M7: Petroleum Spills

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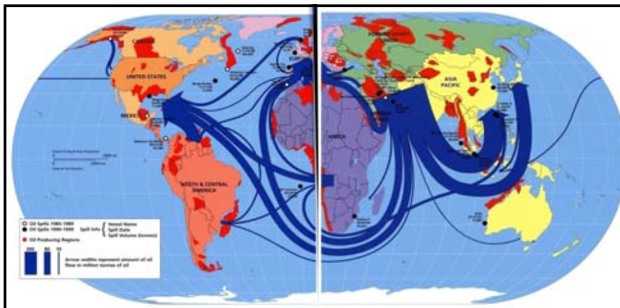
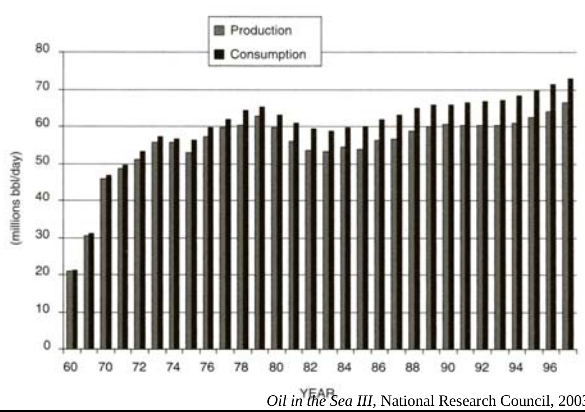
Photo: NOAA Office of Response and Restoration



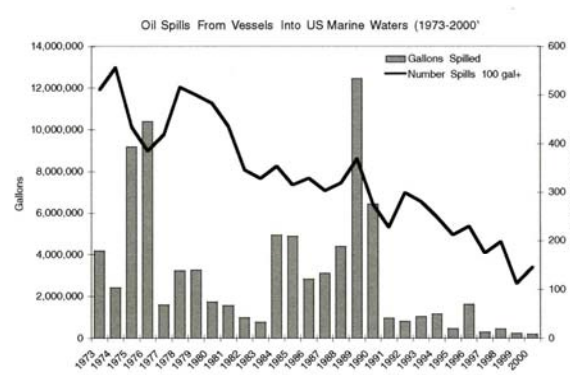
Movement of Oil in 1999

Oil in the Sea III, National Research Council, 2003.

Oil Production Between 1960 and 1998



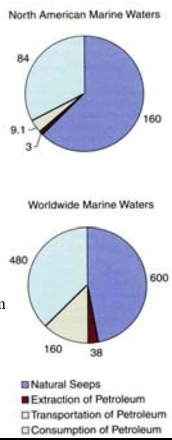
Oil in the Sea III, National Research Council, 2003.

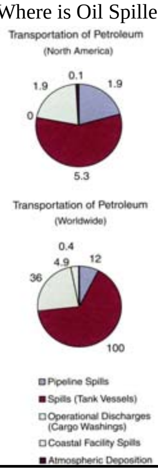


Oil in the Sea III, National Research Council, 2003.

Where Does the Oil Go? Where is Oil Spilled?

Relative contribution of average releases (1990-1999) of petroleum hydrocarbons from natural seeps and activities associated with the extraction, transportation, and consumption of crude oil or refined products to the marine environment.





Relative average, annual input (1990-1999) of petroleum to North American and worldwide marine environment from sources associated with the transport of petroleum.

Oil in the Sea III, National Research Council, 2003.

Potential Oil Spills: *Submarine Pipelines*

Extensive provisions are made to minimize the volume of oil released in the event of a leak, including:

- Additional steel wall thickness on product transfer lines.
- Cathodic protection.
- Somastic coatings (or coal tar wrap).
- Concrete weight coating over somastic coatings to increase stability and provide negative buoyancy for empty lines.
- Burial of lines in surf zone.
- Pressure safety valves.
- Submarine hoses of strength several times the operating pressures.

Pipelines are by far the most common method of transporting crude oil and petroleum products in the United States. The possibility of a crude oil and/or petroleum product spillage could occur at any point along submarine pipelines. An analysis by the National Petroleum Council (1972) of spill incidents from pipeline systems in the United States indicate that approximately 2.8 bbl/mi/yr were lost, even in that early year of oil transport.

Potential spills volumes for offshore spills are categorized by the National Oil Spill Contingency Plan as follows:

Minor Spill - a discharge of oil less than 10,000 gals (238 bbl*);
Moderate Spill - a discharge of oil of 10,000 to 100,000 gals (238 to 2,380 bbl); and
Major Spill - a discharge of oil of more than 100,000 gals (2,380 bbl).
*Based on 42 gal/bbl

Potential Oil Spills: *Tanker Operations*

Tankers can contribute to oil pollution of the marine environment through five principal sources:

- Cargo tank cleaning operations;
- Discharges from bilge pumping;
- Hull leakage;
- Spills during cargo handling operations; and
- Vessel casualties.

There are three principal causes of unintentional discharges of oil during tanker-terminal operations: (1) mechanical failures, (2) design failures, or (3) human error. Incident reports of spills during tanker-terminal operations show that human error is the pre-dominant cause and is the most difficult to remedy. Mechanical failures include cargo transfer hose bursts, and piping, fittings, or flange failures, either on shore or on the tankers.

Oil Spills of 100,000 Tons (640,000 Barrels), or More
Source: International Tanker Owners Federation, 2001 New York Times Almanac

Date	Cause	Location	Barrels Spilled	Rank, by Spilled Volume
1942	German U-boats attacks on tankers after U.S. enters World War II	U.S. East Coast	590,000	4
1967	Tanker *Torrey Canyon* grounds	English Channel, off Land's End, UK	119,000	12
1970	Tanker *Othello* collides with another ship	Tralhavet Bay, Sweden	60,000 to 100,000	15
1972	Tanker *Sea Star* collides with another ship	Gulf of Oman	115,000	13
1976	Tanker *Urquiola* grounds	La Coruna, Spain	100,000	14
1978	Tanker *Amoco Cadiz* grounds	Northwest France	223,000	9
1979	Itox 1 oil well blows	Southern Gulf of Mexico	600,000	2
1979	Tankers *Atlantic Empress* and *Aegean Captain* collide	Off Trinidad and Tobago	300,000	6
1983	Blowout in Norwuz oil field	Persian Gulf	600,000	3
1983	Fire aboard tanker *Castillo de Beliver*	Off Cape Town, South Africa	250,000	8
1988	Tanker Odyssey flounders	Off Nova Scotia, Canada	132,000	11
1991	Iraq begins deliberately dumping oil into Persian Gulf	Sea Island, Kuwait	1,450,000	1
1991	Tanker *Haven* grounds	Genoa, Italy	140,000	10
1991	Tanker *ABT Summer* founders	700 mi. off Angola	260,000	7
1994	Pipeline bursts, oil enters rivers that flow into Arctic Ocean	Near Usinik, Russia	312,500	5

Notable Oil Spills

The NOAA Office of Response and Restoration has much information concerning large oil spills. This information is available at:

http://response.restoration.noaa.gov/index.html

Other links for oil and hazardous material spills are:

Incident News:
http://www.incidentnews.gov/

NOAA Office of Response and Restoration
http://response.restoration.noaa.gov/index.html
http://response.restoration.noaa.gov/photos/ships/ships.html

The Amoco Cadiz

The AMOCO CADIZ ran aground off the coast of Brittany, France on March 16, 1978, spilling 68.7 million gallons of oil. It currently is #6 on the list of the largest oil spills of all time.

NOAA Office of Response and Restoration

The Argo Merchant

The ARGO MERCHANT ran aground on Fishing Rip (Nantucket Shoals), 29 nautical miles southeast of Nantucket Island, Massachusetts in high winds and ten foot seas.

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On December 21, the ARGO MERCHANT broke apart and spilled its entire cargo of 7.7 million gallons of No. 6 fuel oil

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The Bouchard B155

On August 10, 1993, three ships collided in Tampa Bay, Florida: the BOUCHARD B155 barge, the freighter BALSA 37, and the barge OCEAN 255. The BOUCHARD B155 spilled an estimated 336,000 gallons of No. 6 fuel oil into Tampa Bay. Below is a photo of the OCEAN 255 barge after the collision.

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The Burmah Agate

On November 1, 1979, the BURMAH AGATE collided with the freighter MIMOSA southeast of Galveston Entrance in the Gulf of Mexico. An estimated 2.6 million gallons of oil was released into the environment; another 7.8 million gallons was consumed by the fire onboard. This spill is currently #55 on the all-time list of largest oil spills.

NOAA Office of Response and Restoration

The Cibro Savannah

The CIBRO SAVANNAH exploded and caught fire while departing the pier at the CITGO facility in Linden, New Jersey, on March 6, 1990. About 127,000 gallons of oil remained unaccounted for after the incident: no one knows how much oil burned and how much spilled into the environment.

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The Exxon Valdez

The EXXON VALDEZ ran aground on Bligh Reef in Prince William Sound, Alaska on March 24, 1989, spilling 10.8 million gallons of oil into the marine environment. It is currently #53 on the all-time list of largest oil spills.

The Exxon Valdez was carrying approximately 53 million gallons of crude oil. The picture below was taken 3 days after the vessel grounded, just before a storm arrived.

Web site having many links to other Exxon Valdez spill information sources:
http://response.restoration.noaa.gov/spotlight/spotlight.html

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Ixtoc I

The IXTOC I exploratory well blew out on June 3, 1979 in the Bay of Campeche off Ciudad del Carmen, Mexico. By the time the well was brought under control in 1980, an estimated 140 million gallons of oil had spilled into the bay. The IXTOC I is currently #2 on the all-time list of largest oil spills of all-time, eclipsed only by the deliberate release of oil, from many different sources, during the 1991 Gulf War.

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The Jupiter

The JUPITER was offloading gasoline at Bay City, Michigan on September 16, 1990, when a fire started on board the vessel.

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The Mega Borg

The MEGA BORG released 5.1 million gallons of oil as the result of a lightering accident and subsequent fire. The incident occurred 60 nautical miles south-southeast of Galveston, Texas on June 8, 1990.

BOX 5-4

Gulf War Spill, Arabian Gulf

Over a period of about four months from January-March 1991, crude oil was released into the Arabian Gulf from five tankers, a major tank field, and several offshore terminals, refineries, and battle-damaged tankers as part of the Iraq-Kuwait conflict. Though the actual volume of release will never be known, the best estimate is about 1,770,000 tonnes (520,000,000 gallons) (Tawfiq and Olsen, 1993), making it the largest oil spill in history and three times as large as the next largest spill (the 1979 Ixtoc well blowout in the Gulf of Mexico). Although the massive slicks were initially predicted to spread throughout the Arabian Gulf and out through the Gulf of Hormuz, a seasonal shift in wind patterns held the bulk of the oil along the shoreline between the Kuwait border and Abu Ali Island near Al Jubail, a distance of about 175 km. The oil fate was estimated by Tawfiq and Olsen (1993) as follows: 40 percent evaporated; 10 percent dissolved/dispersed; 10 percent recovered in Saudi Arabia; 15 percent stranded on shore in Saudi Arabia; and 25 percent unaccounted for. There was concern that a significant portion of the unaccounted for oil sank; however, Michel et al. (1993) did not find evidence for any significant sunken oil in the nearshore subtidal zone during diving surveys (197 dives) offshore the most heavily oiled shorelines and bays in Saudi Arabia. None of the researchers studying the Arabian Gulf after the spill reported large-scale oil contamination of bottom sediments (Price and Robinson, 1993).

The spill significantly affected shoreline habitats, with 707 km of shoreline oiled in Saudi Arabia alone, including 124 km of marshes (Gundlach et al., 1993). Very little shoreline cleanup was attempted. An estimated 50-100 percent of the intertidal biota were killed (Jones et al., 1996); in heavily oiled marshes, less than 1 percent of the plants survived (Böer and Warnken, 1996). Followup shoreline surveys in 1992 and 1993 showed that the stranded oil had penetrated up to 40 cm into the sediments, with liquid oil filling burrows in muddy sediments (Hayes et al., 1995). The heavy surface oiling formed persistent pavements along the upper intertidal zone and on the tops of mid-tide bars that showed little evidence of erosion six years after the spill. The surface pavements slowed the rate of subsurface oil weathering and physical removal, effectively sealing the subsurface oil in place. Intertidal species diversity in the lower intertidal zone on sandy and muddy substrates was 50-100 percent of controls by 1994, whereas in the upper intertidal zone, species density and density was 0-70 percent of unpolluted sites (Jones et al., 1996). As of 1997, there was little evidence of recovery of heavily oiled marshes. Much of the heavily oiled shoreline occurred along sheltered bays with little exposure to waves and currents. Thus, natural removal of the stranded oil will be very slow, and full recovery of intertidal communities will likely require decades.

Amazingly, no significant long-term impacts to subtidal habitats and communities were observed, including seagrass beds, coral patch and fringing reefs, unvegetated sandy and silty substrates, and rocky outcrops (Kenworthy et al., 1993; Richmond, 1996). Kuwait crude forms a very stable emulsion that resulted in thick surface slicks that stranded onshore rather than mixed into the water column. Impacts to shrimp stocks, however, were severe: in 1992 spawning biomass dropped to 1 percent and total biomass dropped to 27 percent of pre-war levels (Matthews et al., 1993). Causes of this collapse were attributed to a combination of mass mortality of eggs, larvae, and postlarvae resulting from oil exposure during the entire spawning season, emigration of adults out of the oiled areas, mortality of adults, heavy fishing of adults and juveniles thus further reducing the spawning biomass, and decrease in water temperatures and light intensity because of oil fires smoke and haze.

At least 30,000 seabirds are estimated to have died as a result of the spill. Although the oil spill killed an estimated 25 percent of the 1991 Saudi Arabian breeding population of the endemic Socotra cormorant, these colonies tripled in population by 1995 (Symens and Werner, 1996). Internationally important breeding tern populations in Saudi Arabia and Kuwait escaped direct oiling impacts in 1991 (70,000 pairs breed on offshore islands in summer), but severe declines in breeding success in 1992 and 1993 resulted from an acute shortage of food that was attributed to the oil impacts on fish recruitment (Symens and Alsuhaibany, 1996). In 1994, breeding success was high. During the spill, shorebird populations were reduced by up to 97 percent; however, it is not known whether the birds avoided the noxious oil or were driven away by a lack of food and found good feeding areas elsewhere, became oiled and died, or died from starvation (Evans et al., 1993). The greatest shorebird impacts, however, were likely the indirect effects of long-term degradation of intertidal habitats and the loss of their food supply.

Oil in the Sea III, National Research Council, 2003.

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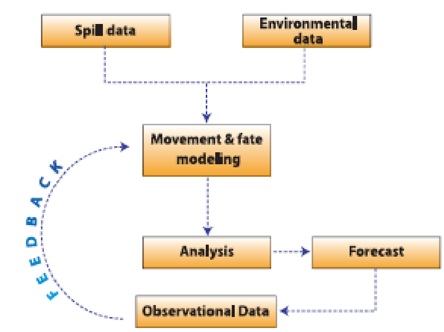
TABLE 2-1 Processes That Move Petroleum Hydrocarbons Away from Point of Origin

Input Type	Persistence	Evaporation	Emulsification	Dissolution	Oxidation	Horizontal Transport or Movement	Vertical Transport or Movement	Sedimentation	Shoreline Stranding	Tarballs
Seeps	years	H	M	M	M	H	M	M	H	H
Spills										
Gasoline	days	H	NR	M	L	L	L	NR	NR	NR
Light Distillates	days	M	L / L	H	L	M	H	L	L	NR
Crudes	months	M	M	M	M	M	M	M	H	M
Heavy Distillates	years	L	M	L	L	H	L	H	H	H
Produced water	days	M	NR	M	M	L	L	L	L	NR
Vessel operational	months	M	L	M	L	M	L	L	L	M
Two-stroke engines	days	H	NR	M	L	L	L	NR	NR	NR
Atmospheric	days	H	NR	M	M	H	NR / NR	NR	NR	NR
Land based	U	M	L	L	L	M	M	M	NR	U

NOTE: H = high; L = low; M = moderate; NR = not relevant; U = unknown

Oil in the Sea III, National Research Council, 2003.

Trajectory Analysis Handbook



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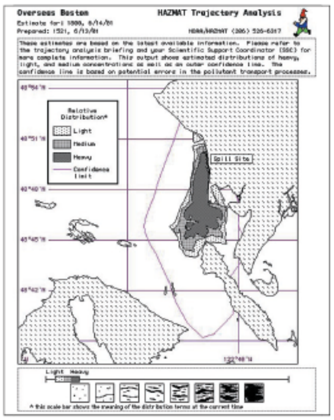

Sample trajectory analysis map.

Trajectory Analyses

Trajectory Analysis

Forecasting the movement of an oil spill is often hampered by insufficient input data, particularly in the first few hours of the release. Detailed **spill data** (location, volume lost, product type) are often sketchy and **environmental data** (wind and current observations and forecasts) are often sparse or unavailable. Nonetheless, the modeler must examine the data and attempt to understand the physics and chemistry that will likely affect the oil **movement and fate** of the particular spill .

Trajectory Analysis

Ideally, the trajectory is displayed in a format that is easy to understand. It should indicate both the forecast and the uncertainty. In this example, the forecast "best guess" of the oil movement is overlaid on a map of the shoreline. The forecast is presented as light, medium, and heavy contours. The scale at the bottom of the map represents the percent coverage of the surface oil within these contours. Plausible errors in the spill and environmental data were explored by the modeling team; the colored outer contour represents a 90% confidence bound. This provides an indication of the uncertainty in the forecast.

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EXXON VALDEZ. During the first few days of the spill, heavy sheens of oil, such as the sheen visible in this photograph, covered large areas of the surface of Prince William Sound

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EXXON VALDEZ. Oil being skimmed from the sea surface. Here, two boats are towing a collection boom. Oil concentrated within the boom is being picked up by the skimmer (the vessel at the apex of the boom).

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Parameters Affecting Oil Spill Movement

The movements, and other characteristics, of a spill of petroleum hydrocarbons lost on water are controlled by weather conditions (wind, temperature, and rainfall), ocean conditions (tides and currents), and physical parameters of the materials which could be spilled. The important physical parameters of the various petroleum hydrocarbons include the following:

•Specific gravity (or density);
•Evaporation rate;
•Boiling range;
•Viscosity;
•Pour point;
•Emulsification ability; and
•Water solubility.

Prediction of the Movement of Oil Spills

The fate of an oil spill in the marine environment depends on the spreading motion of the oil and the translation of the slick by the winds and currents in the surface waters. The required data for the oil spreading equations include surface wind speed and direction, tidal currents, and knowledge of the general circulation of the waters of interest. Estimates of initial spill volume and a spreading equation are required to determine the spreading radius of a hypothetical spill as a function of time. The following discussion presents an example analysis of oil spill movement, based on typical offshore oil spill losses, and hypothetical environmental conditions.

Spill Volume and Resulting Spill Dimensions

In this example, the potential volume of oil that could be released to the environment as a result of a break in a submarine pipeline varies from a minimum of about 500 barrels to a maximum of about 10,000 barrels. A hypothetical oil spill of 500 tons (3750 bbl) is assumed in this example. This volume would be classified as a major spill.

Figures 7-1 and 7-2 describe the oil slick dimensions as a function of time for a 500 ton spill for various wind speeds. It should be noted that the predicted elliptical area defines the envelope in which the oil is found. At later times, and especially under high wind conditions, the slick will have broken up and some fraction will have evaporated and some fraction will have mixed with subsurface waters.

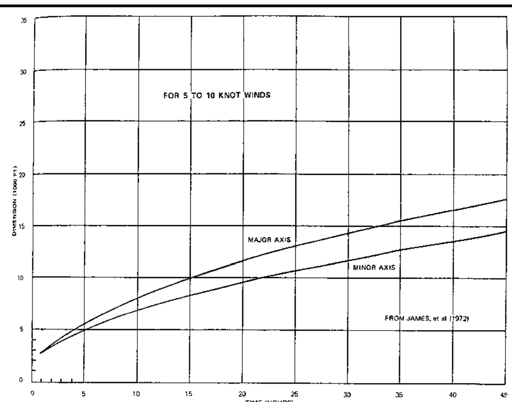


Figure 7-1. Growth of a 500 ton oil spill during five to ten knot winds.

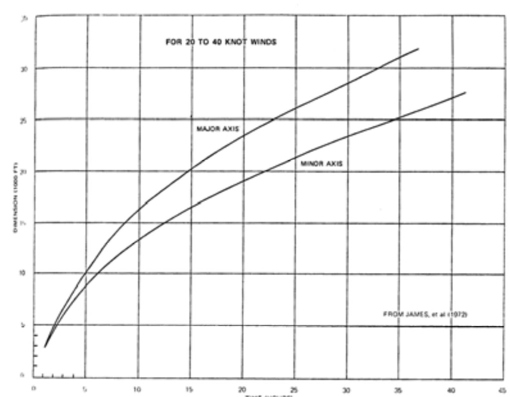


Figure 7-2. Growth of a 500 ton oil spill during twenty to forty knot winds.

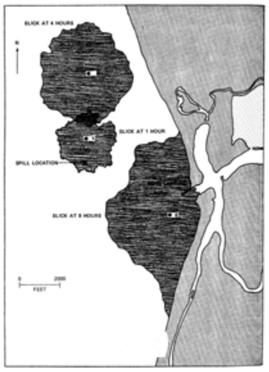


Figure 7-3. Predicted behavior of a 500 ton oil spill under the influence of a 5 knot NW wind and 0.3 knot tidal current (spill initiated at slack water before flooding tide).

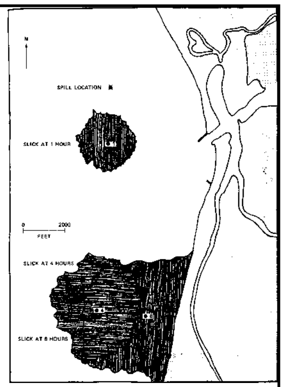


Figure 7-4. Predicted behavior of a 500 ton oil spill under the influence of a 5 knot NW wind and 0.3 knot tidal current (spill initiated at slack water before ebbing tide).

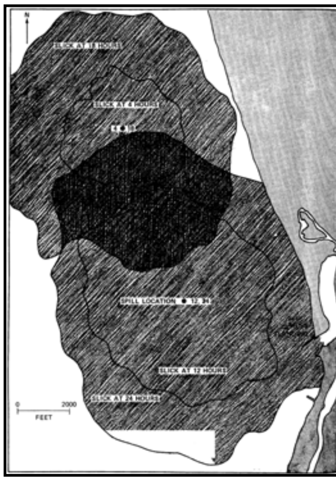
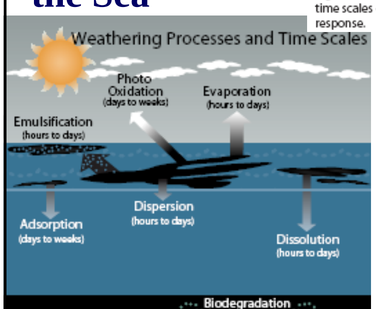


Figure 7-5. Predicted behavior of a 500 ton oil spill under calm winds and a 0.3 knot tidal current (spill initiated at slack water before flood tide).

Fate of Spilled Petroleum in the Sea

Weathering Processes and Time Scales

The physical and chemical characteristics of petroleum change almost immediately when spilled in the marine environment due to evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation. All of these processes interact with each other and are collectively referred to as *oil weathering*. The table following describes some of the weathering processes and the time scales of those processes important for emergency response.



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FACT SHEET: Alaska North Slope Crude Blends

• Crude blends vary tremendously in their chemical composition, depending on the geographical location of their origin and the particular compounds mixed with the petroleum products. Surfactants, often added to aid transport, will affect physical properties when spilled.

• Hydrocarbons are by far the most abundant compounds in crude oils, accounting for 50-98% volume. All crude blends contain lighter “fractions” (similar to gasoline) of hydrocarbons as well as heavier tars and wax-like hydrocarbons.

• Alaskan North Slope (ANS) crude blends are Group III oil products, and considered medium grade. The BP ANS crude from Pump Station #9 has a relatively high viscosity (23.9cSt @50°F) and an API of 29.6.

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• ANS crude blends tend to emulsify quickly, forming a stable emulsion (or mousse). The rate of emulsification while difficult to model is known to be accelerated by wind mixing, and is thought to be related to the blend's wax content . This blend of ANS is thought to form a mousse after it experiences about 14% evaporation of its lighter ends.

• 15-20% of this product evaporates in the first 24 hours of a spill, depending on the wind and sea conditions, and very little oil is dispersed into the water column. The weathered oil then starts to form a stable mousse with up to 75% water content (thereby increasing the slick volume four-fold), and undergoes dramatic changes in its physical characteristics.

• The viscosity of the oil-in-water mixture increases rapidly and the color usually turns from a dark brown/black to lighter browns and rust colors. As the water content of the emulsion increases, weathering processes (e.g. dissolution and evaporation) slow down.

• As the mousse is subject to increased mixing from energetic wave action, the crusts can be torn or ruptured and the less weathered mousse released. The continued exposure of weathered mousse to wave action continues to stretch and tear patches of mousse into smaller bits, resulting in a field of streaks, streamers, small patches and eventually small tarballs.

• While organisms are not at high risk from crude oil dispersed into the water column, stranded crude tends to smother organisms. In birds, it can cause mortality from ingestion during preening as well as from hypothermia from matted feathers.

• The oil-in-water emulsion is very sticky and makes cleanup and removal more difficult. When stranded on the shoreline, the degree of adhesion varies depending on the substrate type, e.g. this mousse will not penetrate far in finer sediments.

FACT SHEET: No. 6 Fuel Oil (Bunker C) Spills

• No. 6 fuel oil is a heavy oil produced by blending heavy residual oils with a light oil (often No. 2 fuel oil) to meet specifications for viscosity and pour point.

• When spilled on water, No. 6 fuel spreads into thick slicks which can contain large amounts of oil. Oil recovery by skimmers and vacuum pumps can be very effective, particularly early in the spill.

• Very little of this viscous oil is likely to mix into the water column. It can form thick streamers or, under strong wind conditions, break into patches and tarballs.

• It is a persistent oil; only 5-10% is expected to evaporate within the first hours of a spill. Thus, spilled oil can be carried long distances by winds and currents. Previous bunker oil spills have contaminated shorelines over 200 miles from the spill site.

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• The specific gravity of a particular No. 6 fuel oil can vary widely, from 0.95 to greater than 1.03. Thus, spilled oil can float, suspend in the water column, sink, or do all of these simultaneously, if the oil is poorly mixed. Floating slicks may become non-floating when they spread into areas of freshwater influence.

• Floating oil could potentially sink once it strands on the shoreline, picks up sediment, and then is eroded by wave action.

• No. 6 fuel oil can be very viscous and sticky, meaning that stranded oil tends to remain on the surface rather than penetrate sediments. Light accumulations usually form a “bath-tub ring” at the high-tide line; heavy accumulations can pool on the surface.

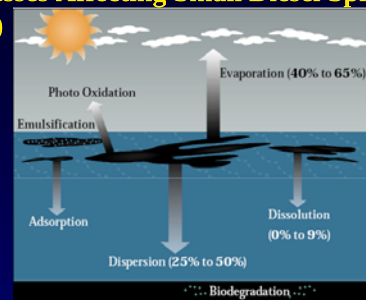
• Shoreline cleanup can be very effective, particularly soon after the spill before the oil weathers, becoming stickier and even more viscous. Removal is needed because degradation rates for heavy oils are very slow, taking months to years.

• Adverse effects of floating No. 6 fuel oil are related primarily to coating of wildlife dwelling on the water surface, smothering of intertidal organisms, and long-term sediment contamination. No. 6 fuel oil is not expected to be as acutely toxic to water column organisms as lighter oils, such as No. 2 fuel oil.

• Direct mortality rates can be high for seabirds, waterfowl, and fur-bearing marine mammals, especially where populations are concentrated in small areas, such as during bird migrations or marine mammal haulouts.

• The most important factors determining the impacts of No. 6 fuel oil contamination on marshes are the extent of oiling on the vegetation and the degree of sediment contamination from the spill or disturbance from the cleanup. Many plants can survive partial oiling; fewer survive when all or most of the above-ground vegetation is coated with heavy oil. However, unless the substrate is heavily oiled, the roots often survive and the plants can re-grow.

Weathering Processes Affecting Small Diesel Spills (500-5000 gallons)



Over 90% of the diesel in a small spill incident into the marine environment is either evaporated or naturally dispersed into the water column in time frames of a couple of hours to a couple of days. Percent ranges, in parentheses above, represent effects of winds ranging from 5 to 30 knots.

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FACT SHEET: Small Diesel Spills (500-5000 gal.)

• Diesel fuel is a light, refined petroleum product with a relatively narrow boiling range, meaning that, when spilled on water, most of the oil will evaporate or naturally disperse within a few days or less. This is particularly true for typical spills from a fishing vessel (500-5,000 gallons), even in cold water. Thus, seldom is there any oil on the surface for responders to recover.

• When spilled on water, diesel oil spreads very quickly to a thin film. Even when the oil is described as a heavy sheen, it is 0.0004 inches thick and contains about 1,000 gallons per square nautical mile of continuous coverage.

• Diesel has a very low viscosity and is readily dispersed into the water column when winds reach 5-7 knots or sea conditions are 2-4 foot.

• Diesel oil is much lighter than water (specific gravity is about 0.85, compared to 1.03 for seawater). It is not possible for this oil to sink and accumulate on the seafloor as pooled or free oil. However, it is possible for the oil to be physically mixed into the water column by wave action, forming small droplets that are carried and kept in suspension by the currents.

• Diesel oil is not very sticky or viscous, compared to black oils. When small spills do strand on the shoreline, the oil tends to penetrate porous sediments quickly, but also to be washed off quickly by waves and tidal flushing. Thus, shoreline cleanup is usually not needed.

• Diesel oil is readily and completely degraded by naturally occurring microbes, under time frames of one to two months.

• In terms of toxicity to water-column organisms, diesel is considered to be one of the most acutely toxic oil types. Fish, invertebrates and seaweed that come in direct contact with a diesel spill may be killed. However, small spills in open water are so rapidly diluted that fish kills have never been reported. Fish kills have been reported for small spills in confined, shallow water.

• Crabs and shellfish can be tainted from small diesel spills in shallow, nearshore areas. These organisms bioaccumulate the oil, but will also depurate the oil, usually over a period of several weeks after exposure.

Weathering processes and time scales important for emergency response

Weathering Process	What is It?	Why is it Important?	Time Scales
Evaporation	Conversion of liquid to a gaseous phase. The lighter fractions in the oil are lost first.	Major process that accounts for the loss of oil, particularly light oils. At 15°C, gasoline evaporates completely over a 2-day period, 80% of diesel fuel evaporates, 40% of light crude, 20% of heavy crude, and only about 5-10% of Bunker C.	< 5 days
Emulsification, or formation of mousse	Very small water droplets are mixed into the liquid oil. Water content often reaches 50-80%. Occurs on water, needs some wave action.	Can increase the amount of pollutant to be recovered by a factor of 2-4. Slows down other mixing processes.	Onset can be delayed for days but the emulsification process happens rapidly.
Natural dispersion	Breakup of an oil slick into small droplets that are mixed into the water by energy.	Removes the oil from the water surface.	< 5 days
Dissolution	Mixing of the water-soluble components of oil into the water.	The most water-soluble components of oil are most toxic.	< 5 days
Biodegradation	Breakdown of oil by microbes into smaller compounds, eventually to water and carbon dioxide.	Rate depends on oil type, temperature, nutrients, oxygen, and amount of oil.	weeks to months
Formation of tarballs	Breakup of slicks of heavy crudes and refined oils into small patches that persist for long distances.	Tarballs are hard to detect, so the slick appears to be going away though it is still a threat.	days to weeks

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Evaporation of Spilled Petroleum

Evaporation can be a major mechanism for removing oil. The amount evaporated depends chiefly on the oil properties, the wind speed, and the water temperature.

Generally, light refined products, like gasoline or jet fuel, evaporate faster than heavier products, such as heavy crude oil. From the table, you can see that most of the gasoline evaporates within a few hours. Lagomedio and Prudhoe Bay crude oils are more persistent in the environment and have much lower evaporation rates, 38% and 28%, respectively. After 120 hours, much of the product would be expected to remain on the water surface.

Percent evaporated over time for an instantaneous release of 100 barrels with winds at 10 knots and water temperature at 20°C

	% Evaporated	Hour
Gasoline	94	1
Lagomedio	38	18
Diesel fuel oil	37	18
Prudhoe Bay	28	70

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Dispersion of Petroleum in the Sea

Breaking waves can drive small droplets of oil into the water column. If the droplets are small enough (diameters less than 50-70 microns) natural turbulence in the water will prevent the oil from resurfacing, just as turbulence in the air keeps small dust particles afloat. The smaller droplets that stay in the water column are considered dispersed.

Dispersion can be a mechanism for removing oil from the water surface. The amount dispersed depends on the oil properties (the viscosity and surface tension, in particular) and water conditions.

Oil products with low viscosity, like gasoline or kerosene, are more likely to disperse into the water with breaking waves than a high-viscosity oil, like an IFO 380 or Oficina heavy crude. Therefore, the dispersed fractions of gasoline or kerosene can be relatively large in heavy seas.

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Dissolution and Solubility of Petroleum in Sea Water

Dissolution begins immediately and is likely to continue throughout the weathering process.

The loss of petroleum product from dissolution is minor when compared to the other weathering processes.

Less than 0.1% (very heavy oil) to 2% (gasoline) of the spilled oil volume actually dissolves into the water column. However, the components of the oil that dissolve into the water column are often more toxic to the environment.

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Sample oil solubilities

Oil	Aqueous Solubility (mg/L)*
Unleaded gasoline	260.9
Diesel	60.4
Prudhoe Bay crude	20.5
Lagomedio	10.0

*Jokuty, P., S. Whiticar, Z. Wang, M. Fingas, B. Fieldhouse, P. Lambert, and J. Mullin. 1999. *Properties of crude oils and oil products.* EE-165. Ottawa, Ontario: Environment Canada.

Emulsification of Petroleums in the Sea

Sample viscosities

Product	Viscosity at room temperature (cP)
water	1
diesel fuel	10
Prudhoe Bay crude	46
Prudhoe Bay crude after emulsification	250,000
Lagomedio	20
Lagomedio after emulsification	300,000
honey	10,000
peanut butter	1,000,000

For many crude oils and some refined products, weathered oil is likely to reach a stage where water droplets are mixed into the oil, forming a water-in-oil emulsion, or "mousse."

The ability to form an emulsion depends on water conditions and the chemical properties of the oil. For example, oils with high wax and asphaltene content, such as Prudhoe Bay crude, emulsify easily if there are breaking waves. Once the oil has emulsified, the viscosity can increase enormously (see table).

Generally, oils must weather a certain amount before forming an emulsion. Although the onset of emulsification may take several days, the emulsification itself can occur within a few hours.

The emulsion can be 70 to 90% water so that the combined volume of oil and water mixture may be much greater than the volume of the original spill.

Emulsions are often classified by their stability. In unstable emulsions, water and oil separate easily under calm conditions with warm temperatures. In stable emulsions, water remains in the oil for weeks to months.

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Fate of Petroleums in the Sea – Sedimentation

Sedimentation is defined as the adhesion of oil to solid particles in the water column. Oil can be sorbed onto sediments in the water column and may eventually be found in the bottom sediments.

Turbulent waters with high sediment load (~500 g/m^3), such as a fast-moving, muddy river, can move the oil through the water column within hours of the initial release.

Waters with low sediment load (< 5 g/m^3), as in the open ocean, will allow oil to remain on the surface much longer (weeks), spreading the slick over a wider area.

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Crude oil also has a greater likelihood to sink as it weathers as the lighter fractions are preferentially removed, leaving a higher specific gravity material which requires less ballast to cause it to sink and become incorporated into the bottom sediments.

Fate – Photo-oxidation and Biodegradation

Photograph showing a large patch of weathered oil with a crusty, "skin" layer on the surface. The white spots in the picture are 3-inch by 4-inch drift cards cast into the water to help track the movement of the oil.

Kelp attached to weathered oil or "tarballs"

Photo-oxidation

Sunlight changes the spilled oil's chemical and physical properties.

This process is limited to the surface of the oil and can result in a thin, crusty "skin" on slicks and tarballs.

The "skinning" of the oil is thought to limit evaporation because the lighter oil components can no longer diffuse through the surface of the slick.

Photo-oxidation may increase the ease of emulsification and is considered a long-term weathering process taking weeks to months.

Biodegradation

The spill is finally removed when the oil biodegrades. The microbes that degrade oil occur naturally in the environment.

The rate at which the organisms degrade the oil depends on the properties of the water and the oil and microbial activity. This process is thought to occur over time scales of weeks to years.

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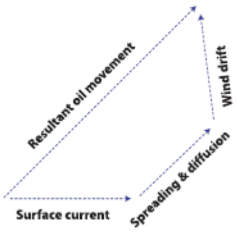
Petroleum Transport on the Sea



Two major processes transport oil spilled on water: spreading and advection. For small spills (<100 barrels), the spreading process is complete within the first hour of the release.

Winds, currents, and large-scale turbulence (mixing) are advection mechanisms that can transport oil great distances.

In general, the oil movement can be estimated as the vector sum of the wind drift (using 3% of the wind speed), the surface current, and spreading and larger-scale turbulence (diffusion).

Summary

To develop a trajectory "picture," the analyst must look at the components considered in any model and consider the proceses outlined in this guide. The major components of any model will be:

Spill Data

- location of spill
- type of oil
- volume lost
- time/type of loss (instantaneous or continuous? stationary? moving?)

Environmental Data

- wind
- currents (large-scale, tidal, river flow, etc.)
- tidal heights
- diffusion

Some of the processes in this guide are typically not modeled well and the modeler must account for these in the uncertainty included in the final trajectory analysis:

- oil thickness
- convergences
- local variations on astronomical tides
- small-scale currents (i.e., around piers, small groins, or jetties)
- small-scale meteorology

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Color-enhanced image of a test spill (<50 barrels).

Transport of Spilled Petroleum in the Sea - Spreading

The spreading process occurs quickly and, for most spills, mostly within the first hour. In the open ocean, winds, currents, and turbulence will quickly move the oil.

Spreading will occur quicker for lighter and for less viscous oils in warm water temperatures and for warm oils.

The slick does not spread uniformly but will often have a thick part surrounded by a larger, but thinner sheen. The figure shows a color-enhanced image of an experimental spill. The orange portion is the thick part of the slick and the pink area, sheen. Note that about 90% of the oil is found in 10% of the slick area (the orange portion of the figure).

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Wind Drift and Current Affects on Oil Slick Movement

Windrows

Observations of actual oil spills and controlled experiments indicate that the wind drift can range from 1 to 6% of the wind speed (most modelers use an average of 3%). The lower windage value of 1% reported may be due to some of the oil droplets being submerged by waves. Langmuir circulation can also result in wind drift variability. The oil within the windrows may move up to 5.5% of the wind speed. This hypothesis would account for the higher windage value of 6% reported at spills.

It should be noted that wind direction is commonly reported as the direction *from* which the wind is blowing and the surface current is reported as the direction *toward* which the water flows. This means that a north wind and a southerly current are moving in the same direction.

The surface current is a mechanism for transporting oil. Currents are an important factor in determining the length and time scale of a spill.

- Ocean circulation can transport oil for thousands of miles in months to years
- Ocean coastal flow can transport oil for hundreds of miles in weeks
- Estuarine circulation can transport oil tens of miles in days

Rivers can transport oil tens of miles in hours to days

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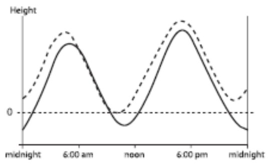
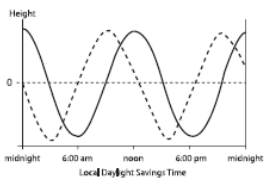
Tidal Currents in Near Coastal Areas





Strongest tidal currents are found in shallow-water areas or through narrow channels that connect large bodies of water.

Currents in channels (i.e., entrances to bays and estuaries) are constrained to flow either up or down the channel. In open waters, the flow depends on the direction of the tide wave.

Along the outer coasts, the tidal currents and heights are more closely in phase (progressive wave).

Tidal currents are generally out of phase with tide heights for stations inside an enclosed bay (standing wave). Phase change can also be caused by bottom friction.

Tidal currents and heights at the entrance to Galveston Bay. Solid line is tidal heights and the dashed line is tidal currents. (top)

Tidal currents and heights at the entrance to Portland Harbor, Casco Bay, Maine. Solid line is tidal heights and the dashed line is tidal currents. Note max flood is about 3 hours earlier than high tide. (bottom)

$$\text{Tidal excursion} = V\frac{T}{\pi}$$

To calculate the tidal excursion, let

T = Time from low slack to low slack (high slack to high slack)

V = Maximum tidal current velocity

Tidal Excursion

The trajectory analyst is often asked whether an offshore spill will move into a bay or estuary. To answer this question, one of the first things you should look at is the tidal excursion for the inlet. If the spill is anywhere near the extent of the tidal excursion, oil could move into the bay with the tide.

It is important to keep in mind that the tidal excursion is very much dependent on the bathymetry. In areas where the bottom is very broad and flat, the tidal influence will drop off quickly. In long, narrow channels, the tidal influence could be much larger.

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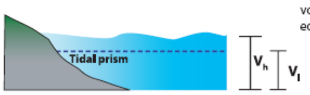
Flushing

The volume of water exchanged between an estuary and the open sea during a complete tidal cycle is often called the tidal prism. In the figure, the difference between the volume of water at low tide (below the dashed line) and high tide (below the curved line) is the tidal prism.

The tidal prism method for estimating flushing assumes that the water entering on the flood tide is fully mixed with the water inside the estuary. It also assumes that the volume of river water and sea water during the flood tide equals the tidal prism.



Vertical profile of a simplified shoreline. Area between the curving and dashed lines indicates the tidal prism.

To calculate the flushing time, first measure the area of the estuary from a map. Second, calculate the volume of the estuary at low water, by selecting a depth that best represents the estuary. Third, calculate the volume of the estuary at high water, V_h. Finally, the flush time can be calculated from $f_t = \left(\frac{V_h}{V_h - V_l}\right)t_c$.

where t_c is the time of one tide cycle (from low tide to low tide) and V_l is the volume of water in the estuary at low tide

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Turbulent Mixing

Oil spilled into water is subjected to turbulent flow. Oceanic turbulence is generated by winds and current, and by heating and cooling. Flow in the upper layers of water becomes more turbulent as the wind and current increases.

Turbulent diffusion, caused by random bulk movements of water, tears oil slicks into smaller patches that are distributed over a wider area.

The diffusion of oil occurs mainly in the horizontal direction. Horizontal diffusion of the surface water ranges from 100 to 1, 000,000 cm^2/s.

Diffusion in the vertical direction is much smaller by orders of magnitude than horizontal diffusion and generally decreases with depth.

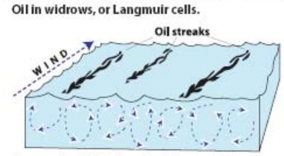
Turbulent diffusion is not to be confused with mechanical dispersion (i.e., mixing caused by breaking waves).

Langmuir Circulation

Langmuir circulation is the result of the interaction between wind-driven surface currents and surface waves. Though Langmuir circulation may be present in weak or no-wind situations, it is most often seen when the wind speed is 1.5 m/s or greater. Langmuir circulation is a major mechanism for breaking the slick up and may be important for transporting oil droplets into the water column. Predicting the onset and strength is difficult at best, but we do know the following:

1) The windrows, or streaks, tend to last from 5 to 30 minutes, then dissipate and reform.
2) The surface current, stronger in windrows, can be up to 5.5% of the wind speed.
3) Downwelling (vertical) speeds at convergence range from 5 cm/s to 20 cm/s.

Oil in widrows, or Langmuir cells.



Langmuir cells in the mixed layer depth.

Reference: Special Issue Langmuir Circulation and Oil Spill Modeling. *Spill Science and Technology Bulletin Vol. 6*

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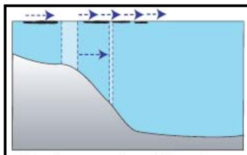
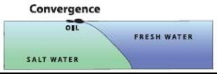


Water column moves from shallow water to deeper water.

Freshwater-saltwater interface with oil sheen moving into the convergence.



Tidal Convergences

Convergences are natural collection areas for oil, especially tarballs. Because they are close together, the tarballs in a convergence may coalesce and form a cohesive slick.

Tidal convergences can be formed by water moving from shallow to deeper water (ebb tide) that is stretched. To conserve mass, the surface velocity decreases.

Flotsam, rafting birds, and oil can collect in these areas.

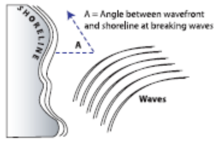
Under weak winds, the oil may not cross convergences. Strong winds may rupture the convergence. However, tidal convergence can appear consistently in the same general area during ebb tides.

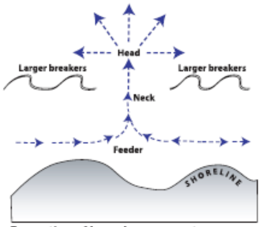
Freshwater-saltwater Interface

As with tidal convergences, the freshwater-saltwater interface is also a natural collection area for oil. However, this type of convergence is formed by river water flowing into the sea and spreading out over the seawater.

The fresh water is less dense than the seawater, creating a convergence at the surface.

Strong winds can rupture these convergences.





Formation of longshore currents

Reference: Horikawa, K. 1978. *An Introduction to Coastal Engineering*. New York: John Wiley and Sons. 403pp.

Longshore Currents

Longshore currents are produced by waves approaching, at an oblique angle, a coastline having a gently sloping beach.

Speed and direction of the longshore current increase with wave height and with an increase in the angle of the wave front.

Typical speeds of longshore currents range from 0.3 m/s to 1.0 m/s.

As the current approaches 1.5 m/s, a jet often forms that returns flow seaward in the form of rip currents.

This type of current is very important for trajectory purposes as it provides a mechanism for transporting oil in nearshore areas beyond the breakers and offshore.

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Oil in marsh.

Oil streaks moving parallel to the shoreline.

Beaching/Refloating

Ocean currents cannot actually bring the oil into contact with the shoreline unless there is some kind of flow that penetrates the shoreline (e.g., marshes and mangroves). The first photograph shows an oil spill moving into a marsh on a flood tide.

The second photograph shows streaks of oil moving along the shoreline. For the oil to beach, the wind must typically be blowing onshore.

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Analysis of the Environmental Impact of an Offshore Oil Spill: *Fate of Oil*

The impact of an oil spill will depend upon the volume of the spill, duration, type of petroleum product, and physical factors such as wind, wave, and current conditions under which the spill occurs. The fate of oil in an oil spill depends on a complex interaction between the several arbitrarily defined categories. Some of the lighter fractions of oil will evaporate very rapidly (evaporation), others are sensitive to sunlight and oxidize to innocuous or inert compounds (photo--oxidation), and still other fractions will either dissolve (dissolution), emulsify (emulsification), or adsorb to sediment particles (sedimentation), depending on their physical properties.

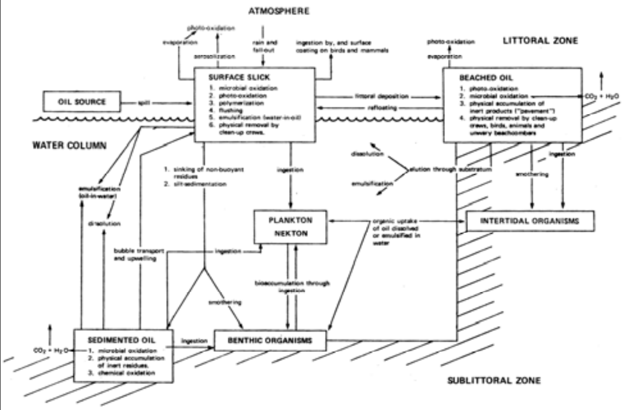


Figure 7-6. Fate of an oil spill in the marine environment.

In an oil spill, the relative importance of each of the categories in the fate of an oil spill diagram (Figure 7-6) is influenced by several physical and chemical parameters and other events, including:

- Type of petroleum product (Bunker "C", diesel fuel, naphtha, gasoline, crude oil, etc.);
- Volume of spill;
- Distance from shore;
- Sea and weather conditions (air and water temperature, wind direction and speed, wave height, etc.);
- Oceanographic conditions (currents, tide, salinity, etc.);
- Shoreline and bottom topography (sand or rock beaches, relief, degree of exposure to surf, etc.);
- Season of year, especially with reference to biological activities such as breeding, migration patterns, feeding habits, etc.; and
- Cleanup and restoration procedures.

Effects of Oil on Marine Water Quality

The most obvious effect on water quality associated with an oil spill would be the physical presence of floating oil slicks which would deter boaters, bathers, divers, and others from using the affected area. Also, oil coming ashore would be aesthetically objectionable and would interfere with shoreline recreational activities such as picnicking, sunbathing, beachcombing, clam digging, and surf fishing.

Depending on the specific oil material, dissolved hydrocarbon concentrations in the water column also could significantly increase, especially for a material containing large amounts of soluble components.

Low-viscosity, high-API-gravity crude oils, and refined products generally break up and dissolve or emulsify in sea water. Individual oil droplets become attached to sediment particles either by adsorption or adherence, particularly in the intertidal-shallow sublittoral or surf zones, and disperse with these suspended particles. By this mechanism, oil becomes diluted and may finally become incorporated in sediments, animals, and plants.

High-viscosity, low-API-gravity crude oils and refined products such as Bunker "C" fuel behave like soft asphalt. When lower molecular weight hydrocarbons evaporate or dissolve, the remaining portion of these oils may become more dense than seawater and sink. This will be particularly true if they form water-in-oil emulsions which can also then pick up suspended silt particles and become heavier than water. The sunken oil may reside on the bottom in sediments as relatively inert material or it may undergo further chemical and biological degradation, converting the residues to lighter molecular -weight materials which rise to the surface and repeat the original chain of reactions until most of the oil is consumed. Some of these lighter fractions may also dissolve or emulsify on the way back to the surface. These dense oils can form water-in-oil emulsions which may sink or be cast up on the beach.

Biological Dispersion

Hydrocarbons are not foreign to the marine environment; they are synthesized by most, if not all, living organisms. The conditions under which microbial attack occurs and the rate of biodegradation are a function of such diverse factors as the type and number of bacteria in the given marine environment, the quantity and type of oil spilled, the spill concentration, water temperature, salinity, oxygen concen-tration, nutrients, and pH. Some reported values for marine biodegradation of oils vary from 35 to 55 percent of oxidizable crude oil degraded within 60 hr, to between 26 and 98 percent of oil degraded by mixed cultures within 30 days at 77°F.

Effects of Oil on Marine Ecosystems

The effects of petroleum products on marine ecosystems has been the topic of much research and many publications. Three kinds of effects (and the resultant biotic responses) exist:

FIRST ORDER EFFECTS include the direct effect of petroleum products on the biota. These effects may be toxic physically (such as suffocation), or physiologically (such as internal disturbances following ingestion). Effects within hours or days.

SECOND ORDER EFFECTS include changes in populations of each species with respect to size-frequency and age structure, productivity, standing crop, reproductive abilities, etc. Effects within weeks to years.

THIRD ORDER EFFECTS include changes at the community or ecosystem level with respect to relationships within or between trophic levels, species composition and/or abundance, and other aspects of community dynamics. Effects within months to years.

First order effects have been well documented in several instances. Second and third order effects are generally less well documented, except for a few large. Even in these cases, the data interpretation may be open to criticism.

The severity of both short-term and long-term effects is predicated on certain conditions. The following generally increase the severity of an oil spill:
1. A massive oil spill relative to the size of the receiving and affected area.
2. A spill of primarily refined oil.
3. The spill being confined naturally or artificially to a limited area of relatively shallow water for a prolonged period.
4. The presence of sea bird and/or mammal rookeries in the affected area.
5. The absence of oil-oxidizing bacteria in the marine environment.
6. The presence of other pollutants, such as industrial and municipal wastes in the affected area.
7. The application of detergents and/or dispersants as part of the cleanup operation.

Summary of Recorded Historical Major Oil Spills

Spill	Date	Quantity Spilled (1000 gal)	Detergents Used in Cleanup	Time to Recovery
Tampico Maru	1957	2,500	No	1 - 10 years
Fawley, England	1960	52	Yes	> 2 years
Torrey Canyon	1967	29,400	Yes	> 2 years
Milford Haven	1968	70 - 150	Yes	Several months
Santa Barbara	1969	4,200	Yes	Several months
West Falmouth	1969	175	No	< 2 years
Tampa Bay	1970	10	Yes	Days to weeks
Nova Scotia	1970	3,800	No	Months to years
San Francisco	1971	840	No	10 months +

Santa Barbara Spill

Oil released from the offshore well in the Santa Barbara Channel eventually affected most of the mainland beaches in the channel and some areas of the Channel Islands. Slicks initially covered large areas of the channel and tended to accumulate on the beaches in the upper littoral zone. Phytoplankton studies in the Santa Barbara Channel showed no conclusive evidence of any major effect which could be directly attributed to the spilled oil. These studies were based on 11 stations which were resampled 12 times from 1969 to 1970. The data showed higher productivity occurring inshore, seasonal variations in productivity, and the presence of a phytoplankton bloom in August 1969. No low productivity values resulting from the presence of oil on the surface of the water were found. There was a reduction in the reproduction in *Pollicipes polymerus*, a barnacle. The breeding in *Mytilus californianus*, a mussel, was probably reduced as a result of oil pollution.

The major damage to the marine invertebrates following the Santa Barbara spill resulted principally from the oil-removal operations along the mainland shore. The steam cleaning of rocks to remove the oil killed all sessile invertebrates that were attached to them. Further, cleaning the beaches with skip loaders to remove the oily straw and debris undoubtedly took its toll on some of the invertebrates inhabiting those beaches.

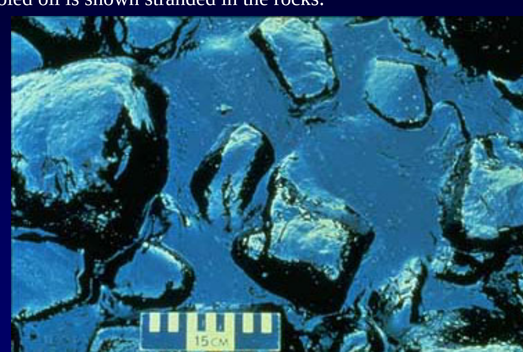
No permanent damage to marine plants was observed by California Department of Fish and Game divers during repeated surveys in 1969. On Santa Cruz Island, the algae *Hespherophycus harveyanus*, originally heavily coated by oil in February, was clean by August. In addition, numerous young plants were found to be present. The surf grass *Phyllospadix torreyi* was heavily coated by oil and suffered high mortalities but the beds had come back by the time of the later surveys. Most of the other plants and algae surveyed on the islands and the mainland appeared relatively unaffected by the oil pollution.

San Francisco Spill

The discharge of 20,000 bbl of Bunker C oil near the Golden Gate Bridge in San Francisco Bay in January 1971 caused extensive coverage of the intertidal zones within portions of the bay and seaward as far north as Bolinas and to a lesser extent south of Half Moon Bay.

An investigation on the effect of the spill on Duxbury Reef, a marine reserve, indicated that heavy oil deposits on the reef area caused kills by smothering certain species such as acorn barnacles and limpets. Marine snails suffered less mortality than did the sessile barnacles and other sedentary animals. The normally large population of striped shore crabs (*Pachygrapsus crassipes*) was missing from the rocky crevices. The condition of Duxbury Reef in December 1971 was one of apparent good health; the recruitment of some marine animals appeared to be approaching normal levels and the oil had disappeared from much of the reef surfaces and was barely discernible in the most heavily deluged areas.

EXXON VALDEZ. Beginning 3 days after the vessel grounded, a storm pushed large quantities of fresh oil onto the rocky shores of many of the beaches in the Knight Island chain. In this photograph, pooled oil is shown stranded in the rocks.



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EXXON VALDEZ

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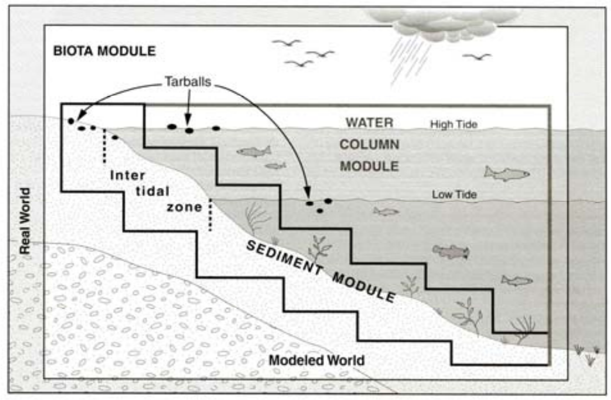
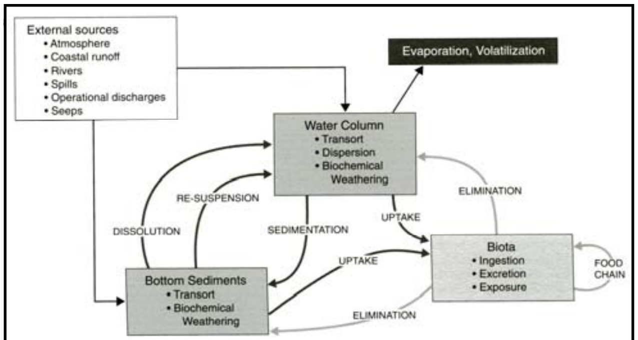


Oil in the Sea III, National Research Council, 2003.



Oil in the Sea III, National Research Council, 2003.

EXXON VALDEZ. In many locations in Prince William Sound, the action of tides and currents distributed oil throughout the entire intertidal zone. In Northwest Bay on Knight Island, tides have deposited oil on this rocky beach face up to the top of the intertidal zone.

NOAA Office of Response and Restoration

EXXON VALDEZ. Workers using high-pressure, hot-water washing to clean an oiled shoreline. In this treatment method, used on many Prince William Sound beaches, oil is hosed from beaches, collected within floating boom, then skimmed from the water surface. Other common treatment methods included cold-water flushing of beaches, manual beach cleaning (by hand or with absorbent pom-poms), bioremediation (application of fertilizers to stimulate growth of local bacteria, which degrade oil), and the mechanical relocation of oiled sediments to places where they could be cleaned by wave and tide action.

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EXXON VALDEZ. A brown sediment plume and sheens of refloated oil drift away from this oiled beach as it is cleaned by a team applying high-pressure, hot-water washing. Refloating of oil and release of sediment are often unavoidable consequences of shoreline cleanup that can cause additional environmental harm.

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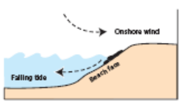
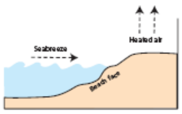
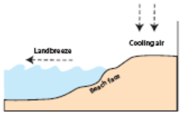
Land/Sea Breeze



Oil beaching with a falling tide and onshore wind.



Heating of the land and a sea breeze (from sea to land) during the day.



Cooling of the land and a land breeze (from land to sea) during the night.

A falling tide with an onshore wind greatly increases the amount of shoreline oiling (see first figure). A sea breeze may strand the oil on the shore.

The land and sea breeze cycle occurs in many coastal areas and is caused by heating of the land during the day and cooling at night (see second and third figures). In some areas, the land and sea breeze can extend many miles off-shore.

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Office of Response and Restoration • Hazardous Materials Response Division

TABLE 5-1 Indirect, chronic, or delayed responses of birds to the *Exxon Valdez* oil spill (after Peterson, 2001)

Species	Foraging Ecology	Type of Response	Period/Duration	References
Black Oystercatcher	Intertidal invertebrates	Numbers declined post 1989	1990, with recovery by 1993	Klosiewski and Laing, 1994
		Chicks fed oiled mussels required more food for less growth and fledged later	1990 only	Andres, 1996, 1997
		Laid fewer eggs on renesting	1990 only	Andres, 1996, 1997
		Nesting disrupted on oiled island as compared to unoiled island	Recovery by 1993	Sharp et al., 1996
Harlequin Duck	Shallow sub-tidal invertebrates	Lack of recovery in numbers present in oiled areas	Not until at least 1991	Klosiewski and Laing, 1994; Day et al., 1995, 1997; Irons et al., 2000
		Decline in winter counts in western (oiled) vs. eastern (unoiled) Sound	Through 1997-1998	Rosenberg and Petrula, 1998; Rosenberg, 1999
		P450 1A induction	Tested for in 1998	
Barrow's Goldeneye	Shallow sub-tidal invertebrates, mussels	Declining numbers in oiled vs. unoiled areas	Through 1998	Holland-Bartels et al., 1999; Irons et al., 2000
		Elevated P450 1A levels	1996-1997	Trust et al., 2000
Cormorants, black-legged kittiwakes, murres, pigeon guillemot, mergansers, and loon	Shallow subtidal fishes	Continued depression in census counts along oiled shores vs. expectation	Through 1998 (except for 1993 for loons)	Irons et al., 2000

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TABLE 5-4 Examples of Oil-impacted Marshes with Recovery Times of Five Years or More, Documented by Follow-up Studies (from Hoff et al., 1996).

Location	Vegetation	Oil Type	Time of Oiling	Cleanup	Recovery Time
Chile *Metula*[a]	*Salicornia ambigua* *Suaeda argentinensi*	Arabian crude Bunker C	Aug. 1974	none	> 20 yrs
Quebec *Miguasha*[b]	*Spartina alterniflora* *Spartina patens*	Bunker C	Sept. 1974	sediment removal manual burning digging	> 11 yrs
Brittany, France *Amoco Cadiz*[c]	*Salicornia* *Suaeda* *Halimione*	Arabian light Iranian light Crude Bunker C No. 2 fuel	March 1978	sediment removal	5 – > 8 yrs
West Falmouth, Mass. *Florida*[d]	*Spartina alterniflora* *Salicornia europaea* *Spartina patens*	No. 2 fuel	Sept. 1969	?	> 8 yrs
Buzzard's Bay, Mass. *Bouchard 65*[e]	*Spartina alterniflora* *Salicornia virginica*		Oct. 1974	?	> 3 yrs

[a]Baker et al., 1993
[b]Vandermeulen and Jotcham, 1986
[c]Baca et al., 1987
[d]Burns and Teal, 1979; Teal et al., 1992
[e]Hampson and Moul, 1978

Oil in the Sea III, National Research Council, 2003.

TABLE 5-5 Examples of Oil-impacted Marshes with Recovery Times of 3 Years or Less, Documented by Follow-up Studies (from Hoff et al., 1996)

Location	Vegetation	Oil Type	Time of Oiling	Cleanup	Recovery Time
Hackensack estuary, N.J. Wellen tank farm[a]	*Spartina alterniflora*	No. 6 fuel	May 1976	none cutting	?
Galveston Bay, Tex. Bayou pipeline[b]	*Spartina alterniflora* *Juncus roemerianus*	light crude	Jan. 1984	none sorbents flushing	8 mos – > 2-5 yrs
Harbor Island, Tex. Am Petrofina pipeline[c]	*Spartina alterniflora* *Avicennia germinans*	crude oil	Oct. 1976	none sorbents burning clipping	6 mos – > 6 mos
Aransas River, Chiltipin Creek[d]	*Spartina alterniflora*	S. Texas light crude	Jan. 1992	burning	> 2 yrs
Neches River, Tex. *Exxo Bayway*[e]	*Spartina patens*	Arabian crude	Jan. 1979	none sorbents flushing burning cutting	7 mos > 7 mos
Neches River, Tex. Unocal[f]	*Spartina alterniflora*	light crude	April 1993	none sorbents	?
Nairn, La. Shell pipeline[g]	*Spartina patens* *Spartina alterniflora* *Distichlis spicata*	Louisiana crude	April 1985	flushing trampling	< 1-5 yrs

[a]Mattson et al., 1977
[b]Alexander and Webb, 1987
[c]Holt et al., 1978
[d]Tunnell and Hicks, 1994
[e]McCauley and Harrel, 1981; Meyers, 1981; Neff et al., 1981
[f]NOAA, 1993
[g]Mendelssohn et al., 1990; Fischel et al., 1989

Oil in the Sea III, National Research Council, 2003.

Summary of Documented Spills

The following is a summary of the effects of the historical oil spills, based on field investigations. The results of the different studies often have quite varied conclusions (likely due to a combination of factors including spill and material characteristics, and environmental conditions, but the following is a list of generally accepted conclusions concerning the effects of oil spills.

• The principal damage from oil spills is to birds. The literature is remarkably unanimous on this point. The data are conclusive and can be taken without reservation. While no bird damage has resulted from some spills, it is believed that this resulted from accidental circumstances, and the danger to birds is present wherever a spill occurs.

• The effects in the intertidal zones, beaches, marshes, and rocky shores are sometimes of significant severity. The intertidal zone is subject to heavy concentrations of oil, and damage may be expected if concentrations reach a critical level. Usually the damage to biotic communities from the oil itself is quite small even when heavy concentrations reach the shore. Humans are among the most affected when beaches are made uninhabitable.

• Little documented evidence of any significant damage to marine bottom communities in deep or shallow water. There appears to be an intermediate zone between the intertidal area and “deep” water in which some relatively small damage occurs under adverse circumstances (such as heavy wave action in surf zones).

• Damage to fisheries appears to be confined to those cases where animals (such as the mussel *Mytilus*, oysters, or clams) live in intertidal zones. Any fishery animal can become tainted with oily taste and smell.

• Recovery from damage caused by oil spills is usually rapid and complete so far as the marine communities are concerned, and in some cases these communities may be stimulated to higher productivity by the process.

• No significant damage to plankton has been observed in oil spills.