

Environmental Considerations for Marine Oil Spill Response

Regulatory and Scientific Affairs

PUBLICATION NUMBER 4706
JULY 2001

Environmental Considerations for Marine Oil Spill Response

API Publication Number 4706

prepared under contract by:

Debra Scholz, Ann H. Walker, and
Janet H. Kucklick (currently with NOAA Coastal Services Center)
Scientific and Environmental Associates, Inc.
325 Mason Avenue, Cape Charles, VA 23310

July 2001

iii

FOREWORD

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

API is not undertaking the duty of employers, manufacturers, or suppliers to either warn, properly train, or equip their employees, or other exposed people, on health and safety risks and precautions, nor is API undertaking their obligations under local, state, or federal laws.

Information concerning safety and health risks and proper precautions with respect to particular materials and conditions should be obtained from the employer, the manufacturer, or supplier of that material, or from the material safety data sheet.

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to ensure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication, and hereby expressly disclaims any liability for loss or damage resulting from its use or for the violations of any federal, state, or municipal regulation with which this publication may conflict.

The recommendations in this document are not intended to obviate the need to apply sound judgment and are not intended to, in any way, inhibit anyone from using other practices.

This publication will be reviewed and revised, reaffirmed, or withdrawn at least every five years. This publication may no longer be in effect five years after its publication date; status of the publication may be ascertained from the regulatory and scientific affairs (RASA) information specialist [telephone (202) 682-8319]. Suggested revisions are invited and should be submitted to the RASA information specialist, American Petroleum Institute, 1200 L Street, Northwest, Washington, DC 20005.

ACKNOWLEDGMENTS

THE FOLLOWING PEOPLE ARE RECOGNIZED FOR THEIR CONTRIBUTIONS OF TIME AND EXPERTISE DURING THIS STUDY AND IN THE PREPARATION OF THIS DOCUMENT:

API Staff Contact:

Alexis Steen, Health and Environmental Sciences Department

Members of the Marine Manual Update Work Group

David Fritz, BP Amoco, Chairperson
James Clow, Equiva Services LLC
Ronald Goodman, Imperial Oil Ltd.
Maget Hamed, Exxon Production Research Company
LT. Vickie Huyck, US Coast Guard
Bela James, Equilon Enterprises LLC
Royal Nadeau, USEPA - ERT
Robert Pavia, NOAA HMRD
LCDR Dave Skewes, US Coast Guard

Individuals who participated in the initial planning stages for the development of this document are detailed in Appendix F. The habitat and shoreline sketches developed for this document were provided by the National Oceanic and Atmospheric Administration (NOAA), Hazardous Materials Response and Assessment Division, Seattle, WA (1998). The *In-Situ* burn figures, unless indicated otherwise, were developed for this document by Alan A. Allen, Spiltec, Inc., Woodinville, WA (1998).

ABSTRACT

When planning response activities for an oil spill, decision-makers must react to a wide range of circumstances. Decisions will vary depending on the type of petroleum product spilled and the nature of the impacted habitat. Response decisions will be based on tradeoffs dealing with the environmental consequences of the spilled oil and the response method selected, as well as the efficiency and effectiveness of the method. Selecting appropriate protection, response, and cleanup techniques, both before and following an oil spill, affects the ultimate environmental impact and cost resulting from a spill. The American Petroleum Institute, the National Oceanic and Atmospheric Administration, the US Coast Guard, and the US Environmental Protection Agency jointly developed this document as a tool for contingency planners and field responders to identify response techniques that have minimal ecological impacts and also minimize the impact of the oil. Guidance is provided through matrix tables indicating the relative environmental consequences of the different response options used for various categories of oil in open water and shoreline habitats. The document provides information on 28 response methods and classifies their relative environmental impacts for combinations of five oil types and 25 marine habitats.

x

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
Foreword	v
Acknowledgments	vii
Abstract.....	ix
1.0 How to Use This Document	1-1
2.0 Technical Background	2-1
2.1 Properties and Fate of Oil	2-1
Oil Classification.....	2-1
Processes That Change the Location and Properties of Oil on Shorelines.....	2-11
2.2 Effects of Oil on Marine Ecosystems	2-14
Overview of Marine Ecosystems.....	2-14
Effects of Oil on Marine Life	2-19
Post-spill Recovery.....	2-21
2.3 Strategies for Selecting Response Methods.....	2-23
Setting Priorities: Environmental Vulnerability	2-24
3.0 Summary of Spill Response Methods	3-1
3.1 Impact of Methods in the Absence of Oil.....	3-1
3.2 Approach Used in the Evaluation of Methods	3-4
Classification of Oil Response Impacts	3-4
Evaluation of Relative Impact of Methods	3-5
Integrating Response Methods	3-5
Proper Application of Methods.....	3-5
Interpreting the Tables	3-5
Restrictions for Using Response Methods.....	3-6
3.3 Response Techniques	3-7
Introduction.....	3-7

TABLE OF CONTENTS (cont.)

<u>Section</u>	<u>Page</u>
3.3 Response Techniques, (cont.)	
Natural Recovery	3-8
Booming	3-9
Skimming	3-11
Barriers/Berms.....	3-13
Physical Herding.....	3-14
Manual Oil Removal/Cleaning.....	3-15
Mechanical Oil Removal.....	3-16
Sorbents	3-18
Vacuum	3-20
Debris Removal.....	3-21
Sediment Reworking/Tilling.....	3-22
Vegetation Cutting/Removal	3-23
Flooding	3-24
Low-pressure, Ambient Water Flushing.....	3-25
High-pressure, Ambient Water Flushing.....	3-26
Low-pressure, Hot Water Flushing.....	3-27
High-pressure, Hot Water Flushing.....	3-28
Steam Cleaning.....	3-29
Sand Blasting	3-30
Dispersants.....	3-31
Emulsion-treating Agents.....	3-32
Elasticity Modifiers.....	3-33
Herding Agents	3-34
Solidifiers	3-35
Shoreline Cleaning Agents (Surface Washing Agents).....	3-36
Nutrient Enrichment (Biostimulation).....	3-37
Natural Microbe Seeding (Bioaugmentation).....	3-39
<i>In-situ</i> Burning	3-41

TABLE OF CONTENTS (cont.)

<u>Section</u>	<u>Page</u>
4.0 Guidelines for Developing Response Actions	4-1
Goals	4-1
Objectives.....	4-1
Strategies	4-2
Tactics	4-2
Windows of Opportunity	4-3
4.1 Incident-specific Feasibility Issues	4-5
On-water Feasibility Issues	4-7
Shoreline Feasibility Issues	4-17
4.2 Process for Developing Incident-specific Strategies	4-21
Integration of On-water Response Options	4-21
Shoreline Strategies.....	4-23
5.0 Evaluation of Response Options in Various Habitats	5-1
5.1 Introduction	5-1
5.2 On-water Habitats	5-2
Feasibility and Effectiveness.....	5-4
Relative Environmental Impacts for On-water Response Options	5-7
Offshore	5-8
Bays and Estuaries.....	5-13
5.3 Shallow Subtidal	5-18
Coral Reefs	5-20
Seagrasses.....	5-26
Kelp.....	5-33
Soft Bottom.....	5-38
Mixed and Hard Bottom	5-43

TABLE OF CONTENTS (cont.)

<u>Section</u>	<u>Page</u>
5.4 Shoreline Intertidal	5-48
Exposed, Rocky Shores	5-50
Exposed, Solid, Man-made Structures.....	5-56
Exposed, Wave-cut Platforms.....	5-61
Sand Beaches.....	5-67
Tundra Cliffs	5-74
Mixed Sand and Gravel Beaches	5-80
Gravel Beaches	5-88
Riprap	5-95
Exposed Tidal Flats	5-101
Sheltered, Rocky Shores and Clay Scarps	5-107
Sheltered, Solid, Man-made Structures	5-113
Peat Shores	5-118
Sheltered Tidal Flats.....	5-124
Salt to Brackish Marshes	5-130
Mangroves.....	5-136
Inundated, Lowland Tundra.....	5-142
5.5 Ice	5-148
Habitat Description.....	5-148
6.0 Evaluation of Response Options by Oil Type	6-1

TABLE OF CONTENTS (cont.)

Appendices

Page

A	Regulatory Considerations.....	A-1
B	Oil Characteristics.....	B-1
C	Grain-size Scale	C-1
D	Shoreline Habitat Synonyms	D-1
E	Additional Reading List	E-1
F	Synopsis of Document Preparation.....	F-1

LIST OF FIGURES

<u>Figure</u>	Description	<u>Page</u>
1	A comparison of the environmental consequences of three different response methods, plus natural recovery, on a single spill over time.....	2-25
2	Types of response options during a major oil spill	4-4
3	Schematic representation of areal coverage rates for selected spill response systems	4-8
4	Average oil thickness versus potential response options	4-9
5	Primary spill response options under various wind/sea conditions and oil film thicknesses.....	4-14
6	Spatial considerations for integrated operations on a continuous release spill	4-24
7	Coral Reef Sketch	5-22
8	Seagrasses Sketch	5-28
9	Kelp Sketch	5-34
10	Soft Bottom Sketch	5-39
11	Mixed and Hard Bottom Sketch	5-44
12	Exposed, Rocky Shores Sketch	5-51
13	Exposed, Solid, Man-made Structures Sketch	5-57
14	Exposed, Wave-cut Platforms Sketch	5-62
15	Sand Beaches Sketch	5-69
16	Tundra Cliffs Sketch	5-75
17	Mixed Sand and Gravel Beaches Sketch	5-82
18	Gravel Beaches Sketch	5-89

LIST OF FIGURES (cont.)

<u>Figure</u>	<u>Description</u>	<u>Page</u>
19	Riprap Sketch	5-96
20	Exposed Tidal Flats Sketch	5-102
21	Sheltered, Rocky Shores and Clay Scarps Sketch	5-108
22	Sheltered, Solid, Man-made Structures Sketch.....	5-114
23	Peat Shores Sketch	5-119
24	Sheltered Tidal Flats Sketch	5-125
25	Marshes (Salt to Brackish) Sketch	5-131
26	Mangroves Sketch	5-137
27	Inundated, Lowland Tundra Sketch	5-143

LIST OF TABLES

<u>Table</u>	Description	<u>Page</u>
1	Characteristics of the five oil classifications used in this document.....	2-2
2	Approximate evaporation percentages for various classes of oil.....	2-7
3	Relative impacts of response methods in the absence of oil in on-water and shallow subtidal environments.....	3-2
4	Relative impacts of response methods in the absence of oil in shoreline intertidal and ice environments	3-3
5	Incident-specific on-water strategy issues	4-5
6	Incident-specific shoreline strategy issues.....	4-6
7	Factors favoring feasibility and effectiveness of on-water spill response.....	5-5
8	Estimate of wind speed and sea height influences on effectiveness and feasibility of on-water response options by oil type.....	5-6
9	Relative environmental impact from response methods for OFFSHORE.....	5-9
10	Relative environmental impact from response methods for BAYS AND ESTUARIES.....	5-14
11	Relative environmental impact from response methods for CORAL habitats	5-23
12	Relative environmental impact from response methods for SEAGRASS habitats	5-29
13	Relative environmental impact from response methods for KELP habitats.....	5-35
14	Relative environmental impact from response methods for SOFT BOTTOM habitats.....	5-40

LIST OF TABLES (cont.)

<u>Table</u>	<u>Description</u>	<u>Page</u>
15	Relative environmental impact from response methods for MIXED AND HARD BOTTOM habitats	5-45
16	Relative environmental impact from response methods for EXPOSED, ROCKY SHORES.....	5-52
17	Relative environmental impact from response methods for EXPOSED, SOLID, MAN-MADE STRUCTURES.....	5-58
18	Relative environmental impact from response methods for EXPOSED, WAVE-CUT PLATFORMS.....	5-63
19	Relative environmental impact from response methods for SAND BEACHES.....	5-70
20	Relative environmental impact from response methods for TUNDRA CLIFFS.....	5-76
21	Relative environmental impact from response methods for MIXED SAND AND GRAVEL BEACHES.....	5-83
22	Relative environmental impact from response methods for GRAVEL BEACHES	5-90
23	Relative environmental impact from response methods for RIPRAP	5-97
24	Relative environmental impact from response methods for EXPOSED TIDAL FLATS.....	5-103
25	Relative environmental impact from response methods for SHELTERED, ROCKY SHORES AND CLAY SCARPS.....	5-109
26	Relative environmental impact from response methods for SHELTERED, SOLID, MAN-MADE STRUCTURES.....	5-115
27	Relative environmental impact from response methods for PEAT SHORES	5-120

LIST OF TABLES (cont.)

<u>Table</u>	<u>Description</u>	<u>Page</u>
28	Relative environmental impact from response methods for SHELTERED TIDAL FLATS.....	5-126
29	Relative environmental impact from response methods for SALT TO BRACKISH MARSHES.....	5-132
30	Relative environmental impact from response methods for MANGROVES.....	5-138
31	Relative environmental impact from response methods for INUNDATED, LOWLAND TUNDRA.....	5-144
32	Relative environmental impact from response methods for ACCESSIBLE ICE environments.....	5-149
33	Relative environmental impact from response methods for INACCESSIBLE ICE environments	5-153
34	GASOLINE PRODUCTS (Category I): Relative environmental impact from response methods for ON-WATER habitats.....	6-2
35	DIESEL-LIKE PRODUCTS AND LIGHT CRUDE OILS (Category II): Relative environmental impact from response methods for ON-WATER habitats.....	6-3
36	MEDIUM GRADE CRUDE OILS AND INTERMEDIATE PRODUCTS (Category III): Relative environmental impact from response methods for ON-WATER habitats	6-4
37	HEAVY CRUDE OILS AND RESIDUAL PRODUCTS (Category IV): Relative environmental impact from response methods for ON-WATER habitats	6-5
38	NON-FLOATING OIL PRODUCTS (Category V): Relative environmental impact response methods for ON-WATER habitats	6-6
39	GASOLINE PRODUCTS (Category I): Relative environmental impact from response methods for SHALLOW SUBTIDAL habitats.....	6-7

LIST OF TABLES (cont.)

<u>Table</u>	<u>Description</u>	<u>Page</u>
40	DIESEL-LIKE PRODUCTS AND LIGHT CRUDE OILS (Category II): Relative environmental impact from response methods for SHALLOW SUBTIDAL habitats.....	6-8
41	MEDIUM GRADE CRUDE OILS AND INTERMEDIATE PRODUCTS (Category III): Relative environmental impact from response methods for SHALLOW SUBTIDAL habitats	6-9
42	HEAVY CRUDE OILS AND RESIDUAL PRODUCTS (Category IV): Relative environmental impact from response methods for SHALLOW SUBTIDAL habitats.....	6-10
43	NON-FLOATING OIL PRODUCTS (Category V): Relative environmental impact from response methods for SHALLOW SUBTIDAL habitats	6-11
44	GASOLINE PRODUCTS (Category I): Relative environmental impact from response methods for SHORELINE INTERTIDAL habitats.....	6-12
45	DIESEL-LIKE PRODUCTS AND LIGHT CRUDE OILS (Category II): Relative environmental impact from response methods for spills in SHORELINE INTERTIDAL habitats.....	6-13
46	MEDIUM GRADE CRUDE OILS AND INTERMEDIATE PRODUCTS (Category III): Relative environmental impact from response methods for SHORELINE INTERTIDAL habitats.....	6-14
47	HEAVY CRUDE OILS AND RESIDUAL PRODUCTS (Category IV): Relative environmental impact from response methods for SHORELINE INTERTIDAL habitats	6-15
48	NON-FLOATING OIL PRODUCTS (Category V): Relative environ- mental impact from response methods for SHORELINE INTERTIDAL habitats.....	6-16
49	GASOLINE PRODUCTS (Category I): Relative environmental impact from response methods for ICE habitats	6-17

LIST OF TABLES (cont.)

<u>Table</u>	<u>Description</u>	<u>Page</u>
50	DIESEL-LIKE PRODUCTS AND LIGHT CRUDE OILS (Category II): Relative environmental impact from response methods for ICE habitats.....	6-18
51	MEDIUM GRADE CRUDE OILS AND INTERMEDIATE PRODUCTS (Category III): Relative environmental impact from response methods for ICE habitats	6-19
52	HEAVY CRUDE OILS AND RESIDUAL PRODUCTS (Category IV): Relative environmental impact from response methods for ICE habitats.....	6-20
53	NON-FLOATING OIL PRODUCTS (Category V): Relative environmental impact from response methods for ICE habitats.....	6-21
54	Visual observations and estimating volume of undispersed oil	B-1
55	Grain-size scale.....	C-1
56	Habitat schemes used in other manuals.....	D-2

CHAPTER 1.0

HOW TO USE THIS DOCUMENT

Oil is a complex and variable natural substance. When released into the sea it can be transported long distances, undergo various physical and chemical changes, and adversely affect marine ecosystems. Oil's fate and effects depend on the type and quantity of oil spilled, properties of the oil as modified over time by physical and chemical processes, the organisms and habitats exposed, and the nature of the exposure. All these factors should be considered when evaluating response methods. Interactions among these variables result in an infinite range of spill situations. Accordingly, spill responders need a wide variety of tools.

Response techniques have "windows of opportunity," specific timeframes when each response method works the best. These windows are defined by the type of product spilled, the initial spill conditions, product weathering and emulsion rates, and the very different environments and ecosystems that are, or will be, impacted. When the techniques are used within these windows, they are more effective and less damaging to populations that survive the oil, allowing the affected ecosystem to recover quicker.

In every oil spill, government and industry decision-makers are presented with a unique set of challenges requiring timely application of appropriate response methods.

- How does an on-scene coordinator or a responsible party sort through the myriad of options and select those methods that will effectively mitigate and clean up the oil in the given circumstance?
- What is the rationale for selection?

This document addresses these issues to provide appropriate information to decision-makers relating to tradeoff decisions for specific habitats and response options. It focuses on maximizing response while minimizing impacts to resources.

This document provides the technical basis and rationale for pre-spill planning and response decision-making, and will assist the user in selecting response options to minimize adverse environmental impacts of a marine oil spill. On-water, shallow subtidal, shoreline intertidal, and ice habitats are discussed. Specific response options, including natural recovery, mechanical, chemical, biological, and *in-situ* burning, are evaluated.

CAUTION!

Deciding on response methods during an actual spill usually also depends on legal, social, and economic factors specific to the incident, as well as the practicality and timeliness of using the response method.

The user must remember that the selection of a proper response method is highly dependent on incident-specific conditions, and that the strengths and weaknesses of a given response tool affect the suitability for its employment in a given habitat for a specific spill. Accordingly, using multiple methods simultaneously throughout an incident may produce a more effective response and minimize environmental impacts.

The selection of response options, including natural recovery, involves considering tradeoffs among their potential environmental impact, appropriateness for habitat, and application timing.

This document has been developed primarily to facilitate pre-incident response decisions which, since the Oil Pollution Act of 1990 (OPA 90), are made by Area Committees (ACs), Regional Response Teams (RRTs), and industry. During pre-spill planning, this document may be used to assist with:

- Developing response strategies for contingency plans and identifying equipment needs for response;
- Evaluating the area-specific response strategies and related adequacy of area equipment stockpiles;
- Assessing consistent application of effective response strategies across and between regions by RRTs;
- Assessing industry planning strategies as laid out in their facility, vessel, or pipeline response plans;
- Assessing the continuing vitality of the response community in a given area or region by exercise designers, executors, and evaluators; and
- Training for developing and implementing Area Contingency Plans.

During an oil spill response, this document can be used as a reference by the On-scene Coordinator and the Unified Command for communicating with government, the news media, and the public concerning the rationale for, and confidence in, the efficiency and effectiveness of the response methods employed. However, this document is not a cookbook decision text nor a substitute for training, qualified technical advice, or good sense. Proper use of the guidance contained in this document during response operations requires timely, expert

assessment of existing and projected environmental conditions, and an assessment of the probable effectiveness of each response method under these conditions.

This document may be customized for specific geographic areas to address special priorities and concerns, but it does not address:

- Environmental considerations for chemical spills;
- Wildlife management;
- Spills on land;
- Human-health and safety concerns;
- Non-ecological resources (e.g., recreation, tourism, aquaculture);
- Legal or regulatory issues; nor
- Planning, organizing, and conducting a spill response effort.

The document is organized to provide the user with a progressive understanding and rationale for selecting response options that minimize adverse environmental effects. The general organization for the present document, and much of the information on response options, has been adapted from a 1994 API/National Oceanic and Atmospheric Administration (NOAA) publication which focuses on response options in the freshwater environment. Information on shoreline habitats was taken, in part, from a 1992 NOAA Shoreline Countermeasure Manual.

The document is structured to allow the reader to obtain information on an oil type and a habitat type, and then find out the various options to respond to a spill of that oil in that habitat. For instance, the reader can find out about the characteristics of a Category III oil by referring to Table 1, obtain information on sand beaches by reading the discussion in Chapter 5, and then look at Table 19 to see what response options are recommended for dealing with a spill of Category III oil on a sand beach.

Chapter 2 provides a discussion of technical concepts and information to lay a foundation for subsequent chapters. This chapter:

- Summarizes oil properties and classification, physical and chemical fate of oil on water and shorelines, and effects of oil in marine ecosystems; and
- Discusses strategies for selecting response methods.

Chapter 3 contains detailed descriptions of the response methods listed in the

matrices. For each, the following information is provided:

- Objective;
- Description;
- Applicable Habitats;
- When to Use;
- Biological Constraints;
- Environmental Impact; and
- Waste Generation.

To understand the relative impact of oil plus the response method, the reader must first have an understanding of the baseline impact of methods in the absence of oil. This information is also presented in Chapter 3.

Chapter 4 describes guidelines for developing strategies for on-water and shoreline response.

Chapter 5 presents the “bottom-line” portion of the document by identifying the appropriateness of using different response methods in the various habitats. This chapter is organized by habitat and, for each, contains:

- A detailed description of the habitat;
- A discussion of habitat sensitivity; and
- A matrix, along with associated text, of response methods recommended for use in that habitat for each of the five general oil categories (oil categories are discussed in Section 2.1).

Chapter 6 presents the matrices from Chapter 5 in a slightly different format: by oil type instead of by habitat.

The appendices include:

- Regulatory considerations (A);
- Oil characteristics (B);
- Grain-size scale (C);
- Table of synonyms of shoreline types (D);
- References and additional reading (E); and
- Synopsis of document preparation (F).

CHAPTER 2.0

TECHNICAL BACKGROUND

Understanding important technical concepts is essential to lay a foundation for selection of response options that minimize adverse environmental effects. Summaries are provided of oil properties and classification, physical and chemical fate of oil on water and on shorelines, and effects of oil in marine ecosystems. An overview of response objectives and strategies follows.

2.1 PROPERTIES AND FATE OF OIL

This section summarizes basic information on oil properties and classification and then discusses physical and chemical fate of oil on water and on shorelines.

OIL CLASSIFICATION

A common oil classification scheme, based primarily on specific gravity, defines five categories. Table 1 summarizes the properties of the five oil categories used in the document. Although diesel is often classified as a Category I oil (because it is considered non-persistent), it is placed in Category II because methods used to respond to a diesel spill are similar to those used to respond to a Category II spill.

Weathering changes the physical and chemical properties of oil over time, generally making it less volatile, more viscous, and heavier (increased specific gravity); so, response methods should be re-evaluated as the oil changes in character.

Marine oil spills occur within the full range of crude oils and refined products, and an understanding of the type of oil spilled and its properties is critical to the development of effective response strategies. The following information highlights key considerations relative to the oil properties most critical to marine oil spill response.

Table 1. Characteristics of the five oil classifications used in this document.¹

Gasoline Products (Category I)	Diesel-like Products and Light Crude Oils (Category II)	Medium-grade Crude Oils and Intermediate Products (Category III)	Heavy Crude Oils and Residual Products (Category IV)	Non-floating Oils - Heavier than Water (Category V) ²
Examples – Gasoline types of products • Very volatile and highly flammable • High evaporation rates; narrow cut fraction with no residues • Low viscosity; spread rapidly to a thin sheen • High acute toxicity to biota • Does not emulsify • Will penetrate substrate; nonadhesive	Examples – No. 2 fuel oil, jet fuels, kerosene, West Texas crude, Alberta crude • Moderately volatile • Refined products can evaporate to no residue; crude oils leave a residue after evaporation is complete • Low to moderate viscosity; spread rapidly into thin slicks • Specific gravity of <0.85; API gravity of 35-45 • Moderate to high acute toxicity to biota; product-specific toxicity related to type and concentration of aromatic compounds • Can form stable emulsions • Tend to penetrate substrate; fresh spills are not adhesive • Stranded light crudes tend to smother organisms	Examples – North Slope crude, South Louisiana crude, No. 4 fuel oil, IFO 180, lube oils • Moderately volatile • Up to one-third will evaporate in the first 24 hours • Moderate to high viscosity • Specific gravity of 0.85-0.95; API gravity of 17.5-35 • Variable acute toxicity, depending on amount of light fraction present • Can form stable emulsions • Variable substrate penetration and adhesion • Stranded oil tends to smother organisms	Examples – Venezuela crude, San Joaquin Valley crude, Bunker C, No. 6 fuel oil • Slightly volatile • Very little product loss by evaporation • Very viscous to semisolid • Specific gravity of 0.95-1.00; API gravity of 10-17.5 • Low acute toxicity relative to other oil types • Can form stable emulsions • Little penetration of substrate likely, but can be highly adhesive • Stranded oil tends to smother organisms	Examples – Very heavy No. 6 fuel oil, Residual Oils, Vacuum Bottoms, Heavy slurry oils • Very low volatility • No evaporation when submerged • Very viscous to semisolid • Specific gravity greater than water • Low acute toxicity relative to other oil types • Can form stable emulsions • Little penetration of substrate likely, but can be highly adhesive • Stranded and submerged oil tends to smother organisms

¹ Source: modified from API and NOAA, 1995.

² Work by the National Research Council (1999) has renamed Category V oils from "Low API Oils" to "Non-floating Oils". To reflect the most current terminology and research, Category V Oils will be labeled as Non-floating Oils.

Flash Point and Evaporation

Flash point is the temperature at which the vapors of a substance ignite when exposed to a flame or spark. Highly volatile oils that evaporate rapidly may pose significant fire and explosion risks. Often, the safest option is to allow such products to evaporate. Evaporation is an important mechanism for removing the oil because it can lessen the need for response and concern for associated impacts. Highly volatile oils, e.g., Category I, can completely evaporate in one to two days under most conditions.

Specific Gravity/Density/API Gravity

Specific gravity is the density of a substance relative to fresh water. API gravity is related to specific gravity as follows:

$$\text{API Gravity} = \frac{141.5}{\text{Specific gravity at } 60^{\circ}\text{F}} - 131.5$$

Oils with a specific gravity greater than 1.00 (API gravity < 10) will sink in fresh water. Oil will sink in seawater if its specific gravity exceeds approximately 1.02 (API gravity < 7). When lighter oils have stranded on a shoreline, incorporated sediment can cause sinking if the oil re-enters the water.

Viscosity/Pour Point

Viscosity is an oil's internal resistance to flow and is measured in centistokes (cST). Viscosity controls the rate that oil spreads on water and its likely depth of penetration into the substrate once on shore. Low-viscosity oils spread rapidly into thin sheens, increasing their surface area and making recovery difficult. They readily penetrate sediments and debris. Oils can be so viscous that they do not spread, particularly in cold water, and such oils are more likely to coat, rather than penetrate, surfaces. Viscosity changes with temperature. For example, viscosity reduces with increasing temperature and vice versa. Oils at temperatures greater than the pour point will flow, below the pour point, they won't. However, they are generally not solid and will "creep", which is an important consideration in some situations such as with sunken vessels where oil below the pour point still leaks. An oil's pour point is the temperature below which oil will not flow. A highly viscous oil will have a higher pour point compared with less viscous oils.

Processes that Change the Location and Properties of Oil on Water

When oil is spilled on water, it immediately begins to move and its physical and chemical properties change. These changes can have a significant influence on spill response activities. Understanding how an oil spill changes through time is important in order to understand how the appropriateness of different spill response options changes through time.

If oil stayed put once it was spilled, cleanup would be easier and environmental impacts would be less. Unfortunately, the oil's location will be changed by advection, spreading, and submersion.

Advection

Oil moves on the water's surface due to forces generated by winds and water currents in a process known as advection. Wind, when blowing over the water's surface, produces a surface current of about 3% of the wind speed in the direction the wind is blowing.

There are several types of ocean currents (ocean current direction is described as the direction to which the current is flowing). Long-term or seasonal currents are generated by regional changes in ocean circulation and are influenced by the effect of the earth's rotation, bathymetry, and coastal geometry. Currents cannot be assumed to be constant over the course of an incident.

Tidally-generated currents vary on a tidal time scale (12 or 24 hours), depending on the region. In water depths greater than about 30 feet (10 meters), these currents transport the oil backward and forward (i.e., they do not cause a net motion of the oil when averaged over a long time scale). If the tidal motion causes the oil to come near shore or into shallow water, these currents can force the oil near a shoreline or cause a net motion of the oil. An on shore wind is necessary for the oil to strand on a shoreline.

Estimating or predicting oil movement on water is called oil spill trajectory modeling. Using the concepts discussed above, oil spill movement can be estimated by hand, using graphical techniques, or predicted in a more sophisticated fashion, using a computer. It is important to remember that the speed and direction of the wind can vary rapidly over time; therefore, weather forecasts must be frequently obtained when calculating oil spill trajectories.

Spreading

As soon as oil is spilled in the water, it starts to spread, driven by gravity. In the initial stage of spreading, the oil's viscosity provides most of the retarding force; thus, a light oil will spread more rapidly than a heavy oil.

In the final stage of spreading when the oil layer is very thin, the main driving force is the surface tension of the oil, rather than gravity.

During the gravity-spreading phase, the oil separates into two slick-thickness regions. Most of the oil will form thicker patches [from 0.004 to 0.04 inches (0.1 to 1 millimeter)] for temperate regions and medium oil. Surrounding these patches will be large areas of thinner oil [0.000004 to 0.0004 inches (0.1 to 10 micrometers)], commonly called sheen. Since most of the volume of the oil is in the thick regions, a rule of thumb is that 90% of the oil is in 10% of the oiled area, and, conversely, 10% of the oil is in 90% of the oiled area. Oil thickness will not be homogeneous, and response activities may need to be focused on small areas of the thicker oil in order to be effective.

Due to a combination of wind and wave action, the contiguous slick will soon become discontinuous, forming windrows, which are typically a few meters wide, and are separated by areas of clear water or sheen. Under suitable conditions, skimmers can effectively collect oil from windrows.

The rapid spreading of oil on water can limit certain response options. For example, *in-situ* burning requires a minimum thickness of 0.08 to 0.2 inches (2 to 5 millimeters). Since most oils spread rapidly to an average thickness of between 0.00394 and 0.04 inches (0.1 and 1 millimeter), such slicks cannot be burned without the use of fire-resistant booms or other types of containment to help maintain this thickness. Spreading increases the area of a slick, thus limiting skimmer encounter rate and recovery effectiveness.

Submersion

Most oils float because they are less dense than water. If oil is (or becomes) more dense than water, it will submerge; but, this is a relatively rare occurrence. Sea water specific gravity varies depending on the salinity, temperature, and depth (pressure), but a typical value is 1.02.

Oils increase in density as the lighter fractions evaporate, and, for Categories IV and V oils, the increasing density may result in the weathered oil submerging. Submerged oil will sink below the surface and "float" above more dense water,

deeper in the water column. Some *in-situ* burn residues also may become heavier than water and submerge.

If the oil is (or becomes) neutrally buoyant (has exactly the same density as the water), it will quickly diffuse into the water column, achieving a very low concentration after a few hours to days. Submerged or neutrally buoyant oil that attaches to suspended sediment may sink to the bottom and remain there, unless resuspended by heavy wave action.

Early Processes that Change Oil Properties

The processes of evaporation, dispersion, and dissolution that occur in the early stages of an oil spill are most important within the first few hours to days of a spill and cause significant changes to the physical and chemical properties of the oil. Collectively, these processes are known as weathering. These changes help drive the decision-making process as responders consider their response options.

Evaporation

For light oils, evaporation will be the most rapid and extensive weathering process, as the lighter ends of the oil vaporize. The amount and rate of evaporation is a function of the properties of the spilled oil and the existing environmental conditions. For example, low temperatures and light winds reduce the rate of evaporation.

Different oils will evaporate at varying rates and proportions (Table 2). Precise evaporation calculations can be made if the oil's specific properties are available. Most computer models can provide specific time-dependent information on evaporation, but they require detailed information about the boiling curves or composition of the oil.

For very light crudes and products, such as gasoline, evaporation may eliminate nearly all the spilled oil in a few hours. Under certain environmental conditions, the vapors may develop into a flammable mixture, so it is generally advisable not to contain a gasoline spill.

Evaporation of the light ends (the lower molecular weight molecules) causes an increase in the oil's viscosity, and changes the ratios among the different kinds of molecules. These changes alter the oil's behavior, thus influencing the selection and success of response actions. The increase in viscosity generally reduces the

Table 2. Approximate evaporation percentages for various classes of oil.¹

Oil Category	12-hour Evaporation	48-hour Evaporation	Total Fraction Evaporated
I. Gasoline	50-100%	100%	100%
II. Diesel and Light Crude Oils	10-40%	25-80%	up to 100%
III. Medium Crude	5-30%	15-40%	45%
IV. Heavy Oils	1-3%	5-10%	15%
V. Non-floating Oils	0-2%	1-5%	10%

¹ Lower limits are for 5°C (40°F) and the upper limit for 30°C (85°F). For this table, a moderate wind speed of 5 m/sec (10 kts) has been assumed. These calculations are based on OILMAP algorithms. Other models may produce slightly different results, but modern models will predict within the ranges in Table 1.

effectiveness of both skimmers and dispersants. The loss of light ends makes ignition (*in-situ* burning) of the oil more difficult. The change in the ratio of aromatics, resins, and asphaltenes increases the likelihood of emulsification.

Evaporation may be so complete for gasoline that no removal action is needed. In the case of a light to medium crude, evaporation may reduce the amount of oil on the water by half.

Dispersion

Dispersion is the breaking up of a surface slick into small particles [0.0004 to 0.004 inches (10 to 100 micrometers) in size] that are subsequently mixed into the water column. The amount of dispersion depends on the properties of the oil and the amount of wave energy involved.

For low viscosity oils, a controlling parameter of dispersion is the interfacial tension between the oil and the water. The higher the interfacial tension, the more wave energy is needed to form the dispersible small particles. Viscosity becomes the controlling parameter for more viscous oils.

Wind-induced vertical eddy motion will move small oil particles into the water column to a depth of about four times the significant wave height. If this vertical mixing stops, the dispersed particles will eventually resurface (smaller particles take longer). In even

a low sea state (Beaufort 2), particles as large as 0.004 inches (100 micrometers) will remain in the water column as long as their rise velocity is less than the orbital velocity of the waves.

Natural dispersion, for a medium oil and moderate sea state, can remove between 1% and 15% of the slick from the surface. Oil particles in the water column will experience a rapid horizontal diffusion, reducing the dispersed oil concentration by two orders of magnitude in less than an hour. Thus, dispersion results in only a short-term exposure in the top few meters of the water column.

Because the small oil particles in the water column have a much larger surface area in contact with the water than those in the surface slick, the rates of dissolution (see below) and biodegradation (see below) are increased. Whether dispersion reduces or increases the environmental impact of the spill depends on the environmental situation and the oil properties. For most spill situations, removing oil from the water surface before it disperses (and the subsequent rapid reduction of the oil concentration in the water column) will reduce the overall environmental impact. In some situations, chemical dispersion may be desirable. Chemical dispersants lower the interfacial tension by an order of magnitude or more, accelerating both the rate of dispersion and the amount of oil dispersed into the water column.

Dissolution

The old adage that “oil and water do not mix” is not true. The light ends of oil are partially soluble in water in a process called dissolution. The rate of dissolution depends on the contact surface area between oil and water as well as the oil’s chemical composition. As the slick spreads or is dispersed (naturally or chemically), the resulting larger surface area will increase both the rate of dissolution and the amount of oil dissolved. Only a few components of oil are soluble in water, so dissolution involves only a small fraction of the oil, generally a few parts per thousand of most crude oils.

Some of the dissolved components (water-soluble fraction) are toxic to marine organisms, so even though the volume of oil may be low, the process is important for assessing a spill’s environmental impact.

Water-in-Oil Emulsification

Physical mixing of water into the oil can produce an emulsion, a fluid that can be larger in volume (i.e., 80% water and 20% oil) and orders of magnitude greater in viscosity than the original oil. Often called “chocolate mousse,” this type of emulsion consists of small water droplets [0.00004 to 0.0004 inches (1 to 10 micrometers)] surrounded by a thin film of oil; the water droplets are closely packed, and the oil is contained in the interstitial spaces.

In the initial stages of emulsification, only a small amount of water is mechanically incorporated into the oil. Such emulsions are very unstable and will readily separate into oil and water if left undisturbed. As the amount of water in the oil increases, droplet size decreases, and natural surfactant (in the oil) accumulates at the interfaces, and the emulsion becomes stable and viscous. A “mousse” emulsion generally has a brown or orange tinge when viewed from the air, as opposed to black for unemulsified oil.

The increase in volume and viscosity significantly impacts the effectiveness of most response techniques:

- An emulsion does not flow easily into skimmers;
- A larger amount of material must be removed;
- Viscous emulsified oil is difficult to pump;
- Dispersants are not as effective (due to the high viscosity and water in the fluid), but there is evidence that dispersants can break some emulsions, allowing the oil to disperse normally; and
- *In-situ* burning is more difficult (or impossible) because of the water in the oil. Also, continued burning is inhibited because it depends on the release of volatile compounds by radiant heat; but, since much of the radiant energy is used in vaporizing the water and breaking the emulsion, volatile compound release is limited.

Long-term Processes that Change Oil Properties

A number of long-term weathering processes can alter spilled oil's chemical or physical nature. These processes, which take place over days to months, include biodegradation, photo-oxidation, auto-oxidation, and sedimentation.

Biodegradation

Biodegradation (aerobic or anaerobic) is a process in which indigenous microorganisms (e.g., fungi, bacteria) degrade oil (use it as an energy source, i.e., food), producing carbon dioxide, water, and biomass. Aerobic degradation of oil requires the presence of oxygen; anaerobic degradation does not. The rate of biodegradation depends on the oil type, the surface area of the oil, and the concentrations of oxygen, nitrogen, and phosphorus (the aerobic process is faster). Increasing the surface area of a slick by spreading and/or dispersion will increase the rate of biodegradation. The ultimate removal of oil from the sea, whether from spills or natural seeps, is largely due to biodegradation.

Photo- and Auto-oxidation

In photo-oxidation, an oil's chemical characteristics are changed when solar radiation (particularly in the near ultraviolet) interacts with it to produce hydrocarbon oxides and hydroxides. The resulting compounds have very different properties than the parent oil; they are generally more soluble in water.

For most spill situations, the amount of oxidized compounds is very small and dissolution of these compounds will reduce the spilled oil volume only slightly. While the most dominant process is photo-oxidation, oxidation can result from bacterial fermentation or by simple contact with the atmosphere (auto-oxidation).

Sedimentation

If sediment particles are suspended in the water column, oil can stick to them, forming a sediment-oil agglomeration that is likely to be denser than water. In general, the oil particles will be smaller and will, therefore, coat the sediment. In some situations, sedimentation can deposit oil on the ocean floor, resulting in its incorporation into the bottom sediments and slower degradation. A number of mechanisms have been proposed to explain the oil sedimentation process but, to date, there is no detailed, published explanation of the processes.

PROCESSES THAT CHANGE THE LOCATION AND PROPERTIES OF OIL ON SHORELINES

Some weathering processes that affect oil on the water will also affect it on shorelines. Dispersion, dissolution, and emulsification do not affect oil on shorelines, but still can affect oil in the near-shore aquatic environment; and, since near-shore breaking waves may generate more energy than those in the open ocean, dispersion and emulsification rates may be higher closer to shore. Oil on shorelines can be remobilized and transported to adjacent areas by nearshore currents. Where oil is stranded, the dominant physical processes are evaporation, biodegradation, spreading, demulsification, subsurface movement, natural removal, oil/fine-particle interaction, and adhesion.

Evaporation

This is the same process that occurs on the sea surface. Because the shoreline is a thermal insulator, solar energy may heat the oil to higher surface and internal temperatures than on water, thus increasing evaporation. The higher temperatures will also allow the oil to flow more readily, increasing the surface area exposed to sunlight and further increasing evaporation. There have been few studies of oil evaporation on shorelines, and most models either exclude the process or use the same rate as for water.

Biodegradation

When stranded on a beach, oil is generally immobile, and biodegradation becomes an important weathering process. Adding nutrients (phosphorous, nitrogen) or microbes to stranded oil to enhance natural biodegradation is known as bioremediation and is used to remove small amounts of oil after other cleanup activities have removed the bulk. In the case of lightly oiled shorelines, bioremediation may be the favored cleanup option. Since oil is a natural product, native oil-degrading bacteria are frequently in abundance, and the rate of biodegradation will depend on temperature, oil properties, and nutrient availability.

Demulsification

Heating emulsified oil may cause some semi-stable emulsions to break down, releasing the water and reducing the mousse volume by a factor of two or more.

Subsurface Movement

If the spilled oil has a low viscosity, or if the impacted shoreline is composed of pebbles and cobbles, the oil will penetrate the beach. This means that weathering and biodegradation can slow or cease, and the oil may remain for months to years.

Natural Removal

If the shoreline is a medium-to-high energy environment, the shoreline material may be moved during storms, exposing any beached oil and mixing it into the nearshore water column.

Oil/Fine-particle Interactions (OFI)

There is considerable evidence that fine mineral particles present in the water will help to gradually remove stranded oil from the shoreline in the form of clay-oil flocculations. This material has a density near 1.0, and may float, be neutrally buoyant, or submerge. This process is only beginning to be understood, but oil/fine-particle interactions may account for the natural cleansing observed in many beach spill situations.

Adhesion

There is a limited understanding of the physics of oil adhesion to rocks, and attempts to predict the amount of oil adhesion, using either computer models or adhesion theory, have not been successful. Under certain conditions, some oils adhere strongly to rocks; in other situations, the oil is often easily removed by tidal action. Moisture seems to be important, as wet rock is less prone to oil adhesion, and rock coated with a microbial film seems to be resistant to adhesion. The amount and strength of adhesion seem to depend on the oil type, with heavier oils or weathered oils being more adhesive than light oils.

Heavy oil on shorelines may spread and increase in area due to surface heating from solar radiation.

Sedimentation

Asphalt Pavements on Shorelines

Asphalt pavements form when oil penetrates porous sediments (sand, gravel, shell, or mixtures of these), filling the pore spaces between the sediments with oil. A minimum amount of oil (estimated to be 10-20 percent by volume) is required to create asphalt pavements, though the "oil" that fills the pores can be emulsified oil, containing up to 60-80 percent water. The oil has to be relatively viscous and

adhesive so that it plugs the pore spaces; otherwise, the oil continues to penetrate to the point that the oil concentrations are too low to form pavements. Surface pavements are most likely for viscous black oils because they form a heavy surface layer. They usually occur in the mid-to-upper intertidal zone, where the water table is lowered below the sediment surface at low tide, allowing oil to penetrate the drained sediments. They persist where wave energy is low or episodic, such as oil stranded during storms high above the normal zone of reworking by waves, or on sheltered gravel beaches. The oil forms a hard, weathered skin or crust, which tends to slow weathering of the oil inside the pavement. This process was well-documented for pavements formed during the 1974 *Metula* spill in the Strait of Magellan. Surveys conducted 12.5 years later reported fresh oil inside of hardened pavements 10-15 cm thick (Owens, *et al.*, 1987).

Surface pavement can be buried by the deposition of clean sediments on top, which further slows weathering processes. Pavements can also form in subsurface sediments, though this is not common. Subsurface pavements usually form where there is a change in sediment grain size with depth. That is, the oil penetrates to a finer-grained layer where it accumulates at concentrations high enough to form pavements.

Tarmats in Nearshore Subtidal Habitats

Tarmats are thick (>2-3 cm) accumulations of oil-sediment mixtures which form when oil strands onshore, picks up sand or broken shell, and then erodes from the beach and deposits in nearshore areas. They can also form without the oil stranding onshore, where the oil mixes with sand suspended by nearshore breaking waves. In both cases, a buoyant oil becomes heavier than seawater by picking up only a few percent sand or shell. Key factors which lead to formation of subtidal tarmats from intertidal oil are: 1) heavy accumulations of a highly viscous oil which does not penetrate the sediment after stranding onshore, but picks up some sediment by adhesion; 2) moderate wave energy which erodes the oil in large pieces (very high wave energy would break up the oil into too small pieces; low wave energy would lead to asphalt pavement formation onshore); and 3) troughs between offshore bars or other depressions in the near subtidal zone where the heavy oil/sediment mixture can accumulate into thick mats. Classic examples of tarmat formation were the *Ixtoc I* oil after it stranded in Texas and the *Alvenus* spill of heavy Venezuela crude which stranded near Galveston (Michel and Galt, 1995). Tarmats are soft but stiff, and they weather very slowly.

2.2 EFFECTS OF OIL ON MARINE ECOSYSTEMS

This section describes the diversity and basic functions of marine life and ecosystems, the effects of oil on them, environmental sensitivity, and post-spill recovery.

OVERVIEW OF MARINE ECOSYSTEMS

During a spill response, the news media often show video of an oiled bird or marine mammal to capture the public's attention. In reality, such portrayals fall far short of the actual complexity and diversity of marine life that must be considered in an effective spill response. We must also be conscious of what is not easily seen: the small species of seaweed, worms, slugs, snails, and microbes that contribute greatly to marine biodiversity and provide the basic building blocks of marine food webs.

Organization of Marine Ecosystems

Life in the sea and on shore is concentrated in many different habitats and zones, each of which poses unique challenges for responders, as detailed below and in Chapter 5. The broad categories of habitats include the sea surface, the water column, the nearshore and deep water sea floor, and the intertidal shoreline.

Life on the Surface (Neuston)

The first environment affected by a marine oil spill is the sea surface.

- Birds, mammals, turtles, and many kinds of fish and invertebrates live and/or concentrate at the sea surface, putting them at high risk.
- For short periods of the year (days, weeks) the eggs, larvae, and juveniles of fish, crab, and many other species congregate at the surface, together with high concentrations of bacteria and phytoplankton (single-celled plants).

Life at the surface is not evenly distributed, but occurs in concentrations and patches created by the same ocean processes that disperse and concentrate oil. For example, convergence zones near headlands serve not only to concentrate oil, but also the eggs and larvae of various fish and invertebrates.

Life in the Water (Nekton and Plankton)

Pelagic (free-swimming) fish, squid, and krill live throughout the water column, but are more abundant nearshore and are most often concentrated as schools, shoals, and patches.

- The water column has “life-zones” at various depths, with different mixes of species in each; however, many species undergo vertical migrations, rising at night and descending in the day, a fact that might be of concern during oil dispersion; and
- The drifting life – plankton – includes not only short-lived plants (phytoplankton) that remain small and microscopic, but also the eggs and larvae of both pelagic and nearshore fish and invertebrates.

Life on the Bottom (Deep Water and Shallow Subtidal)

- Much life in the sea is attached to, buried in, or lives just above, the bottom;
- A square meter of healthy, muddy sea floor can contain 5,000-10,000 small animals (1 mm-1 cm) including clams, snails, stars, shrimp, amphipods, ostracods, crabs, etc. These serve as prey for dozens of species of bottom-dwelling fish and many commercially-important species of crab, lobster, and shrimp;
- One cubic centimeter of marine mud or sand contains one to ten thousand bacteria of hundreds of species, dozens of which are capable of degrading alkanes and polycyclic aromatic hydrocarbons (PAHs); however, when sediment is oiled, the bacteria counts go up to one hundred thousand to ten million oil-degrading organisms per cubic centimeter;
- Generally, diversity (numbers of species) remains constant, but abundance decreases with water depth;
- In well-lit, shallower water nearshore (less than 100 m deep), long stretches of sandy or muddy bottom are often interspersed with cobble and rocky reefs, all home to a wide variety of conspicuous and inconspicuous marine plants and animals;
- Tropical barrier reefs are totally composed of, and built by, marine plants and animals (corals);
- Along temperate coasts, sediments harbor large populations of worms, crustaceans, and clams. These and their reproductive products provide food for a variety of sea stars, sea urchins, brittle stars, bottom fish, rays, sharks, squid, lobster, and other larger animals; and
- Rocky reefs are colonized by hundreds of species of attached animals (soft corals, barnacles), forests of kelp, and layers of seaweeds that provide expanded cover and protection for fish, crab, lobster, and shrimp.

Life Between the Tides: Intertidal Communities

- The intertidal shoreline offers a wide variety of densely-populated habitats, including bedrock, boulder-cobble, sand, mudflats, marshes, and other environments. Because these habitats vary in sensitivity to oil, the shoreline countermeasures described in Chapter 5 are tailored specifically to protect them and the types of plants and animals that live there;

- Intertidal mud- and sand-flats contain high densities of clams, oysters, crabs, urchins, and other shellfish; during low tide, a kilometer of beach can daily provide several tons of food to migrating and resident shorebirds;
- Several hundred species of seaweed, including kelp, grow on intertidal bedrock and rocky outcrops; during their brief lives (annuals and some perennials), they provide spawning habitat for some fish (herring) and refuge for the young of many nearshore and offshore fish and shellfish. In their senescence and death, seaweeds provide nutrients for complex detrital food chains nearshore and offshore;
- Mangrove forests extend seaward, protecting inshore, quiet waters that can include dense stands of marsh plants; and
- Intertidal shores are home to hundreds of species of shore and wading birds; beaches, mudflats, and marshes are areas of intense feeding and reproduction for many migratory species.

Connections Between Them

- Marine ecosystems are not isolated from one another, and most species depend on several ecosystems for survival, feeding, and reproduction;
- Some seaweeds, intertidal shellfish, or eggs of deepwater fish can briefly appear at the sea surface or offshore in the water column; and
- Many bottom-dwelling fish, shrimp, and crab make round-trips into the intertidal zone to feed or reproduce.

Marine Ecological Processes: Economy of Life in the Sea

It is important that response activities are planned with due regard for the dynamics of life in marine environments since the public expects that affected areas will return to some norm following a spill and response. Volumes have been written about marine life processes, but only a few examples need be presented here to underscore the kinds of changes that take place.

Life in the water, on the seafloor, and on the shoreline is constantly changing as food supplies, reproductive products, and predators rise and fall with the tides, currents, and seasons. Only in a few specialized – and sensitive – environments such as coral reefs, kelp beds, and perhaps the deep sea itself, is there some semblance of permanence of structure, species, and individuals. Everywhere else, turnover and replacement are the norms.

Food Webs and the Flux of Materials

There are numerous physical and biological sources of inorganic and organic material in the sea and coastal zone.

- The initial input of food in the sea, in the form of microscopic dispersed particles (detritus, phytoplankton), restricts the nature of marine life: except for terrestrial expatriates – marine mammals and birds – all marine life begins and ends with microscopic forms;
- Runoff discharges tons of silt, soil, and sand that create and build beaches, shorelines, and marshes. Delta ecosystems and wetlands are constantly changing and evolving, especially where river flow is relatively uncontrolled and subject to major year-to-year variations in flooding and drought;
- Organic compounds and inorganic nutrients seep from decaying vegetation and dead animals, as well as from nonbiological sources such as eroding land; and
- Phytoplankton, zooplankton, eggs, mucus, urine, feces, and detritus from decaying shoreline plant and animal material provide the bulk of dissolved and particulate organic material input to the sea.

Primary Production: Bacteria and Plants

- With a notable exception (hydrothermal vents), marine life starts and ends with plants – mainly single-celled phytoplankton and bacteria;
- Plants require sunlight, oxygen, major nutrients (nitrogen, phosphorous, potassium), and some minor trace elements (e.g., iron) to convert carbon dioxide to organic compounds (including hydrocarbons) and their own tissues;
- Production of marine life requires chemical building blocks (hydrogen, carbon, nitrogen, phosphorous), adequate oxygen and temperatures, and a variety of trace substances. If even one of these is limited, production will be limited, even when all the others are abundant or in excess. Thus, except in nearshore areas exposed to high inputs of nutrients, production in most areas is limited. Therefore, it would be unproductive to artificially enhance a building block that is not itself the limiting factor. In some situations, this is potentially the case for bioremediation; and
- There are many functional kinds of marine bacteria. Some are autotrophic, capable of self-nutrition. Other bacteria (and fungi) degrade organic material, and require nutrients, although not necessarily light.

Secondary Production: Herbivores

- Many animals are specialized to feed on marine plants, the next step in production of sea life;
- In open water, many species of copepods, isopods, and small forage fish capture or filter-feed on tiny phytoplankton, growing rapidly during the brief periods of bloom. Inshore, mollusks such as limpets, chitons, and some snails graze continuously on thin mats of benthic algae, keeping rock surfaces relatively free of slime growths. For example, the once-dense Chesapeake Bay

oyster population effectively filtered most of the phytoplankton, keeping the waters relatively clear; and

- Larger algae and vascular plants are less subject to consumption; and many seaweeds produce organic chemicals toxic to grazing fish and invertebrates.

Secondary Production: Detritivores and Carnivores

- *Food and Feeding.* Herbivorous animals (some types of zooplankton, forage fish, snails, and many clams) are prey for the more conspicuous species of invertebrates, fish, birds, and mammals of the sea and shore. To appreciate the magnitude of predation and feeding, Thorson (1976) describes how 30,000 overwintering Oyster Catchers (a wading bird) consumed 642 million cockles (a clam) from one British mud flat over a period of several weeks.;
- *Excretion.* Animals convert some of their food to energy and the rest is excreted in the form of fecal material, urine, mucus, and material such as skin molts. The nutrients and organic material from these excreta are recycled by the sea's bacteria, phytoplankton, and detritivores. One theory holds that urination by schools of forage fish provides centers of excess nutrients that re-stimulate discrete patches of production;
- *Growth.* Unlike most terrestrial animals and marine birds and mammals, most species of marine creatures continue growing (and, therefore, diluting incoming toxins), subject only to limiting factors of food supply, predation, and disease;
- *Reproduction.* Again, unlike their terrestrial counterparts, most marine creatures annually produce and disgorge much of their body weight as eggs, sperm, and other reproductive products, most of which is consumed and recycled near the beginning of the food web. These reproductive products, together with the excreta, are thrown back down the food web. Survivors owe their lives to protection from predation either through huge numbers or hiding;
- *Recruitment.* For most marine plants and animals, those that survive to adulthood represent one percent or less of the original eggs and larvae; the exceptions are the sea mammals and birds, where fewer young are produced with greater survival to adulthood. Successful recruitment is neither assured nor predictable: there are many populations of adult clams, shrimp, and fish composed of adults that came from only one or two "good" year classes per decade; and
- *Migration.* Unattached marine organisms can move considerable distances over various time scales. Plankton can be transported dozens or hundreds of miles in ocean currents, or become trapped in ocean and coastal eddies and gyres. Many bottom and demersal (near-bottom) fish and macro-invertebrates (shrimp, crab, lobster) undergo seasonal inshore-offshore, round-trip migrations. Tropical fish, transported north by the Gulf Stream, are common off New York in the summer, but may not survive falling

temperatures. Salmon are classic migratory fishes, entering the coastal zone as “smolts” in the winter or spring, then migrating in large loops around the North Pacific or North Atlantic, returning to natal streams one, two, three, or four years later (depending on species and stock). Offshore, many species of deep sea fish and crustaceans rise to the surface at night and return to the depths by daylight. The longest migration paths are made by sea turtles, marine and shore birds, whales, and seals and sea lions. Arrival dates at specific locations are often very precise and predictable.

Given these and many other dynamic processes, responders, resource trustees, and the public must be alert to sudden appearances, as well as disappearances, of marine organisms and must not presume that a response or restoration will return things to the way they were just prior to a spill.

EFFECTS OF OIL ON MARINE LIFE

Although oil affects marine organisms in many ways, there are some very predictable impacts. Following are the effects of most concern.

Coating and Smothering

Adhesive, viscous oils can coat and smother organisms that come into direct contact with it. Species that penetrate the water surface to breathe, feed, or rest are at particularly high risk of direct exposure. Sea birds and fur-bearing marine mammals are especially vulnerable because feathers and fur absorb oil, interfering with buoyancy, locomotion, and insulation. Oil ingested during preening can cause death directly from acute toxicity, or indirectly from starvation, pneumonia, and internal injury. Contamination of fur and feathers can cause drowning and hypothermia. Oiled birds returning to nests can contaminate eggs, which may be highly sensitive to even very small quantities of fresh oil.

Oil stranded on shorelines can coat vegetation, smother clam and other shellfish beds, and penetrate gravel, cobble, and sand beaches, possibly resulting in prolonged exposure and death of sediment-dwelling organisms. Heavier oils can form highly persistent pavements that alter shoreline habitats.

Toxicity

At high enough concentrations, with long enough exposure, many of the soluble chemicals in oil can cause adverse effects (kill, injure, or narcotize) to small marine animals and plants. Soluble components – including benzene, toluene, and naphthalenes – are highly toxic but not very persistent, and can be quickly diluted in

areas of strong currents and wave action (or may accumulate for longer periods in areas of poor circulation and flushing). Exposure for several days to concentrations as low as a few parts per million can cause adverse effects in many small plants and animals in the water column. Conversely, dispersant use on slicks in the open sea can result in lethal concentrations only in the upper few meters of the water and for much shorter periods (minutes to hours).

Toxicity of various compounds in oil is determined by exposing small plants and animals to a range of concentrations in laboratory experiments. Numerous studies show that refined fuels are generally more toxic (due to their relatively higher aromatic content) than crude oils.

Carcinogenicity and Mutagenicity

Oil contains compounds that can cause cancer (carcinogenicity) and mutations (mutagenicity) in marine organisms at high enough concentrations and long enough exposure times. These processes are extremely complex and their occurrences depend on many variables. In birds, mammals, fish, and a few other animals, these disorders result after long-term (weeks, months) exposure to polycyclic aromatic hydrocarbons (PAHs), generally taken in via ingestion of contaminated food. Bacteria, in contrast, multiply so fast (several times a day) that they can experience mutations in a few hours, and are often used to monitor the presence of mutagens and carcinogens in environmental samples.

Bioaccumulation

Marine organisms can bioaccumulate high concentrations of some pollutants in their tissues, and can also purge pollutants when returned to clean water. Dissolved aromatic oil compounds, such as naphthalenes, are primarily absorbed through skin and gills, whereas heavier compounds, such as the carcinogenic PAH benzo(a)pyrene, are mainly accumulated through feeding. Regardless of the method of accumulation, such contaminants may cause adverse effects either to the organism itself or to its consumers and predators, including people. Oil can also temporarily taint – cause an off-odor or off-flavor – fish and shellfish. The specific compounds responsible for tainting are not completely known, though sulfur-containing compounds are considered to be among this group. It is not clear whether tainting compounds are also toxic.

Some pollutants (mercury, DDT) biomagnify – increase in concentration up the food web from prey to predators. Petroleum hydrocarbons, especially the PAHs, do not biomagnify because they are broken down (metabolized) in higher organisms such

as mammals, birds, fish, and some crustaceans, and the resulting metabolites are excreted via the bile. In fact, once exposure ceases, most animals completely lose petroleum hydrocarbon contamination through depuration. Tainting chemicals and smaller aromatic compounds (naphthalene) are readily metabolized and eliminated from live fish once they spend time in clean (contaminant-free) water. PAHs accumulated by shellfish (mussels and oysters) are also readily lost, with half-lives on the order of several days to a few weeks, depending on the species, its fat content, and the level of exposure to hydrocarbon accumulated.

Thus, when a marine ecosystem is contaminated by oil mixed into the water column, exposed species can experience short-term (hours, days) contamination by low molecular-weight aromatic and tainting compounds. Fish and other vertebrates will rapidly eliminate petroleum hydrocarbons, taking somewhat longer in invertebrate species low in the food web (plankton, shellfish), but petroleum hydrocarbon contamination will not biomagnify through the food chain. The fate of petroleum hydrocarbons in marine food webs, then, is basically the reverse of what happens to highly bioaccumulative pollutants, such as mercury and DDT, which persist and biomagnify.

POST-SPILL RECOVERY

Marine ecosystems are dynamic, constantly changing in response to such influences as major climatological events. For example, alternating periods of flood and drought alter the supply of sediment, fresh water, and nutrients to coastal and estuarine systems, influencing habitats such as marshes and mangroves and their associated flora and fauna. On the western coast of the United States, El Niño/Southern Oscillation events can cause fluctuations in the abundance and distribution of seaweed, fish, shellfish, and other marine species over thousands of miles. These changes can, in turn, affect populations of predator species, such as sea birds. Against such a background of natural change, returning marine systems affected by oil spills to pre-existing conditions may not be possible.

The expectation following an oil spill response is that injured habitats and populations will “recover,” implying a return to conditions the way they were before a spill. But “recovery” has different meanings to different people. Some consider a site recovered when all the oil is gone. Others may consider a site recovered when all species have returned to their former abundance. Still others

acknowledge the variability in natural communities: recovery is complete when ecological conditions have returned to those within the normal range of variation.

Loss of Oil and Toxicity

The process of recovery is complex, difficult to define, and occurs over variable time frames. The rate at which oil is lost from a system and the rates of biological recovery are not necessarily the same nor even related. For example, oil remaining in shorelines following response activities may rapidly lose its toxicity in days, whereas biological recovery may take months to years. Several research studies have documented how long it takes for untreated oil to disappear naturally and become non-toxic. One of the most recent, involving an intentional release of light crude oil on a sandy beach in Delaware, was conducted in the summer of 1994. The oil initially was very toxic to several species, but began to lose its toxicity within two weeks; after 14 weeks one-tenth of the initial oil remained, and it was not toxic to four of five test species. In the absence of treatment, half the remaining oil was lost every 28 days, mostly due to washout from wave and tidal action, and natural biodegradation processes produced an even faster loss of toxic compounds such as PAHs. In comparison, about half of the oil spilled by the *Exxon Valdez* in the spring of 1989 was removed or treated; the rest underwent dispersion, biodegradation, or was buried deep in shoreline substrates. However, shoreline toxicity from the *Exxon Valdez* spill occurred only during the first few months of the spill: toxicity and mutagenicity decreased rapidly during the first summer and disappeared completely between the first and second summers after the spill.

Another factor affecting spill recovery is background contamination. Low-level petroleum hydrocarbon contamination is ubiquitous in many coastal areas; although some is due to past spills, the majority of existing contamination in the US coastal sediments and shellfish is from other sources, mainly combustion and runoff. In some areas, natural oil and gas seeps are sources of contamination. Sediments, water, and shellfish in many urbanized areas contain PAHs up to several hundred times background levels. Consequently, when a spill occurs in populated areas, responders will need background contamination information.

Biological Recovery

When life in a marine environment is decimated by a toxic spill, intrusive cleanup, or a natural "disaster," it does not long remain barren. The area will be initially re-colonized by opportunistic species and then, over periods of months to years, the newly-developing community will undergo a somewhat predictable succession of

species of plants and animals. Biota that survive oiling aid in the oil removal and subsequent recovery process. For example, surviving motile animals like snails and limpets may loosen thin layers of weathered oil as they move in and resume feeding on freshly-attached algal mats that grow within the first year following a spill. Plant seedlings may germinate, forming new root systems that aerate soils and promote biodegradation. On substrate surfaces laid bare by oiling or high-impact cleanup techniques, new planktonic larvae will settle, attach, and begin growing.

2.3 STRATEGIES FOR SELECTING RESPONSE METHODS

During emergency response operations, available information may be highly uncertain and fragmented at best, as will forecasts of environmental conditions or evaluations of response equipment needs. Nonetheless, the response community must sort out what is actually known about the spill, and select and deploy equipment as soon and as effectively as possible. What information is needed to help guide the response? What can be done to promote any gains in environmental protection?

Because the goal of oil spill response is to minimize the overall impacts on natural and economic resources, some resources will be of greater concern than others, and response options offering different degrees of resource protection will be selected accordingly. Decisions regarding cleanup method(s) must balance two factors: 1) the potential environmental impacts with the no-action alternative, and 2) the potential environmental impacts associated with a response method or group of methods. The first factor incorporates an evaluation of:

- Spilled and/or weathered oil toxicity; and
- Organisms which may be exposed to oil.

The second factor considers the potential impact(s) and benefits associated with each of the various cleanup techniques.

Potential impacts can be determined prior to considering the need for, or type of, response strategies. For example, evaluating a gasoline spill in an exposed seawall environment might lead to the conclusion that, due to environmental fate processes (i.e., evaporation) and low habitat use, minimal environmental effects will occur and further evaluation is unwarranted. On the other hand, assessing a spill of a middle-weight crude oil in a soft intertidal area would likely indicate a

high potential for environmental effects; therefore, response methods would need to be evaluated.

The decisions to select response methods should consider the potential of each possible method for reducing the environmental consequences of the spill and the response (including a natural recovery alternative). The method, or combination of methods, that most reduces consequences effectively, should be the preferred response strategy. A method that increases impacts in the short term can be the preferred alternative if the time for recovery is accelerated. In Figure 1, this situation is illustrated by the curve representing response method 1. Among the idealized impact/recovery curves that Figure 1 illustrates, methods 1 and 2 reduce the overall environmental consequences in comparison to no cleanup. Method 3 would have greater environmental consequences than the other methods. In many situations, method 3 would not be chosen for environmental reasons. Recovery cannot be defined as pre-spill conditions since natural changes in biological communities will introduce variability to organisms affected by the spill.

The environmental consequences of a spill and the response will depend on the specific spill conditions, such as the type and amount of oil, weather conditions, and effectiveness of the response methods. It is imperative that planners and responders discuss and develop resource protection priorities during contingency planning so that valuable time is not lost during an actual response.

SETTING PRIORITIES: ENVIRONMENTAL VULNERABILITY

Environmental vulnerability is only loosely defined in most people's minds, and significant misunderstandings can result when various participants in the oil spill planning and response process have very different ideas about what this concept means. If rational and justifiable environmental response decisions are to be made, the concept must be accurately defined.