ASSESSMENT OF RISKS ASSOCIATED WITH THE SHIPMENT AND TRANSFER OF GROUP V FUEL OILS

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CONTENTS

PAGE

Introduction 1

How and Why Group V Fuel Oil is Different From Conventional #6 Fuel Oil 1

Summary of Spills Where the Oil Sank 6

SS *Sansinena*, Los Angeles, California, 1976 6

T/S *Mobiloil*, Columbia River, Oregon/Washington, 1984 7

Tank Barge MCN-5, Puget Sound, 1988 8

Bouchard 155, Tampa Bay, Florida, 1993 8

Barge *Morris J. Berman*, San Juan, Puerto Rico, 1994 9

Behavioral Models for Spilled Group V Fuel Oils 11

Model 1, Oil Remains Liquid, Majority Floats 11

Model 2, Oil Remains Liquid, Majority Does Not Float 11

Model 3, Oil Remains Liquid, Initially Floats, But Sinks After Picking Up Sand 14

Summary of Group V Fuel Oil Behavior 15

Resources at Risk 16

Shoreline Habitats 16

Marine and Estuarine 16

Freshwater 17

Benthic Habitats 18

Submerged Aquatic Vegetation 18

Biological Resources at Risk 19

Birds 19

Fish 20

Shellfish 20

Reptiles 21

CONTENTS (cont.)

PAGE

Marine and Terrestrial Mammals 22

Response Issues for Location, Containment, and Recovery........ 23

Location 23

Containment... 23

Recovery 24

Conclusions 26

References 28

LIST OF FIGURES

		PAGE
Figure 1.	Plot of viscosity versus API gravity for selected residual oils used by utilities (from Campbell and Rahbany 1991)..	3
Figure 2.	Plot of pour point versus API gravity for selected residual oils used by utilities (from Campbell and Rahbany 1991)..	5
Figure 3.	Model diagrams for how Group V fuel oils are predicted to behave when spilled	12

INTRODUCTION

Public utilities that use residual oils to generate electricity have started to evaluate the use of heavier-than-usual oils because of their lower costs and higher BTU values. These oils are defined as Group V oils because they have an API gravity less than 10° at 60°F, meaning that the specific gravity is less than or equal to 1.00 mg/l, the same as fresh water. Thus, Group V oils can float, be neutrally buoyant, or sink in water, depending on the properties of the specific oil and the salinity of the receiving waters. The utility industry refers to these heavy fuel oils as low-API oils, or LAPIO. In a regulatory sense, they are considered to be Group V fuel oils, to differentiate them from other types of Group V oils, such as asphalt, asphalt cutter stock, and very heavy crude oils.

This report provides a detailed review of the chemical and physical properties of Group V fuel oils, an analysis of the resources at risk that may result from spills of this type of oil, and a review of potential response considerations when dealing with spills. Case histories of spills of Group V fuel oils are also provided as examples of the diverse issues associated with an oil product of this nature. Although the emphasis of this report is on Group V fuel oils, the results may be applicable to crude oils with an API less than 10°.

HOW AND WHY GROUP V FUEL OILS ARE DIFFERENT FROM CONVENTIONAL #6 FUEL OILS

Conventional #6 fuel oil is a mixture of the heavy residual oil left after the lighter components of crude oil are removed through a refining process, which is then blended with lighter oils to meet specifications for viscosity, pour point, and API gravity. Group V fuel oils can also be a blend of heavy and light oils, but they generally contain more of the heavier components. Therefore, Group V fuel oils can be considered, at one level of understanding, as very heavy #6 fuel oils. However, there are subtle differences that are important in assessing the behavior and effects of Group V fuel oil in the event of a spill. Group V fuel oils are not only heavier, but may differ in chemical composition. To understand these differences, it is necessary to understand how Group V fuel oils are produced.

Residual oils used for blending are derived primarily from three sources (Campbell and Rahbany 1991):

1. *Atmospheric reduced crude*. This oil is the residue left when crude oil is heated to boiling and the distillate collected, which is the simplest refining process. Few refineries still use this process.
2. *Vacuum bottoms*. This oil is the residue from vacuum distillation of the residuum from atmospheric reduced crude. These residues are the most common source of heavy oils since most refineries use the vacuum distillation process.
3. *Heavy slurry oils*. These are heavy aromatic oils produced as a byproduct from catalytic cracking. These oils have very different properties than the first two.

In the U.S., refiners have modified their process to include catalytic cracking, which produces more of the light refined (and more valuable) fuels from crude oil. In fact, the amount of residual oil generated from a barrel of crude oil dropped from 12 percent in 1978 to 7 percent in 1984 (Campbell and Rahbany 1991). As a result, less residual oil from the U.S. is available for sale to utilities. Much of the residual oil sold today is obtained from foreign refiners who have not upgraded their refining processes. For East Coast markets, common sources of residual oils are refineries in the Caribbean, South America, and on the east coast of Canada (Campbell and Rahbany 1991). The lowest-cost residual fuels will be the vacuum bottoms from heavy crudes, which also have high aromatic contents. Thus, Group V fuel oils are likely to be chemically different than conventional crude oils, because of market-driven changes in source and production. Furthermore, there has been a shift in marketing of residual oils, in that oil jobbers now are the dominant suppliers, acting as middlemen who buy residual oils from refineries then blend them for resale on the spot market to electric utilities. Sale of the heavy fractions also solves potential waste disposal problems for the heaviest residues not otherwise marketable. Therefore, residual fuels today can vary even more widely in source and properties than before.

Another difference between #6 fuel oil and Group V fuel oil is the amount and source of the cutter stock blended with the residual oil to meet client specifications. No. 2 fuel oil is a common blending agent, used to reduce the viscosity of conventional #6 fuel oils. However, Group V fuel oil can be blended only to meet client specifications for viscosity, pour point, and sulfur, without having to meet a minimum API gravity requirement.

The least expensive Group V fuel oil would be compatible blends of any of the residual oils listed above without any light cutter stock. Again, this difference in blending can result in a very different chemical composition of Group V fuel oil. Figure 1 shows a plot of viscosity versus API gravity for conventional #6 fuel oils and Group V fuel oils. Viscosity increases as API gravity decreases, with the exception of heavy slurry oils. Electric utilities often have to make adjustments to their equipment and/or operating procedures to use Group V fuel oils.

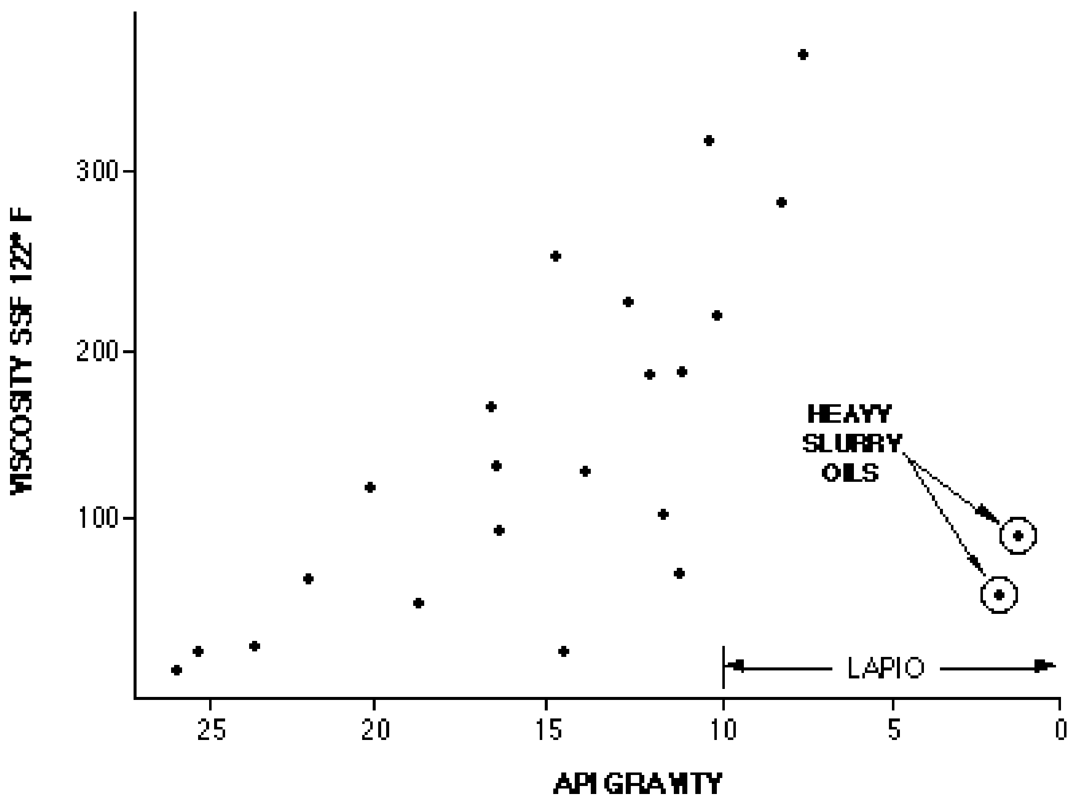


Figure 1. Plot of viscosity versus API gravity for selected residual oils used by utilities (from Campbell and Rahbany 1991). In general, viscosity increases with API gravity, with the exception of heavy slurry oils.

A third difference between #6 fuel oil and Group V fuel oil is the stability and compatibility of the blended oil. When compatible products are used as the cutter stock, such as #2 fuel oil which is a good solvent for many residual fuel oils, the blended oil is usually stable and does not tend to separate during storage or when spilled. The light component can be lost by evaporation, which is a change in the physical state, from a liquid to a gas. However, problems arising from mixing of incompatible oils are often magnified with Group V fuel oil, particularly asphaltene precipitation during transportation and storage. Asphaltenes are kept in solution and/or suspension in oil by the presence of aromatic compounds, and they can precipitate and settle out when the aromatic content of the oil drops. Blending with a cutter stock that is low in aromatics or mixing incompatible oils in the same tank can cause asphaltene precipitation, which leads to changes in the physical properties of the oil and problems during combustion. #2 fuel oil is generally high in aromatics and is a good universal blending agent, whereas other residual products may not be as good. Poorly blended or incompatible oils can physically separate into components that float, sink, and/or become neutrally buoyant when spilled on the water. Samples of visually homogeneous Group V fuel oil have been observed to separate when simply poured into water in a beaker. This potential for physical separation appears to be unique to residual fuel oil blends.

Some people tend to think of Group V fuel oil as similar to asphalt, but this is a poor analogy. Asphalt spills rapidly cool to form solid masses of product, whereas Group V fuel oils tends to remain liquid at ambient temperatures. Figure 2 is a plot of pour point versus API gravity for selected residual oils. Trends are difficult to discern because pour point is strongly influenced by the composition of the original crude oil. High paraffinic oils tend to have high pour points and high aromatic oils tend to have low pour points. Thus, when all of these types of oils are plotted together, there is no clear pattern. However, it is important to note that of the 26 Group V fuel oil samples plotted in Figure 2, only six had pour points greater than 50°F. Most residual oils are heated during storage and transport, though unheated barges can be used for short hauls. Based on these data, Group V fuel oils are likely to remain liquid, so they will act like fluids when spreading and are less likely to adhere to sediments and debris in the water column. Weathering and cooling will increase the viscosity, but solidification is a medium-term process.

It is important to note that there is no clear break in these properties at an API = 10°. Rather, there is a gradational trend, with some Group IV fuel oils having similar properties to Group V fuel oils. API gravity is not the critical parameter in predicting the characteristics of these heavy fuel oils, except whether they will initially float or not. The composition and compatibility of the blend are much more important, yet such information is seldom available for each blend. Also, each blend could be different, because widely different products could be used, depending on cost and availability.

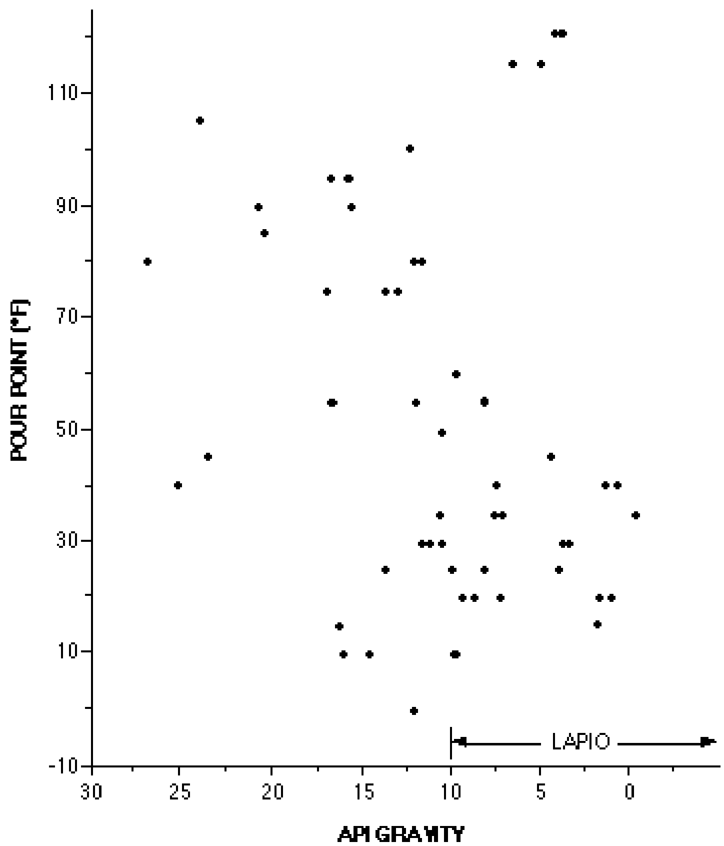


Figure 2. Plot of pour point versus API gravity for selected residual oils used by utilities (from Campbell and Rahbany 1991). Trends are hard to see because the pour point is closely related to paraffin content of the source crude oil. Note that most Group V fuel oils have pour points below 50°F, meaning that they are liquid at most ambient seawater temperatures.

SUMMARY OF SPILLS WHERE THE OIL SANK

Most of our knowledge regarding petroleum spills is derived from experience with lighter-than-water oils. There is very little information available that deals with response to oils that have a density which allows them to sink or exist in a neutrally buoyant state in the water column. Each documented case to date has been unique and highly problematic. There have been several spills in the U.S. that involved Group V fuel oils or oils that behaved like them: the SS *Sansinena* spill in 1976 ; the *Mobiloil* spill in 1984; the tank barge MCN-5 in Puget Sound in January 1988; the Tampa Bay spill in August 1993; and the *Morris J. Berman* spill in San Juan, Puerto Rico in January 1994. Brief summaries of these case histories are provided to identify the spill response issues of concern when dealing with oils that do not float.

SS Sansinena, Los Angeles, California, 1976

The tanker SS *Sansinena* exploded while berthed at Pier 46 in the process of loading more than 1,260,000 gallons (gal) of bunker fuel oil on December 17, 1976 (Hutchison and Simonsen 1979). The bunker fuel oil had an API gravity between 7.9° to 8.8° and a viscosity of approximately 180 (no units reported) at 60°F. Approximately 8,400 gal of oil were reported to be floating on the water surface, however, the majority of the oil sank. Divers reported large pools of oil on the harbor bottom, where the oil had settled into depressions along the bottom's uneven surface and collected in pools up to three meters deep. By December 29, divers from the California Department of Fish and Game (CDF&G) found the oil "to have a wrinkled surface with algae growing on it" (White and Kopeck 1979). The oil was stationary and unaffected by tidal action.

Initial recovery operations included using vacuum trucks and separation tanks mounted on a barge. An air eductor was used to further boost the suction of the vacuum trucks. This method was abandoned because the divers were having great difficulty moving the suction along the bottom. Next, diver-guided hydraulic pumps were used. The divers were immediately covered in oil after reaching the bottom, so they had to direct the pumps by "feel." This method of recovery was terminated after the thick accumulations close to the pier were removed, because it was slow and limited by the crane boom reach. Specially designed pumping units consisting of a prime mover and hydraulic pumps mounted on a barge were then used to collect oil from various depressions on the bottom. However, this method was only marginally successful once the large oil pockets had been recovered. In total, nearly 675,000 gal of the sunken oil were recovered during the initial recovery operations.

Eventually, a suction head and pump device was designed on-site for recovery of the large quantities of oil still remaining on the bottom. This device had to be operated using directions from a diver because some of the oil pools had become silted over and even had marine life living in the silt, making the oil difficult to locate. After using this specialized suction device for nearly sixty days, an additional 420,000 gal of the oil were recovered from the harbor bottom.

After a third survey, divers estimated that approximately 4,200 gal of oil remained on the bottom. However, after another month of continuous effort with the modified suction head device, about 11,000 gal of oil were recovered. By March 1, 1978, all recovery efforts were halted when CDF&G divers reported that recovery efforts were ineffective and that the remaining oil was unrecoverable. CDF&G divers reported a "healthy benthic community" on the harbor bottom.

In total, nearly 1,386,000 gal of the oil were recovered over a sixteen-month period, indicating that most of the spilled oil was recovered. Multiple techniques were required to recover the spilled oil at a cost of more than three million dollars.

T/S Mobiloil, Columbia River, Oregon/Washington, 1984

On March 19, 1984, the tank ship *Mobiloil* grounded on the Columbia River near St. Helens, Oregon. The tanker was carrying five different oils, including an industrial fuel oil with an API gravity of 5.5° and a pour point of 30°F. The river currents in the spill area dispersed the industrial fuel oil throughout the water column and along the river bottom. Some of the oil sank directly to the bottom, where it was transported downstream by strong river currents at nearly the same rate as the floating oil slick. In the lower river sections, the bottom oil slowed as it became caught up in the salt wedge circulation pattern. The sunken oil was difficult to locate and track. Sorbent pads wrapped around anchors were used to search for bottom oil.

The majority of the floating slicks was flushed from the river within several days. Some of the oil that spilled had pooled behind the vessel in an area protected from the river currents. When the vessel was moved, this pooled oil quickly dispersed and, within a day or so, no pooled oil remained near the grounding. Oil suspended in the water column remained for up to one week. The oil on the river bottom was predicted to remain in the river for a period of several weeks (Kennedy and Baca 1984).

Tank Barge MCN-5, Puget Sound, 1988

On January 31, 1988, the tank barge MCN-5 capsized while under tow and eventually sank in 120 feet of water in the Rosario Straits (Yaroch and Reiter 1989). It held 415,000 gal of heavy cycle gas oil, with a specific gravity of 1.086 and a pour point of 40°F, of which 91,500 gal were released and sank. The currents were quite strong, and because of the initial response focused on salvage of the barge and the remaining oil, no oil was recovered from the bottom. Some oil was observed to settle in the lee of the bow, but this pooled oil would be mobilized by the reversing tide, thus there was no significant accumulation on the bottom.

NOAA staff conducted experiments in a flume tank to observe the oil behavior in the water column and predict it's fate. They reported that the oil broke into small drops that did not adhere to the glass walls or recombine in the water column during mixing. Rather, they broke into smaller and smaller droplets which were predicted to disperse over a large area (J. Galt, NOAA, pers. comm.).

Bouchard 155, Tampa Bay, Florida, 1993

On August 10, 1993, a collision involving three vessels at the entrance to Tampa Bay, Florida resulted in the release of an estimated 325,000 gal of #6 fuel oil. The API gravity of the oil was between 10 and 11°, thus it was not a true Group V oil, as defined. The oil weathered on the water surface for nearly five days before it came ashore during a small storm. Cleanup efforts were successful in removing a significant amount of the floating oil slicks and oil stranded on the shoreline. However, thick mats of submerged oil were found in the nearshore subtidal habitats. This spill was a good example of the problems to be addressed in recovery of oil from the bottom.

Submerged oil occurred on the intertidal and shallow subtidal flats fronting a small island just inside an inlet. This oil was successfully removed using vacuum transfer units mounted on barges and grounded on the flat at low tide. However, removal rates were extremely slow, particularly where the oil had stranded in a mangrove forest.

Divers conducted surveys of the offshore areas along nearly six miles of shoreline and found mobile tarballs on the bottom with a frequency ranging from 1 per 10 square feet to 1 per 100 square feet. They also found a mat of submerged oil that was 150-200 feet long, 10-20 feet wide, and two inches thick. Three such mats were observed from aerial surveys. The volume of oily material in the mats was estimated to be 7,800 gal, although the oil contained 37-60 percent water. The oil contained about 2.6 percent sand by volume and had a density of 1.17 g/ml. Thus, it was determined that the oil sank because it had picked up sediment suspended in the water column or after stranding onshore. The submerged oil remained on the bottom and did not refloat. The submerged oil was highly viscous, with a consistency similar to peanut butter.

Attempts to remove the submerged offshore oil had very low success rates. Various vacuum-pumping strategies, including air injection, failed because of the high viscosity of the oil. Very large amounts of contaminated water were generated for very small amounts of oil recovered. Six possible removal techniques were evaluated, with manual removal determined the most feasible option for this spill (Michel and Benggio 1993). Manual removal of the submerged oil by divers was successfully conducted in a dead-end, seawalled bay. The offshore mats were not removed, and oil continued to wash ashore for at least six months following the spill.

Barge Morris J. Berman, San Juan, Puerto Rico, 1994

On January 7, 1994, the towline to the *Morris J. Berman* barge parted, and the barge grounded within a few hundred meters of shore off San Juan. The grounding resulted in the release of about 750,000 gal of a Group V fuel oil (API gravity of 9.5°). Although much of the oil floated, responders reported submerged oil within the first 24 hours, and eventually extensive amounts of submerged oil were found in both offshore areas and in sheltered bays. This submerged oil was not emulsified and remained fluid enough to flow (described as having the consistency of maple syrup). Over time, the submerged oil became more viscous and, in some areas, mixed with sediment. It also tended to refloat each afternoon, when the winds picked up. Where the water was very clear and shallow, the areas of submerged oil were readily located. Most of the identified patches were in protected lagoons, embayments, or on the landward side of reefs.

The submerged oil caused many difficult cleanup issues (Burns *et al*. in press). Shoreline cleanup could not be completed until the submerged oil was removed, because of the continued refloating of the submerged oil and re-oiling of the adjacent shoreline. Three different removal methods were used: diver-directed vacuuming of the more liquid oil; manual pickup by divers of the more viscous patches; and dredging. Although the submerged oil was being effectively removed by diver-directed vacuuming and manual pickup, the process was extremely slow. Because of the need to open the beaches as soon as possible, it was decided that both large and small dredges would be used to remove the oil more quickly. Dredges generate large amounts of contaminated water and sediment. Three settling pools were used to handle these volumes. Most of the oil separated from the sand during the dredging and pumping operations and re-floated in the pools where it was recovered. Fortunately, the submerged oil was close to shore and in very limited areas, so removal operations could be shore-based, greatly decreasing the logistics and costs. Even so, removal cost estimates as of June 1994, including divers, dredging, miscellaneous support, and treatment, but excluding disposal, totaled $8 million. About 145,000 gal of submerged oil were recovered, thus costs were about $55 per gallon of recovered oil.

BEHAVIORAL MODELS FOR SPILLED GROUP V FUEL OILS

Based on an understanding of the general physical and chemical properties of Group V fuel oils and observations during spills, the following behavioral models are proposed for spills of these types of oil. These are descriptive, qualitative models that attempt to predict how Group V fuel oils might behave when spilled in coastal settings. These predicted behavioral models for Group V fuel oil are used in the next section to assess the potential resources at risk during spills. Figure 3 shows schematic diagrams for each model.

Model 1: Oil Remains Liquid, Majority Floats

Under these conditions, a Group V fuel oil would behave in a manner similar to conventional #6 fuel oils. At 60°F, oils with an API gravity of about 6.5° would still be lighter than full-strength seawater. Many Group V fuel oils are likely to float and remain liquid during the early stages of a spill (Figure 3A). The light fractions will be lost by evaporation, and the floating oil will initially form contiguous slicks. Eventually the slicks will break up into widely scattered fields of pancakes and tarballs, which can persist over large distances and concentrate in convergence zones. Because of the higher viscosities of these oils, the tar balls may more persistent than expected for conventional #6 fuel oil spills.

Model 2: Oil Remains Liquid, Majority Does Not Float

In this case, the oil has a specific gravity greater than the receiving water. Some of the oil will float, but the majority will not. As the oil mixes in the water column, it will form small drops. When oil encounters water-wet surfaces, it generally will not stick, thus the oil is not expected to adhere to debris or vegetation in the water column. Where currents are greater than about 0.1 knots, the oil droplets will be kept in suspension (Figure 3C). An oil with an API gravity of 0.0° at 60°F has a specific gravity of 1.076, so even very heavy oils can be suspended by alongshore currents. Thus, in most nearshore coastal settings, the oil is not likely to accumulate on the bottom because the currents are strong enough to mobilize the oil. The size of the oil drops is likely to range from 0.5 microns to one millimeter or so. Weathering processes such as evaporation and photo-

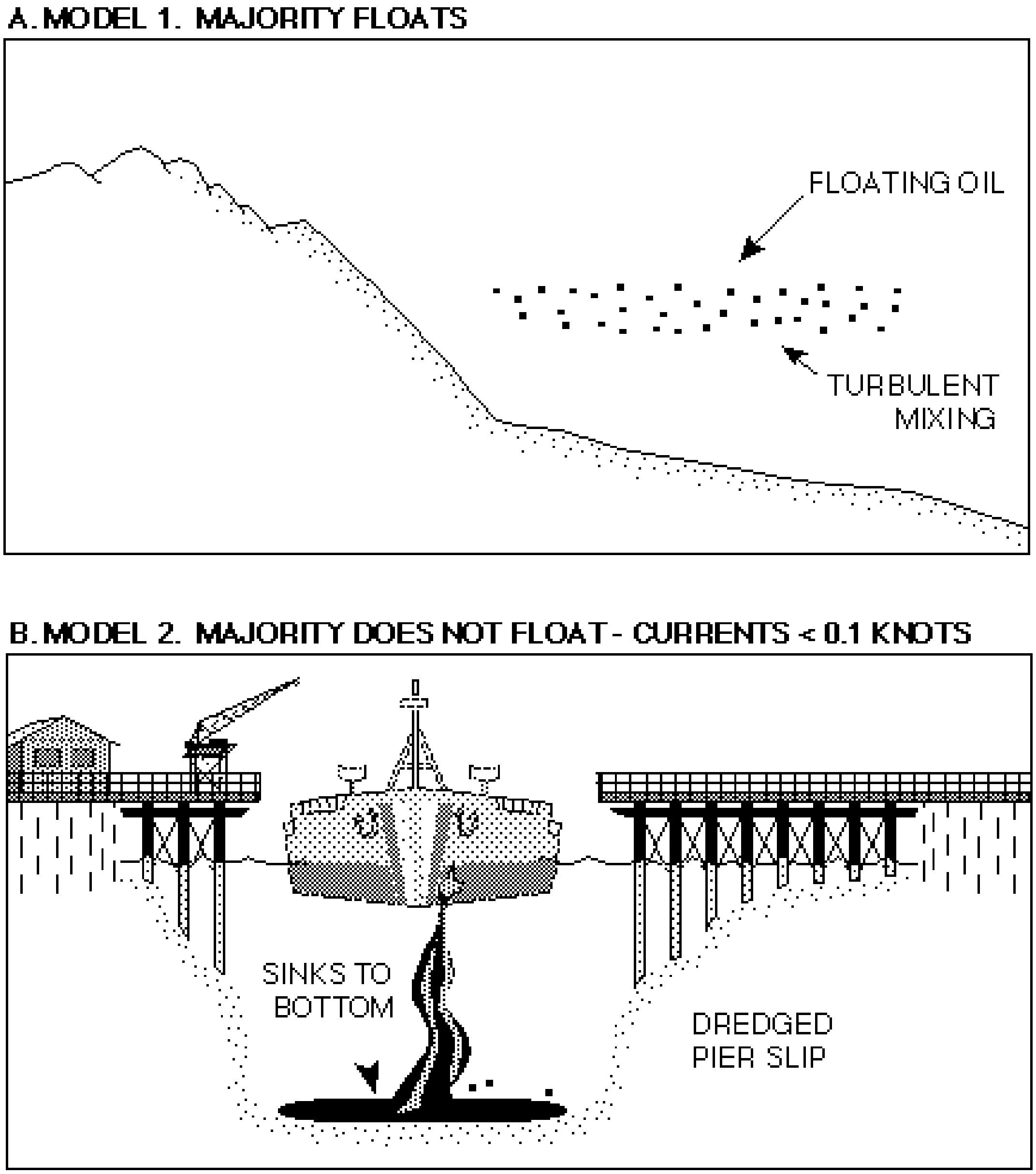
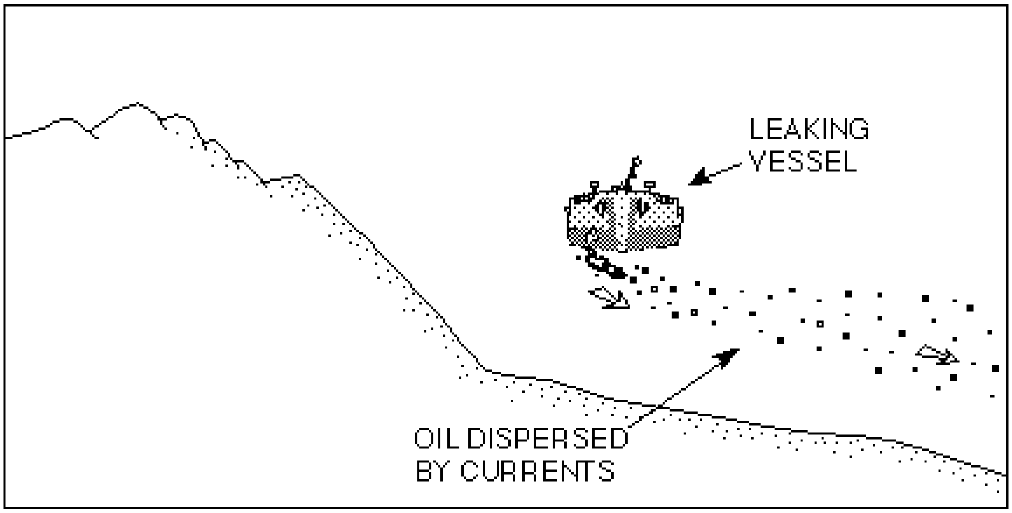
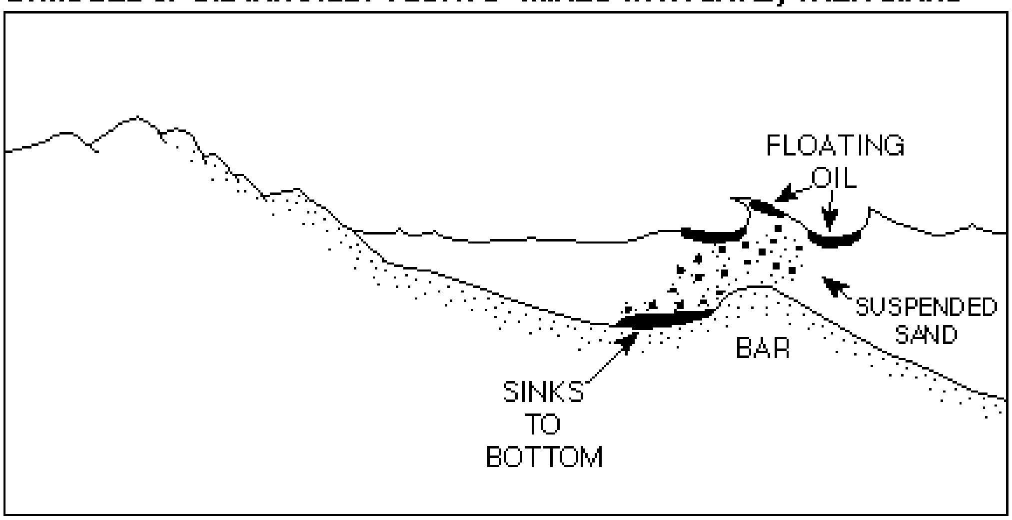


Figure 3. Model diagrams for how Group V fuel oils are predicted to behave when spilled. A. The majority of the oil initially floats, behaving like a traditional #6 fuel oil spill. B. The majority of the oil initially does not float; in the presence of currents greater than 0.1 knots, the oil forms small droplets that mix into the water column and disperse with the currents. C. The majority of the oil initially does not float; the oil only sinks and accumulates in depressions on the bottom in the absence of currents. D. The majority of the oil initially floats but eventually sinks after mixing with sand as both are suspended in the water by waves breaking on offshore sand bars or rocky platforms. E. The majority of the oil initially floats, but eventually sinks after the oil strands onshore, picks up sand, is eroded by waves, and forms tar mats at the toe of the beach or in nearshore troughs. Rollers of oil/sand are formed by wave-generated currents.

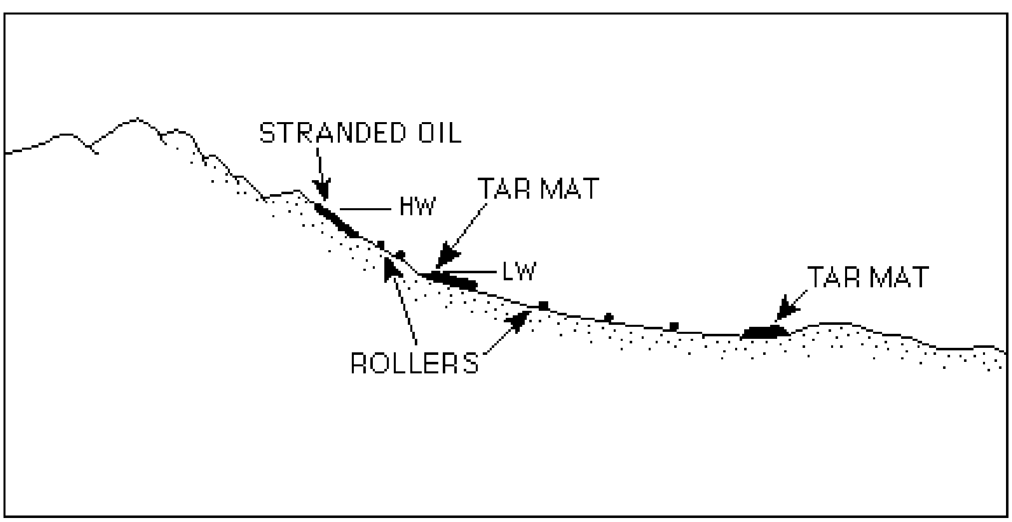
C. MODEL 2. MAJORITY DOES NOT FLOAT - CURRENTS > 0.1 KNOTS



D. MODEL 3. OIL INITIALLY FLOATS - MIXES WITH SAND, THEN SINKS



E. MODEL 3. OIL INITIALLY FLOATS - STRANDS ON BEACH - OIL/SEDIMENT MIXTURE TRANSPORTED TO NEARSHORE BOTTOM



oxidation will be slower relative to floating slicks, but the drops should eventually weather faster than floating tarballs because of their smaller size.

In low-flow zones (less than about 0.1 knots), the suspended oil could sink and accumulate on the bottom (Figure 3B). Direct sinking in low-flow areas was observed during the *Sansinena* and the *Mobiloil* spills. Thus, it is possible that suspended oil could settle out and accumulate in estuaries in locations similar to those where fine-grained sediments are deposited during slack periods of the tide. However, oil drops are expected to be readily remobilized by tidal currents, so long-term accumulation is likely only in areas little affected by tidal or riverine currents. Examples of such areas would include abandoned channels, dredged channels or pits, depressions adjacent to piers caused by prop wash of anchoring vessels, dead-end canals, and in the lee of manmade structures. If the oil does accumulate on the bottom, the oil drops will re-coalesce into pools of liquid oil, which can be up to feet thick, although it can also spread into a thin layer when there are no depressions.

Model 3: Oil Remains Liquid, Initially Floats, But Sinks After Picking Up Sand

This behavior was observed recently during the Tampa Bay and Puerto Rico spills. The oil behaves very much like a conventional #6 fuel oil at first, including rapid loss of the light fractions by evaporation and an increase in viscosity. However, when the oil is transported into shallow water, it is more likely to be temporarily mixed into the water column by wave turbulence because it is relatively heavy (Figure 3D). Where the bottom is sandy, the sand is also suspended in the water column by the waves, and some sand is mixed with the oil. The specific gravity of quartz is 2.65 and calcium carbonate is 2.71, so it only takes about 2-3 percent sand by weight mixed into oil with a specific gravity of 1.00 to make it heavier than seawater. The oil/sand mixture is deposited in relatively sheltered areas where it can form extensive, thick layers of oil on the bottom. In Puerto Rico, submerged oil was found in sheltered pockets in the lee of offshore rocks in an otherwise relatively high wave energy setting.

It appears that oil sinks in this manner only when it is mixed with sand (and not clay or silt). There have been several spills where oil has picked up sand after being stranded on sand beaches such as the IXTOC I (Gundlach *et al*. 1981) and *Alvenus* (J. Galt, NOAA, pers. comm.). After being eroded from the beach by wave action, the oil/sand mixture was deposited at the toe of the beach or just offshore in the form of tarmats (Figure 3E). However, the Tampa Bay and Puerto Rico spills were the first documented instances of oil sinking caused by oil mixing with sand in the surf zone, prior to contact with intertidal sediments on the shoreline.

Submerged oil can form thick, continuous deposits that are hundreds of feet long, or widely scattered small tarballs. Where there is current activity, especially generated by waves, the oil/sand mixture can form cigar-shaped "rollers" that can be scattered on the bottom or accumulated into mats. These rollers pick up more sand and shell fragments as they move, making them heavier. They can eventually be deposited on adjacent beaches after storms. The extent to which the oil weathers prior to sedimentation has a profound effect on the viscosity and character of the resulting oil/sediment mixture.

Submerged oil can refloat, as was observed during the Puerto Rico spill. There are two possible mechanisms for refloating: 1) the sand can separate from the oil and 2) wave-generated turbulence can loosen and resuspend pieces of oil from the bottom.

Summary of Group V Fuel Oil Behavior

Spills of Group V fuel oil can have complex behavioral patterns, depending on the API gravity of the oil, the homogeneity of the mixture, the density of the receiving water, and the physical setting of the spill site. Denser-than-water oil is expected to mix in the water column as oil drops rather than large, cohesive mats. Oil can accumulate on the bottom under calm currents, so releases of very heavy oil in harbors with dredged channels and berths in canals could readily sink and form pools of oil on the bottom. Releases in areas subject to tidal and riverine flow are likely to be kept in suspension in the water column by currents. If the oil is poorly mixed or unstable, the spill could separate into components that can float, suspend, and sink simultaneously. Therefore, it is more correct to consider these oils as *non-floating*, rather than *sinking*, oils. Loss of the light components through evaporation is not thought to be an important mechanism by which floating oil slicks eventually sink. Also, incorporation of sand, not silt or clay particles, makes these oils sink.

RESOURCES AT RISK

During a lighter-than-water petroleum spill, spill responders typically have to deal with recovery of floating oil slicks and shoreline cleanup. The focus is on the water surface and shoreline "bath-tub" ring; water column and benthic resources are usually considered to be at lesser risk of exposure and injury. Group V fuel oil spills may significantly change these risks. In this section, the predicted impact of Group V fuel oil spills are compared with those resulting from floating-oil spills for shoreline and benthic habitats and major assemblages of fish and wildlife.

Shoreline Habitats

Marine and Estuarine

Salt marshes and mangroves are highly susceptible to oiling impacts from traditional oil spills. Floating oil slicks readily adhere to the vegetation, whereas oil stranded on the substrate tends to be lifted off the water-saturated sediments by rising tides. Floating and neutrally buoyant Group V fuel oils could pick up enough sediment in the marshes and mangroves to accumulate on the sediment surface and not re-float during high tide. Efforts to remove oil stranded on soft, muddy, vegetated sediments would likely cause extensive additional disruption of roots, mix oil deeper into the sediments, and prolong recovery. Oil effects in marshes and mangroves are greatest for spills where the sediments have been contaminated (Michel and Hayes 1992).

Marshes and mangroves are often associated with tidal flats, both exposed and sheltered. Many species of larval fish, shellfish, bivalves, gastropods, and other invertebrates are obligate inhabitants of tidal flats. Floating oil slicks are usually lifted off tidal flats with the rising tide. Group V fuel oil could strand on the flats during low water and pick up enough sediment to prevent re-floating. Weathered oil is also likely to be very viscous and strand in thicker deposits or globules; these larger oil deposits would be more resistant to natural removal. As a result, stranded Group V fuel oil on tidal flats may be more persistent and result in higher impacts to tidal flats and the animals associated with them. Stranded oil could be removed from sandy tidal flats, although there is a high likelihood that some oil would be mixed deeper into the sediment by foot traffic. Removal of heavy, viscous oil from soft, muddy flats would be extremely difficult, and natural removal rates very slow. Thus, impacts to animals and plants using these habitats could be more likely.

Gravel beaches and riprap structures have been shown to accumulate oil, often to depths exceeding one meter (Hayes *et al*. 1990). Fresh oil often penetrates the large interstitial spaces and fills the voids, thus providing a source of long-term contamination to intertidal and near-shore subtidal biota. With Group V fuel oils, thick coating of the individual clasts is expected. It is predicted that there will be less penetration of Group V fuel oil into the sediments because of its increased viscosity. In these habitats, Group V fuel oil is not expected to behave much differently than a typical #6 fuel oil. However, gravel beaches and riprap structures are extremely difficult to clean. As was determined during the *Exxon Valdez* cleanup, surface cleanup can be accomplished through various methods (Michel and Hayes 1993), but the only effective way to treat persistent subsurface oiling is through sediment reworking, or removal and replacement—a very costly endeavor in terms of actual dollars and to the habitat and those species that use it.

On sand beaches and mixed sand and gravel beaches, oil will accumulate along the high tide swash line, and under heavy oiling conditions, the entire beach face can be covered. However, there is little oil penetration into the sediments, usually to depths less than 25 cm. In areas undergoing beach accretion, stranded oil can be rapidly buried by clean layers of sand. A Group V fuel oil spill is unlikely to significantly alter the oiling of these habitats, although the depth of penetration of more viscous oils into the sediments is likely to be reduced. As a result, cleanup can be relatively easy—mechanical and manual cleaning of these beaches is often logistically feasible. Oil that has sunk offshore could provide a source of long-term re-oiling of cleaned beaches.

Coastal structures include exposed and sheltered man-made structures like seawalls, bulkheads, and piers. Oiling of these structures usually takes the form of a continuous band of oil along the high-tide line. Oiling effects from Group V fuel oils are unlikely to differ significantly from spills of other oils; coating of these coastal structures may be thicker and may occur throughout the intertidal and subtidal zone, but response operations are unlikely to be significantly altered. In exposed settings, cleanup is not necessary except in areas where it is required for aesthetic reasons. For these areas, high-pressure, hot-water washing is often used.

Freshwater

Many of the riverine and lacustrine environments in the U.S. have extensive freshwater marshes and swamps associated with them. There is less likelihood of oil penetrating deep into freshwater wetlands from oil spills in lakes because of stable water currents and only small changes in water level under normal conditions. For spills in a riverine environment, heavy oil contamination typically occurs along the wetland fringe, in side channels with significant river flow, and in river bends (point bars) where the oil may accumulate. However, only during high-water conditions would there be enough current to transport the oil into the wetland more than a meter or so. Spills of Group V fuel oil are unlikely to significantly alter the extent of injury to freshwater marshes and swamps. However, Group V fuel oil is much more likely to sink in freshwater. In areas of low flow and natural collection sites, non-floating Group V fuel oil would tend to accumulate. Tracking sunken oil in riverine and lacustrine environments will be difficult because of poor water visibility. Under weak currents, the oil would be less likely to spread, so the effects would be very localized.

The bottomland hardwood forests that often border rivers and lakes are considered least at risk from exposure to Group V fuel oil spills. For the most part, the plants associated with this habitat have deep root systems. Any coating of the exposed portion of these plants is unlikely to result in injury other than stress. If the leaf matter is coated, the plant's photosynthetic abilities could be impaired, resulting in defoliation of the affected areas on the plants.

Benthic Habitats

Submerged Aquatic Vegetation

Submerged aquatic vegetation beds are important primary producers and nursery habitats (DeMort 1991). Wigeon grass, eel grass, and turtle grass are several of the more common species in habitats in the nearshore environment of the Atlantic coast of the U.S. During most oil spills, seagrass habitats are not generally considered to be at great risk, unless the beds are intertidal. However, based on observations of submerged and neutrally buoyant oil in seagrass habitats at the recent San Juan, Puerto Rico oil spill, non-floating Group V fuel oil spills are likely to: readily adhere to the seagrass blades; affect the animals and plants that are associated with the vegetation; become buried in areas exposed to some currents and mobile, sandy substrates; and be a long-term source of shoreline contamination as the submerged oil is re-floated when disturbed or warmed.

Biological Resources at Risk

Many of the resources considered to be at risk from exposure to Group V fuel oils are the animals themselves. Many species utilize multiple habitats, and therefore can be associated with particular habitats during different life stages. The various factors that are important to each species are discussed in terms of preferred habitat and life-stage data. The general species categories considered at risk include birds, fish, shellfish, reptiles, and marine mammals.

Birds

U.S. waters and waterways are host to numerous bird species, including the general categories of seabirds, shorebirds, wading birds, waterfowl, gulls and terns, raptors, and songbirds. In general, the degree and extent of injury from exposure to Group V fuel oil is dependent on each species' feeding and nesting behavior (RPI 1988).

Shorebirds (e.g., oyster-catchers, plovers) and wading birds (e.g., herons, egrets, wood storks) forage at the water's edge and in wetlands. Historically, these birds have been only moderately affected during oil spills because they do not tend to immerse their bodies in water. Oil can cause loss of their preferred prey items, and external coating of legs, feet, and bills during foraging efforts. Effects on these birds from Group V fuel oil spills are likely to be similar to a No. 6 fuel oil spill, or even lower if most of the oil sinks. The only increase in impact may be where a Group V fuel oil spill contaminates the sediments on tidal flats where the birds rest or forage.

Waterfowl, gulls and terns, and seabirds, by their very nature, are likely to be affected by floating Group V fuel oil in ways expected during usual oil spills. These birds are closely associated with the water surface in feeding and resting activities and, as such, there is the potential for these birds to become oiled and die from hypothermia or loss of buoyancy (RPI, 1988). It is not known whether these birds experience additional oil exposure when diving for prey if the oil is mostly mixed into the water column and not floating on the water surface. Suspended oil is not expected to be sticky but some birds spend so much time underwater searching for food (e.g., cormorants) that they may have some risk of exposure. In general, however, oil-related impacts to water birds are likely to reduced for non-floating oils.

The bald eagle, osprey, and peregrine falcon are common raptors found nesting and foraging throughout the coastal zone. Osprey are at risk of being directly oiled because they feed on live fish; eagles and falcons are subject to secondary contamination through the consumption of oiled food, such as dead, oiled birds or rodents. Group V fuel oil spills are thought to pose no additional risks to raptors; rather, they are likely to be reduced because of the fewer number of oiled birds in the impact zone.

Fish

Floating oil spills usually have limited impacts on adult and juvenile fish, as most oils have very low water-soluble fractions, and the mobile fish are able to avoid petroleum products (NAS 1985). Larval stages that float at or close to the water surface are at greatest risk. Non-floating oil spills are likely to have significantly *different* impacts to fish. Sinking oil can smother and kill bottom feeders and their food, though impacts are likely to be localized. In addition, oils that quickly sink or suspend in the water column could have greater impacts to water-column organisms because more of the water-soluble fraction of the oil could actually dissolve rather than be lost by evaporation, which usually is the dominant process for floating slicks. During the Puerto Rico spill, diving scientists observed dead fish, living fish with lesions and tumors, and many lethargic nearshore, territorial fish in nearshore waters adjacent to the point of oil release (Vincente 1994). Mobile species may be able to move to uncontaminated areas, thus reducing these impacts.

Group V fuel oil is often high in aromatics, which are the primary source of both acute and chronic toxicity to aquatic organisms. The naphthalene compounds, which are two-ringed aromatics, have been shown to be more toxic than the light-weight aromatics such as benzene and toluene (Anderson *et al*. 1987). If only the water-soluble fraction is considered, bunker C is rated as toxic as diesel (Markarian *et al*. 1993). Thus, even though heavy residual oils are not usually considered to be acutely toxic to fish, spills that mix into the water column without first weathering (by evaporation) on the water surface may increase the amount of oil that dissolves and the acute toxicity to fish.

Shellfish

Various species of shrimp, crab, lobster, clams, oysters, scallops and other important gastropods and cephalopod molluscs are found in coastal waters. Most adult and juvenile shellfish are primarily bottom dwellers that scavenge the substrate or filter the overlying waters for food items. Floating oil spills usually have limited impacts to these organisms (RPI 1989b). In contrast, sinking and neutrally buoyant Group V fuel oil spills are expected to have direct impacts to crabs and shrimp, as well as clams, oysters and other molluscs due to both acute toxicity and tainting of the flesh. The aquatic toxicity of oil to shrimp is closely related to the naphthalene content (Anderson *et al*. 1987), so any process that tends to increase the amounts of these compounds in the water would also increase the impacts to shrimp.

There have been multiple spills of heavy oil that sank in the Delaware River where oiled crabs were found in crab pots many miles downstream of the spill. Crabs and shrimp are described as "opportunistic omnivores" (Lassuy 1983; Perry and McIlwain 1986), meaning that they eat almost anything they can catch, and they will attempt to feed on oil, oiled prey, and oiled sediments. Thus, even though heavy oils are not normally considered to be biologically available to most marine organisms, crab and shrimp may be more susceptible than other organisms because of their benthic scavenging habits.

Reptiles

Within coastal waters, sea turtles, alligators, crocodiles, and terrestrial turtles have the potential to be affected by Group V fuel oil spills in their preferred habitats. Many exposed beaches along the Gulf and Atlantic coasts of the U.S. are nesting beaches for loggerhead turtles in spring and summer. Other turtle species which may be encountered less frequently include green turtles, hawksbill turtles, Atlantic Ridley's turtles, and leatherback turtles (SJRWMD 1993). It is assumed that offshore Group V fuel oil spills are likely to be difficult to recover and thus generate persistent tarballs that could eventually concentrate in convergence zones where turtles also concentrate to feed. Thus, adult and juvenile turtles are more likely to be affected by floating Group V fuel oil spills through ingestion of tarballs, having tarballs stuck in their mouths, and/or having tarballs adhering to their flippers and shells (Vargo *et al.* 1986) because of the higher persistence of the tarballs.

Group V fuel oil stranded on sand beaches is less likely to penetrate the sand than more fluid oil because of its viscosity. However, oil that sank offshore could provide a source of episodic oiling during the nesting season as the submerged oil is re-mobilized during storms, weeks to months after cleanup of stranded oil was completed. Also, juvenile sea turtles are known feed on crabs and other benthic inhabitants of the nearshore zone, making them susceptible to bottom oil in the form of tar balls, rollers, and submerged mats.

Although American alligators, crocodiles, and endangered terrestrial turtles use both the water surface and the water column, impacts from a spill of Group V fuel oil are not likely to be much different than usual oil spills.

Marine and Terrestrial Mammals

There are numerous species of marine mammals that may be affected by an oil spill, including baleen whales, toothed whales, dolphins, porpoise, walrus, sea lions, seals, sea otters, and manatees. In the terrestrial environment, large rodents, river otter, and other small mammals could also be affected by a spill of petroleum products in inland waterways. The effect of spilled oil depends largely on the individual species thermoregulatory process, the amount of time the animals are associated with the water surface, and their dietary requirements. Marine and terrestrial mammals are likely to be impacted by spilled oil in four ways: direct surface fouling; inhalation; ingestion; and the direct disturbance to the animals due to the presence of cleanup workers.

In general, whales, dolphins, porpoises, manatees, walrus, and sea lions are largely unaffected by spilled petroleum products. These mammals have thick blubber layers for insulative purposes—a surface coating of oil would be more of an irritant than life-threatening. Typical injuries to these mammals is thought to include irritation of mucosal membranes of the nose and mouth from volatile fractions, and coating of the mouth and flippers through contact during feeding activities (RPI 1989a; Geraci 1990; St. Aubin and Lounsbury 1990). Heavy oils have little volatile fractions so the risk of exposure via inhalation would be reduced. Suspended oil is not likely to adhere to these animals, so the only route of concern would be through ingestion of oil in their food. It is unlikely that the concentrations of fish or plankton in an area affected by suspended oil would be high enough to induce feeding by marine mammals.

The furred mammals, such as the furred seals, sea otters, and terrestrial mammals are more at risk to oil impacts because their fur coat is the basis for their thermoregulatory systems. Oiling of their coats results in increased metabolism as their bodies try to counteract the reduction in their thermoregulatory system effectiveness. If oiled, furred mammals can ingest oil while trying to clean their coat and burn up their energy reserves in order to regulate their body temperatures, while ignoring foraging efforts (St. Aubin 1990a; 1990b; Geraci and Williams 1990). In most cases, impacts to these animals would be reduced for non-floating oil spills, when less oil was on the water surface or likely to strand on haul outs and pupping sites. However, sunken oil would be less weathered, persistent, and more likely to come in contact with animals when they are resting and feeding on the bottom. During foraging efforts, the eyes, nose, mouths, and paws or flippers of these mammals could become coated in ways typically not incurred from spills of floating oils, primarily if tar mats were to accumulate in their preferred feeding areas. Over time, the mats do weather and the oil can become sticky.

RESPONSE ISSUES FOR LOCATION, CONTAINMENT, AND RECOVERY

Location

Spills of Group V fuel oils that sink or become neutrally buoyant are likely to be difficult to locate and assess. The options for locating sunken oil include aerial observations in clear water, diver transects, underwater video, and sonar equipment. All remote observations have to be verified with diver surveys. Diving conditions can be very difficult because the divers are likely to become heavily contaminated from oil in the water column and re-suspended from the bottom. During the *Morris J. Berman* spill in Puerto Rico, divers had to undergo extensive decontamination after each assessment and removal dive. There are no proven techniques for locating the oil that is neutrally buoyant and suspended in the water column.

Containment

Historically, sunken oil was not actually contained but instead tended to accumulate in natural collection areas. Any oil that was mobilized by currents was not contained. Although bottom booms have been proposed, it is not likely that they will be effective in any kind of bottom currents, or even properly deployed on the bottom in an effective location. Realistically, the only likely containment of sinking oil will occur naturally as the oil accumulates in low areas on the bottom at the spill site.

Containment of oil that is suspended or mixed into the water column is feasible only where the currents are very weak. Options include silt curtains or fine-mesh nets coupled with a surface boom to contain the floating or re-floating fraction of the oil. The only known case where this kind of curtain boom was used was in Louisiana to isolate leaking, abandoned barges in a dead-end canal (M. Barnhill, NOAA, pers. comm.). The use of the curtain boom was successful until local vessel traffic disrupted it. Use of silt curtains may be promising. However, contractors experienced in the proper deployment and maintenance of the equipment would be required. It should be noted that effectiveness would drop rapidly with any currents. Fishing nets could be attached to floating booms on the surface and heavy weights along the bottom. It would be difficult to modify existing rigging into an effective containment system.

Recovery

Recovery of sunken oil has proven to be very difficult and expensive. During the Tampa Bay oil spill, various options for recovery of the submerged oil were researched and evaluated (Michel and Benggio 1993). Options included and discussed below are:

- Manual removal by divers
- Removal by diver-directed pump and vacuum systems
- Dredging
- Use of robotic pumping systems

Manual removal involves the collection of the oil by divers into bags or containers. The advantages of manual removal are:

1. The volume of material removed is the lowest of all options. Little additional water or sediment would be removed, thus there will be no need to treat oily water or dispose of large amounts of oiled sediment.
2. Divers will be able to pick up relatively small pieces, which may be widely scattered over large areas.
3. The recovered oil can be placed directly into suitable containers for disposal. There would be less need for intermediate storage or transfers.

The biggest disadvantage of manual removal is the slow rate of recovery. The potential for the oil to spread to other areas may force a more rapid recovery strategy.

Removal by pump and vacuum systems have historically been the most successful removal strategy for sunken oil. Such systems can include vacuum trucks, units mounted on barges, and submersible pumps. They often are diver-directed and the suction head modified so that the diver manually opens and closes the valve. The oil must be liquid to be pumped. Because large volumes of oily water are generated, there must be facilities for oil/water separation and discharge of the separated water back into the water. Separation can be very problematic for some Group V fuel oils, especially when they are heavier than water and only part of the oil tends to re-float. During the *Morris J. Berman* spill, vacuum removal was effective but very slow.

Dredging is the fastest method for removing sunken oil from the bottom, but is likely to generate very large volumes of oily water and sediment that must then be handled, treated, and disposed of. Pumping rates of 1,000 gallons-per-minute are typical of small dredges. Even under careful control, dredges often remove the top 0.5 m of material, removing and contaminating a large amount of clean sediment. Logistics and costs are reduced if the material can be handled on land, compared to using barges or temporary storage and separation. Time can be of concern because oil that is still fluid could be re-mobilized by storm waves, increased river flow following heavy rains, or ship traffic.

Recovery of oil that is suspended in the water column poses the most difficult challenge. Fish nets have not been very successful for recovery of firm tarballs; they are likely to be even less effective with liquid oil droplets. The net mesh size would have to be matched to the droplet size. Heavy accumulations would clog the nets, resulting in breakage or failure. Liquid oil would drain from the nets as they were lifted from the water. The nets could be used only once, then disposed of. During the Puerto Rico spill, strings of snare were tied to lines throughout the water column to recover oil resuspended during dredging operations in the quiet lagoon.

Another important consideration is that the contractors involved in location, containment, and recovery phases of the cleanup of Group V fuel oil spills must meet all federal training requirements for workers and supervisors involved in hazardous material operations.

CONCLUSIONS

Because Group V fuel oil can float, sink, become neutrally buoyant, or separate and possess all three characteristics, it poses significantly greater risks to natural resources, compared to floating oil spills, for the following reasons:

1. Neutrally buoyant or sinking Group V fuel oil weathers very slowly by evaporation, a process which tends to remove the more toxic fractions from floating oil slicks and greatly reduces the acute toxicity of the spilled oil. As a result, the toxic components of a Group V fuel oil spill can be introduced directly into the water column at concentrations greater than traditional spills. Animals in the water column, such as fish, shellfish, and marine mammals, can be exposed to these higher concentrations.
2. Group V fuel oil that is denser than the receiving waters is not expected to sink immediately to the bottom and remain there. More likely, it will be suspended in the water column by tidal or riverine currents. Accumulation of oil on the bottom is expected only in depressions or zones of low flow, such as dredged channels, dead-end waterways, abandoned channels, or protected bays and lagoons.
3. Benthic organisms are seldom at risk from traditional oil spills. However, with heavier-than-water spills, additional impacts to benthic resources are likely to occur from smothering as well as increased exposure to residual oil that was not recovered. As a corollary, impacts to shoreline habitats and animals that use both the shoreline and water surface should be less from sinking oils.
4. Containment and removal efforts for sinking oil will have low effectiveness. As experienced during the Puerto Rico oil spill, removing submerged oil is very slow and usually generates large volumes of contaminated water and sediment. In fact, removal of the submerged oil in Puerto Rico was conducted only where the oil was contained by natural or existing features. Oil sank in other areas, but tidal currents dispersed the oil over large areas, making it impractical to recover.
5. Containment and removal efforts for neutrally buoyant oil will likely be ineffective. There are no proven techniques for containing oil in the water column, or for removing oil from large volumes of water.
6. Even standard techniques for location, containment, and recovery will fail unless they are conducted by contractors experienced in the proper deployment and maintenance of the equipment and the special requirements of oil-spill response.

A spill of Group V fuel oil is not likely to affect any one resource of special importance. The potential for a widespread presence of spilled Group V fuel oil on the water surface, in the water column, and on the bottom will tend to affect the entire range of resources (e.g., fish, shellfish, marine mammals, birds, etc.). Additional injuries to fishery and shellfish resources are more likely to occur. Present response technology is ill-equipped to deal with the potential water-column and benthic habitat impacts from a spill of Group V fuel oil.

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