M7: Petroleum Spills

Robert Pitt
University of Alabama

Photo: NOAA Office of Response and Restoration

Movement of Oil in 1999


Oil Production Between 1960 and 1998

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: **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.

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.
### Notable Oil Spills

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


Other links for oil and hazardous material spills are:

**Incident News:**  

**NOAA Office of Response and Restoration**


### 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.

![The Amoco Cadiz](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.

![The Argo Merchant](NOAA_Office_of_Response_and_Restoration)

---

### Oil Spills of 100,000 Tons (640,000 Barrels), or More


<table>
<thead>
<tr>
<th>Year</th>
<th>Cause</th>
<th>Location</th>
<th>Barrels Spilled</th>
<th>Rank by Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1942</td>
<td>German U-boat attacks on tankers after USS Andrew Jackson</td>
<td>U.S. East Coast</td>
<td>984,000</td>
<td>1</td>
</tr>
<tr>
<td>1967</td>
<td>Tanker Trinity Bay搁浅</td>
<td>English Channel, off Land's End, UK</td>
<td>1,194,000</td>
<td>1</td>
</tr>
<tr>
<td>1970</td>
<td>Tanker Othello collides with another ship</td>
<td>Tralhavet Bay, Sweden</td>
<td>114,000</td>
<td>10</td>
</tr>
<tr>
<td>1972</td>
<td>Tanker Sea Star collides with another ship</td>
<td>Gulf of Oman</td>
<td>114,000</td>
<td>10</td>
</tr>
<tr>
<td>1976</td>
<td>Tanker Urquiola grounds</td>
<td>La Coruña, Spain</td>
<td>103,000</td>
<td>11</td>
</tr>
<tr>
<td>1978</td>
<td>Tanker Amoco Cadiz runs aground</td>
<td>Northwest France</td>
<td>223,000</td>
<td>9</td>
</tr>
<tr>
<td>1979</td>
<td>Itox 1 oil well blows</td>
<td>Southern Gulf of Mexico</td>
<td>600,000</td>
<td>2</td>
</tr>
<tr>
<td>1979</td>
<td>Tankers Atlantic Empress and Aegean Captain collide</td>
<td>Off Trinidad and Tobago</td>
<td>300,000</td>
<td>6</td>
</tr>
<tr>
<td>1983</td>
<td>Blowout in Norwuz oil field</td>
<td>Persian Gulf</td>
<td>600,000</td>
<td>3</td>
</tr>
<tr>
<td>1983</td>
<td>Fire aboard tanker Castillo de Belisario</td>
<td>Off Cape Town, South Africa</td>
<td>250,000</td>
<td>8</td>
</tr>
<tr>
<td>1988</td>
<td>Tanker Odyssey flounders</td>
<td>Off Nova Scotia, Canada</td>
<td>132,000</td>
<td>11</td>
</tr>
<tr>
<td>1991</td>
<td>Iraq begins deliberately dumping oil into Persian Gulf</td>
<td>Sea Island, Kuwait</td>
<td>1,450,000</td>
<td>1</td>
</tr>
<tr>
<td>1991</td>
<td>Tanker Haven grounds</td>
<td>Genoa, Italy</td>
<td>140,000</td>
<td>10</td>
</tr>
<tr>
<td>1991</td>
<td>Tanker ABT Summer founders</td>
<td>700 n mi. off Angola</td>
<td>260,000</td>
<td>7</td>
</tr>
<tr>
<td>1994</td>
<td>Pipeline bursts, oil enters rivers that flow into Arctic Ocean</td>
<td>Near Usinik, Russia</td>
<td>312,500</td>
<td>5</td>
</tr>
</tbody>
</table>
On December 21, the ARGO MERCHANT broke apart and spilled its entire cargo of 7.7 million gallons of No. 6 fuel oil.

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.

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.

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.
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

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.

The Jupiter

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

TABLE 2.4 Processes That Move Petroleum Hydrocarbons Away from Point of Origin

| Input Type | Penetration | Dispersion | Adsorption | Oxidation | Evaporation | Transport | Movement | Sedimentation | Resuspension | Tails | Track
|------------|-------------|------------|------------|-----------|-------------|-----------|----------|----------------|-------------|-------|-------
| Spills     | H           | M          | M          | M         | H           | L         | L        | NR             | NR          | NR    | NR    |
| Light Oil  | M           | L          | L          | L         | M           | L         | L        | NR             | NR          | NR    | NR    |
| Heavy Oil  | L           | L          | L          | M         | H           | L         | L        | NR             | NR          | NR    | NR    |
| Precipitated | M         | NR         | M          | L         | L           | L         | L        | NR             | NR          | NR    | NR    |
| Chlorinated | M         | NR         | M          | L         | L           | L         | L        | NR             | NR          | NR    | NR    |
| Acid        | M           | NR         | M          | L         | L           | L         | L        | NR             | NR          | NR    | NR    |
| Load Beck  | M           | L          | L          | M         | M           | M         | M        | M              | U           | NR    | NR    |

**NOTES:** H = high, L = low, NR = not relevant, U = unknown.
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.

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.

Trajectory Analyses

Trajectory Analysis

Forecasting the movement of an oil spill is often complicated by insufficient input data, particularly in the first few hours of the release. Detailed spill data (location, volume lost, product type), as often short-burst and environmental data (wind and current observations and forecasts) are often sparse and unavailable. Nonetheless, the modeller 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 in 4-km models, white on the coast. The scale at the bottom of the map indicates the percent coverage of the colour oil within those contours. Plausible errors in the spill and environmental data were explored by the modelling team the colored outer contour represents a 90% confidence bound. This provides an indication of the uncertainty in this forecast.

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).
**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.

\[ \frac{4}{3} \times 10^6 V \times A \]

\[ \frac{4}{3} \times 10^6 V \times A \]

\[ \frac{8}{3} \times 5.72 \times V_r \]

\[ \frac{2}{1} \times \frac{3}{2} \times V \times u \times t \]

**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.**
Fate of Spilled Petroleum in the Sea

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

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 at 50°F) and an API of 29.6.
• 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.

• 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.

• 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 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.

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.
• 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.

---

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, such as 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. Logamatic and Prudhoe Bay crude oils are more persistent in the environment and how much fewer evaporation rates, 28% and 3.3%, respectively. After 120 hours, much of the product would appear to remain on the water surface.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>% Evaporated</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>94</td>
<td>1</td>
</tr>
<tr>
<td>Logamatic</td>
<td>38</td>
<td>18</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>37</td>
<td>18</td>
</tr>
<tr>
<td>Prudhoe Bay</td>
<td>28</td>
<td>20</td>
</tr>
</tbody>
</table>

---

Dispersion of Petroleum in the Sea

Breaking waves can drive small droplets of oil into the water column. If these 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 aloft. The smaller droplets that stay in the water column are considered dispersed.

Dispersion can be a mechanism for removing oil from the 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 F 380 or even heavy crude. Therefore, the dispersed fractions of gasoline or kerosene can be relatively large in heavy seas.
**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 29%) 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.

<table>
<thead>
<tr>
<th>Sample oil solubilities</th>
<th>Organic (mg/L)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unleaded gasoline</td>
<td>260.0</td>
</tr>
<tr>
<td>Diesel</td>
<td>60.4</td>
</tr>
<tr>
<td>Prudhoe Bay crude</td>
<td>20.3</td>
</tr>
<tr>
<td>Lagomayo</td>
<td>10.0</td>
</tr>
</tbody>
</table>


**Emulsification of Petroleums in the Sea**

For many crude oils and some refined products, emulsification is a process that allows the oil to form an oil-in-water emulsion, or "mousse." The ability to form an emulsion depends on weather conditions, the chemical properties, and the surface tension of the oil. For example, oils with high van and pseudohexane content, such as Prudhoe Bay crude, are more likely to form emulsions if there is a breaking wave. Once the oil has emulsified, the viscosity can increase significantly (see table).

**Fate of Petroleums in the Sea – Sedimentation**

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

Turbulent waters with high sediment load (>900 g/m²), such as a first-moving muddy flow, can move the oil through the water column within hours of the initial release. Water with lower sediment load (<5 g/m²) in the open ocean will allow oil to remain on the surface much longer. Gravitational settling of the droplets can result in the formation of the slick. 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**

Photo-oxidation: Sunlight changes the spilled oil's chemical and physical properties. This process is limited to the surface of the oil and can evaporate thin, sticky "vapors" or spills and ballasts.

Biodegradation: The oil is finally removed when the oil biodegrades. Microbes that degrade oil occur naturally in the environment. The rate at which the oil is degraded 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.
Petroleum Transport on the Sea

Two major processes transport oil spilled on the water: spreading and advection. For small spills (<50 barrels), the spreading process is complete within the first hour of the release.

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

In general, oil movement can be estimated as the vector sum of the wind drift (using 2% of the wind speed), the surface current, and spreading and large-scale turbulence (diffusion).

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 around a lighter and move towards the coasts in warm water temperatures and for warm oils. The slick does not spread uniformly and will often have a thick point surrounded by a larger, thinner shear. The figure shows a color-enhanced image of an unspotted slick. The orange portion is the thick point of the slick and the pink area, which is about 90% of the oil, is found in 10% of the slick area (the orange portion of the figure).

Wind Drift and Current Affects on Oil Slick Movement

Observations of actual oil spills and controlled experiments indicate that the wind drift can range from 1 to 5% of the wind speed. The lower end of the range may be due to some of the oil droplets being submerged by waves. Large-scale turbulence can also result in wind drift. The oil within the wind will move up to 5% of the wind speed. This hypothesis would account for the higher wind speed value of 8% 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 southward 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 currents can transport oil for thousands of miles in months to years.
- Ocean currents can transport oil for hundreds of miles in weeks.
- Surface currents can transport oil for tens of miles in days.

Rivers can transport oil to the sea in hours to days.

Summary

To develop a trajectory picture, the analyst must input all the key component variables into a computer model and calculate the results. A typical trajectory model would include:

- Oil thickness
- Currents
- Local variations on atmospheric winds
- Small-scale currents like wind, river flow, etc.
- Oil volume
- Oil type
- Time of day (solar variation vs. stationary)
- Stationary movement

Environmental Data

- Wind
- Currents (large-scale, tidal, river flow, etc.)
- Oil volume
- 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
- Currents
- Local variations on atmospheric winds
- Small-scale currents like wind, river flow, etc.
Tidal Currents in Near Coastal Areas

Tidal Currents in Near Coastal Areas

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

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

Along the outer coast, the tidal currents and heights are more closely in phase. Progressive waves.

Tidal currents are generated out of phase with tidal heights for stations that lie an extended bay (standing waves). 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. Rough seas build about 3 hours earlier than high tides. (Bottom)

Tidal Excursion

Tidal excursion 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 area of the tidal excursion, oil could move into the bay with the tides.

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

Turbulent Motion

Oil spilled into water is subjected to turbulent flow. Turbulent flow is generated by winds and currents and to varying degrees. In the upper layer of water, waves become more turbulent as the wind and current increase. Turbulent diffusion is caused by random movements of water particles of the smaller particles that are distributed over a larger area.

The diffusion of oil occurs mainly in the horizontal direction. Horizontal diffusion of the surface range from 180 to 1,000,000 cm².

Diffusion in the vertical direction is much slower 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. This interaction may be present over wind speeds of 5 m/s over large ocean areas. The circulation is sometimes referred to as the wind-driven circulation due to the wind speed being the driving force and may be important in the dispersion of oil spills into the water column. Reducing the wave and wind strength is difficult at times, but we do what we can.

1. The streams or eddies, last from 5 to 30 minutes, then disperse and reform.
2. The surface current turns in windows, can be up to 5% of the wind speed.
3. Overlooking low wind speeds at convergence range from 5 (m/s) to 20 (m/s).

Oil slicks disperse in windows, or Langmuir cells.

Langmuir cells in the mixed layer depth.

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.
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 concentration, 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.

Summary of Recorded Historical Major Oil Spills

<table>
<thead>
<tr>
<th>Spill</th>
<th>Date</th>
<th>Quantity Spilled (1000 gal)</th>
<th>Detergents Used in Cleanup</th>
<th>Time to Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampico Maru</td>
<td>1957</td>
<td>2,500</td>
<td>No</td>
<td>1 - 10 years</td>
</tr>
<tr>
<td>Fawley, England</td>
<td>1960</td>
<td>52</td>
<td>Yes</td>
<td>&gt; 2 years</td>
</tr>
<tr>
<td>Torrey Canyon</td>
<td>1967</td>
<td>28,400</td>
<td>Yes</td>
<td>&gt; 2 years</td>
</tr>
<tr>
<td>Milford Haven</td>
<td>1968</td>
<td>76 - 150</td>
<td>Yes</td>
<td>Several months</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>1969</td>
<td>4,200</td>
<td>Yes</td>
<td>Several months</td>
</tr>
<tr>
<td>West Falmouth</td>
<td>1969</td>
<td>175</td>
<td>No</td>
<td>&lt; 2 years</td>
</tr>
<tr>
<td>Tampa Bay</td>
<td>1970</td>
<td>10</td>
<td>Yes</td>
<td>Days to weeks</td>
</tr>
<tr>
<td>Nova Scotia</td>
<td>1970</td>
<td>3,800</td>
<td>No</td>
<td>Months to years</td>
</tr>
<tr>
<td>San Francisco</td>
<td>1971</td>
<td>840</td>
<td>No</td>
<td>10 months +</td>
</tr>
</tbody>
</table>

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.
**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 *Hesperophycus 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.
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.
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.

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.
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 bird 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.