Effects of Oil and Chemically Dispersed Oil in the Environment

Health and Environmental Sciences Department
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Prepared Under Contract by:
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American Petroleum Institute

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BACKGROUND ON THIS BOOKLET SERIES

Beginning in 1994, the Marine Spill Response Corporation (MSRC), and later the Marine Preservation Association (MPA), sponsored a study to examine the reasons for the apparent differences between expert and non expert perceptions of dispersant use and the ecological effects of dispersant use. Using a prescribed risk communication methodology, this study compared the mental models (an individual's thought processes in making a decision regarding a particular issue) of US dispersant decision-makers and other stakeholders to an expert model (expert consensus of the relevant decision concepts that might be used), specifically looking at the fate and effect of spilled oil in comparison to chemically-dispersed oil. Through a series of interviews and written questionnaires, a number of dispersant misperceptions were identified. These misperceptions were translated into topics for booklets that would provide dispersant information in a concise and reader-friendly format. For more information on the MSRC/MPA study, please see Bostrom *et al.*, 1995, Bostrom *et al.*, 1997, and Pond *et al.*, 1997.

As a result of the MSRC/MPA work, in 1996, the American Petroleum Institute (API) commissioned the preparation of three dispersant-related booklets:

- Fate of Spilled Oil in Marine Waters: Where Does It Go? What Does It Do? How Do Dispersants Affect It? An Information Booklet for Decision Makers.
- A Decision-Maker's Guide to Dispersants: A Review of the Theory and Operational Requirements.
- Effects of Oil and Chemically Dispersed Oil in the Environment.*

*This booklet is the third in the series. In the previous two booklets it was referenced by a draft title - "Defining the Links Between Fate and Transport Processes with Exposure and Effects of Oil and Chemically Dispersed Oil in the Environment."

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OVERVIEW

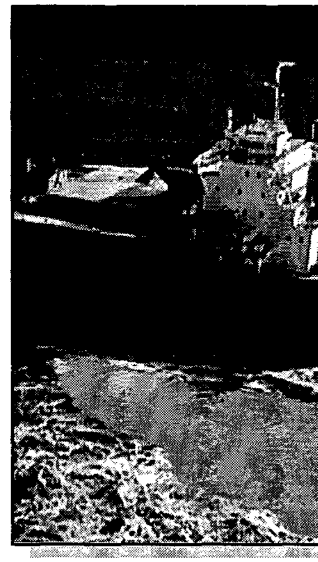
- The American Petroleum Institute commissioned the preparation of three booklets to help bridge the gap in the understanding of dispersant use, effectiveness, and effects.
- This third booklet focuses on exposure and effects of untreated oil and chemically dispersed oil in the marine environment.
- Crude oil is a complex, highly variable mixture of hydrocarbons and other trace compounds. Exposure may cause a variety of adverse effects, including narcosis, slowed growth, reduced reproduction, and death.
- Dispersants are mixtures of chemicals known as solvents and surfactants. Solvents reduce the viscosity of both the oil and the dispersant, and help surfactants penetrate into the oil. The surfactants then help the oil break up and disperse into the water column.
- Toxicity is the "inherent potential or capacity of a material (in this case, oil or dispersed oil) to cause adverse effects in living organisms".
- To be toxic, oil components must be bioavailable to the organisms being exposed. Many of the components in oil are considered toxic, but have limited bioavailability in the environment. Toxic effects depend on the duration of exposure, and the concentration of the chemical(s) involved.
- Concentrations of chemicals and oil are often measured in parts-per-million (ppm) or parts-per-billion (ppb). To quantify toxicity data, endpoints are often expressed in terms of the concentration necessary to kill 50% of the test organisms over a specified time period (LC_{50}) or the concentration necessary to cause a particular effect in 50% of the test organisms over a specified period of time (EC_{50}).
- Toxic effects can be lethal (causing death) and sublethal (e.g., disorientation, reduced growth and reproduction).
- Toxic effects can also be acute (caused by short-term exposure) or chronic (caused by long-term exposure).
- The amount of oil exposure an organism will experience depends on many factors, including:
    1. Oil type
    2. Spill volume
    3. Shoreline type
    4. Tide stage
    5. Weather conditions

- There are four main routes of exposure for organisms during a spill:
    1. Direct contact - an organism contacts or becomes coated with a substance.
    2. Ingestion - an organism eats or drinks a substance.
    3. Inhalation - an organism inhales a substance in the form of a vapor, mist, or spray.
    4. Absorption - an organism absorbs a substance directly through its skin or respiratory membranes.
- After oil is spilled, it typically undergoes eight main fate and weathering processes, which may all occur simultaneously in different degrees:
    1. Spreading and advection - When spilled, oil spreads out on the surface of the water. This increases the surface area of the oil, thus increasing the potential for exposure by all routes.
    2. Evaporation - Many components of oil evaporate. This creates a vapor that can lead to inhalation of toxic compounds as they pass from the water surface to the atmosphere.
    3. Dissolution - Some components of the oil will go into solution in the surrounding water. This increases the chance of exposure through direct contact, ingestion, or absorption for water column resources.
    4. Natural dispersion - Oil breaks up into droplets in the water beneath the slick and may float away. As a result, water column resources can be exposed through direct contact, ingestion, and absorption.
    5. Emulsification - Oil and water combine to form a mousse. Exposures can result from direct contact or ingestion.
    6. Photo-oxidation - Sunlight transforms some oil components into new by-products, which may be more toxic and water-soluble than the original components. Water surface and water column resources can be exposed to the by-products through inhalation, direct contact, absorption, and ingestion.
    7. Sedimentation and shoreline stranding - Oil washes ashore and also sinks after sticking to particles in the water. Exposure can occur through direct contact and ingestion of stranded or sunken oil.
    8. Biodegradation - Oil is slowly broken down by resident bacteria into H_2O and CO_2. Biodegradation is a slow process, with little effect on exposures.
- Different resources are at varying risk of exposure to untreated oil and chemically dispersed oil. These resources are discussed in the following groups:
    1. Surface-dwelling resources - This typically includes birds, marine mammals, and reptiles. These resources are at high risk of exposure to oil floating on the surface during a spill.
    2. Water column (pelagic) resources - This group includes fish and plankton. They are typically at lower risk of exposure to oil during a spill. Dispersion can temporarily increase the risk of exposure to these resources.

3. Bottom-dwelling (benthic) resources - This includes all resources that live on, or in, the bottom. Typical examples are many species of crabs, bivalves, and plants. They are usually at lower risk of exposure during a crude oil spill and are most affected by sinking oil.
4. Intertidal resources - These resources live in the areas that are exposed to air during low tides, but submerged during high tides. They also include many species of crabs, bivalves, and plants. If a spill reaches the shore, these resources are at high risk of exposure, as successive layers of oil can be put down by tides and winds.

- Bioaccumulation and biomagnification of hydrocarbons are not believed to be of great concern to vertebrates (fish, mammals, etc.) since they are able to metabolize them. Some invertebrates, however, have limited, if any, capability to metabolize hydrocarbons (e.g., shellfish). Long term contaminated shellfish may be able to eliminate (depurate) hydrocarbons over time if they can be placed in uncontaminated waters. The effects (if any) of oil on these organisms have not been clearly established.
- Tainting (the presence of an "off-taste" or smell in seafood) is a concern after a spill. Tainting cannot be easily tested. Tainting will cause the greatest problems in shellfish, which have a limited, if any, ability to metabolize hydrocarbons. Finfish can metabolize the oil within several days after exposure ends.
- Field tests and spill studies on dispersant use have generally found that the use of dispersants has some drawbacks and may increase adverse effects to some resources in the short-term. However, this can be outweighed by the immediate and longer-term beneficial effects to other resources that can result from dispersant use.
- Dispersants and chemically dispersed oil will affect different resources in different ways, depending on the exposure conditions and the manner in which the dispersants are used. The potential environmental benefits and impacts of dispersant use tradeoffs among resources should always be carefully weighed.
- To minimize adverse effects on water column resources, dispersant use in waters less than 10 meters deep, in bays, or in areas with low flushing rates has historically been avoided. However, dispersant use need not be ruled out automatically. In these areas, dispersant use should be examined and compared to other response options in order to determine the optimal response in terms of net environmental benefit. The response method providing the greatest net environmental benefit should be the determining factor in these areas.
- Ecological risk assessments enable the methodical comparison of ecological tradeoffs of various response methods. Ecological risk assessments should be part of pre-spill planning activities to speed the decision-making process for possible dispersant use during actual incidents.

Introduction



Consider this scenario – an oil tanker has been involved in an accident near mangroves and a large salt marsh. Some of the tanker's cargo has been released in the accident. One member from the team of decision-makers is assigned the responsibility of recommending countermeasure options. While dispersants are one option, he is concerned about their possible effect on resources in the area, including all resident plants and animals. Many papers are available which provide information on the different effects of chemically dispersed oil on biological resources. However, applying the findings from numerous scientific experiments to a real-world emergency is not easy. What this person wants is a concise booklet that in layman's terms explains the general effects of oil and chemically dispersed oil on various biological resources. Such a booklet would have made preparing for, and now dealing with, dispersant use issues less time consuming, while making the information more comprehensible. This booklet was designed to fill that planning need. Ideally, it should be read along with other reference material as part of pre-spill planning activities, not just during a response emergency.

Purpose of the Booklet

This booklet has been developed as a reference document for oil spill response decision-makers, to provide an accurate summary of exposure and effects of oil and chemically dispersed oil in the marine environment. During both pre-spill planning and actual response, decision-makers are faced with many questions concerning exposure and effects. For instance:

- What will the oil do to a particular biological resource, both to individuals and the entire population?
- Is dispersant alone likely to cause adverse effects?
- Will adding chemical dispersants change the way oil affects plants and animals?
- Would it be better to expose one resource to the oil so that another resource could be protected?

These are the types of questions addressed in this booklet.

Part One of the booklet provides a general, background discussion on concepts necessary for understanding the potential sources of oil and dispersed oil contamination that can cause adverse effects. This information provides the foundation for understanding oil chemistry, toxicity, and exposure. **Part Two** focuses on the effects of undispersed oil and **Part Three** discusses how chemically dispersing oil changes exposure and effects to marine animals and plants. Resources are discussed in groups, according to their distribution in the environment and their likelihood of exposure to oil and chemically dispersed oil (i.e., surface-dwelling, water column, bottom-dwelling, and intertidal). **Part Four** provides information on the tradeoffs of various decisions and information on conducting an ecological risk assessment.

This booklet also identifies and explains specific terms associated with oil that may be used by technical experts during planning or response operations. The first time a new technical term is used within this booklet, it will appear in an ALL CAPS format; this signifies that a more detailed explanation or definition is present in the right or left margin near where the word(s) is first used within the main text.

PART I: SOURCES OF CONTAMINATION AND INJURY

The type of oil spilled is a key variable in determining its impact on a biological resource. The composition of crude oil is different from refined products, and both compositions can vary greatly. For instance, one crude oil may have many components that evaporate quickly into the atmosphere, whereas, another crude oil may be composed of many heavy components that can persist in the environment for a long time. General oil properties are reviewed below. A more detailed discussion on oil chemistry can be found in the first booklet in this series, "Fate of Spilled Oil in Marine Waters: Where Does It Go? What Does It Do? How Do Dispersants Affect It?: An Information Booklet for Decision-Makers."

Purpose of Part I, Section I

To review oil composition and properties.

Hydrocarbons *are chemical compounds composed solely of carbon and hydrogen atoms. In crude oils, hydrocarbons are the most abundant compounds-up to 85 percent of the overall mixture (Gilfillan, 1993).*

SECTION I: WHAT IS OIL?

HYDROCARBONS are the most abundant organic compounds in crude oil (NRC, 1989; Gilfillan, 1993). There are essentially three groups of hydrocarbon components in every crude oil type:

1. Lightweight components (low molecular weight)
   - contain 1 to 10 carbon atoms (C1 to C10);
   - evaporate and dissolve more readily than medium or heavyweight components, and also leave fewer residual weathering compounds (often called residue) than medium or heavyweight components;
   - are thought to be more BIOAVAILABLE to animals (readily absorbed by an organism) than medium or heavyweight components; and
   - are potentially flammable and readily inhaled, so, are of concern for human health and safety.

   Examples: Benzene, Toluene, Ethyl-benzene, Xylene, ALKANES (see the first booklet in this series for more information).

   Because lightweight components are biologically available to organisms and can be readily inhaled, their potential TOXICITY to animals and humans is of concern.

2. Medium-weight components (medium molecular weight)
   - contain 11 to 22 carbon atoms (C11 to C22);
   - evaporate or dissolve more slowly, over several days, and may leave behind some residual weathering compounds which can appear as a coating or film;
   - are sometimes regarded as more toxic than the lightweight components; and
   - are not as bioavailable as lower-weight components, resulting in lower chemical toxicity to animals.

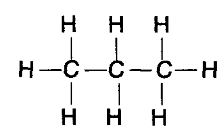
   Example: POLYCYCLIC AROMATIC HYDROCARBONS (PAHs) (see the first booklet in this series for more information).

3. Heavyweight components (high molecular weight)
   - contain 23 or more carbon atoms (≥C23);
   - undergo little to no evaporation or dissolution;
   - can cause long-term affects via smothering or coating by residual weathering compounds. These residuals may remain in the water column and sediments indefinitely (Helton, 1996); and
   - are not very bioavailable, resulting in lower chemical toxicity to animals when compared to light or medium-weight components.

   Example: Asphaltenes (see the first booklet in this series for more information).

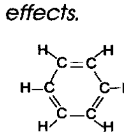
To be ***Bioavailable*** *is to be in a form that is conducive to uptake by organisms. Bioavailability is the tendency of a substance (in this case, individual oil components) to be taken up by a biological organism (Rand and Petrocelli, 1985).*

Alkanes *are petroleum hydrocarbon compounds, also called normal paraffins and isoparaffins. Alkanes are characterized by branched or unbranched chains of carbon atoms with attached hydrogen atoms and contain only single carbon-carbon bonds (no double or triple bonds between carbon atoms).*



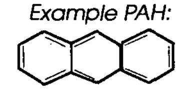
Toxicity *represents the degree of danger a substance poses to animal and plant life. The words "toxic" and "poisonous" have, essentially, the same meaning. Therefore, it can be said that something with high toxicity is highly poisonous, and vice versa.*

Polycyclic Aromatic Hydrocarbons (PAHs) *are a class of hydrocarbons characterized by multiple rings with six carbon atoms each. PAHs are considered to be the most acutely toxic components of crude oil, and are associated with chronic and carcinogenic effects.*



Six-carbon Ring

Example PAH:



Anthracene

***Persistence** refers to an oil's or refined product's tendency to remain in the environment for a long period of time following a discharge. Persistent oils are those crude and refined oil products that may not be completely removed from an affected environment as a result of weathering processes or cleanup operations. When reading persistence measurements, higher numbers mean greater persistence.*

***Non-persistent** oils and products will be rapidly and completely removed from the affected environments through natural weathering processes. They are largely composed of light-weight components. Only short-term effects are expected from non-persistent oils.*

***Pour point** is the temperature above which an oil begins to flow.*

Crude oils are composed of various combinations of compounds in each of the three component categories. When comparing crude oils, the concentration of the larger molecular-weight compounds (medium and heavyweight) relative to the amount of lightweight components within the oil affects PERSISTENCE. Oils with greater concentrations of medium and heavyweight components will typically have greater persistence. Because oils with greater persistence remain in the environment longer, they lengthen the period of time during which organisms are at risk of exposure. Oils composed primarily of the lightweight components are usually considered NON-PERSISTENT.

For purposes of illustration, Table 1 lists some of the differences in common petroleum products. For more information on this topic, a full discussion of the properties of different oil types can be found in the first booklet, "Fate of Spilled Oil in Marine Waters: Where Does It Go? What Does It Do? How Do Dispersants Affect It?: An Information Booklet for Decision-Makers."

Table 1. Comparison of oil properties for several commonly used refined oil products.

Oil Type	Components	Relative persistence*	POUR POINT (average)	Boiling Point Range
Gasoline	Mostly lightweight (<10 C atoms)	1	NA (<0° F)	104-302°F
Fuel oil #2 (diesel)	Light- and medium-weight (10 to 20 C atoms)	8	0° F	93-365°F
Fuel oil #6 (bunker)	Mostly heavy-weight (25 to 50 C atoms)	400	60° F	615-826° F

* Relative persistence values were calculated by Markarian *et al.* (1993), and are based on the persistence of the product in the environment, divided by the persistence the least persistent oil product (gasoline), which has a persistence value of 1.

The effects of oil depend on the chemical composition of the oil itself. To be harmful, oil components must be bioavailable to the organisms. Some components which are considered harmful (i.e., alkanes in the C1 to C10 range) have a high volatility. This means that, unless the concentration of oil is very high, they will usually evaporate before becoming bioavailable to organisms in the water column. Other oil components are also considered harmful, but their molecules are very large, making them less soluble in water. Because these components are less soluble, they are also less biologically available to organisms in the water column. The two classes of oil components thought to be the most bioavailable, and, thus, most dangerous for water column organisms, include the alkanes in the C12 to C24 range and the two and three-ring polycyclic aromatic hydrocarbons (PAHs) (NRC, 1985; 1989; Gilfillan, 1993; Neff and Sauer, 1995). Potentially hazardous levels of bioavailable oil components such as these usually exist in the water column for only a short period of time after a spill. According to Neff and Sauer (1995), "potentially toxic concentrations of (dissolved) petroleum hydrocarbons, if they are attained at all, probably persist in the water column for only a few days or weeks." This time period is considered to be even shorter by other researchers.

Purpose of Part I, Section II

To review the basic composition and properties of dispersants.

Surfactants *are naturally occurring and chemically manufactured molecules often referred to as surface active agents or "detergents." Surfactant molecules contain both water-seeking (hydrophilic) and oil-seeking (oleophilic, or hydrophobic) portions that orient themselves at the oil-water interface so that the oil-seeking portion of the molecule attaches to the oil and the water-seeking portion of the molecule faces outward into the surrounding water.*

Solvents *are chemical compounds that are included in dispersants to assist the surfactants in penetrating the oil.*

SECTION II: WHAT IS A DISPERSANT?

Chemical dispersants are mixtures that contain "surface-active" chemicals (SURFACTANTS) and SOLVENTS. The surfactants actually cause the oil to "disperse" into tiny droplets that remain suspended in the water column. As the saying goes, oil and water do not mix...without surfactants. In simple terms, surfactant molecules have one end that sticks to oil and another end that sticks to water. This means that the surfactant will work to lightly attach water and oil molecules together, allowing the oil to mix in with the water as small droplets. More information about the action and chemical composition of dispersants can be found in the second paper in this series "A Decision-Maker's Guide to Dispersants."

Purpose of Part II, Section I

To define toxicity and explain how it is typically measured.

Exposure *is contact of an organism with a chemical, physical, or biological agent (e.g., oil). Exposure increases with the amount of time an agent is available for absorption at the exchange boundaries of the organism (e.g., skin, lungs, digestive tract).*

Technically, exposure to a toxin equals dose plus concentration. The dose is the actual quantity of an agent an organism is in physical contact with and the concentration is the amount of the toxin in a given volume of that agent.

PART II: TOXICITY AND EXPOSURE

SECTION I: TOXICITY

WHAT IS TOXICITY?

Rand and Petrocelli (1985) define toxicity as the "inherent potential or capacity of a material [in this case oil or dispersed oil] to cause adverse effects in a living organism." Adverse effects are responses outside the "normal" range for healthy organisms and can include behavioral, reproductive, or physiological changes, such as slowed movements, re-

Solubility *is the capability of a substance to be dissovled in a liquid, such as water. Technically, it is the equilibrium concentration of the product (e.g., components of oil) when in contact with the solution (e.g., water).*

Vapor Pressure *is the pressure at which a liquid (oil components) and its vapor are in equilibrium at a given temperature.*

Salinity *is the salt content of the water. Salinity of typical seawater ranges from 32 to 35 parts per thousand.*

Parts-per-million *(ppm) is one part chemical (e.g., oil) per 1,000,000 (10^6) parts of the medium (e.g., seawater) in which it is contained. For water, the ratio commonly used is milligrams of chemical per liter of water; 1mg/L ≅1 ppm.*

Parts-per-billion *(ppb) is one part of chemical (e.g., oil) per 1,000,000,000 (10^9) parts of the medium (e.g., seawater) in which it is contained. For water, the ratio commonly used is micrograms of chemical per liter of water, 1ug/L ≅1 ppb.*

*An **LC_{50}** (also written as LC50), or median lethal concentration, is the concentration of a chemical required to cause death in 50 percent of the exposed population when exposed for a specified time period, and then observed for a specified period of time after the exposure ends.*

*An **EC_{50}** (also written as EC50), or median effective concentration, is the concentration of a chemical in water to which test organisms are exposed that is estimated to be effective in producing some sublethal response in 50 percent of the test organisms.*

duced fertility, or death. Toxic effects are a function of both the duration of EXPOSURE to the chemical and the concentration of the chemical. In the aquatic environment, the concentration of a chemical, as well as its transport, transformation, and fate, are controlled by: 1) physical and chemical properties of the compound (such as a compound's SOLUBILITY or VAPOR PRESSURE); 2) physical, chemical, and biological properties of the ecosystem (such as SALINITY, temperature, or water depth); and 3) sources and rate of input of the chemical into the environment (Rand and Petrocelli, 1985; Capuzzo, 1987; Gilfillan, 1992).

How is Toxicity Measured?

The objective in measuring toxicity is to estimate the range of chemical concentration that produces some selected, readily observable, and quantifiable response during a given time of exposure (Rand and Petrocelli, 1985). This is referred to as a dose-response relationship and is usually measured in PARTS-PER-MILLION (ppm) or PARTS-PER-BILLION (ppb).

Often, toxicity data are expressed as LC_{50} or EC_{50}. For LC_{50}, the ENDPOINT is mortality over a specified time. Length of exposure is usually 24 to 96 hours and chemical exposure usually remains constant over the entire time period. In some tests, the endpoint is not mortality, but a non-lethal response such as immobility, developmental abnormality, etc. In these cases, results are expressed as EC_{50}, where a significant, defined effect is seen in 50% of the population over a specified time period, usually 24 or 48 hours (Rand and Petrocelli, 1985). Although these tests can be used to produce a numerical measure of a substance's toxicity and provide us with important information about the effects of oil, they cannot accurately reproduce the different types of exposures organisms experience during actual oil spill. During an actual incident, organisms may see exposures of much longer time periods as well as exposures that vary greatly over time; as tides change or currents shift exposures may increase, decrease, or even stop, only to start again hours later.

There are some complicating factors that one should keep in mind when looking at toxicity data. Markarian *et al.* (1993) cautions that use of the term "LC" or "LETHAL Concentration" is inappropriate for testing with oil products. This is because an LC_{50}, for example, should measure the lethal concentration of a *single* compound. However, oil is a mix of compounds and often the exact mixture is not known. Seeing an LC_{50} result for oil does not immediately indicate how the measured concentration was developed. This can make comparisons of oils difficult, because various approaches can provide different results, which are of different scientific relevance (Markarian *et al.*, 1993).

Another complicating factor for those reading toxicity tests with oil products is how the concentration is expressed. Concentrations expressed as the total oil per unit volume (nominal concentration) are misleading because much of the oil is not soluble in the water and, therefore, not bioavailable to water column organisms. Using this nominal concentration will produce overestimates of exposure concentrations and toxicities (NRC, 1989; Lewis and Aurand, 1997). More realistic testing methods measure concentration based on the water-accommodated fraction (WAF) of the oil, which is the fraction of an oil product that remains in the water phase after mixing and settling (CONCAWE, 1983).

Although different species may react to toxic substances in unique ways, animal testing can be used to produce some basic categorizations about the toxicity of substances. Table 2 provides general guidance to the relative toxicity of substances.

Table 2. Relative toxicity of substances (from USFWS, 1984; Hunn and Schnick, 1990). See sidebar for conversion to ppm.

Toxicity Rating	Aquatic 96-hour LC_{50}	Avian Oral 96-hour LD_{50} ($mg_{substance}/Kg_{bird}$)	Mammalian Oral 96-hour LD_{50} ($mg_{substance}/Kg_{animal}$)
Practically Nontoxic	100-1,000 mg/L	> 5,000	>15,000
Slightly Toxic	10-100 mg/L	1,000-5,000	5,000-15,000
Moderately Toxic	1-10 mg/L	200-1,000	500-5,000
Highly Toxic	0.1-1.0 mg/L	40-200	50-500
Extremely Toxic	< 0.1 mg/L	<40	5-50

An ***Endpoint*** *is an observable or measurable biological or chemical event used as an index of the effect of a chemical on a cell, tissue, organ, organism, etc.*

Lethal *means resulting in death. (e.g., lethal effects).*

LD_{50} *is the lethal dose required to kill 50% of the animals tested. "Dose" means that the substance is ingested directly by the animal, not mixed in the surrounding water, as is the case with a lethal concentration.*

mg/L *can usually be converted directly to ppm (i.e., 1 mg/L ≅1 ppm) for rough approximations.*
Here is a general explanation of the math involved: One mg of water is 1 millionth of a liter (1 ppm). If a substance has the same density as water, the conversion is completely accurate. For substances with slightly different densities, such as oil, this conversion provides a quick estimation.

Section II: Exposure

Purpose of Part II, Section II
To explain what exposure is and how it imay be affected by dispersant use.

What is Exposure?

Exposure refers to the amount of contact an organism has with a chemical, physical, or biological agent. When assessing toxicity, it is necessary to know the exposure. The most significant factors are the kind, duration, and frequency of exposure, as well as the concentration of the chemical (Rand and Petrocelli, 1985). NOAA's Damage Assessment Center summarized the factors to be considered when assessing exposure to subtidal and intertidal organisms along shorelines (NOAA, 1996):

- **Oil type** – physical and chemical characteristics of the oil.
- **Spill volume** – size of the discharge and/or amount in shoreline area.
- **Shoreline type** – high energy shorelines may reduce the chance for long-term aquatic exposure, but may also result in the oil being deposited along or above the high tide line. Sediment grain size will also affect exposure, with coarse-grained sediments allowing for more rapid and deeper penetration.
- **Tide stage** – subtidal organisms are at less risk than intertidal organisms, since they won't come in contact with the floating oil.
- **Weather conditions** – floods or storm-driven tides may strand oil in places it would not normally go. Weather conditions can also accelerate or retard oil weathering.

__Acute__ refers to an effect in which the organism of interest is exposed to the contaminant (e.g., oil) for only a small portion of its life cycle (i.e., generally equal to, or fewer than, 4 days). Typical effects endpoints include mortality or immobility.

__Chronic__ refers to an effect in which the organism of interest is exposed to the contaminant (e.g., oil) for a significant stage of its life cycle or the entire life cycle (i.e., generally weeks to years, depending on the reproductive life cycle of the test organism). Typical effects endpoints include non-lethal reproduction, growth, or developmental impairment as well as behavioral changes.

Toxic effects can be produced by ACUTE (short-term) or CHRONIC (long-term) exposure. Acute exposure occurs when an organism is in contact with a chemical for a brief time period. Toxicity testing for acute effects usually involves effects that occur within a four-day period (96 hours) or less. In the case of oil spills, negative effects from acute exposure are usually seen early in the spill. This is because the oil, including the light and medium-weight components which may evaporate, is most concentrated during the first few days. Alternatively, chronic exposures are longer duration (weeks to years), and generally involve daily exposure to smaller amounts of oil or residual weathering compounds from oil.

Changes in Exposure with Dispersant Use

When dispersants are applied during a spill, they act to break up the oil into droplets, moving it from the surface and moving downward into the water column. As a result, dispersants will increase oil exposure to some organisms while reducing it for others. When dispersants are applied, exposure to oil will typically decrease for surface-dwelling and intertidal resources, but increase for water column and bottom-dwelling resources. This is one reason that dispersants are not usually applied to a spill directly over a shallow coral reef. Without dispersant application the oil may stay on the surface and not contact the reef, whereas with dispersant application the reef may be exposed to large numbers of oil droplets.

Section III:
Routes of Exposure

Purpose of Part II, Section III
To discuss the ways organisms can be exposed to oil and how natural changes in spilled oil can affect exposure.

Following a spill, resources can be exposed to oil through four different routes:

1. Direct Contact – This is the most visible route of exposure to an observer. When a plant or animal comes into direct contact with oil, it may only become lightly oiled. It could also become completely coated with oil, making it unable to move, function, or survive. Once an organism is physically coated with oil, the chances of exposure through ingestion, inhalation, and absorption will increase dramatically.

2. Ingestion – Both direct and indirect. Direct ingestion occurs when an organism eats food coated with oil or even ingests the oil itself. Direct ingestion of oil may occur accidentally, such as when a bird attempts to clean oil from its feathers. Indirect ingestion occurs when an organism eats prey or food tainted with oil. This food is not necessarily coated with oil itself, but has been exposed to it previously. For example, an eagle could ingest oil indirectly by eating an animal which swallowed oil during a spill the week before.

3. Inhalation – Inhalation may occur when animals breathe in evaporating oil components or oil mists from storm and wave action. Inhalation usually occurs when animals on the surface (e.g., seabirds, otters, seals) breathe while swimming within a slick. It may also occur when an animal along the shore breathes after getting its head and face coated with oil from feeding or swimming.

4. Absorption – This occurs when an organism absorbs the oil, or toxins from the oil, directly through its skin or outer membranes. Typical examples of organisms to which this could apply are benthic or intertidal molluscs, worms, fish, and plants.

As the oil slick WEATHERS and various oil components are transported into the water column and air, the degree of exposure and, consequently, the impact on living resources, will change. Each weathering process is briefly described below along with a discussion of how the process influences exposure. The reader is reminded that, although the processes are discussed separately, many occur simultaneously. For a detailed explanation of each process, the reader is referred to the first booklet in this series, "Fate of Spilled Oil in Marine Waters: Where Does It Go? What Does It Do? How Do Dispersants Affect It?"

*To **Weather** or **"Weathering"** is the combination of physical and chemical changes in oil composition over time, as it is exposed to the environment. It may result in the removal of oil from the water's surface to the atmosphere, water column, sediments, and shorelines.*

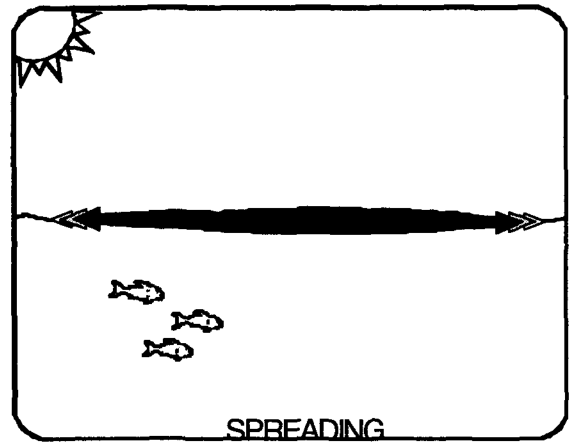
Spreading and Advection

Viscosity *is a fluid's internal resistance to flow. A highly viscous oil will not flow easily. This physical property of the oil or refined product is important to understand, as it helps determine the oil's behavior during a spill.*

Surface Tension *is an attractive force exerted between the molecules of a liquid. For example, water sticks together in droplets due to surface tension. In general, surface tension hinders the spreading of a slick.*

A ***Current*** *is a stream of ocean or river water moving continuously in about the same path, and distinguished from the surrounding water through which it flows mainly by temperature and salinity differences.*

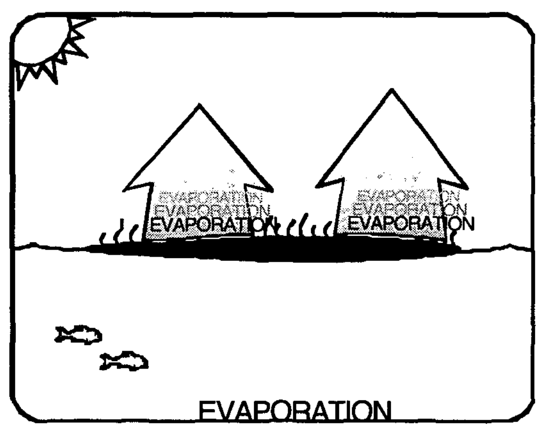
Spreading is just that, the actual spreading out of oil on the surface of the water. Oil spreads on water much like a glass of liquid would when poured on a table. Oil spreading occurs because of the effects of gravity, inertia, friction, VISCOSITY, and SURFACE TENSION. On calm water, spreading occurs in a circular pattern outward from the center of the release point (CONCAWE, 1983). Advection is a type of spreading caused by the influence of overlying winds and/or underlying CURRENTS (NRC, 1985). Due to the effects of advection, spreading is not uniform, and can result in large variations in oil thickness within the slick (ITOPF, 1987). Since spreading increases the surface area of the slick, it also increases the probability that any biological resource on the surface of the water will be exposed to the oil through direct contact (e.g., birds diving through the slick).



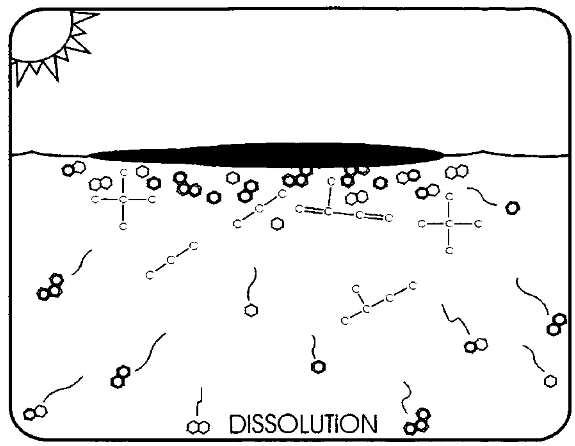
Evaporation

Volatile *describes a state of matter; oil will "give off" or lose components of its original makeup through evaporation when exposed to the atmosphere. The more volatile the componant, the faster it evaporates. The components that volatilize are rapidly removed from the original product (e.g., the oil).*

Evaporation is the preferential transfer of light and medium-weight oil components from the liquid phase to the vapor phase (into the atmosphere) (Exxon, 1985). The oil slick is physically and chemically altered as these components evaporate. Some of these components are highly VOLATILE and fairly toxic (Lewis and Aurand, 1997). Evaporation influences exposure by creating a vapor which can lead to inhalation of toxic compounds as they pass from the water surface into the atmosphere. Time of such exposure is relatively short, due to rapid air dispersion.

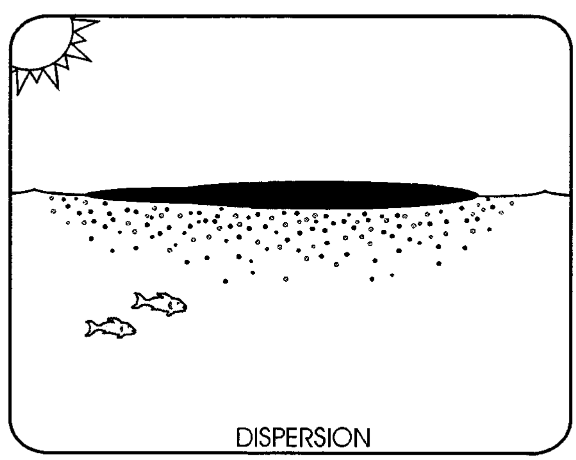


Dissolution



is the preferential transfer of oil components from a slick on the water's surface into solution in the water column (Exxon, 1985). Certain lighter-weight components of the spilled oil tend to be the most soluble and, therefore, the ones that dissolve into the water column. However, many soluble components are also volatile, with evaporation occurring 10 to 1,000 times faster than dissolution (CONCAWE, 1983; ITOPF, 1987; Lewis and Aurand, 1997). Consequently, only a slight fraction (2 to 5%, at most) of the spill is removed by dissolution (Neff, 1990). Although concentrations of dissolved components are usually very low, water column resources can be exposed to them through direct contact, direct and indirect ingestion, and absorption through the body surface.

Natural Dispersion

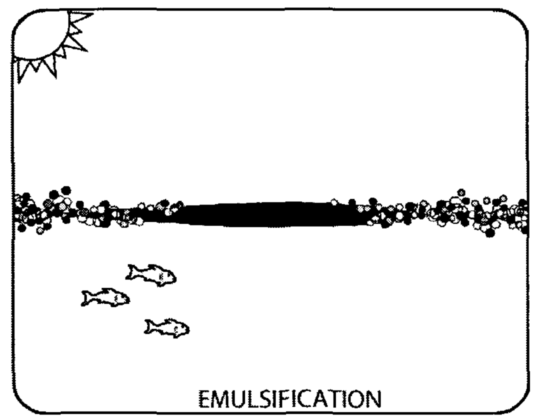


Natural dispersion is the process of forming small oil droplets that become incorporated into the water column in the form of a dilute oil-in-water suspension (CONCAWE, 1983; Exxon, 1985). This process occurs when breaking waves mix the WHOLE OIL into the water column. Large droplets (greater than 0.1 mm in diameter) that are formed when mixing occurs tend to "coalesce, rise rapidly, and concentrate near the water surface. Small droplets (typically less than 0.1 mm in diameter) break away from the main mass and become dispersed in the water column" (Neff, 1990). A simple demonstration can be done with a bottle of oil and vinegar salad dressing; although the bottle starts out with separate oil and vinegar layers, when it is shaken the oil is dispersed throughout the vinegar. However, after a few minutes most of the oil coalesces and rises to the top again.

Whole Oil *is a reference to the oil itself. When referencing the "whole oil", we are NOT referring to the individual components of the oil; however, the "whole oil" will continue to change in composition over time as weathering processes act on it.*

Water-column organisms can be exposed to naturally dispersed oil through direct contact, direct and indirect ingestion, and absorption through the body surface. Dispersion causes organisms to be exposed to whole oil in the form of small droplets, not just the dissolved light and medium-weight oil components associated with dissolution.

Emulsification



*A **Water-in-oil Emulsion** is formed when water is incorporated into the oil, forming a new product which is relatively resistant to other weathering processes.*

Emulsification is the mixing of seawater droplets into oil on the water surface (WATER-IN-OIL EMULSION). Unlike dissolution, emulsification does not necessarily involve oil physically separating from the slick but, instead, involves the combination of oil and water to produce what is often referred to as "mousse" or "chocolate mousse." This name comes from the brown color and consistency of the emulsion, which typically contains 30 to 80 percent water (Mielke, 1990; Neff, 1990; Gilfillan, 1993). Some of the heavier components tend to precipitate out of the emulsion in the form of very fine, solid particles. These particles help stabilize emulsions in the presence of natural surfactants (Lewis and Aurand, 1997). Resources on the surface of the water can be exposed to the emulsified oil through direct contact or via direct and indirect ingestion.

Photo-oxidation

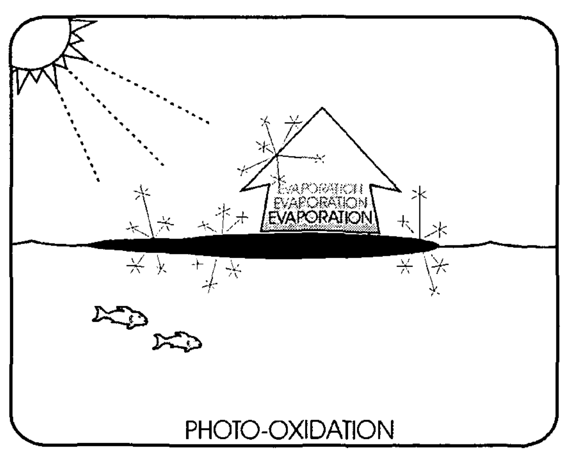
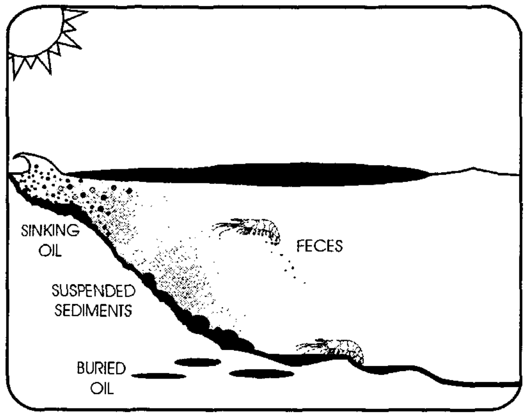


***Photo-oxidation** is the process by which components of oil are chemically transformed through a photo-chemical reaction (in the presence of oxygen) to produce new compounds which tend to be more water-soluble and toxic (in the short-term) than the parent compounds (Neff, 1990).*

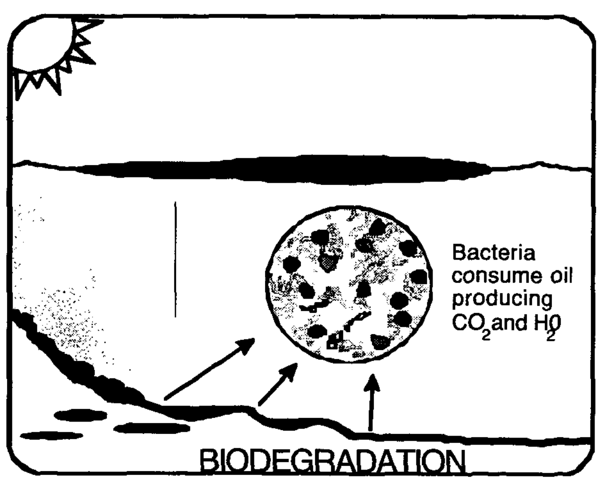
This process occurs when sunlight, in the presence of oxygen, transforms hydrocarbons through PHOTO-OXIDATION into new by-products, which may be more toxic than their parent compounds (Mielke, 1990). Because the hydrocarbon molecules must be exposed directly to sunlight for photo-oxidation to take place, this process only occurs at the very surface of the spilled oil. Photo-oxidation also occurs with components which have already separated from the whole oil during evaporation or dissolution. The ultimate fate of these by-products of photo-oxidation is removal to and dissipation into the atmosphere (evaporation) and the water column (dissolution). Water surface and water column organisms are exposed to the by-products through inhalation, direct contact, absorption, and direct and indirect ingestion.

Sedimentation and Shoreline Stranding



Whole oils, especially heavier oils or oil fractions, are sticky and tend to adhere to particles in the water column and on the sea floor. This results in sedimentation, which is simply the incorporation of oil within sediments. It usually occurs with medium and heavy-weight oil components that will not dissolve into the surrounding water. Sedimentation can also occur as organisms consume and process the oil into fecal matter, which may then settle to the bottom. Shoreline stranding is the visible accumulation of petroleum along the water's edge following a spill. This "beached" oil can also contribute to sedimentation, as the stranded oil becomes sediment laden and sinks or becomes buried along the shoreline. Water-column, bottom-dwelling, and INTERTIDAL resources can be exposed to the oil through direct contact and via direct and indirect ingestion.

Biodegradation



This process occurs when naturally occurring bacteria and fungi (microbes) use hydrocarbons as a food source and then ultimately excrete carbon dioxide and water as waste products. Biodegradation occurs on the water surface, in the water column, in sediments, and on the shore (Lewis and Aurand, 1997).

***Intertidal**, littoral zone, or foreshore refers to the strip of land along the shoreline that is covered by the highest normal tides and exposed by the lowest normal tides.*

Although the microbes are year-round residents of the water column, they grow and multiply after an oil spill because of the additional "food" available. Biodegradation also creates intermediate by-products which can be either more or less “toxic” than original oil components. Organisms can be exposed to these by-products via direct contact and absorption, as well as by intake of food and water.

PART III: EFFECTS OF OIL AND CHEMICALLY DISPERSED OIL

SECTION I: POTENTIAL EFFECTS

Purpose of Part III, Section I
To discuss the general effects of untreated oil and chemically dispersed oil on organisms utilizing the water and intertidal areas.

The reader is cautioned that the information presented in this section contains generalities. Specific impacts are very species- and situation-dependent. This discussion presents generalized guidelines derived from various laboratory, MESOCOSM, and field studies. Readers interested in obtaining more specific research information should consult references cited. For spill preparation and incident response, experts on the local species and environment must always be consulted.

Mesocosm *studies are a type of experiment that are conducted at scales larger than normal laboratory size, yet smaller than full-scale field studies. This intermediate-scaled experimental stage can provide useful information with greater control and at less expense than if conducted as a full field study. The scaled environment in which the experiments are actually conducted is called the "mesocosm."*

In this section, biological resources are grouped according to their distribution in the environment and their likelihood of exposure to oil or chemically dispersed oil, i.e., surface-dwelling, water column, bottom-dwelling, and intertidal. Some resources are found in more than one area in the environment (e.g., marine mammals are at the water’s surface and in the water column); however, information presented is for the area where they are most likely to be exposed to spilled oil. There are many different organisms in each of these areas; however, we only present the ones of most common concern here.

Sublethal *effects are those that do not immediately, or perhaps ever, result in death (e.g., reduced egg production, reduced ability to swim, disorientation, slow growth).*

Impacts *are adverse effects caused, in this case, by spilled oil.*

Often, toxicity is primarily associated with the ability of a substance to kill an organism. It is important to keep in mind that toxic substances usually cause effects other than death in most organisms. What these effects are depends on a number of conditions. SUBLETHAL effects are often difficult to quantify or even observe and may, or may not, be important to the future survival of the organism. Mackay and Wells (1981), NRC (1985), and Mielke (1990) summarize factors that determine the severity of ecological and organismal IMPACTS from an oil spill. These include:

- organism habits and behavior (e.g., birds that dive through the water surface for food);
- concentration of oil and the duration of the exposure;
- type of oil involved;
- whether the oil is fresh, weathered, or emulsified;
- whether a coastal, estuarine, or open ocean area is involved and whether it is a nesting, wintering, or migratory ground for sea birds or other resources;
- season of the year with respect to bird migration and whether organisms are dormant or actively feeding and reproducing;
- oceanographic conditions such as currents, sea state, coastal topography, and tidal action;
- life stage - whether adult or juvenile life forms are present;
- whether the oil is in solution, suspension, or absorbed onto suspended particulates or sediment;
- distribution of oil in the water column;
- effects of oil on competing biota;
- an ecosystem's previous history of exposure to oil or other pollutants; and
- cleanup procedures used.

Climatic and hydrographic conditions and food availability cause natural fluctuations within species populations. It is often difficult to clearly separate short- and long-term effects caused by oil from this natural population variability (ITOPF, 1987). This variability must be considered when establishing whether or not an environment has biologically recovered.

Some biological species produce large numbers of young to overcome natural losses, making it less likely that any localized impacts will have a discernible effect on the adult population (ITOPF, 1987). It is important to remember that, although most vertebrates of concern during a spill do not do this (e.g., seabirds, marine mammals), it is still unlikely that there will be serious effects on the population in most spill situations. However, it must be emphasized that this is not always the case, especially with threatened and endangered species. The loss of only a few individuals of a threatened or endangered species could have a large impact on the entire population. Also, early life stages (larvae and juveniles) of most resources are generally more sensitive to the effects of oiling than adults (ITOPF, 1987). This increased sensitivity may be related to life stage-specific or seasonal dependency on metabolic processes that are not critical functions in the adult forms (Capuzzo, 1987; Lewis and Aurand, 1997).

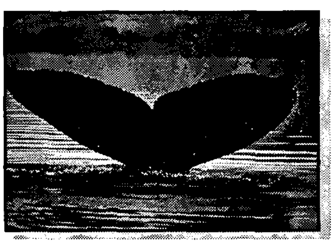
Section II:

Effects of Untreated Oil

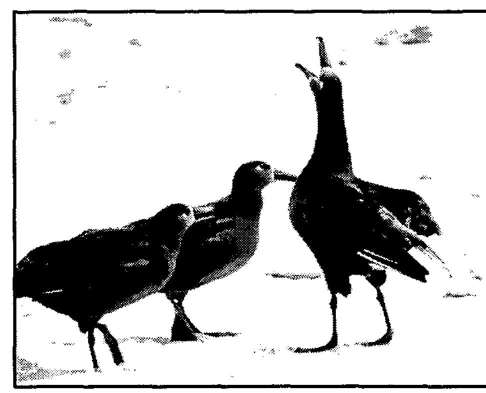
Surface-dwelling

Purpose of Part III, Section II
To discuss the most likely effects of untreated oil on organisms utilizing the water and intertidal areas.

Birds, marine mammals, and reptiles are surface-dwelling resources. In general, birds that spend all, or part, of their time on the water are highly vulnerable. The marine mammals most likely to be impacted are fur-bearers (seals, sea otters, sea lions), because the oil can coat their fur. Oil interferes with the insulating properties of fur and feathers, making fur-bearing mammals and birds especially susceptible to HYPOTHERMIA. Smooth-skin mammals (e.g., dolphins and whales) are generally considered to be at low risk from problems associated with direct oil contact. Exposure of their thick skin would usually cause minimal damage. Little is known on the effects of oil on reptiles, however, research on sea turtles indicates they may be at risk from surface oiling, oiling of nests, or from direct ingestion of oil or oiled prey (RPI, 1991).



Humpback whale



Hypothermia *is the term used for a subnormal body temperature. An animal's body temperature may be lowered when it becomes soaked to the skin with cold water or oil. Hypothermia can result in death.*

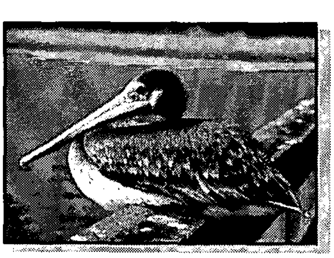
Most Likely Routes of Exposure

- Direct contact;
- Direct and indirect ingestion; and
- Inhalation.

Effects

(Lindstedt-Siva *et al.*, 1984; NRC, 1985; Exxon, 1985; Neff, 1990; RPI, 1991; Gilfillan, 1992; Scholz *et al.*, 1992):

- In birds and fur-bearing marine mammals, direct contact causes fouling of plumage or fur. This destroys the insulating properties of the plumage and fur, allowing water to penetrate to the body surface, resulting in hypothermia and loss of buoyancy.
- Direct contact can also cause irritation to eyes and skin.
- Direct contact to bird eggs reduces survival, depending on the species, especially during the early stages of incubation. Adults exposed to sublethal doses may produce fewer eggs. Nests exposed to oil are abandoned by some bird species.



Brown pelican

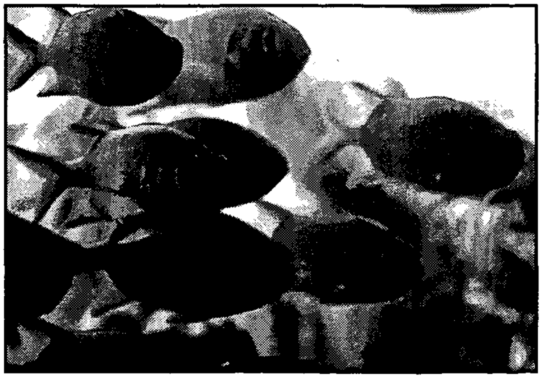
- Birds that ingest oil may experience ANEMIA, pneumonia, intestinal irritation, kidney damage, altered blood chemistry, decreased growth, and decreased production and viability of eggs.
- Ingestion of oil in marine mammals can cause irritation and/or destruction of intestinal linings, organ damage, and neurological effects. Ingestion through grooming can result in liver lesions and kidney failure.
- Inhalation can result in problems with the circulatory system and may cause mild irritation or even permanent damage to lungs and mucous membranes.
- Possible effects of oil on sea turtles can include egg and hatchling mortality, a reduction of hatchling size and weight, and an increase in respiratory rate.
- When the mouth and digestive tracts become coated, turtles can also experience increased toxicity and problems with feeding, which could lead to starvation.

Anemia *is a condition in which the blood is low in red cells or hemoglobin. Anemia commonly results in weakness.*

Sea lions

WATER COLUMN (PELAGIC)

Biological resources in the water column include PLANKTON, invertebrates, and fish. Although exposure to oil can kill fish, biological effects are typically brief and localized because of rapid dilution of the oil, especially in the open ocean (Lewis and Aurand, 1997). An oil spill may cause extensive fish kills, but this is relatively uncommon (Spies, 1987).



MOST LIKELY ROUTES OF EXPOSURE

- Direct contact;
- Respiration;
- Ingestion; and
- Absorption.

Effects

(NRC, 1985; Exxon, 1985; ITOPF, 1987; Spies, 1987; Howarth, 1989; Gilfillan, 1992; Scholz *et al.*, 1992).

- In plankton, effects are difficult to discern due to naturally high seasonal and spatial variability. Depending on the species, growth of PHYTOPLANKTON can be inhibited or enhanced. How-

Plankton

Plankton *refers to tiny organisms whose transport is directly affected by currents; these organisms may passively drift or weakly swim. Includes mostly microscopic algae, protozoa, and larval forms of animals.*

ever, phytoplankton populations are not generally affected in the long-term by exposure to hydrocarbons because their regeneration period is short, initial numbers are typically high, and recruitment from other areas can be rapid.

- In laboratory experiments, ZOOPLANKTON have been found to be sensitive to oil exposure and experience developmental abnormalities as well as lower rates of feeding and reproduction. However, oil concentrations required to cause sublethal effects in laboratory tests are often in excess of levels likely to be encountered under or near slicks of undispersed oil (NRC, 1985; Gilfillan, 1992). Typically, oil concentrations beneath undispersed slicks are in the ppm range (Lewis and Aurand, 1997) and do not exceed 250 ppm (Gilfillian, 1992). Organisms can experience direct mortality, external contamination, tissue contamination, or abnormal development. Population recovery is fairly rapid due to recruitment from other areas and to other factors such as wide distribution, large numbers, short generation times, and high FECUNDITY (NRC, 1985; Exxon, 1985). Both vertebrate and invertebrate zooplankton can be affected by exposure to oil.
- Sublethal effects may include fin and tail rot, altered reproduction, decreased growth rates, and lowered immune function.
- Juvenile and adult fish can be fairly resistant to dissolved oil. Only a few spills have been associated with extensive fish kills (Spies, 1987). If a resource is already stressed (e.g., change in food availability, parasitic infection), then they are more likely to be affected by an oil spill.

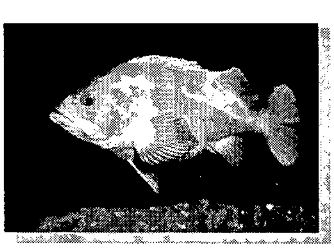
Phytoplankton *refers to plants that are mostly microscopic, as well as some floating forms of algae. Phytoplankton transport is directly affected by currents, as they passively drift within the water column.*

Zooplankton *refers to very small animals, including protozoa, and larval forms of animals, such as finfish and crustaceans. Zooplankton is directly transported by currents; these organisms may passively drift or weakly swim.*

Fecundity *refers to an organism's rate of production of offspring.*

Bottom-dwelling (Benthic)

Bottom-dwelling biological resources include fish, invertebrates, and plants. Organisms in waters greater than 10 meters in depth are typically unaffected by oil, except for oil that undergoes sedimentation or is naturally dispersed or dissolved, as most of the oil remains near the surface or on the shoreline (Howarth, 1989; Lewis and Aurand, 1997). Bottom-dwelling organisms in shallow waters (<10 m), however, are more likely to be exposed to oil (ITOPF, 1987; Lewis and Aurand, 1997).



Grouper

Chronic or persistent oil discharges, such as a continuous platform discharge or natural seep, can result in elevated levels of hydrocarbons in sediments. Massive kills of fauna have occurred when sufficiently large quantities of oil have reached the bottom following spills (Teal and Howarth, 1984). Oil can change the community structure, with sensitive species either dying or emigrating out of the area to be replaced by OPPORTUNISTIC

species (Howarth, 1989). Persistence of oil in sediments can be long-lasting, depending on the environment. In high energy environments, fine-grained organic-rich sediments hold oil longer compared to coarse-grained sediments. In low energy environments, oil can persist for long periods, depending on the particular environment. In very low energy environments, heavy oil components may settle and remain indefinitely (years).

Opportunistic *refers to organisms that will utilize or adapt to the resouces that are currently available.*

Most Likely Routes of Exposure

- Direct contact;
- Respiration;
- Ingestion; and
- Adsorption.

Effects

(Lindstedt-Siva *et al.*, 1984; NRC, 1985; Capuzzo, 1987; ITOPF, 1987; Gilfillan, 1992; Scholz *et al.*, 1992)

- Being in constant contact with contaminated sediments increases the likelihood of impacts. In bottom fish (e.g., flounder), effects may include changes in feeding, growth, development, and recruitment that may result in alterations in both reproductive and development success, and changes in community structure and dynamics.
- Invertebrates, both INFAUNA and EPIFAUNA, can experience impacts. Infauna actually live within an oiled sediment; therefore impacts are more likely. Effects can include growth reduction, feeding impairment, and behavioral changes.
- Macroalgae, such as kelp, may experience decreased reproduction, bleaching, and mortality. If animals that graze on the algae are affected by the oil, the opposite may also occur. If algal grazers, such as sea urchins, are killed, then macroalgae may experience an increase in growth and total abundance.

Infauna *refers to animals which live within the sediment of the sea bottom (e.g., worms).*

Epifauna *refers to benthic animals which crawl about on the sea bottom or sit firmly attached to it (e.g., oysters, lobsters).*

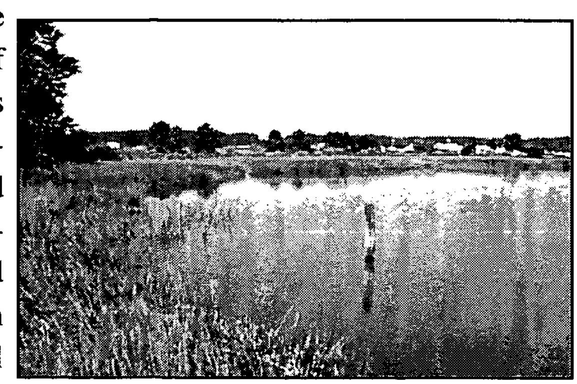
Kelp

Rhizome *refers to a horizontal, underground (or buried) part of sea grasses and plants. Rhizomes are not true roots, but are more like underground stems from which new plants bud.*

- At low tide, benthic plants may be in direct contact with oil; however, the oil rarely sticks to them for long and oil may be rinsed off as the tide rises again. In seagrasses, most biomass is in their RHIZOMES. Because rhizomes are buried in the sediment, and therefore less exposed to any oil, lethal impacts are less likely.
- In shallow water areas, more severe effects to benthic plants can be expected, although renewed growth is typically found within several years. Loss of the upper green or leafy portion of the plant has been observed following heavy oiling, but re-growth from still-living rhizomes within the sediments is evident as early as one year later. Canopy plants, such as kelp, have a large exposed surface area and are at a greater risk from spilled oil than benthic plants.

INTERTIDAL

Biological resources in the intertidal area primarily include invertebrates and plants. Some shorebirds, wading birds, and other animals that contact stranded oil, can also be affected in the intertidal area. Impacts on intertidal areas are especially important, because these areas serve as habitat for many juvenile and adult organisms during certain times of the year. An intertidal area impacted in the fall may not provide shelter for juvenile crabs and fish in the spring. Intertidal areas occur at the land/water interface, immediately along a shoreline. As the tide rises and falls, immobile organisms in the intertidal area are exposed to the water column, the surface, and the air. Passing through all of these different environments increases the potential for exposure. If spilled oil comes ashore, the most damage typically occurs in intertidal areas that are exposed to the stranded oil. This is especially important in low energy environments, where layers of oil are deposited with each falling tide and the oil is not removed by wave action. Resources in intertidal areas can experience chronic effects because of continued exposure (Lewis and Aurand, 1997). The effects noted here are limited to those which occur frequently with organisms and habitats of most common concern during marine oil spills.



Most Likely Routes of Exposure

- Direct contact;
- Ingestion; and
- Absorption.

Effects

(Lindstedt-Siva *et al.*, 1984; NRC, 1985; Exxon, 1985; ITOPF, 1987; Gilfillan, 1992)

Sessile *means permanently attached to the substrate and not free to move about.*

- Intertidal invertebrates (infauna and epifauna) can be killed outright by heavy coatings or smothering, especially SESSILE species such as barnacles, which cannot escape the oil. Mobile invertebrates can become embedded in the oil, which may smother them or make them easy prey for birds and other predators. Sublethal effects include alterations in respiration, growth, reproduction, and behavior.
- Coral reefs can be impacted by oil. Effects may include interference with reproductive processes, reduced or suspended growth, and mortality or abnormal behavior of reef organisms. Sublethal effects observed in the laboratory include decreased calcium uptake and tissue death.
- Plants occupying intertidal areas are most at risk (compared to subtidal plants) as they can be directly coated by stranded oil for long periods of time. Loss of plant-covered areas may impact the community at large, because many organisms use plants as habitat and a source of food. Although the faunal community may recover within a year or two, final return of the entire ecosystem to non-oiled condition can take up to a decade (NRC, 1985).

Coral reef

Algae & barnacles

continued on page 24

For More Information....

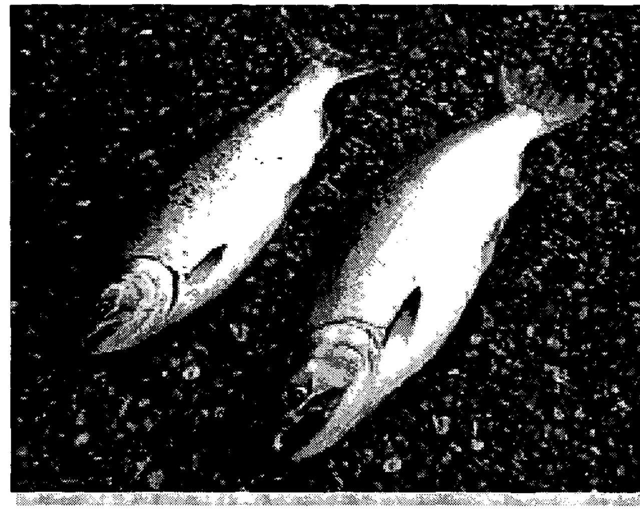
What About Bioaccumulation and Biomagnification?

Bioaccumulation is the uptake of a contaminant (e.g., oil and oil components) by an organism directly from the water, or through consumption of contaminated food. Bioaccumulation is dependent on the availability of hydrocarbons in a soluble or droplet form suitable for consumption, length of exposure, and the organism's ability to metabolize the hydrocarbons (Capuzzo, 1987). Capuzzo (1987) states that sublethal effects from oil exposure may be modified by the ability of the organism to accumulate and metabolize various hydrocarbons. Fish have the ability to metabolize hydrocarbons, but some invertebrates (e.g., bivalves) do not. According to Markarian *et al.* (1993), bioaccumulation is not necessarily "an indication that negative impacts are being exerted on the organism" and "the overall significance of bioaccumulation from a spill has by no means been fully evaluated nor is there a body of evidence demonstrating cause and effect."

Biomagnification is the increase of hydrocarbon concentration over two or more food-chain levels. For example, one organism (e.g., a crab) can take in and retain, or bioaccumulate, hydrocarbons and then be eaten by an organism on a higher feeding level (e.g., a sea otter). If biomagnification were occurring, the organism at the higher level (the otter) would receive an increased exposure to hydrocarbons by eating the contaminated food (the crab). The issue of biomagnification is important because of the concern that humans may eat fish or other animals that were previously exposed to oil through biomagnification, causing potential health impacts. However, biomagnification of hydrocarbons does not appear to occur in the higher organisms of the food chain (Mielke, 1990; Markarian *et al.*, 1993), primarily because hydrocarbons can be metabolized and excreted by vertebrates (including humans) and, therefore, do not normally reside in tissues for a long enough time (NOAA, 1994). Studies associated with the *Exxon Valdez* oil spill did not show any biomagnification (ERCE, 1991).

For More Information....

What About Tainting?



Tainting is defined as the presence of an "off taste" in fish or invertebrates consumed by humans (NRC, 1985; NOAA, 1994). An off taste is sometimes due to natural causes (e.g., thermal decomposition of naturally-occurring components in fish) and not to the spilled oil (NOAA, 1994). Tainting is a concern because it can affect the fishing industry (commercial and recreational) and subsistence fishing. Tainting may not only decrease the marketability of the affected fish, but may also decrease the marketability of all the seafood caught in the same region. Just the perception of possible tainting can affect the economics of an area's fishing industry for a long time (NOAA, 1994).

In 1989, following the *Exxon Valdez* oil spill, a study was undertaken by the National Oceanic and Atmospheric Administration (NOAA) to assess subsistence food contamination. Researchers found that there are no quick screening methods available to provide quantitative assessment and guidance for seafood safety. Most testing is "organophilic" or sensory testing. Organophilic testing consists of odor and flavor tests by a panel of judges. To produce the most comprehensive and credible study possible, NOAA scientists collected tissue samples from shellfish and fish and chemically analyzed them for various oil components. Results indicated that finfish were safe for human consumption, but some shellfish collected from heavily contaminated areas were not safe (Walker and Field, 1991). The major drawback to analyzing tissue samples is the time involved before results are obtained. In the case of the *Exxon Valdez* work, chemical analysis of the samples was not completed until the summer harvest had passed.

Exposure levels that cause tainting vary depending on the oil, species affected, and the exposure duration. In animals, the literature has generally reported that tainting results from exposure to water with concentrations of petroleum products ranging from 4 to 300 ppm, depending on species. Tainting can persist even after the source of the contamination is removed, especially with shellfish. Tainting can persist from one to several days following exposure in finfish, which have the enzyme systems necessary to metabolize petroleum (NOAA, 1994). Because bivalves do not have the ability to metabolize petroleum, fishing restrictions may be required for months, depending on exposure and species. Recent examples of shellfish fishing restrictions were seen after the *Sea Empress* spill (Law *et al.*, 1997). Eventually, toxins may be eliminated from shellfish by DEPURATION.

***Depuration** is a the elimination of a chemical from organisms, such as shellfish, by desorption, excretion, diffusion, or another route. Depuration only begins to occur once the chemical contamination is no longer present in the surrounding waters.*

Table 3. How tainting occurs (NOAA, 1994).

Adsorption	• (adhesion) of petroleum components on the skin • from direct contact of naturally (not chemically) dispersed oil droplets to the lipid surfaces in the gills
Absorption	• sorbing dissolved petroleum components from the water through the skin • sorbing dissolved petroleum components through the gills
Ingestion	• consumption of petroleum products directly or from food contaminated with petroleum.

- In salt marsh plants, oiling of the lower portion of plants and roots is more damaging than coating of leaves and stem, especially if oiling occurs outside of the growing season. More damage is experienced if there is repeated contamination of sediments in areas where the oil may persist.
- Shorebirds and wading birds can be affected by oil in the intertidal area. Effects on birds are discussed under surface-dwelling on page 16.
- Land animals, such as raccoons, that scavenge for food on intertidal areas and use them for shelter may ingest oil while eating exposed prey and may become coated in oil while exploring exposed flats and grassbeds.
- Mangroves have complex breathing roots which may be blocked by oil, resulting in death. Cleaning oiled mangroves is possible, but difficult. Recovery can occur if the impact is not severe, and oil is not mixed into the sediment.

SECTION III: EFFECTS OF CHEMICALLY DISPERSED OIL

Purpose of Part III, Section III

To present information about how dispersants interact with oil, and discuss the possible effects of exposure to dispersants and chemically dispersed oil.

Dispersant Review

Dispersant chemistry and technology are discussed in detail in the second booklet of this series, "A Decision-Maker's Guide to Dispersants: A Review of the Theory and Operational Requirements." A short review of dispersants is presented here.

Dispersants are used to enhance natural dispersion, which is the formation of small oil droplets that become incorporated into the water column in the form of a dilute oil-in-water suspension. Dispersants are chemicals which contain a mixture of surfactants and solvents. The surfactant enhances the formation of oil droplets into the water column, helps keep these droplets suspended in the water, and reduces the oil's tendency to attach to other oil droplets or solid surfaces. The surfactant must reach the oil/water interface to work. The solvent is added to reduce the viscosity of both the dispersant and the oil, in order to facilitate uniform dispersant application, dispersant penetration into the oil, and oil dispersal (NRC, 1989).

Once applied to an oil slick, the chemical dispersant undergoes the same weathering processes as the oil itself (evaporation, dissolution, biodegradation, etc.). Much of the solvent fraction of the dispersant will evaporate, while the majority of the surfactant portion will leach out of the oil droplet over time (Neff, 1990; Payne, 1994) where it can be degraded by microbes and metabolized by a number of organisms (NRC, 1989).

Dispersants are most effective when applied in the presence of turbulence in the water (SEA STATE), which is needed to promote the surfactant's ability to disperse the oil slick (Kucklick and Aurand, 1995). Mixing energy is required to move the oil into the water column so that small oil droplets will travel away from the slick. Some oils are considered more dispersible than others, based on their API GRAVITY and pour point. Generally, oils with an API gravity of over 45 (low viscosity oils), do not need to be dispersed because the oil is non-persistent and will evaporate quickly (e.g., gasoline products and condensates). Weathered oils with an initial API gravity of 45, or those with lower API gravities are candidates for dispersal. Dispersants can be less effective on oils with an API gravity of less than 17 (high viscosity), making them more difficult to disperse (this includes products such as very heavy No. 6 fuel oil, residual oils, and heavy slurry oils). It has been generally believed that heavy fuel oils were not dispersible. However, recent research has shown that some, but not all, heavy oils can not only be dispersed, but also have a greater time window for dispersion than previously thought and require less dispersant than normally recommended (Lunel and Lewis, 1999).

Oils with API gravities between 17 and 45 are usually considered dispersible, depending on the oil's pour point. If the pour point is less than 41°F (average ocean temperature), the oil should be dispersible. Oil is only dispersible if the water temperature is above the pour point. (John G. Yeager and Assoc., 1985). If the water temperature is below the pour point, the oil will become too stiff to be effectively dispersed. The degree of weathering an oil has undergone also affects its dispersibility. In general, a fresh oil which still retains the lighter oil components is more easily dispersed than weathered oil. Weathered oil is harder to disperse because it is typically more viscous, as the lighter oil components have already been lost and water may have been incorporated to form a mousse.

Sea state *is a numerical code that describes the height of wind-generated waves. It is often compared to the average wind speed generating those waves. Common conditions range from a sea state of 0 (1 to 3 knot winds = 0.04 ft. average wave height) to 5 (20 to 24 knot winds = 5.5-6.6 ft. average wave height). The full scale ranges from 0 to 9 (Thurman, 1987; Kucklick and Aurand, 1995).*

API Gravity *is a scale for measuring fluid-specific gravities based on an inverse relationship with specific gravity. This scale was primarily developed to expand the scale for specific gravity so that larger values are used. An oil with a low specific gravity (e.g., gasoline = 0.73) will have a high API gravity (°API = 62); inversely, an oil with a high specific gravity (e.g., very heavy crudes; specific gravity = 0.98) will have a low API gravity value (°API = 13).*

*API gravity = (141.5 / SG *) - 131.5*
** at 60 °F*

Potential Acute and Chronic Effects

Remember, just as was the case with the discussion in Part II of this booklet on the effects of oil alone, all impacts are very species- and situation-dependent. The same factors that determine the impact from exposure to untreated oil also apply to chemically dispersed oil (see page 15). Although the goal when using chemical dispersants is the complete dispersion of the surface slick, usually less than 100 percent of the treated oil will disperse. This means that effects from undispersed oil will also occur.

Much of the research on the effects of chemically dispersed oil has been performed in the laboratory. There are also a few field tests which can be mentioned, and they will be discussed in the next section. Examining individual test results can be confusing, especially when it is not clear if the concentrations cited are nominal concentrations (total oil per unit volume) or based on the water-accommodated fraction (see previous discussion under toxicity, page 6). Depending on the evaluation method, laboratory exposure may be overestimated or underestimated (NRC, 1989).

The two main factors influencing aquatic toxicities of dispersant-oil mixtures are:

- **Dispersed Hydrocarbons** – properties and toxicity of oil; quantity and location of treated oil spill; characteristics, including mixing behavior upon dispersion, persistence, stability of emulsions and dispersions; degree of weathering; and chemical and/or physical toxicity of dispersed oil which depends on the species, life stages, habits, season, physiology, biochemistry, behavior, and ecology of exposed organisms (Mackay and Wells, 1981).
- **Dispersant** – historically, the view was that the dispersants themselves contributed greatly to the toxicity of the dispersant-oil mixture. However, current studies indicate that low levels of dispersant contribute less to the toxicity of the mixture than the oil itself does (Lunel and Lewis, 1999). Dispersant factors include: composition and toxicity; ratio of dispersant to oil required for proper application; and potential interaction between dispersant solvent and surfactants with particulate and dissolved oil.

Exposure Considerations

Dispersants are considered controversial by some in the response community because their use represents a deliberate introduction of chemicals into the water and, if they are effective, this results in an increased hydrocarbon concentration in the water column (ITOPF, 1982; IT Corporation, 1993). Although they are much less toxic than in the past, dispersants *are* toxic, just as oil is. Despite this fact, dispersant use may be the best, and least ecologically damaging, response option in certain spill situations.

The key to understanding the effects of dispersed oil is exposure, which includes both amount and duration (NRC, 1989). In areas where the dilution potential is the greatest (i.e., open ocean), concentrations of dispersed oil high enough to cause adverse effects are unlikely to persist for more than several hours (ITOPF, 1982; NOAA 1994). Oil concentrations are typically less than 50 ppm below dispersed slicks, although slightly different upper levels are reported by the different authors (Gillfillian, 1992; Lewis and Aurand, 1997). Field data indicate that concentrations of dispersed oil are usually less than 1 ppm at depths below 10 meters (Lewis and Aurand, 1997).

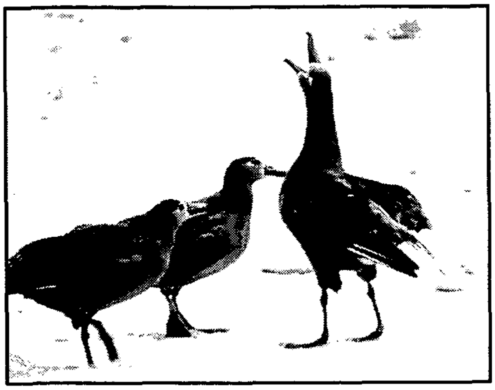
In more shallow waters, where circulation is more restricted (e.g., near shore environments or in bays and estuaries), dispersed oil in the water column may not be diluted as quickly. In situations like this, dispersant use may be inappropriate, due to potential impacts. However, there could still be benefits to dispersing the oil in such situations, especially if dispersant use will protect highly sensitive shorelines, like mangroves or salt marshes. This is when it is important to examine tradeoffs to determine the best options for the environment in question. A more detailed discussion of tradeoffs and risk assessment is found in Part IV of this booklet.

Types of anticipated exposures and effects from dispersed oil on surface-dwelling, water column, bottom-dwelling, and intertidal organisms are discussed below.

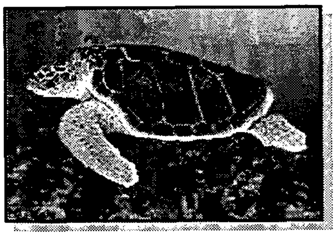
Surface-dwelling

Based on a 1987 study with seabirds, the "hazard of chemically dispersed oil to seabirds depends primarily on differing exposures under naturally and chemically dispersing conditions" (NRC, 1989). Removing the oil from the surface of the water with the use of dispersants will benefit surface-dwelling birds and mammals because the chance for exposure is reduced.

***Hazing** refers to attempts at scaring away birds by low aircraft flyovers or other means, such as sound devices.*



Some bird experts have expressed concern over the effect of the dispersant itself on birds' plumage. Some studies have shown reduced water repellency because the dispersant causes a loss of natural oils necessary for insulation and buoyancy (IT Corp., 1993; Kucklick *et al.*, 1997). If HAZING of birds is not effective prior to dispersant spraying, and they are, thus, inadvertently sprayed with the dispersant, there may be some short-term impact. However, for birds and fur bearing mammals, the long-term benefit of removing the oil from the surface may outweigh the chance of a short-term impact (Kucklick *et al.*, 1997).

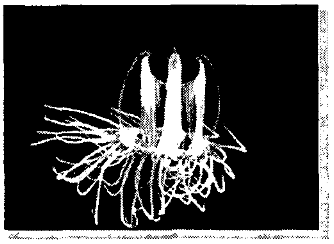


Loggerhead Turtle

In shallow waters, the chance of adverse effects being caused by dispersed oil may be slightly greater than in deeper waters (Kucklick *et al.*, 1997); a fact that should be considered when estimating impacts upon endangered species, such as sea turtles. The likelihood of adverse effects is greater because dispersed oil in shallow water environments is not carried away from the area as quickly as it would be in deeper waters. However, as with birds and mammals, reptiles are still generally thought to be at less risk with dispersed oil due to decreased exposure to oil floating on the surface.

Water Column (Pelagic)

Water column resources are often of primary concern when the use of dispersants is being considered. Conditions are different at every incident, making the use of risk assessments and tradeoff considerations of utmost importance. Both topics are discussed later in the booklet.



Jellyfish

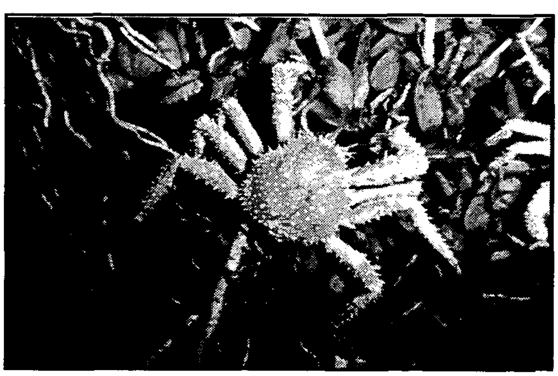
A 1995 workshop in Leesburg, Virginia, of government and industry scientists as well as decision-makers was convened to generate consensus recommendations on how best to interpret and apply chemical countermeasure product toxicity and effectiveness data in the decision-making process. The participants concluded that:

- For planning purposes, it is unlikely that exposure concentrations of 10 ppm dispersed oil, and 2 to 4 hour duration, will be exceeded in open marine waters at depths below the top 10 meters of the water column (SEA, 1995).
- The available acute toxicological data support the conclusions that, at water column concentrations at or below 10 ppm, exposures to dispersed oil for 2 to 4 hour durations are not expected to cause adverse ecological effects (SEA, 1995).

The group based these consensus statements on a conservative interpretation of published data. They believed these were somewhat conservative statements since, under some environmental conditions, exposure at a higher concentration or longer duration is not expected to cause negative effects either.

In general, plankton, invertebrates, and fish are thought to be at no more risk from dispersed oil compared to undispersed oil (Kucklick *et al.*, 1997). As was the case with oil alone, fish are likely to detect and avoid the dispersed oil. Water column resources in shallow water environments are more likely to be exposed to dispersed oil than they are in deep waters. In one study, tests on the effects of untreated and dispersed oil on the homing mechanism of adult salmon found no significant difference in the percentage of return or in the time it took the fish to return (NRC, 1989).

Bottom-Dwelling (Benthic)



In shallow-water environments, benthic organisms are more likely to be exposed to and, therefore, affected by, dispersed oil than floating oil. Shallow environments are defined as being less than 10 meters deep and fewer than three miles offshore (Kucklick *et al.*, 1997).

In the short-term, toxicity from dispersed oil may be high enough to cause both lethal and sublethal effects in some benthic resources; however, over the long-term, undispersed oil will cause more effects to these resources (NRC, 1989) due to the eventual sinking and settling of oil and oil-coated particles from the slick. The long-term effects to shallow water benthic organisms may be reduced by chemically dispersing the oil (IT Corp., 1993).

Clams

Dispersed oil may pose more of a risk to immobile or slow-moving invertebrates than to fish due to the fact that fish are likely to avoid the dispersed oil, while slow-moving invertebrates in shallow environments are not able to avoid it as easily, if at all.

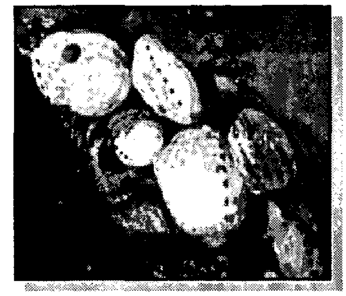
Studies with seagrass beds have shown them to experience no increase in effect with exposure to dispersed versus undispersed oil (NRC, 1989; Gilfillan, 1992). The American Society for Testing and Materials (ASTM) recommended guidelines concerning seagrass beds, including (ASTM, 1998):

- If it is possible that oil will strand on a seagrass bed, dispersant use would be most effective while the oil slick is still offshore.
- Use of dispersants to treat oil already over a seagrass bed is not recommended, but responders should weigh the potential impacts to the seagrass beds against impacts that might occur from allowing the oil to impact other sensitive habitats on shore.
- Dispersant use should be considered to treat oil over seagrass beds in waters greater than 10 meters if the alternative is to allow the oil to come ashore.
- Dispersant use is not recommended in shallow lagoons nor areas with low flushing rates. Mechanical cleanup is preferred here, but dispersant usage should remain an option to protect any more sensitive shoreline environments.
- Dispersant use is not recommended in highly polluted waters or enclosed bays, because the resulting biological activity may lower dissolved oxygen concentrations to harmful levels (Levine, 1999).

Intertidal

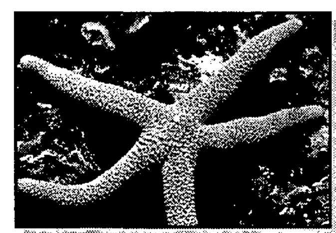
Dispersing oil *before* it impacts intertidal habitats and organisms is the preferred solution in most instances (NRC, 1989; IT Corp., 1993; Kucklick *et al.*, 1997). In studies where dispersant was applied directly to the intertidal habitat (e.g., mud flat, rocky shore, salt marsh, etc.) after oil had been deposited, ecological damage was increased in some cases. This was because

the dispersant facilitated the penetration of the oil into the sediment. However, it is important to note that this is not the intended method of dispersant application. Dispersants should typically be applied to the slick before it reaches the shore, not directly to the oiled habitat or sediment. In cases where the oil is appropriately dispersed prior to impacting these habitats, the net ecological effect was much less than it was when the oil was allowed to wash ashore (NRC, 1989; IT Corp., 1993).



Intertidal Abalone

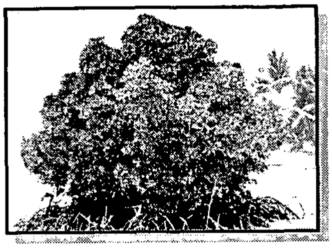
Toxicity studies of chemically dispersed oil on invertebrates in shallow, intertidal environments have shown that chemically dispersing the oil results in the same or less toxicity than undispersed oil alone (NRC, 1989). Dispersed oil should also pose the same or less of a risk than undispersed oil for intertidal plants, like marsh grasses, especially in the long-term. This is because exposure to the oil is reduced with the application of dispersants, which work to decrease or eliminate the layers of oil that are normally deposited by the slick each time the tide recedes.



Blood Star

For coral reefs, the NRC (1989) concluded that "if it is able to reduce exposure to oil, [dispersants] will benefit the reef in the long run even though there may be short-term deleterious effects on photosynthesis of symbiotic algae within the coral and on other reef organisms." Studies have shown that there was no difference in growth of coral after one year between reefs which experienced short-term exposure (24 hours) to oil and chemically dispersed oil (NRC, 1989). A ten-year study, discussed in detail in the next section, also found no differences between coral reefs oiled with chemically dispersed oil and undispersed oil after ten years (Lewis and Aurand, 1997). ASTM has issued guidelines on the use of dispersants in waters with corals which include the following (ASTM, 1998):

- Whenever an oil spill occurs in the general vicinity of a coral reef, the use of dispersants should be considered to prevent floating oil from reaching the reef.
- The use of dispersants over shallow submergent reefs is generally not recommended, but responders should weigh the potential impacts to the reef against impacts that might occur from allowing the oil to come ashore.
- Dispersant use should be considered to treat oil over reefs in water depths greater than 10 meters if the alternative is to allow the oil to impact other sensitive habitats on shore.
- Dispersant use is not recommended to treat oil already in reef habitats having low water exchange rates (for example, lagoons, atolls) if mechanical methods are possible.



Red Mangrove

Oil should also be dispersed prior to impacting mangroves. According to the NRC (1989), "short-term toxicity to individual organisms within the mangrove ecosystem may be higher, but community recovery is enhanced by the oil being dispersed prior to entry." The ten-year 'TROPICS' study (see next section) found little impact on mangroves exposed to chemically dispersed oil immediately after exposure. After ten years, some impact was found, but much less than the impact experienced by mangroves exposed to undispersed oil (Lewis and Aurand, 1997).

Purpose of Part III, Section IV

To present information gathered from field tests and oil spill studies.

Section IV: Spill Studies of Undispersed Versus Dispersed Oil

Discussion of Field Test Results

A great deal of information from laboratory research on the effects of dispersed oil exists, but only a handful of studies from actual spills or field tests can be found in the literature. Data from actual spills, along with spill and field testing is important since, as mentioned previously, dilution in the "real world" usually reduces concentrations and exposure times significantly (ITOPF, 1982). In many cases, this type of research provides more useful information about the effects of exposure to oil than laboratory data can. Consequently, these studies are especially desirable to decision-makers.

SUBTIDAL *- That part of the coastal zone that lies below the lowest tide, so that it is always underwater. "Shoreline counter measures manual," 1993, NOAA*

Searsport Study – 1981; Intertidal and Nearshore Subtidal

(original references include: Gilfillan *et al.*, 1983, 1984, 1985; Page *et al.*, 1983, 1984, 1985)

In 1981, Bowdoin College researchers conducted a study in Long Cove, Searsport, Maine, in which they examined the effects of dispersed and undispersed crude oil. The cove was divided into control and test areas and two small spills were simulated in this nearshore environment. Both spills involved the release of oil over the intertidal zone at high tide. In one spill, 25 gallons of dispersant was mixed with 250 gallons of crude oil (1:10 dispersant to oil ratio) and released into water 2.5 to 3.0 meters deep. In the other spill, 250 gallons of untreated crude oil was released into water 1.5 to 2.0 meters deep. Five sample sites were used, taking samples near the surface and above the benthos. The deepest samples were taken near the cove's center, at approximately 18 meters water depth.

The treated oil quickly dispersed into the water and concentrations of 15 to 20 ppm of dispersed oil were measured 10 cm from the bottom; exposure of dispersed oil totaled 20 to 30 ppm per hour at these bottom sampling locations. In the test area using the dispersant, no crude oil could be found in sediments following the discharge. Studies of the benthic community found that population abundances were not affected in the dispersed area (API, 1986).

The untreated oil coated a tidal flat as the tide receded and was cleaned from the beach the next day after two tidal cycles, using conventional methods. This was done to approximate events during a real spill. Unlike the sediments exposed to the dispersed oil, significant amounts of crude oil were found in the sediments exposed to the untreated oil. In the benthic community of the undispersed area, population abundances were reduced or eliminated. Researchers attributed this difference between the two test areas to the greater persistence of undispersed oil in the intertidal sediments (API, 1986).

Baffin Island Oil Spill Project (BIOS) - 1981; Nearshore Subtidal

(original references include: Boehm *et al.*, 1982; Blackall and Sergy, 1983; Boehm, 1983; Cross *et al.*, 1983)

In 1981, researchers released partly weathered crude oil at high tide in two bays off Baffin Island, Canada. In one bay, 94 bbl of oil was released onto the surface over a period of six hours; and, in the other, 94 bbl of oil was mixed with 9.4 bbl of dispersant (1:10 dispersant to oil ratio) and released subtidally over the same amount of time. Deepest sampling was done at 10 meters depth.

In the bay with the dispersant-oil mixture, the highest oil concentrations on the seafloor were 55 to 167 ppm. Dispersed oil stressed some benthic organisms, causing NARCOSIS. Within one to two weeks following exposure to dispersed oil, benthic organisms appeared to regain normal functions. Long-term monitoring of the benthic organisms in the dispersed areas did not show large-scale mortality. After one year, there were no statistically-significant differences between benthic community composition in the dispersed area and an un-oiled control area. Also, hydrocarbon concentrations were less than 0.1 ppb in the waters of the dispersed area (API, 1986).

***Narcosis** is a state of stupor, unconsciousness, or arrested activity produced by the effects of oil and chemicals.*

Of the untreated oil discharged on the surface, some of the oil was lost to evaporation, and some naturally dispersed. The majority of the oil stranded along the intertidal zone. The oil remaining on the water surface was skimmed. Subtidal benthic organisms were not affected immediately by the untreated oil; however, some intertidal organisms and larval fish experienced a coating of oil. Oil concentrations in the top one meter of the water ranged from 0.01 ppm to 2.8 ppm. After one year, waters in the intertidal region of the untreated bay had hydrocarbon concentrations up to 3 ppb and visible oil sheens remained (API, 1986).

TROPICS - 1984 AND 1994; INTERTIDAL AND SUBTIDAL

(original references include: Ballou *et al.*, 1989; Dodge *et al.*, 1995)

In 1984, researchers conducted an experiment in Panama examining the effect of oil and dispersed oil on seagrasses, mangroves, and corals. With a water depth of approximately 0.6 meters over the corals, 30 meter by 30 meter sites were enclosed by booms and exposed, to simulate a 100 to 100 bbl spill, to either untreated oil or dispersant oil mixed with at a 1:20 ratio. 4.5 barrels of the oil/dispersant mixture were released into one site over a 24 hour period. Over a similar time period, six barrels of untreated oil was released into another site. More oil was released in the untreated site to achieve target water column concentrations of 50 ppm for both test sites.

After two years of monitoring, mangroves exposed to undispersed oil were severely affected, with many killed, while those exposed to dispersed oil suffered little damage. Seagrass beds were not affected by either dispersed nor undispersed oil; however, invertebrates living within the beds were affected by the dispersed oil. Corals were affected more by the dispersed than undispersed oil (Lewis and Aurand, 1997).

The site was revisited ten years later to examine long-term impacts. In the mangroves exposed to untreated oil, the viable tree population was only half the original number, while no direct mortality of trees exposed to the dispersed oil was observed. Also, corals appeared to have recovered from the effects of the dispersed oil. Overall, there was no significant difference between the experimental and control sites (Lewis and Aurand, 1997).

NORTH CAPE OIL SPILL - 1996; INTERTIDAL AND NEARSHORE

(original references include: French and Rines, 1997; Michel *et al.*, 1997; De Alteris *et al.*, 1999)

On January 19, 1996, the tank barge *North Cape* grounded and spilled approximately 828,000 gallons of No. 2 fuel oil on the south shore of

Rhode Island. Seas of 15 to 20 feet mixed the oil into the shallow waters and the resulting plume was transported over an area of about 400 km^2. Using the ADIOS fate model, NOAA estimated that 80% of the oil dispersed naturally within eight hours of being discharged. Measurements taken two days after the spill occurred showed that concentrations of oil ranged from 1 to 6 mg/l in the near-shore zone.

The spill resulted in high water column toxicity because of the large volume of oil dispersed into the shallow waters by heavy surf. There was high mortality of benthic organisms (e.g., lobsters, surf clams, crabs) and approximately 400 birds died, or had to be euthanized. A fishing closure was put in place over 250 square miles of coastal waters and seven coastal ponds. Studies on the recovery of surf clams in the area showed a particularly dramatic rate of re-colonization. Only one year after the spill occurred, young surf clam densities in the impacted areas were far higher than the density of surf clams in unimpacted areas. This most probably occurred because the oil spill killed the major predators of young surf clams (crabs) in the area, thereby allowing the clams to exist in much higher densities than previously possible.

Sea Empress Oil Spill – 1996; Intertidal and Nearshore

(original reference: Sea Empress Environmental Evaluation Committee, Initial Report. July, 1996; Law *et al.*, 1997; Lunel *et al.*, 1997)

Over the period of February 15 to 21, 1996, the *Sea Empress* released approximately 72,000 tons of crude oil and 360 tons of heavy fuel oil after grounding off of Milford Haven in South Wales, UK. Conditions included high spring tides and shifting winds of up to 35 knots. The coast became heavily oiled, killing many birds and invertebrates. Mechanical methods were used for some recovery at sea. To stop the further spreading of the slick, 445 tons of chemical dispersants were applied (target dispersant to oil ratio of 1:20). Dispersants were not applied within 1 kilometer of the shoreline to avoid use in any areas less than 20 meters deep.

It was estimated that approximately 50% of the spill volume dispersed into the water column as a result of both natural and chemical dispersion. Because of the high level of dispersion, it was also estimated that 57,000 to 110,000 tons of emulsified oil was prevented from stranding on the shore. Oil that did reach the shoreline was generally less sticky and more easily removed; most likely due to treatment with dispersants (J.C. Clow, personal observation during response operations). The initial report on the spill noted that the dispersants appeared to have been much more effective than expected at the 1:20 dispersant to oil ratio, especially on fresh crude oil.

Rapid dilution resulted in dispersant levels in the water column being generally too low to be detected. During the dispersant operation, concentrations of dispersed oil exceeded 10 ppm for periods of up to 10 seconds, in areas no larger than $1 m^3$. Between February and July, 1996, over 500 samples of shellfish and finfish were analyzed for hydrocarbon content. Finfish were found to have little or no hydrocarbon contamination. Also, no tainting was found when finfish were tested by a trained panel. Other than in the area of Millford Haven itself, crustaceans were also found to have low hydrocarbon concentrations and no tainted crustaceans were detected. Bivalves were found to be more heavily contaminated, with total hydrocarbon contents of over 1,000 mg/L in some cases. These animals experienced rapid increases in hydrocarbon concentrations, which generally peaked about day 40 and then decreased over the next four months.

Part IV: Examining Tradeoffs and Conducting a Risk Assessment

Every oil spill presents a unique situation with different concerns and different capabilities. Even with the best information available, the most appropriate response is not always obvious. Generally, in offshore areas, the use of dispersants is more beneficial than letting the oil come ashore. In nearshore environments, the decision is more complex. Although there are some relevant generalities we can make in terms of effects (Parts II and III above), the decision to use a dispersant is very dependent on specific spill conditions, such as oil type, oil amount, weather conditions, as well as the proximity and kind of sensitive resources. This is when tradeoff decisions must be made for the local area. Is it better to disperse the oil over a seagrass bed in order to prevent oiling of mangroves? Should oil be allowed to wash onto a beach, or chemically dispersed, risking damage to a coral reef? Questions like these will never have a predetermined answer, and tradeoff decisions will always have to be made. For example, a particular sandy beach might not be considered ecologically sensitive; however, during the tourist season, it may be highly valuable economically and might need to be protected from oiling above many other resources. Tradeoff decisions must address the full range of ecological, economic, and social values associated with the resources or habitats.

To more effectively prepare for an oil spill, regional and local managers can conduct pre-spill planning activities. These may include the use of an ECOLOGICAL RISK ASSESSMENT (ERA) to compare and evaluate the relative risks and benefits of response options. According to Aurand (1995), an ecological risk assessment must focus on the ecosystem at risk and must be a comparative analysis of risks and benefits. Endpoints, such as expected outcome, predicted effects, and so forth, must be clearly defined, and the systems well enough described so that impacts can be quantitatively determined. Ecological risk assessments do not include economic impacts. Aurand (1995) proposes a methodology for use of ecological risk assessments in oil spill planning that includes three phases: problem formulation, analysis, and risk characterization.

Ecological Risk Assessment *is a process to evaluate the possible ecological consequences of human activities and natural catastrophies. This methodology emphasizes the comparison of an exposure to a stressor (e.g., untreated oil or chemically dispersed oil) with an ecological effect (e.g., population alteration, changes in community structure or function, etc.) in as quantitative a way as possible.*

- **Problem formulation** - identification of stakeholders, ecological resources of priority concern, endpoints for protection and recovery, response measures to be evaluated, effects of both oil and countermeasures, and the development of a conceptual model of affected ecosystems.

- **Analysis** - defining exposure levels and characterizing the ecological effects and data for the oil and various response options.

- **Risk characterization** - estimation of potential effects, optimization of endpoints, and integration of results into contingency plans, along with periodic review.

Use of this methodology, if conducted in advance, will help all parties involved make informed decisions regarding the use of dispersants, as well as other countermeasures, during an oil spill.

The US Coast Guard, American Petroleum Institute and the Texas General Land Office sponsored an ecological risk assessment of the Galveston Bay area of Texas. A similar effort was also conducted with the support of the California Office of Prevention and Response for San Francisco Bay. The purpose of these ERAs was to examine the ecological tradeoffs involved in employing various response options in attempting to mitigate the impacts of oil spills in Galveston Bay and San Francisco Bay. Response options studied included mechanical recovery on water, in situ burning on water, chemical dispersion on water, shoreline cleanup and natural recovery. Participants in the ERAs included representatives from federal and state trustee and response agencies, the oil industry, oil spill clean-up contractors and non-governmental environmental and conservation groups. Participants attempted to quantify the relative ecological impacts of each of the response options in numerous water surface, water column, water bottom and shoreline habitats. Quantification allowed side-by-side comparison of the potential impacts of each option to determine which options offer the best potential for optimum mitigation of adverse impacts. Process participants in both San Francisco and Galveston arrived at several significant conclusions, most notably:

- Optimum mitigation can be achieved through the use of a mix of response options; and
- Dispersant use in Galveston Bay or San Francisco Bay on spills of 500 to 4,000 barrels may offer the single most effective option in mitigating adverse impacts of a spill.

Despite these findings, the ERAs do not represent an endorsement of dispersant use in either Galveston Bay or San Francisco Bay. Each ERA only examined a single type of oil at a single location within the Bay. Further assessment involving other oil types and locations will have to be conducted before any definitive conclusions can be drawn resulting in changes to response strategies outlined in existing Area Contingency Plans.

Nevertheless, the findings of these ERAs are a strong message to the Area Committees in San Francisco and Galveston Bay that further intensive investigation of the potential environmental benefit of dispersant use on small spills in shallow water estuaries is warranted. A possible result of those investigations may be the adoption of response strategies that encourage stockpiling of dispersants and dispersant delivery vehicles to accommodate expeditious dispersant application in shallow water estuarine systems because such application is in the best interest of the environment.

In Review

This reference document was developed to provide decision-makers with an accurate summary of exposure and effects from oil and chemically dispersed oil in the marine environment. This booklet was not developed to replace the need for pre-spill planning and actual response decision-making; it is assumed that decision-makers will still need to consult with resource trustee experts when evaluating the potential impacts from exposure to oil and chemically dispersed oil. This document was designed to assist decision-makers in understanding and answering many questions concerning exposure and effects, including:

1. **What will the oil do to a particular biological resource, both to the individuals and the entire population?**

These, but not all, questions are addressed in broad generalities for a variety of species based on their distribution (potential to be oiled) in the environment (refer to Part III Effects of Oil and Chemically Dispersed Oil). Oiling impacts on individual species depend on a wide variety of factors, including, but not limited to, the season, lifestage, species distribution, and oil type. Some species are known to suffer significant impacts (including death) when exposed to even small quantities of oil (e.g., sea otters, diving birds). Conversely, in other species groups (e.g., plankton, fish), individuals that are exposed to oil appear to recover quickly, thus limiting the overall impact from the exposure.

In general, little population effects are expected for most species exposed to oil. However, exceptions do exist, including threatened or endangered species.

2. **Would it be better to expose one resource to the oil so that another resource could be protected?**

This booklet will not provide the decision-maker with concrete answers to every situation. Rather, using the information detailed in Part II of this booklet, decision-makers, in coordination with resource trustees, can develop informed decisions by conducting trade-off analyses as discussed in "Part IV: Examining Tradeoffs and Conducting a Risk Assessment" of this booklet.

3. **Will adding chemical dispersants change the way oil affects plants and animals?**

The effects of chemically dispersed oil on biological resources, again, are addressed in broad generalities for a wide variety of species based on their distribution in the environment (refer to Part III, Section II of this booklet). Using the information provided in this section, decision-makers can evaluate the potential impact that exposure to chemically dispersed oil will have on a particular resource. This information can then be used as part of the trade-off analysis that is part of every decision-maker's job during oil spill response.

CONCLUSIONS

- Although the public has traditionally viewed the use of dispersants as ecologically risky, scientific evidence indicates the reverse; that there are situations where their use is an appropriate and ecologically beneficial response. This idea is supported by data from both scientific testing and real world spills. Dispersants and their use can have some environmental drawbacks, but, in certain cases, the ecological benefits outweigh the risks.

- Research has shown that within the normal range of operating dosages, ecological effects are often due to the dispersed oil and not the dispersant itself. The dispersant alone is unlikely to contribute significantly to adverse effects, even in multiple applications.

- In general, dispersants provide the greatest benefits and fewest environmental costs when used in deep offshore waters. When dispersants are used in waters close to shore, the likelihood of impacts to some organisms may increase. This is especially true in bays or restricted water bodies. However, the impacts caused by such dispersant use are sometimes an acceptable tradeoff, considering the damage that may be caused by undispersed oil to waterfowl, marine mammals, or when it washes ashore in sensitive and productive habitats.

While scientific studies have indicated various benefits associated with dispersant use, clearly there are situations in which dispersant use is ecologically inappropriate and might result in more damage to environmental resources than undispersed oil. An example is dispersing oil in an enclosed bay during a time when it is inhabited by the larvae of an important species. However, by carefully weighing the costs and benefits, decision-makers will be able to appropriately evaluate the unique opportunities and problems of each spill situation.

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