains is significantly toxic, even that trapped in shoreline pockets. We saw biological evidence for this, such as animals living in sediments with residual oil. In addition, green shoots of upper-shore grasses were sprouting normally from the oily sediment.

### **Are birds and wildlife threatened by oil sheens?**

In our on-site inspection, we looked for sheens from the air and on heavily oiled beaches. From the air, we saw only a few sheens and they were quite small in area and very thin, as indicated by their colour. It is very unlikely, therefore, that they would be harmful to wildlife, including birds and sea otters, the animals most at risk. There is no past evidence to suggest otherwise. Animals exposed to these sheens would, in the normal course of living, groom

## COMMONLY ASKED QUESTIONS

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themselves.

Small sheens emerged from some sediments we disturbed on the beaches, but they were too small to have any significance for birds and other wildlife.

### **Has the oil entered the food chain and disrupted it?**

Animals may accumulate petroleum hydrocarbons while their environment is oily, but they subsequently purge themselves in a relatively short time and return to normal levels. It is important to understand that oil is not like pesticides, mercury and other substances that cannot be metabolized, cannot be excreted, and thus build up in the flesh.

### **Have any species been irretrievably lost by this spill?**

This is unlikely for a number of reasons. First, only portions of Prince William Sound and the Gulf of Alaska were affected. The sea is continuous and the abundant plant and animal life in the vast unaffected areas provide a reservoir of organisms to move in and replace losses created by the one-time, short-term occurrence of the oil spill. Secondly, the number of bird mortalities caused by the spill was small compared to those caused by naturally occurring phenomena such as extremely cold weather, harsh storms and old age. Finally, sea otters, which were also impacted, have a rapid reproduction rate.

### **Are the fish after an oil spill safe to eat?**

Yes. There is ample evidence that fish avoid floating oil and are unaffected by it. Impounded fish that are exposed to fresh oil may acquire a taste of oil, but this is temporary and quickly dissipates once the fish are returned to clean waters. Even if the fish acquires an oily flavor, there is no evidence that this poses a toxicological hazard.

### **There are reported although unconfirmed sightings of abnormal fish and other animal life in Prince William Sound since the oil spill. Would you comment on that?**

Some fish may have developed in an abnormal way if they were exposed to oil in their early stages. But it is most unlikely that these abnormalities would be passed on to the next generation. Any grossly abnormal members of the population would not survive long in the struggle for existence. On the other hand, genetic mutations, which also could

lead to abnormalities, occur naturally, and there is no evidence from previous spills that link these to oil.

### **How has the habitat in Prince William Sound been damaged or compromised?**

The short-term impact from the spill was serious. From our observations, it is difficult to say anything definite about the long-term impacts, although recovery is well under way. Experience from other oil spills indicates that long-term impacts will be minimal.

### **Is there any reason to restrict normal human use of Prince William Sound for tourism, hiking, camping, hunting, fishing, kayaking, etc?**

No. We were struck by the magnificent beauty of the area. We visited the most heavily oiled areas and found nothing indicating that human use should be or need be restricted because of the spill.

### **How can you say this "pristine and fragile" area has not been irreparably damaged by the introduction of 11 million gallons of oil?**

We saw nothing to indicate the Prince William Sound environment is particularly fragile. The marine environment is a lot tougher and more resilient than most people give it credit for. Life forms in that rather harsh environment have to be hardy to survive. All the evidence suggests Prince William Sound is a robust, resilient environment well on its way to recovery.



**Basking group of seals, one of many spotted on rocks throughout the region.**

## THE NATURAL RECOVERY PROCESS

The following are excerpts from *Natural Recovery of Cold Water Marine Environments after an Oil Spill* published by the authors and Dr. Rowley H. Jenkins, deputy director of the UK Institute of Offshore Engineering, in March 1990. These findings are based on an extensive review of research into major oil spills into cold water environments throughout the world.

### BASIC CONCEPTS

- Current evidence indicates that hydrocarbons are present in all environments. They originate from both natural and human sources and serve to define background levels of petroleum hydrocarbons.
- Recovery of an ecosystem damaged by petroleum hydrocarbons begins as soon as the toxicity or other adverse property of the oil has declined to a level that is tolerable to the most robust colonizing organisms. Recovery processes can begin in the presence of residual oil.
- Recovery of an ecosystem is marked by the re-establishment of a healthy biological community in which the plants and animals of the community are functioning normally. It may not have the same composition or age structure as that which was present before the damage and will continue to show further change and development. It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have developed in the absence of the spill.
- Ecosystems are in a constant state of flux due to natural causes. These fluctuations can be as great as, or even greater than, those caused by the impact of an oil spill.

### NATURAL CLEANING

- Most of the toxic components in a fresh oil spill on the surface of the sea rapidly evaporate. After evaporation, these toxic components disperse into the atmosphere and are rapidly diluted to background levels. Most of the remaining toxic components that did not evaporate, dissolve and disperse in the water column to low concentrations.
- Generally, the higher the aromatic content of an oil, the higher the toxicity. Weathered crude is less toxic than fresh crude because most of the toxic compo-

nents have evaporated. Most of the toxic components are readily degradable.

- Oil concentrations in the water column below oil slicks are very low.
- The persistence of oil slicks on the sea surface is dependent upon the type of oil spilled and sea state conditions. Some slicks can be removed by natural processes within a few days. Other oils can form stable, highly viscous emulsions (mousses), which may persist for weeks or months in the open ocean. Eventually these slicks will form tarballs that are relatively harmless to biological systems.
- High-energy rocky shores usually do not accumulate oil, and if impacted are subjected to rapid cleaning by wave action.
- Oil does not penetrate easily into fine sediments in the intertidal zone, but can sink into shingle, gravel, and coarse sand. In some cases oil may penetrate to the water table, which forms a natural barrier to further penetration.
- On sheltered shores with high biological productivity, oil can penetrate down biological pathways, e.g., worm burrows and plant root systems. Oil may persist for many years in the sediments, especially if oxygenating biological activity (e.g., new burrow formation) is depressed.
- Physical 'removal' of oil by natural processes alone does not eliminate oil from the environment; it redistributes it. This redistribution can be beneficial - e.g., when wave action cleans the shoreline, it facilitates dispersion of the oil in the water column, and increases the surface area of the oil droplets, thereby encouraging other degradation processes. However, such redistribution may also involve sediment-bound oil being transported to the seabed.

### NATURAL RECOVERY

- Diving seabirds suffer heavy mortalities from oil. However, the mortalities arising from a single oil spill are not significantly different from natural mass mortalities experienced from time to time and are significantly less than annual mortalities from fishing activities.

## THE NATURAL RECOVERY PROCESS

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- There is no evidence that seabird populations are declining as a result of oil spills. In fact, North Atlantic populations of most species have been increasing in recent years despite heavy annual losses from oil pollution.
- Kills of adult fish from exposure to oil are rare. The only important casualties from oil spills are rockfish and shellfish in near-shore waters, and fish in mariculture installations.
- Loss of pelagic eggs and fish larvae, when these are present at the time of an oil spill, has had no detectable impact on the fish stocks available to the fishing industry.
- Although the toxic components of petroleum hydrocarbons kill planktonic organisms, there is no evidence that these effects have any ecological significance in open waters. In closed waters, effects may persist for several months.
- Estimates of recovery times vary depending upon the environment. Past experience has shown that exposed, rocky shores usually recover in 2 to 3 years. Other shorelines show substantial recovery in 1 to 5 years with the exception of sheltered, highly productive shores (e.g., salt marshes), which may take 10 years or more to recover.
- Subtidal sand and mud systems recover in recognizable successions. Usually, recovery times are 1 to 5 years, but they can be 10 years or longer in exceptional cases.
- The early colonizers, once the physical and toxic effects of the oil ameliorate, play an active role in the breakdown of the remaining hydrocarbons.
- Removal of oil using drastic cleaning methods, beyond initial bulk oil removal, can actually delay recovery because the cleanup also removes living organisms and damages the habitat.

## BIOGRAPHICAL SKETCHES OF THE AUTHORS

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### Dr. Jenifer M. Baker



Dr. Baker is a biological consultant who conducts research on oil-pollution problems for conservation organizations, corporations, and government and United Nations agencies throughout the world. She is the former research director of the UK Field Studies Council, an independent environmental education and research organization. Her doctoral studies at the University of Wales involved research into the effects of oil and cleaning methods for salt marshes, and she later served as a staff member in the botany department of the University College, Swansea. She recently helped assess potential oil pollution problems on the great lakes of Africa for a conference organized by the International Association of Theoretical and Applied Limnology. A fellow of the British Institute of Biology and the Institute of Petroleum, Dr. Baker has published numerous papers in the scientific literature on the recovery of impacted shoreline ecosystems.

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### Dr. Robert B. Clark

Dr. Clark, professor emeritus of zoology at the University of Newcastle upon Tyne, received his Ph.D. from the University of Glasgow and a D.Sc. from the University of London. He has served as director of the seabird research unit of the British Advisory Committee on Oil Pollution of the Sea (1969-75) and as director of the Natural Environment Research Council's Unit on Rocky Shore Surveillance (1980-87). He has served as a member of the zoology faculty of the University of California at Berkeley and has worked with numerous national and international scientific bodies, including the United Nations Group of Experts on Scientific Aspects of Marine Pollution and the UK Royal Commission on Environmental Pollution. Dr. Clark is the author of the textbook *Marine Pollution* and is founder and editor of the monthly *Marine Pollution Bulletin*.



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### Dr. Paul F. Kingston

Dr. Kingston is the assistant director of the UK Institute of Offshore Engineering and a former member of the marine biology faculty at Heriot-Watt University in Edinburgh, Scotland. He obtained his doctorate from the University of London and joined Heriot-Watt University in 1975 following a three-year research fellowship at the University of Newcastle upon Tyne. Dr. Kingston has extensive experience assessing the environmental impact of the offshore oil industry and has worked on most major North Sea petroleum developments. His research centers on the structure and dynamics of seabed communities. He has published extensively and currently serves as news editor of the *Marine Pollution Bulletin*.



Copies of this report or the review  
"Natural Recovery of Cold Water Marine Environments After an Oil Spill"  
may be obtained by writing:  
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# CRS Report for Congress

## Oil in the Ocean: The Short- and Long-Term Impacts of a Spill

James E. Mielke  
Specialist in Marine and Earth Sciences  
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July 24, 1990



## OIL IN THE OCEAN: THE SHORT- AND LONG-TERM IMPACTS OF A SPILL

### SUMMARY

This report describes the short- and long-term impacts of an oil spill. The short-term impact is the incident as generally portrayed immediately following the spill, and the long-term impact is the life cycle of the spilled oil itself. Not surprisingly, the impacts are often different. The media presentation is commonly one of a catastrophic occurrence, and a major oil spill is indeed that. Media coverage also tends to focus on the more emotional aspects of destruction to the local environment, to which irreparable harm is often claimed. Rarely does media coverage convey the fact that oil is a natural substance, and that natural processes, over time, will do much to remove it.

Oil that is spilled or seeps naturally into the ocean is eventually accommodated by natural physical, chemical, and biological processes, including spreading, evaporation, solution, emulsification, tar lump formation, photochemical oxidation, microbial degradation, uptake by organisms, and sedimentation and shoreline stranding. Factors particular to each spill influence the effectiveness of these processes, and determine the severity of the ecological impact. Although human intervention can help to make a shoreline look clean, it has rarely been very effective in removing oil, and improper clean-up methods can be detrimental to the ecological restoration of the area. Historically, it has been unusual for more than 10 to 15 percent of the oil to be recovered from a large spill.

The life cycles of six major oil spills were chosen for examination because they occurred sufficiently long ago for long-term effects to have become apparent and for attention from the media to have long subsided. Because they are still being studied, the *Exxon Valdez* and the *Mega Borg* incidents are not discussed. The six events chosen are the Santa Barbara and Ixtoc I blowouts and the *Argo Merchant*, *Burmah Agate*, *Alvenus*, and *Amoco Cadiz* tanker spills. Each event received extensive media coverage at the time and are still thought of by many as major environmental catastrophes. In fact, the environmental damage and socioeconomic consequences were relatively modest, and, as far as can be determined, of relatively short duration.

The longest residence time spilled oil appears to have in the marine and coastal environment is generally less than a decade—often much less. The major ecological impact comes at the time of the spill or within the first few months. Beyond a few months, most oil is reduced to tarry residues or is chemically detectable in sediments and resident organisms, which may be of scientific interest, but in terms of further ecological impact, likely to be fairly insignificant. Short-term impacts on marine animal life are dramatic but recovery of species populations in almost every case studied has been swift.

Because many physical and biological processes in the marine and coastal environment are poorly understood, it is difficult for scientists to measure the full impacts of an oil spill and sometimes the results appear contradictory.

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## **OIL IN THE OCEAN: THE SHORT- AND LONG-TERM IMPACTS OF A SPILL**

### **INTRODUCTION**

Crude oil is made by nature and has long been part of the environment. Oil forms largely from the burial and transformation of marine organisms under heat and pressure over geologic time. Most of the oil that ever formed was not trapped in reservoirs, but seeped to the surface where it was decomposed, digested, and recycled. Many of these seeps are small, but many are not. A significant amount of this seepage and recycling occurs in the marine environment. Although difficult to quantify, it is estimated that on the order of 1.5 million barrels of oil enter the oceans from natural seeps each year, and even this amount may be an order of magnitude too low.<sup>1</sup> In any event, oil has been common to the oceans for hundreds of millions of years, long before the advent of humans. When oil seepage or oil spills occur, natural organisms and natural chemical processes act to decompose it. For example, an average liter of seawater normally contains about ten hydrocarbon decomposing bacteria, but after an oil spill their population densities can reach 50 million per liter.<sup>2</sup>

As it comes out of the borehole, crude oil has never been of much practical use. In a refinery, this unpretentious raw material is converted into hundreds of products and chemicals essential to maintaining the quality of life in modern society. Some of these refined products are less common and more toxic than crude oil and are also commonly transported by tanker. A spill of refined products can differ considerably from a spill of crude oil, as will be shown.

Human activities involving oil in the marine environment include drilling for and producing crude oil offshore and transporting both crude oil and refined products by tanker. These activities rarely take place in a pristine environment. Human beings have had an impact on the ocean, particularly coastal areas for many years. Consequently, a return to pre-spill conditions can easily mean a return only from a very disturbed to a less disturbed condition. In addition, "normal" or "baseline" conditions are not static because the environment is dynamic and constantly changing, not only from human disturbance, but also from natural change. Many physical and biological processes are occurring in the marine and coastal environment that are only poorly understood. For these reasons, it is particularly difficult for scientists

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<sup>1</sup> National Research Council. Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., 1985, 601 p.

<sup>2</sup> Coastal Zone Management, June 20, 1990, p. 7.

to measure the full impacts of an oil spill and sometimes the results appear contradictory.

A major oil spill is both tragic and (as long as the world is based largely on a petroleum economy) inevitable, because no technology is without environmental cost and none is fail-safe. A recent study performed for the State of Alaska determined that a catastrophic spill in the Valdez tanker trade, similar in magnitude to the *Exxon Valdez* spill in Prince William Sound (the *Exxon Valdez* spilled 258,000 barrels), would occur on the average of once every 13 years, or about once every 11,600 transits, under the circumstances that existed prior to the spill.<sup>3</sup> Thus, by those estimates, the *Exxon Valdez* spill occurred within the predicted time frame. Improvements already accomplished, and further improvements to be accomplished, will likely extend the average recurrence interval considerably.

Following the *Exxon Valdez* spill, leaders in the House and Senate announced that comprehensive oil pollution liability and compensation legislation was a priority. There appears to be a general consensus among the Administration, Congress, and the oil industry that such legislation is necessary. Subsequently, the House has passed H.R. 1465 and the Senate passed S. 686, which are now in conference (the conferees reached agreement on July 26, 1990). These bills would internalize the immediate costs of pollution cleanup and damages within the oil-handling industry (although ultimately they would be borne by consumers). Also the bills would offer financial protection to a number of industries and businesses affected by a spill, including the fishing and recreation industries that are characterized by many small participants and are subject to natural and seasonal variations. In addition to providing a framework for dealing with a spill event after it occurs, the legislation also addresses spill prevention through technology and operational requirements and safety provisions. These include the establishment of an oil spill research and development program and tanker operation and design regulations including provisions relating to alcohol and drug abuse, access to the National Drivers Registry, and requirements for double hulls. Taxing provisions to establish a \$1 billion compensatory fund were passed as part of the Reconciliation Act (P.L. 101-239, Section 7505. (For a summary of the issues addressed in the differing provisions of the House- and Senate-passed bills, see CRS Issue Brief 89082, *Oil Pollution Liability and Compensation Legislation After the Exxon Valdez Oil Spill*.)

It is possible to think of an oil spill as having two life cycles. One is the short-term life cycle generated by the human environment, including the media and other interests (primarily affected individuals, State and local governments, and environmental groups); the other life cycle is the biogeochemical cycle of carbon and its compounds in the natural environment.

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<sup>3</sup> Spill: The wreck of the *Exxon Valdez*. Report of the Alaska Oil Spill Commission, Jan. 1990, Executive Summary, p. 4.

The former is generally given great attention; the latter is rarely considered outside of the technical and scientific literature. Consequently, the perceived impact of an oil spill may be little related to what ultimately happens to the oil or to the interaction that the oil has on the affected area, but rather to what is said about the event at the time. This is significant because the public and policy decision makers can be influenced by perceived impacts of events.

### **FACTORS THAT DETERMINE THE SEVERITY OF THE ECOLOGICAL IMPACT**

A great number of factors, individually or in combination, govern the effects that an oil spill may have on marine life. Some spills may have a relatively minor effect compared to others which may be much more locally damaging. The biological damage that results depends largely on the following factors:

1. The dosage of oil and the duration of the exposure;
2. The type of oil involved, particularly with respect to its content of the more toxic aromatic compounds;
3. Whether the oil is in a fresh, weathered or emulsified form;
4. Whether a coastal, estuarine or open ocean area is involved, and whether it is a nesting or wintering ground for sea birds, migration route, etc.;
5. Natural environmental stresses imposed by meteorological or oceanographic parameters such as fluctuations in salinity, water temperature, wind conditions, etc.;
6. The season of the year with respect to whether organisms are dormant or actively feeding and reproducing;
7. Whether adult or juvenile forms are involved;
8. Whether the oil is in solution, suspension, or absorbed onto particulate material;
9. Distribution in the water column, such as whether plankton, pleuston, nekton or benthos are involved and which species;
10. The effects of oil on competing biota;
11. The ecosystem's previous history of exposure to oil or other pollutants; and

12. Clean-up procedures, if any, that have been used, and, particularly, whether chemical agents have been used.<sup>4</sup>

### Oil Dosage

Many of these factors are interrelated. The dosage of oil an area receives depends primarily on the size of the spill and the elapsed time before it is dispersed. Physical constraints on the spill, such as embayments, do not allow oil to disperse rapidly and, thus, effective dosage will be increased. The portions of the oil that sink, float, and dissolve also determine the dosage. In general, the biological damage is much more severe if the spill occurs in a coastal or estuarine environment, especially if the intertidal zone is affected, than if it occurs in the open ocean. This greater damage occurs because there are generally many more diverse habitat types and numbers of organisms in the near-shore areas and because of the presence of the sensitive juvenile stages of many species. By comparison, the reported biological damage in the open ocean has been minimal, with the most visible impacts related to oiled seabirds and marine mammals. Although only a few studies have been conducted, no evidence has been found that plankton populations have been significantly altered by oil spills on the high seas.<sup>5</sup> Even if a large number of algal cells were affected during a spill, regeneration time of the cells (9 to 12 hours), together with the rapid replacement by cells from adjacent waters, would likely obliterate any major impact on a pelagic phytoplankton community.<sup>6</sup>

### Type of Oil

Offshore spills can involve both crude oil and refined products. While OCS production spills would primarily involve crude oil, tanker spills could involve either crude oil or refined products. Generally, refined products such as fuel oil or gasoline have greater concentrations of toxic components than crude oil, and spills of refined products would likely have a greater ecological impact. However, because lighter refined products such as fuel oil or gasoline are more volatile than crude oil, the visual impact of the spill will be of shorter duration and the likelihood of shoreline impacts will be less. The greater biological impact from refined products has been cited as one reason

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<sup>4</sup> IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP). Impact of Oil on the Marine Environment. Reports and Studies No. 6. Published by the Food and Agriculture Organization of the United Nations, Rome, 1977, p. 54.

<sup>5</sup> National Research Council. Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., 1985, p. 442.

<sup>6</sup> Ibid., p. 404.

for the severity of the observed effects of the well-studied West Falmouth, MA spill in 1969, which released about 4,000 barrels of No. 2 fuel oil into the waters of Buzzards Bay, and surrounding marsh areas (near Woods Hole Oceanographic Institution). No. 2 fuel oil is enriched in aromatics, some of which are created in the refining process. On the other hand, studies of a large fuel oil spill (54,000 barrels) in Japan's Inland Sea in December 1974 indicated no evidence of lasting damage.<sup>7</sup> The Inland Sea seemed particularly vulnerable to contamination because it is relatively shallow and circulation is restricted, but data indicated that populations of marine organisms and water quality returned to normal after three months.

No. 2 fuel oil was also involved in the spill of the Greek-flagged tanker *World Prodigy* which ran aground on Branton Reef just outside of Narragansett Bay, Rhode Island on June 23, 1989. The spill released approximately 6,900 barrels of fuel oil into the coastal waters of Rhode Island. Some shoreline impact occurred and the Rhode Island fishing industry was disrupted for at least a week, but the majority of the oil evaporated. Two weeks after the spill occurred the general scientific consensus was that any longer-term damage would be minimal due to the rapid dissipation of the oil and timely cleanup response.<sup>8</sup>

### **Fresh Versus Weathered Oil**

The longer a spill is exposed and weathered before it enters a sensitive area, the fewer harmful compounds it will contain. Generally, the lighter and more soluble compounds, which are the more toxic, are removed and degraded early in the weathering process, as will be shown in the following section on the geochemical life cycle. Heavy tarry residues have much less severe biological impact.

### **Location and Natural Environmental Stresses**

The climatic conditions and location of a spill area influence the ecological impact. The effects of oil spilled in a cold marine environment, such as the North American Arctic, might be much more serious and long lasting than in a more temperate area for the following reasons:

1. Cold temperatures do not permit rapid evaporation of aromatics in oil, thus allowing more of these toxic hydrocarbons to enter solution

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<sup>7</sup> Chemical and Engineering News. No Lasting Damage From Japanese Oil Spill, Oct. 20, 1975, p. 13.

<sup>8</sup> U.S. Congress. Senate. Committee on Environment and Public Works, Subcommittee on Environmental Protection. Three Recent Oil Spills. Hearing, July 13, 1989, U.S. Govt. Print. Off., Washington, 1989, p. 62.

in sea water even though the solubility of these compounds is lower at low temperatures;

2. The rate of bacterial degradation and other processes of weathering are comparatively slower at very cold temperatures; and
3. The marine biota of polar regions are generally long-lived, have low reproductive potentials, and do not have wide-ranging dispersal stages.<sup>9</sup>

On the other hand, biodiversity is lower and fewer species would be affected. In general, however, recovery from an oil spill in polar regions would likely be slow.

Another reason that the location of a spill is an important factor in determining the impact is that biota vary greatly from area to area. For example, the habitat of the East Coast of the United States is geologically and ecologically quite different from the West Coast, and the Louisiana coastal environment is not like that of Alaska. Different organisms react to oil pollution in different ways. What kills one species may have little or no effect on another, thus upsetting prey and predator relationships.<sup>10</sup> Individuals within a species may differ--eggs, larvae, and newly molted individuals have different sensitivities to the same level of pollution.

Location is also important in terms of the physiography and physical energy of the area. For example, a spill off a low-energy marshy area can have much longer lasting effects than a spill on a high-energy rocky coastline. Oil from the *Amoco Cadiz* that entered quiet backwaters was still present in sediment two years later, whereas by that time oil was no longer found in the sediment of some of the more energetic offshore areas.<sup>11</sup>

The season of the year a spill occurs is an important factor. Most marine organisms show natural seasonal variations that are related to yearly cycles as well as year to year variations. For example, if a spill occurs during the season when sea birds are nesting, bird mortality would be much higher than at other times the year. If a spill enters an estuary when salmon smolts are going to sea or during a salmon run, much more severe impacts are

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<sup>9</sup> Boesch, D. F., C. H. Herschner, and J. H. Milgram. *Oil Spills and the Marine Environment*. Ballinger Publishing Co., Cambridge, MA, 1974, 114 p.

<sup>10</sup> IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, *Impact of Oil on the Marine Environment*, p. 54.

<sup>11</sup> Gundlach, E. R., P. D. Boehm, M. Marchand, R. M. Atlas, D. M. Ward, and D. A. Wolfe. *The Fate of Amoco Cadiz Oil*. *Science*, July 8, 1983, p. 122-129.

likely.<sup>12</sup> Larvae that float near the surface of the water, and newly set oyster spat will probably be killed if a spill occurs during this stage of their life cycles, whereas these organisms are less vulnerable during later stages of development. Had the January 1969 blowout spill at Santa Barbara, CA happened earlier, some nursing pups of sea lions and elephant seals may have succumbed after ingesting oil coating their mothers teats, and sea bird populations would have been greater (likely resulting in more mortalities).<sup>12</sup>

Oceanographic and meteorological factors such as wind conditions and currents in the spill area vary from day to day, and may drive floating oil either onshore or offshore. Currents and wave action combine to spread and dilute the spilled oil, thus reducing its potential impact. On the other hand, wave action may intensify problems especially near shore, as apparently occurred at West Falmouth. At West Falmouth, onshore winds churned oil with sediments and drove the oil ashore into the surrounding marshlands. The oiled sediments and marshlands then became a reservoir of oil for several years.<sup>14</sup> Recognizable chemical components of the fuel oil persisted in the sediments for at least 8 years.<sup>16</sup>

At Santa Barbara, the spill occurred during a period of heavy storms that brought flood waters bearing great amounts of sediment into the coastal waters. The sediment-laden fresh water provided an adsorptive surface for the spilled oil causing much of it to settle to the bottom rather than reaching shore.<sup>16</sup> Sedimentation is advantageous to intertidal life because this may prevent the oil from reaching the intertidal zone, but it may be detrimental to benthic life.<sup>17</sup>

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<sup>12</sup> National Academy of Sciences, Ocean Affairs Board. Petroleum in the Marine Environment. National Academy Press, Washington, D.C., 1975, p. 83.

<sup>13</sup> Boesch, et. al., Oil Spills and the Marine Environment, p. 38.

<sup>14</sup> Blumer, M., H. L. Sanders, J. F. Grassle, and G. R. Hampson. A Small Oil Spill. Environment, v. 13, no. 2, 1981, p. 1-12; and Sanders, Howard L. The West Falmouth Spill. Oceanus, fall 1977, p. 15-24.

<sup>15</sup> National Research Council, Oil in the Sea: Inputs, Fates, and Effects, p. 551.

<sup>16</sup> Drake, D. E., P. Fleischer and R. L. Kolpack. Transport and Deposition of Flood Sediment, Santa Barbara Channel, California. In Biological and Oceanographical Survey of the Santa Barbara Channel Oil Spill 1969-1970, v. 2, R. L. Kolpack ed. Allan Hancock Foundation, 1971, p. 181-217.

<sup>17</sup> Blumer et. al., A Small Oil Spill, p. 1-12.

### **Damages Due to Clean Up**

An improper method of cleaning up an oil spill can increase the impact of oil pollution rather than diminish it. At sea, mechanical methods are considered the least damaging to the environment. These methods include the use of booms and skimmers or the spreading and retrieval of absorbent material. Sinking agents acting in the same way as naturally turbid water, transfer the effects from intertidal coastal areas to offshore bottom-dwelling fauna, and may extend the duration of the impact. The use of dispersants is controversial and has been shown to be helpful in some cases and harmful in others, depending on the toxicity of the dispersed oil and the nature of the particular organisms one is intending to protect. Low-toxicity dispersants have the advantage of preventing oil from washing ashore, soiling beaches and killing intertidal organisms, but pose an additional burden on the assimilative capacity of the marine environment. (For a discussion of cleanup technologies see CRS Report For Congress, 90-146 SPR, Oil Spill Response Technologies.)

Onshore, cleaning a soiled marsh area may prolong its recovery rather than aiding it. Scrubbing soiled rocky coastlines with hot water to restore their beauty may be done at the sacrifice of the surviving organisms along the shoreline. Providing nutrients to soiled areas to stimulate natural bioremediation is a new technique that would take longer than scrubbing to achieve a clean substrate but is less environmentally damaging.

With such a complex interaction of variables, it is not possible to predict accurately the severity of the ecological impact of an oil spill. However, it would appear predictable that long-term effects, if any, would be minimal. Further insight into the latter can be gained, however, by examining the fate of petroleum in the marine environment.

### **THE BIOGEOCHEMICAL LIFE CYCLE OF OIL IN THE OCEAN**

When petroleum enters the ocean, it immediately begins to undergo a series of weathering and biological processes that distribute the material in the environment and alter its physical and chemical nature. The ultimate result of these processes is the complete removal of essentially all traces of the original crude oil and the geochemical recycling of the carbon. The time involved in this chemical recycling process can range from a matter of minutes and hours for the removal of some components of crude oil to a few years for other components. Figure 1 summarizes the fate of oil in the ocean superimposed with a general indication of the time frame of each process. The width of the lines generally indicates when that process is primarily operating and its relative magnitude compared to the others.

In general, during the aging of a spill in the open ocean, the relative influence of the various dispersive and degradative processes shifts from rapid physical effects to slower chemical and biochemical modifications. Initially the

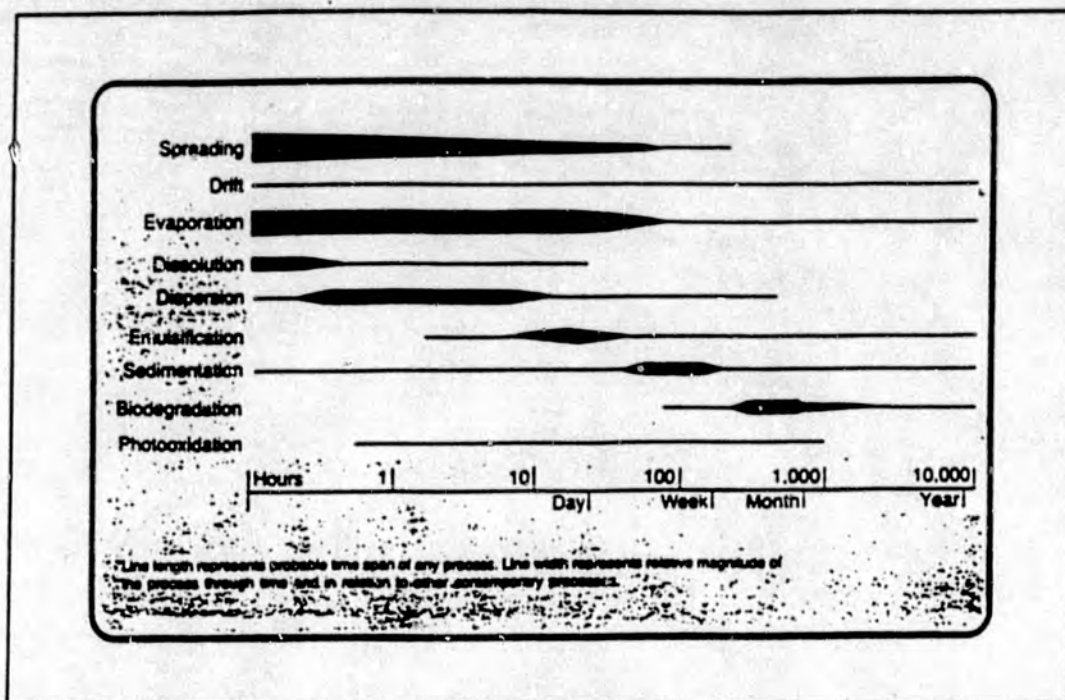


**Figure 1.** Approximate time span and relative magnitude of processes acting on spilled oil.

*Source: Exxon Production Research Company*

oil spreads rapidly through the combined action of gravity and surface chemistry. As the surface to volume ratio increases there is greater exposure to air, sunlight, and sea water. Spreading, evaporation and solution are the primary physical dispersive processes while photooxidation and biological degradation begin to assume a more dominant role as exposure time increases. Eventually, a relatively mature phase is reached when more refractory or resistant tarry residues predominate. Figure 2 is a stylized representation showing various pathways without attempting to quantify reaction rates. Reaction rates are poorly known as they depend on much the same interacting variables that determine the severity of the ecological impact described previously.

The following sections consider the physical, chemical, and biological processes that operate during the life cycle of an oil spill. The physical and chemical processes involved include spreading, solution, evaporation, emulsification, photochemical oxidation, tar lump formation, and sedimentation. Biological processes include degradation by microorganisms and uptake by larger organisms with subsequent metabolism, storage, and discharge. In addition, concerns that have been raised over the possibility of food chain magnification are reviewed.

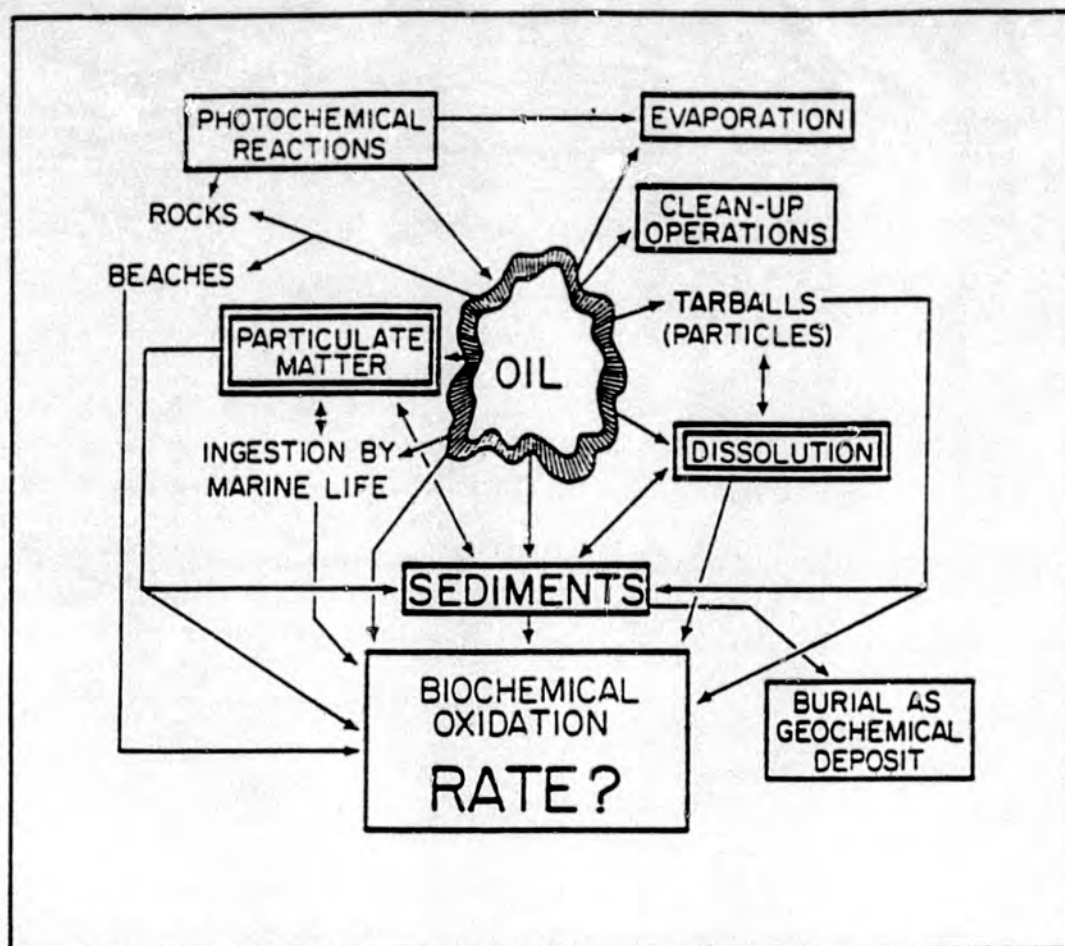


**Figure 2.** Fate of oil inputs to the marine environment.  
*Source: Oceanus, v. 20, no. 4, Fall 1977.*

### Spreading

Spreading begins as soon as petroleum is released into the ocean. Ultimately the area occupied by an oil slick is dependent on the volume spilled. Initially the physical process of spreading is controlled by gravitational effects which are influenced by wind, waves, and currents. After a few hours, the chemical and physical nature of the oil such as viscosity and surface tension become the controlling factors on the extent of spreading. The polar, surface-active constituents, containing nitrogen, oxygen, and sulfur, are influential in spreading a spill into very thin layers that approach monomolecular dimensions at the edges of the slick. Even massive spills eventually spread into thin layers and become fragmented by wind and waves into patches and windrows.

Spreading is important in the life cycle of a spill in that it greatly increases the surface area of the oil, thereby increasing its exposure to air, sunlight, and underlying water. This enhances the rate and effect of the other processes. However, spreading also reduces the effectiveness of mechanical recovery equipment.

## Evaporation

Evaporation is the process in which low to medium weight crude oil components with low boiling points volatilize into the atmosphere. Evaporation is greatly enhanced by spreading. The rate of evaporation is greatest during the early stages of a spill. It appears that most hydrocarbons of around twelve carbon atoms or less are lost through evaporation within the first few days, with heavier hydrocarbons, up to twenty carbon atoms, evaporating over a few weeks. Through the selective processes of evaporation, aided by solution, the specific gravity of the oil increases. As evaporation progresses crude oil begins to resemble Bunker C (heavy) oil in composition. As a spill matures further, these processes contribute to the formation of thick sludge, tar balls, and eventually to sinking if the residual oil becomes denser than sea water.

For the Ixtoc I blowout, evaporation was the predominant weathering mechanism, resulting in a nearly equal loss of saturated and aromatic hydrocarbons with low boiling points.<sup>18</sup> Total evaporation loss is difficult to measure. Indirect evidence from compositional changes and laboratory studies indicate that 20 to 40 percent of an "average" crude oil spread over the sea surface can be removed by evaporation. Researchers studying the *Amoco Cadiz* tanker spill estimated that about 30 percent of the oil was removed through evaporation.<sup>19</sup>

## Solution

Solution is the physical process by which the low molecular weight hydrocarbons, as well as some of the more soluble nonhydrocarbon constituents, enter the water column. The water soluble fractions of crude oil include light alkanes, such as propane, through isopentane and the light aromatics, benzene, toluene, and xylene. The acute toxicity of an oil is largely related to its soluble di- and tri-aromatic hydrocarbon content.<sup>20</sup> Even though solution starts as soon as the oil is released into the sea, it can continue for a long period as more soluble degradation products continue to be formed from biological and chemical oxidation. The rates at which soluble

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<sup>18</sup> Boehm, P. D. et. al. Physical-Chemical Weathering of Petroleum Hydrocarbons from the Ixtoc I Blowout--Chemical Measurements and a Weathering Model. In Proceedings, 1981 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 453-460.

<sup>19</sup> Gundlach, E. R. et al., *The Fate of Amoco Cadiz Oil*, p. 122-129.

<sup>20</sup> IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, *Impact of Oil on the Marine Environment*, p. 25.

components are removed from crude oil are poorly known. Over short periods of time, evaporation will remove highly soluble components more rapidly than solution. Evaporative weathering causes an equivalent depletion of saturated and aromatic compounds with low boiling points, whereas solution preferentially depletes low-boiling aromatics relative to saturated compounds, because of the much greater solubilities of the aromatics. Over a longer period, the solution rate will decline because of the lower solubility of the remaining high molecular weight components.

### **Emulsification**

Most of the components of petroleum are relatively insoluble in seawater and in rough seas tend to form emulsions. Emulsions are of two types: oil-in-water emulsions where fine particles of oil are incorporated into the seawater, and water-in-oil emulsions where the floating emulsion contains 30 to 80 percent water. The latter are formed particularly from heavy crudes and are commonly referred to as "mousse." Emulsification promotes solution of the more soluble components by increasing surface area contact between oil and water. The eventual fate of oil-in-water emulsions appears to be dissolution in the water column or association with particulate matter and eventual biodegradation or incorporation in sediments. Mousse has been suggested as a source of pelagic tar lumps. Mousse can sink or become stranded on shore before degradation is completed.

### **Tar Lump Formation**

The weathering processes described above can lead to the formation of residual lumps of tar which are much slower to degrade. These have been observed in the open ocean and can be a particular annoyance when washed up on beaches. At this stage of the weathering process, very little material lighter than 15 carbon atoms remains. Most tar lumps consist of paraffinic hydrocarbons of up to forty carbon atoms, and frequently contain waxy inclusions. These remain fairly persistent in the marine environment. For example, it was estimated that five to ten percent of the pelagic tar found in the eastern Gulf of Mexico four years after the Ixtoc I blowout originated from that event.<sup>21</sup>

### **Sedimentation and Shoreline Stranding**

For residual fractions of crude oil to sink before reaching shoreline areas, the density must increase sufficiently. This generally occurs through loss of lighter components by evaporation and dissolution and/or sorption of liquid or dissolved components onto denser particulate material. Sedimentation is

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<sup>21</sup> Oil Spill Intelligence Report, v. VI, no. 24, June 24, 1983.

dependent on the availability of dense particulate matter to act as nuclei. This process can be especially important in removing petroleum from the water column in near shore areas or estuaries where there is generally a high concentration of suspended sediment. The chemistry of interactions with particulate material depends on the locale and the composition of the materials. Fine grained clay minerals can remove dissolved petroleum through absorption and adsorption. Sorption increases with salinity and decreases with temperature. Rough seas in shallow waters also stir up sand, silt, clay, and shells on which petroleum can be absorbed or agglomerated.

The further movement and fate of oil in bottom sediments is poorly understood. A succession of chemical studies following the barge spill of No. 2 fuel oil in Buzzards Bay, Massachusetts, in 1969, showed that oil trapped in subtidal sediments continued to expand in areal extent for several years after the spill.<sup>22</sup> Presumably various suspension and resedimentation processes occurred aided by current movement and reworking of surface sediments. In addition, there was an extremely slow rate of degradation of the fuel oil in the sediments with recognizable components present more than eight years later.<sup>23</sup>

Investigations following the *Amoco Cadiz* spill off the coast of France confirmed that oil persistence in subtidal sediments appeared to correlate with the physical energy of the particular site and the type of sediment. For example, of a total of 56,000 barrels of crude oil hydrocarbons estimated to have become incorporated into subtidal sediments in the Bay of Lannion and the Bay of Morlaix during the first month of the spill, only 13,000 barrels were present four months later. After an additional year this had declined to less than 6,000 barrels and little or no oil remained in the sediment after two and one half years.<sup>24</sup> On the other hand, fine grained sediments in lower wave energy, sheltered interior areas of Aber Wrac'h were still found to contain oil after three years, and the heavily-oiled marsh areas, in general, took an additional 2 to 5 years to recover fully.

Shoreline stranding is one of the more distressingly visible intermediate fates of petroleum from an offshore spill. Recovery times depend on the extent of the initial impact, the persistence of the oil, inherent factors of the biological community governing its resiliency, and the extent of biological interactions such as predation, parasitism, and competition. In the case of the high-energy rocky shores at Santa Barbara, California, recovery time was on the order of weeks to a few months, whereas soft-bottom offshore areas and marsh ecosystems such as Ile Grande, France were affected for several

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<sup>22</sup> Sanders, Howard L. The West Falmouth Spill--Florida, 1969. *Oceanus*, v. 20, no. 4, fall 1977, p. 15-24.

<sup>23</sup> *Ibid.*, p. 24.

<sup>24</sup> Gundlach, E. R. et. al. The Fate of Amoco Cadiz Oil. *Science*, v. 221, July 8, 1983, p. 122-129.

years. Oil presumably from the Ixtoc I spill, in the form of tar mats consisting of sediment and mousse, was periodically uncovered by storm action along the south Texas coast for about a year. A field experiment of the persistence of stranded crude oil and mousse on seven shores around the coast of Great Britain showed that the residence times ranged from a few days to one year.<sup>25</sup>

### Photochemical Oxidation

Photochemical oxidation is the process whereby energy from sunlight in the presence of oxygen transforms hydrocarbons into oxygenated compounds (e.g., carboxylic acids, benzoic acid, alcohols, ketones, phenols), with the general result that the oxidation products are more soluble in water than the original compounds. Some products have been found in the laboratory to be more toxic than the parent compounds. Observers studying the *Amoco Cadiz* spill (a tanker spill off the coast of France in 1978) found photooxidation products in environmental samples similar to those found in laboratory studies. The rate of oxidation of hydrocarbons varies with their chemical nature. In photochemical processes, the optical density of the oil, particularly in the ultraviolet, is an important variable. Investigators have made experimental studies of the actual decomposition rates of slicks by photolysis. It was found that photolysis can initiate sufficient oxidation to decompose a thin slick in a few days.<sup>26</sup>

### Microbial Degradation

As the residence time of oil in the ocean increases, biological processes begin to operate and rapidly gain in significance. Hydrocarbon decomposing microorganisms are ubiquitous. Over 90 species of microorganisms (bacteria and fungi) capable of subsisting on petroleum and, therefore, capable of degrading it by biological oxidation, have been identified.<sup>27</sup> Microbial processes also transform hydrocarbons to more soluble oxidized products, which eventually are completely oxidized to carbon dioxide and water.

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<sup>25</sup> Little, D. I. and D. L. Scales. The Persistence of Oil Stranded on Sediment Shorelines. In Proceedings, 1987 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4452, 1987, p. 433-438.

<sup>26</sup> National Academy of Sciences, Petroleum in the Marine Environment, p. 48.

<sup>27</sup> IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, Impact of Oil on the Marine Environment, p. 29.