Sunken Oil Detection and Recovery

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Executive Summary

Most oil spill response strategies, tactics, and equipment are based on the simple principle that oil floats. However, oil does not always float. Sometimes it suspends in the water column; sometimes it sinks to the bottom. Sometimes it does all three: floats, suspends, and sinks. Furthermore, oil that has sunk to the bottom can become re-suspended and spread by currents. Terminology to describe these various behaviors can be confusing; thus, in this report, the following terminology is used.

— **Floating oil.** Spilled oil that is on the surface of the water.

— **Submerged oil.** Spilled oil that is in the water column, below the water surface, including oil that is in temporary suspension due to turbulence and will refloat or sink in the absence of that turbulence.

— **Sunken oil.** Spilled oil that is on the bottom of the water body.

This report addresses only sunken oil.

This report identifies and documents current best practices and alternative technologies to more effectively detect, delineate, characterize, contain, and recover sunken oil. For each technology, it includes a detailed description of the method, advantages, and disadvantages, and summary tables–the kinds of information needed to select the most effective approaches to sunken oil detection and recovery. There is a companion Operational Guide that includes decision support tools to assist responders in the selection of the most appropriate tactics for sunken oil detection, delineation, and characterization, and then recovery, depending on the spill conditions.

There are ten sections to this report:

Section 1: Introduction, Purpose, and Background

This section introduces the topic and states the purpose, which is to:

— identify and document current best practices and proven technologies possessing the potential to more effectively 1) detect, delineate, and characterize, 2) contain, and 3) recover sunken oil, defined as the accumulation of bulk oil on the bottom of a water body; and

— recommend research and development for the highest potential new technologies.

This report builds on all previous works, as well as recent spill experiences and testing of new technologies, to support improved spill planning, preparedness, and response. The goals are to 1) present the technical background in this technical report for planning and training, and 2) provide a more operationally effective decision support guide to be used during emergency responses.

Section 2: Sunken Oil

This section provides guidance on when to expect spilled oil to sink, either initially or later due to processes such as weathering and sediment interactions. It includes a chart to help determine if the oil can sink initially based on its density or API gravity and the salinity of the receiving water. It also includes a chart that shows how turbulence and sediment interaction can cause a floating oil to submerge or sink over time. Summaries for 38 spills, where a significant amount of the oil sank or submerged, describe the conditions of the spill, the methods used to detect and recover the sunken oil, and lessons learned.

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Section 3: Techniques for Sunken Oil Detection, Delineation, and Characterization

The following techniques for sunken oil detection, delineation, and characterization are discussed in this section: 1) sonar systems; 2) underwater visualization systems; 3) diver observations; 4) sorbents; 5) laser fluorosensors; 6) visual observations by trained observers; 7) bottom sampling; and 7) water-column sampling. For each technique, the advantages and disadvantages are summarized. The uses and limitations of all sunken oil detection, delineation, and characterization techniques are summarized, and a matrix is provided to assist in evaluation of detection techniques for specific spill conditions. There is also a section on considerations for sunken oil detection in rivers and under extreme cold conditions.

It is important to note that oftentimes multiple detection, delineation, and characterization methods should be used, in combination and/or in sequence. All remote detection methods require ground truthing, or need bottom sampling to determine the oil thickness on the bottom or determine the oil's viscosity and thus pumpability.

Section 4: Techniques for Sunken Oil Containment

This section is very short–because there are few proven methods to prevent the remobilization of sunken oil on the bottom when turbulence and currents increase. The results of the many methods attempted to prevent the spread of oiled sediments during the response to the 2010 Enbridge Pipeline spill in the Kalamazoo River are summarized, although it is important to note that this spill, like all spills, represents just one set of conditions. Research and development are needed to determine if there are effective methods to contain sunken oil for a range of spill conditions.

Section 5: Techniques for Sunken Oil Recovery

The following techniques for sunken oil recovery are discussed in this section: 1) suction dredge; 2) diver-directed pumping and vacuuming; 3) mechanical removal; 4) sorbent/V-SORs; 5) trawls and nets; 6) manual removal; and 7) agitation/refloat. For each technique, the advantages and disadvantages are summarized. The uses and limitations of all sunken oil recovery techniques are summarized, and a matrix is provided to assist in evaluation of recovery techniques for specific spill conditions. There is also a section on considerations for sunken oil recovery in rivers and extreme cold conditions.

It is important to emphasize that, because sunken oil often becomes mobilized during a response, recovery of sunken oil must be closely coupled with detection to increase overall effectiveness.

Section 6: Diving in Contaminated Water

Commercial divers often play a critical role in the success of sunken oil detection, delineation, characterization, and recovery operations, and diver safety is of paramount importance. This section summarizes the regulatory requirements for dive operations in contaminated water and safety checklists.

Section 7: Waste Stream Management

Waste generation during sunken oil recovery operations is a very important consideration in both the selection of the removal method and the types of waste stream treatment methods to be implemented. This section provides guidance on best practices for handling the oil, liquids, and solids generated during a sunken oil response.

Section 8: Government Regulations to be Considered

This section briefly outlines the state and federal government regulations that may apply to sunken oil response actions, such as protection of cultural resources, species listed under the Endangered Species Act, and permitting for dredging.

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Section 9: Research and Development Recommendations

This section includes recommendations for research and development to advance the state of the practice in sunken oil response.

Section 10: Literature Cited and Suggested Readings

This section includes all of the references cited in the report and suggested further readings.

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Acronyms and Abbreviations

ACP	Area Contingency Plan
ADCI	Association of Diving Contractors International
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
AWI	annular water injection
AUV	autonomous underwater vehicle
bbl	barrel
BTEX	benzene, toluene, ethylbenzene, and toluene
cm	centimeter
DGPS	Differential Global Positioning System
DMT	Diving Medical Technician
EFH	Essential Fish Habitat
ESA	Endangered Species Act
FOSC	Federal On Scene Coordinator
fsw	feet of salt water
ft	feet
g	gram
GPS	Global Positioning System
HAZWOPER	Hazardous Waste Operations and Emergency Response
IMCA	International Marine Contractors Association
IPIECA	the global oil and gas industry association for environmental and social issues
JHA	job hazard analysis
kHz	kilohertz
m	meter
NHPA	National Historic Preservation Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
OSHA	Occupational Safety and Health Administration
PAH	polyaromatic hydrocarbons
ppb	parts per billion
ppm	parts per million
PVHO	pressure vessels for human occupancy
ROV	remotely operated vehicle
SCAT	Shoreline Cleanup Assessment Technique
SCUBA	Self Contained Underwater Breathing Apparatus
SHPO	State Historic Preservation Officer
SIT	Silicon Intensified Target
SOM	submerged oil mat

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THPO	Tribal Historic Preservation Officer
UIS	Underwater Inspection System
USCG	U.S. Coast Guard
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USN	U.S. Navy
UV	ultraviolet
V-SORs	Vessel Submerged Oil Recovery System
VTU	vacuum transfer unit
yd	yard

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Sunken Oil Detection and Recovery

1 Introduction

1.1 Purpose of this Report

The purpose of this report is to:

— identify and document current best practices and proven technologies possessing the potential to more effectively 1) detect, delineate, and characterize, 2) contain, and 3) recover sunken oil, defined as the accumulation of bulk oil on the bottom of a water body; and

— recommend research and development for the highest potential new technologies.

A companion document (API Report 1154-2, 2016) is an Operational Guide that includes decision support tools to assist responders in the selection of the most appropriate tactics for sunken oil detection, delineation, and characterization, and then recovery, depending on the spill conditions.

It is important to note that the majority of oils that are spilled float. If and when spilled oil does sink, then the ability to detect, delineate, characterize, contain, and recover that oil becomes significantly more difficult, compared to floating oil spills. Hence, the need for these two reports to improve responses spills where a significant amount of the oil sinks.

1.2 Background

Most spill response plans are based on the assumption that oil will float when released to water. And most oil spills do just that. However, there are oil types and spill conditions where a significant amount of the spilled oil will not float, requiring a vastly different response approach for all phases of the response.

Starting in the 1990s, there were several efforts to compile what was known about these kinds of spills. There was a session at the 1995 International Oil Spill Conference entitled: “Low API Gravity Oils, Response to Oils that Sink,” with papers by Burns et al., Castle et al., Michel et al., and Michel and Galt. The National Academies convened a committee that published a report in 1999 entitled: “Nonfloating Oils: Risk and Response” (NRC, 1999). Triggered by spills of heavy oils from ships, such as the T/V *Nakhodka* in Japan, the T/V *Erika* off the coast of Brittany, and the T/V *Baltic Carrier* in the Baltic Sea, the Third R&D Forum on High Density Oil Spill Response was convened in Brest, France (International Maritime Organization, 2002).

After the M/T *Athos I* spill in the Delaware River in 2004 and the T/B *DBL-152* spill in 2005 in the Gulf of Mexico, both at which the oil sank and posed significant response challenges, the U.S. Coast Guard Research and Development Center commissioned a current state analysis of methods for the assessment and recovery of submerged oil (Michel, 2006). At a workshop at the Coastal Research and Response Center at the University of New Hampshire, research needs were identified (CRRC, 2007). These two reports were used to develop a multi-year studies program to identify and pilot-test innovative technologies for the detection of oil in the water column and detection and recovery of sunken oil on the bottom (Hansen et al., 2009; Fitzpatrick and Tebeau, 2013; Fitzpatrick et al., 2013).

There have been several international efforts to compile the state of the knowledge of sunken and submerged oil and produce manuals and operational guidance for assessment and removal technologies, including ASMA (2007), Rymell (2009), and International Maritime Organization (2012).

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These new documents build on these previous works, as well as recent spill experiences and testing of new technologies, to support improved spill planning, preparedness, and response. The goals are to:

1) present the technical background in this technical report for planning and training; and

2) provide a more operationally effective decision support tool to be used during emergency responses.

2 Sunken Oil

2.1 Definitions and Properties

Most oil spill response strategies, tactics, and equipment are based on the simple principle that oil floats. However, oil does not always float. Occasionally it suspends in the water column or sinks to the bottom of the waterbody, or does all three: floats, suspends, and sinks. Furthermore, oil that has sunk to the bottom can become re-suspended by an increase in turbulence and spread by currents. Terminology to describe these various behaviors can be confusing; thus, in this guide, the following terminology is used.

— **Floating oil.** Spilled oil that is on the surface of the water.

— **Submerged oil.** Spilled oil that is in the water column, below the water surface, including oil that is in temporary suspension due to turbulence and will refloat or sink in the absence of that turbulence.

— **Sunken oil.** Spilled oil that is on the bottom of the water body.

This guide addresses only sunken oil.

2.2 Conditions for Oil Sinking to the Bottom

Four factors control whether or not spilled oil will float, submerge, or sink:

1) The initial density of the oil relative to that of the receiving water

2) Water turbulence, generated by waves and/or currents

3) Sediment interactions

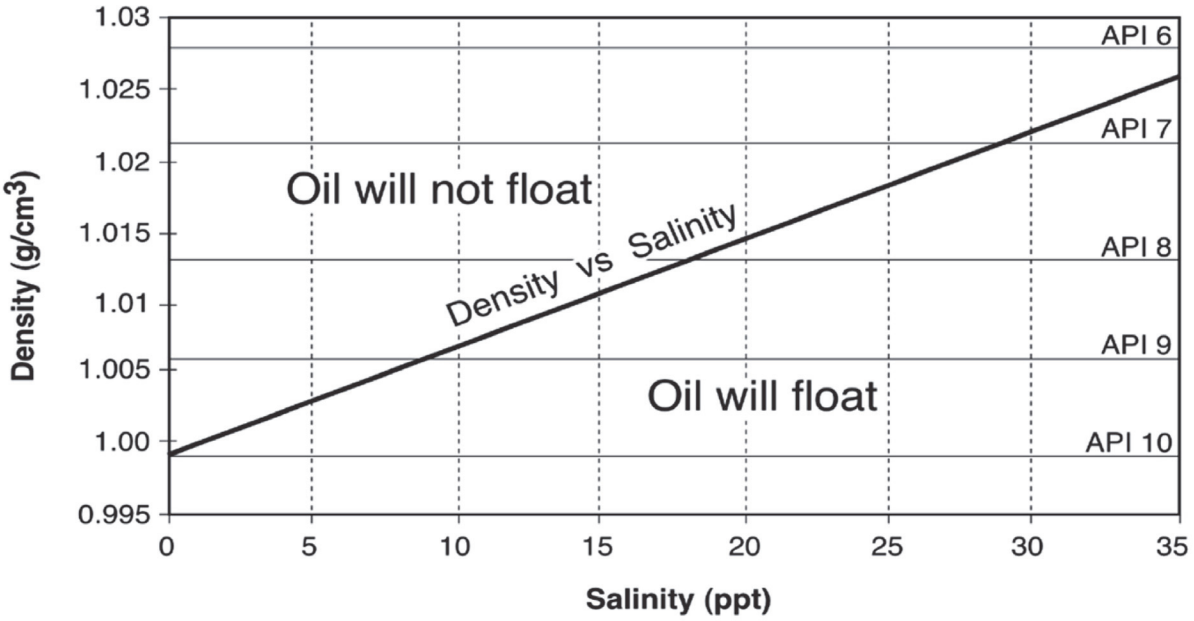
4) Density changes as the oil weathers

The initial density or API gravity of the oil relative to the density of the receiving water determines whether or not the oil will initially float. Figure 2-1 shows the relationship between an oil's density or API gravity and the salinity or density of the receiving water. In fresh water, at a temperature of 60°F, oils with a density less than 0.997 grams per cubic centimeter (g/cm^3) or API gravity greater than 10 will float initially. In sea water, at a temperature of 60°F, oils with a density less than 1.023 g/cm^3 or API gravity greater than 6.7 will float initially.

NOTE Specific gravity for API calculations is always determined at 60°F as: API gravity = (141.5/Specific Gravity) – 131.5.

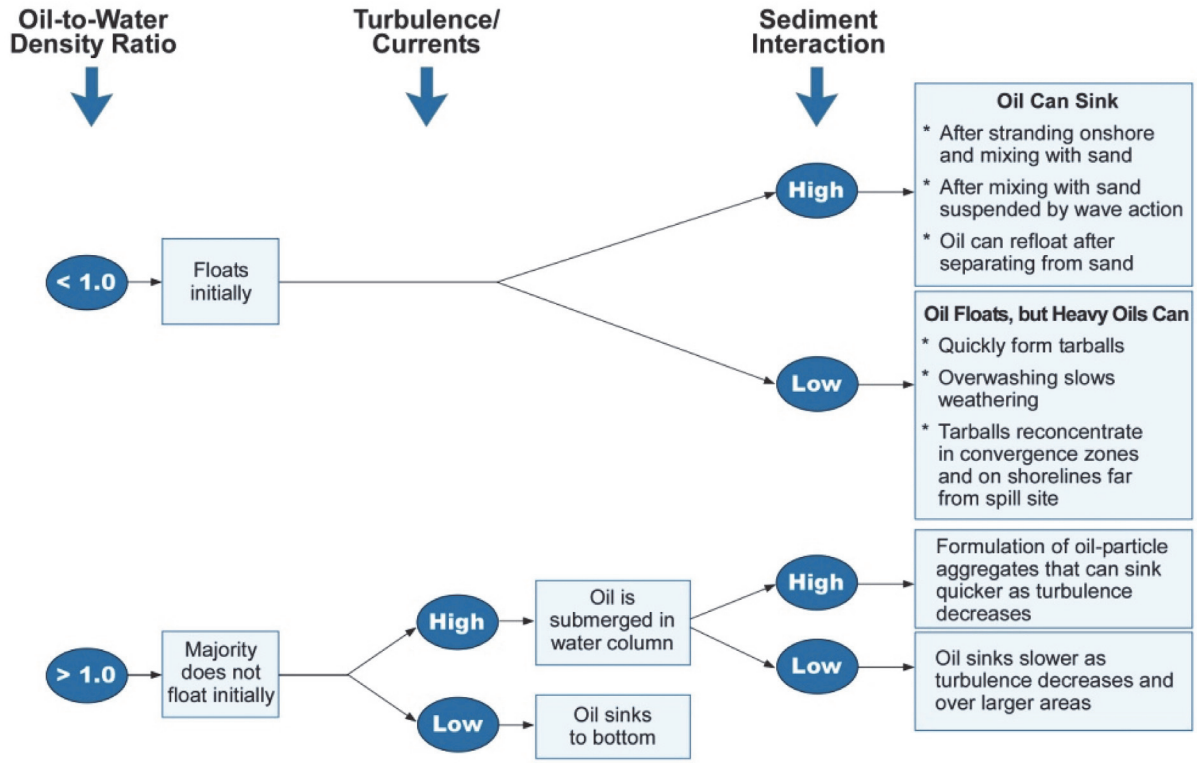
A key factor that controls the behavior of spilled oil is the intensity of turbulence (which is generated when the water flow is constantly changing in speed and direction) and currents in the water body, as shown in Figure 2-2. Turbulence can be generated by wave action, such as waves breaking along the shoreline, over shallow areas, or in deeper water by the passage of large waves that disturb the bottom. Turbulence can also be generated by tidal or river currents. Floating oil can become entrained into the water column by turbulence, but will refloat in quiescent areas. Oil that is denser than the receiving water can become submerged in the water column where the currents and/or turbulence are high, but sink to the bottom where currents and/or turbulence are weak.

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NOTE Oils with values below the line will float initially; oils with values above the line with not float initially (modified after NRC, 1999).

Figure 2-1—Relationship Between Density and API Gravity and Water Salinity



NOTE Modified after NRC, 1999.

Figure 2-2—Conditions by Which Oils Can Sink Based on the Density of the Oil Relative to the Receiving Water, Turbulence, Currents, and Sediment Interaction

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Turbulence triggers another mechanism that can cause an oil to submerge or sink—that is, interaction with sediments that further increases the oil's density. Oil that is lighter than the receiving water and float may still sink after mixing with sediment (in the case studies, most of the time the sediment was sand rather than silt and clay). Oil can mix with sand after it strands on sandy substrates, such as sand beaches or sand tidal flats, and then is eroded from the shoreline. Oil can also mix with sand in the surf zone, without stranding on shore, and sink in the nearshore zone.

Oil can also mix with suspended sediment and organic matter, such as in rivers and estuaries, forming oil-particle aggregates that can become heavier than the receiving water and settle out as turbulence and currents decrease. The denser oil-particle aggregates are heavier than the oil alone, and they tend to settle to the bottom more quickly, which can result in higher amounts of sunken oil in low-flow areas. It is important to note that a buoyant oil that sinks after mixing with sediment can separate from the sediment and refloat, as was observed during several spills, most notably the 1994 *Morris J. Berman* spill of a heavy fuel oil in Puerto Rico and the 2010 spill of diluted bitumen in the Kalamazoo River.

Once spilled, floating oil immediately undergoes weathering, and the density usually increases because evaporation of the lighter fractions. However, laboratory and field experience shows that most floating oils will not become denser than the receiving water due to evaporation of the light fractions alone.

Much research has been conducted on the density of diluted bitumen products once spilled; these products are composed of 70 % to 80 % bitumen extracted from tar sands and 20 % to 30 % condensate (or other types of diluents), blended to make the resulting oil, called diluted bitumen, or dilbit, compliant with oil properties requirements (see Note) for transport in pipelines. Another bitumen product, called synbit, is a blend of synthetic crude oil and bitumen at approximately a ratio of 1:1. Synthetic crude oil is upgraded bitumen, produced by either coking or residue hydrocracking the bitumen, followed by hydrotreating to crack the larger molecules into smaller species and remove sulfur (*Environment Canada*, 2013). Raw bitumen has a density of 0.96 to 1.02 g/cm^3. Therefore, depending on temperature and emulsification, the density of weathered dilbit and synbit can approach that of fresh water and can become submerged in the water column under turbulent conditions. When this occurs, interaction with suspended sediments in the water column can cause diluted bitumen products to form oil-particle aggregates that can be heavier than freshwater and sink in quiescent areas. Laboratory studies and actual spills have indicated that these bitumen products have to become mixed with sediments to become heavier than sea water at any temperatures (Stantec, 2007; SL Ross, 2012; *Environment Canada*, 2013).

NOTE Density must not exceed 0.940 g/cm^3 (API of ~20), and viscosity must not exceed 350 centiStokes measured at the posted pipeline operating temperature (TRB, 2013).

In summary, spilled oil can sink to the bottom of a water body under the following conditions (bold indicates the types of sunken oil addressed in this report).

— Oils that are heavier than water and sink where turbulence and currents are weak, which results in the accumulation of **bulk oil** on the bottom of a waterbody.

— Oils that are lighter than water and sink after mixing with sand, which results in **oil-sediment mats** on the bottom of a waterbody, with the potential for the oil to refloat if the oil separates from the sand.

— Oils that become heavier than water due to formation of **oil-particle aggregates** under turbulent conditions, which eventually settle on the bottom of the waterbody in quiescent areas.

In all cases, the sunken oil on the bottom can become **buried by sediments**.

2.3 Sunken Oil Case Histories and Lessons Learned

Much can be learned from the responses to past spills where the oil sank to the bottom. In the following tables, information on each response is summarized and lessons learned are called out for 38 spills where the oil sank or submerged under different conditions.

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— Table 2-1: Nineteen spills where the oil was heavier than water and sank to the bottom or was suspended in the water column by turbulence.

— Table 2-2: Eight spills where the oil initially floated but a significant amount sank after stranding on sand beaches.

— Table 2-3: Six spills where the oil initially floated but a significant amount then sank or submerged without stranding onshore.

— Table 2-4: Two spills where the oil initially floated then became submerged and moved along the bottom with the currents, with little to no accumulation on the bottom.

— Table 2-5: Three spills where the oil sank after burning or intense heating.

Table 2-1—Case Studies of Spilled Oil That Was Heavier Than the Water and Sank to the Bottom or Was Suspended in The Water Column by High Turbulence

Spill Name/ Date/ Location	Oil Name/ Volume Spilled/ API	Water Type	Response Summary
T/B *Apex 3508*, September 2015 Mississippi River	Clarified slurry oil/ 2871 bbl/ –7.4	Fresh	Occurred when two towing vessels collided at river mile 937 near Columbus, Kentucky, releasing the contents of one tank of the barge. The river currents were 1.8 knots. No floating oil or shoreline oiling was reported. Side scan sonar was used to locate and delineate the sunken oil in two locations: 1) area of 62,000 ft^2 from the center of the channel to where the barge was pushed towards the bank; and 2) area of 14,500 ft^2 in the lee of the barge. It was surmised that the oil leaked from the barge as it was pushed towards the bank; the remaining oil was released during salvage operations. The sunken oil was recovered using an environmental clamshell dredge. Side scan sonar was used to confirm removal to cleanup endpoints.
T/B *Apex 3512*, October 1995 Mississippi River Mile 126 above Head of Passes	Slurry oil/ 4,631 bbl/ –0.6	Fresh	Occurred after collision of two barge tows. Sorbents attached to chains and ponar samplers were used to locate the oil on the bottom; these techniques proved to be very inefficient. River currents were 2 knots so oil was only found in the lee of the barge pushed against the bank. Recovery was by divers protected first by wet suits then adjusted to dry suits. There was no visibility, so divers were directed to the oil by visual observations of the effluent. Recovered 1933 to 3424 bbl over 8 days by pumping into barges (Weems et al., 1977).
Apex Towing, June 1995 Mississippi River	Slurry oil/ 20,000 bbl/ 0.5	Fresh	Occurred when two barges collided with a bridge near Vicksburg, Mississippi during a flood. The river currents were 6 to 8 knots. The oil suspended in the water column under the strong currents and was not located or recovered.
T/B *DBL-152*, November 2005 35 miles offshore Louisiana	Slurry oil/ 64,285 bbl/ 4.5	Salt	Occurred in water depths up to 75 ft. Used V-SORs to detect oil on the seafloor and snare sentinels and snare-stuffed crab pots to track the oil spread when suspended in the water column during storms. Side scan sonar was effective in oil detection. Camera/video by divers and ROV was useful to see the oil but only when visibility was good. Diver-directed pumping recovered 3800 bbl over a 2-month period. The oil was mobilized during frequent storms. Receiving barges were brought into port during adverse weather. Requests were made to decant while in port, but they were denied (Michel, 2006; Pfeifer et al., 2008; Redman et al., 2008).

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Table 2-1—Case Studies of Spilled Oil That Was Heavier Than the Water and Sank to the Bottom or Was Suspended in The Water Column by High Turbulence (Continued)

Spill Name/ Date/ Location	Oil Name/ Volume Spilled/ API	Water Type	Response Summary
Degussa Engineered Carbons, August 2008 Ohio River	Residual fuel oil/ 100 bbl/ –0.2	Fresh	The oil released from the facility flowed into the Ohio River during very low-flow conditions and sank near the outfall. Oil flowed down-current, but also slightly up-current into low spots. Divers located the oil. A clamshell dredge followed by a pumping system was used to remove 1500 tons of material, though very little of it contained oil, so these methods were terminated. The oil flowed into the depressions created by the clamshell. Some oil was removed by diver-directed pumping with a hand wand/stinger. Trace oil amounts were removed using sorbents. A sorbent filter fence was deployed down-current during removal actions; however, no oil was collected on the sorbent fence. The preferred method would have been to use diver-directed pumping prior to and instead of the clamshell dredge followed by V-SORs for recovering trace amounts of residual oil.
Detroit River, February 1996	Coal tar oil/ 830 bbl/ –12.5	Fresh	Released from a storage tank into an outfall to the Detroit River with water temperatures of 33 °F and currents of 3 to 4 knots. Oil was delineated and removal tracked using diver observations in a 10 x10 feet grid. Divers used a duckbill nozzle (with steam injection) and submersible pump to recover 83 bbl of highly viscous/tacky oil. Three tanks were used for decanting, settling, and sand/carbon filtration prior to water discharge into the river. Clamshell dredge was used for recovery of 100 yd^3 of semi-solid material. Underwater barrier placed downstream during dredging consisted of snare on a steel frame. Good example of using different removal methods depending on oil properties. Pumping of liquids preferred over dredging because of cost of material disposal compared to water effluent treatment (Helland et al., 1997).
T/B *EMC-423*, January 2005 Chicago Sanitary and Ship Canal, Illinois	Clarified slurry oil/ ~1,000 bbl/ <10	Fresh	Occurred after an explosion, fire, and partial sinking of the barge. The oil remaining in the barge solidified in –20 °F air temperatures and had to be heated for removal. Divers found oil in a solidified mass on the bottom adjacent to/under the barge. Side scan sonar showed debris but could not be used to locate the sunken oil. An environmental clamshell dredge was used to remove ~535 bbl of oil along with 600 yd^3 of sediment. GPS was used to track removal locations; however, clamshell operation lacked precision due to antiquated crane apparatus. Vessel traffic in the canal caused some of the oil to spread, which lowered recovery (Popa, 2009).
ESSO Puerto Rico, September 1988 Mississippi River	Carbon black feedstock/ 23,000 bbl/ 2.0 to -1.5	Fresh	Oil released over 10-mile distance. Rags and sorbents attached to weights were used to detect sunken oil; found little oil but some small droplets in deeper areas. Pour point was below river water temperatures; the oil was churned into droplets by prop wash. Ten bbl were recovered by divers and suction pumps directly below the ship at its anchorage site (NOAA Hotline Report).
T/V *Gino* April 1979 Brittany, France	Carbon black/ ~250,000 bbl on board/ –2	Salt	The vessel sank in 400 ft of water, taking all of her cargo to the seafloor. The heavy, viscous oil spread in slicks on the sea floor adjacent to the wreck. No oil floated to the surface. The French Navy conducted side-scan sonar surveys and video surveys. About 75 % of the cargo leaked from the tanks, breaking into smaller pieces over time. No oil was recovered (AMSA, 2007).

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Table 2-1—Case Studies of Spilled Oil That Was Heavier Than the Water and Sank to the Bottom or Was Suspended in The Water Column by High Turbulence (Continued)

Spill Name/ Date/ Location	Oil Name/ Volume Spilled/ API	Water Type	Response Summary
Lake Winona, Michigan winter 1979	No. 6 fuel oil/ 176 bbl/ 12	Fresh	Release from a storage tank in winter via storm drain to ice-covered lake. In spring, oil was observed on the surface and removed. Globules of oil repeatedly surfaced. Divers found sunken oil in the 2 ft trench cut by flows from the storm drain and adjacent depressions. Long strands of oil rose from the silt-covered bottom. Divers vacuumed the sunken oil into onshore tanks for separation: the oil floated when disturbed (Fremling, 1981).
T/B *MCN-5*, January 1988 Rosario Strait, Puget Sound, Washington	Heavy cycle gas oil/ 2,177 bbl/ –1.2	Salt	Barge sank in 120 ft of water with 3-knot currents. Salvage of the barge was highest priority to recover the >6500 bbl remaining in intact tanks. Divers reported oil pooled on the bottom in the lee of the sunken barge during slack water but was flushed by the ebb current. NOAA tests showed the oil broke into small droplets in the current; no sunken oil was recovered (Yaroch and Reiter, 1989).
T/B *MM-53*, January 2006 Ohio River, Kentucky	64-22 asphalt/ 5,000 bbl/ N/A	Fresh	The asphalt quickly solidified. Solidified asphalt with air bubbles floated up to 20 miles downstream. Divers used a pike pole to differentiate between rock, gravel, and sticky asphalt to map the oil on the bottom. 333 bbl were recovered by mechanical grab near the barge; the rest dispersed downriver (Howard and Laisure, 2008).
T/V *Mobiloil*, March 1984 Columbia River, 10 miles below Portland, Oregon	Industrial/No. 6 fuel/residual oil/ 3,925 bbl/ 5.5 to 11.3	Fresh	The oils behaved differently based on their density: Some oil floated and formed tarballs. Sunken oil was found in the lee of the grounded vessel, though this oil was lost when the vessel was refloated. Some of the oil moved with the 2-knot river currents and was distributed throughout the water column. Oil suspended in the water column rose to the surface when the salt wedge was reached. Oil that sank from the damaged tanks at the dock was recovered using sorbents attached to a wire mesh screen that was lowered to the bottom (Kennedy and Baca, 1984; Park, 1985).
T/V *Nisa R3*, June 2013 Muscat, Sultanate of Oman	Bitumen/ 1,800 bbl/ 8.6 to 2	Salt	Occurred when the vessel sank approximately 1.4 nautical miles off the Port Sultan Qaboos, Muscat, Oman, The grade 60/70 bitumen was loaded at a temperature of 122 °C. Rapid cooling occurred on contact with sea water and it became very viscous and rapidly formed thick patches which were moved by wind and current along the coastline. Due to the higher specific gravity of the bitumen some patches were partially submerged, making detection more difficult. Observations on site during clean-up operations found that in areas of shallow water, sunken and submerged oil was present and remained mobile due to currents and wave action. With high daytime temperatures some of the oil resurfaced and re-contaminated areas previously cleaned of stranded oil. Sunken and submerged oil was removed by diver activity and manual techniques.
T/V *Provence*, July 1996 Piscataqua River, New Hampshire	Heavy No. 6 fuel oil/ 21 bbl/ 6.2	Salt	Because of high turbulence in the strong currents and convergence zones, the oil was mixed throughout the water column, though some stranded onshore in convergence areas. Oil adhered to lobster pots, fouled lobsters, and contaminated water intakes. Snare attached to lobster lines were used to detect suspended oil. None of the submerged oil was recovered (NOAA Hotline Report).

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Table 2-1—Case Studies of Spilled Oil That Was Heavier Than the Water and Sank to the Bottom or Was Suspended in The Water Column by High Turbulence (Continued)

Spill Name/ Date/ Location	Oil Name/ Volume Spilled/ API	Water Type	Response Summary
SS *Sansinena*, December 1976 Los Angeles Harbor, California	Bunker C/ 20,000 bbl/ 7.9 to 8.8	Salt	Occurred in the harbor with limited currents. Oil remained liquid and accumulated in scour pools near the dock up to 9 ft deep. Initially recovery was by a diver-directed vacuum system. Diver-directed hydraulic pumps were then used on thick accumulations. Divers finally used a custom-built bottom suction head to pump into portable tanks and recovered 33,000 bbl of oil and emulsion over 16 months (Hutchison and Simonsen, 1979).
T/B *SFI 33*, August 1990 Houston Ship Channel, Texas	No. 6 fuel oil/ 500 bbl/ 6.5	Salt	Sunken oil was up to 2 ft thick. Divers with submersible pumps and suction heads removed the oil (Kaperick, 1995).
T/V *Thuntank 5*, December 1986 Baltic Sea off the east Swedish coast	No. 6 fuel oil/ 1200 bbl/ 20.6	Fresh	The oil sank in the cold water; however, the oil became more liquid and buoyant as water temperature increased, and was washed ashore during rough weather for 5 years. Larger pools of oil on the seabed were recovered by diver-directed vacuum system using hot-water injection to create suction and lubrication during pumping. Oil and water separation was carried out on the barge. Substantial volumes of oil were recovered; however, during the operations some of the sunken oil migrated to deeper waters where recovery was not possible. This residual oil caused chronic shoreline oiling (Ansell et al., 2001; Dicks et al., 2002).
M/T *Velopoula* 23 July 2004 3 miles offshore Port Dixon, Malaysia	Carbon black feedstock oil/ 67 tonnes/ –6.6	Salt	Occurred by rupture of the hose connecting to the seabed manifold, releasing oil at both the surface and on the seafloor. Very strong subsea currents. Initial cleaning during diving “windows” was carried out using diver-operated 4 in. airlift system with ~3 tonnes recovered from a depth of 115 ft. Side scan sonar survey was not completed until 13 August. A high-capacity airlift system with annular air injection was built and rigged on a barge to recover oil; however, owing to set-up time requirements and a long delay in interpretation of survey readings and production of maps with GPS locations of oil deposits, start of recovery operations was not possible until 29 August, 5 weeks post-spill. A special “hood” to maintain optimum distance between the seafloor and the suction orifice. Once positioned in the area to be cleaned the crane jib was moved in a series of arcs of increasing radius over the target area. The system was very productive: sea water together with oil and sand were lifted at a rate of over one tonne per minute, but only small amounts of oil were recovered. The resulting recovered material was discharged to the deck of the barge where the gentle trim of the barge allowed solids to be retained at one area while liquid was allowed to flow to the low point before being pumped into an improvised oily water gravity separation system. Discharge from the system was continually monitored by an in-line bilge monitor and residual liquids in the solids removed by harnessing high daily temperatures which heated the barge deck and allowed evaporation leaving behind dry solids. It appeared that strong currents and resulting scour had moved or buried oil in previously mapped locations. Further diver surveys were carried out to try to locate oil patches but none were observed. The conclusion was that strong currents had effectively dispersed the oil over a wide area.

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Table 2-2—Case Studies of Spilled Oil That Initially Floated then Sank After Stranding Onshore (All of These Spills Occurred in Salt Water)

Spill Name/ Date/Location	Oil Name/ Volume Spilled/ API	Response Summary
T/V *Alvenus*, July 1984 Galveston Island, Texas	Merey and Pilon crude/ 65,500 bbl/ 13.8 and 17.3	Release occurred after grounding in the Calcasieu Ship Channel. Slicks moved west for 100 miles and stranded onshore 6 days later. The viscous oils mixed with sand in the surf zone and on the beach and sank in patches between offshore sand bars no more than 100 ft from the shoreline for ~7.5 miles. No sunken oil was found beyond the first bar. Oil was removed by vacuum trucks, cement pumps, 50+ graders, and manual use of screens, with limited success. Interruption of the efforts to push the oiled sand into the supratidal zone likely led to more of the oiled sand being eroded from the beach. Most of the oil:sand mixture was recovered as it came ashore over several weeks (Alejandro and Buri, 1987).
Deepwater Horizon, April 2010 Northern Gulf of Mexico	Macondo-252 crude oil/ 3,190,000 bbl/ 32	Occurred during a blowout from a well 40 miles off the Louisiana coast in 5000 ft of water. The emulsified oil mixed with sand in the surf zone and on the shoreline. Some of the oil:sand mixture was deposited in the nearshore subtidal zone, between the shoreline and the first bar, forming cohesive submerged oil mats (SOMs, containing ~90 % sand) off Gulf-facing sand beaches mostly in Florida and Alabama. Extensive surveys were conducted in Mississippi Sound and bays in Alabama and Florida, consisting of 5880 sorbent drops, 346 ponar sediment grabs, and 410 miles of towed submersible flurorometers, with no sunken oil detected. Sunken oil between the first and second bar off Gulf beaches from Mississippi to Florida was searched for using sonar and 1720 ponar grabs, with no recoverable oil detected. SOMs were repeatedly buried and exposed by beach accretion and bar migration, and were sources of chronic re-oiling of adjacent shorelines as the mats broke apart. Techniques to locate SOMs included: “Snorkel SCAT” where teams would use shovels to delineate the oil; aerial surveys; aerial imagery; Acoustic Doppler Current Profiler, sonar sub-bottom profiler; side-scan sonar; Coda Octopus echosounder; laser fluorometer; video-equipped ROV; and ponar sampler. Snorkel SCAT teams located most of the mats off beaches with chronic re-oiling. Most SOMs were removed by use of long-arm excavators operating from shore, with screened buckets to sieve out the sand and remove only the mat (Gulf Coast IMT, 2010; OSAT3, 2013).
T/V *Eleni V*, May 1978 North Sea, off Norfolk, UK	Heavy fuel oil/ 30,000 bbl/ 14.4 to 19	Oil stranded on the English shoreline over 60 miles to the south; 2 months later, oil stranded onshore The Netherlands. The oil emulsified and picked up sediment after stranding; patches of oil on the seabed and floating just below the surface were observed. Mousse mixed with sediment resulted in oiled fish trawls 1.5 to 8 miles offshore without visible surface oil for months (Blackman and Law, 1980; Kaperick, 1995; Koops and Huisman, 2002).
SE Florida Mystery Spill, August 2000	Heavy fuel oil/ unknown amount or API	Oil from an unknown source stranded along 25 miles of beaches near Ft. Lauderdale. Patches of sunken mat and patties that were up to 3 in. to 4 in. thick and mixed with seagrass and sand were found in the nearshore trough, partially covered with sand, along several miles of beach. Divers manually removed the oiled materials (NOAA Hotline Reports).
M/V *Kuroshima*, November 1997 Dutch Harbor, Alaska	Bunker C/ 930 bbl/ API not reported	Vessel grounded during a storm. Oil mixed with sand in the surf zone and on the shoreline, then entered and sank in 20 ft to 30 ft of water in a freshwater lake. In spring, SCUBA divers mapped the sunken oil using visual observations along 6.5 miles of transects using DGPS and an underwater navigation system. Oil patches ranged from 1-in. tarballs to mats up to 4 ft in diameter with 10 % to 40 % coverage. Divers wearing hard hat dive equipment removed sunken oil by hand, placing it into mesh bags that were lifted to the surface; larger mats were cut into pieces. In all, 8.5 tons were removed by 2 divers working 4 to 5 hours/ day for 2 weeks. Divers conducted post-removal surveys to document cleanup to endpoints (Kane, 2003; Martin et al., 2003).

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Table 2-2—Case Studies of Spilled Oil That Initially Floated then Sank After Stranding Onshore (All of These Spills Occurred in Salt Water) (Continued)

Spill Name/ Date/Location	Oil Name/ Volume Spilled/ API	Response Summary
Lebanon, July 2006	Intermediate fuel oil/ 60 to 90,000 bbl/ API not reported	Release resulted from bombing of a power plant fuels tanks during the Israeli-Hezbollah war. Most of the oil floated; however, some sank as burn residue from the fire and after picking up sand from stranding onshore (containing <5 % sand). Underwater video was used to locate sunken oil, which formed mats 4 in. to 8 in. thick and long "ropes." 50 SCUBA divers removed 1475 bbl of sunken oil in 2.5 months. The hard burn residue was easily placed into flour bags. The cohesive, liquid oil was lifted from the sand by hand-generated currents then rolled like a carpet, cut into pieces, and placed in bags. Oil adhered to rocky substrates had to be cut away in small pieces (Elsarji, 2008; Linden and Rust, 2008; Fichaut, 2008).
T/V *Nissos Amorgos*, March 1997 Maracaibo, Venezuela	Bachaquero crude/ 25,402 bbl/ 11.8	Occurred in the in the Gulf of Venezuela. Oil mixed with sand by large waves in the surf zone that extended >1000 ft from the shore and after stranding on the sand beaches. An estimated 5 % sank in nearshore troughs and eventually stranded on shore (Moller, 1998).
T/V *Volgoneft 248*, December 1999 Turkey	Heavy fuel oil/ 13,000 bbl/ 11.2	Occurred at an anchorage in Istanbul in the Sea of Marmara. Stranded oil became mixed with sand, mussel shells, and other debris and sank in water at or near the shoreline, in depths from 3 ft to 45 ft, causing chronic re-oiling of the shoreline after storms. Sunken oil in shallow water was removed manually with spades or with a front-end loader. In deeper water, divers cut the oil into pieces and placed them in plastic bags that were lifted to the surface. The oil was too viscous to use an airlift system, but it was used to remove clean sand on top of the oiled layer. Diving suits and equipment were severely contaminated (Moller, 2002).

Table 2-3—Case Studies of Spilled Oil That Initially Floated Then Sank or Submerged Without Stranding Onshore

Spill Name/ Date/ Location	Oil Type/ Volume Spilled/API	Response Summary
T/B *Bouchard 155*, August 1993 Tampa Bay, Florida	No. 6 fuel oil/ 8,000 bbl/ 10.5	Oil weathered offshore for 7 days, then came ashore during small storm. The oil mixed with 7 % to 15 % sand by weight in the surf zone and sank in isolated depressions offshore and in bays behind tidal inlets. In 2000, during dredging of Blind Pass, oil from the 1993 spill was found; coring showed up to 3 in. of oil buried by 4 ft of clean sand, which required segregation of oil during handling of the dredged material. At least 475 bbl of oil were recovered (Michel and Galt, 1995; NOAA Hotline Reports).
Enbridge Pipeline, July 2010 Kalamazoo River, Michigan	77.5 % Western Canadian Select and 22.5 % Cold Lake Crude Oil (with diluent)/ 19,500 bbl/ ~20	Spill released into Talmadge Creek during 50-year flood event. Oil initially floated but some of the oil became submerged/sunk after loss of the volatile fraction in combination with sediment mixing caused by water turbulence from flooding and cleanup activity. Sunken oil surveys were conducted for 38 miles of creek/river and three impoundments by "poling" where the river bed was agitated by a pole with a disk on the bottom, and the type and amount of surface oil released recorded. Removal methods included sediment flushing with river water, sediment raking, and/or aeration to liberate the sunken oil and float it to the surface for recovery via sorbents or vacuum. Dredging and excavation were used to remove contaminated sediments: in 2010 in the Ceresco impoundment (6800 yd^3); in 2013 in Ceresco (103,427 yd^3), Mill Ponds (22,283 yd^3), and 4 sediment traps (12,503 yd^3); and in 2014 in the Mill Ponds (1140 yd^3) and Morrow Lake (90,851 yd^3) for a total of 237,000 yd^3. Hydraulic dredging with hydraulic dredge heads with cutterheads was used in 2013 and 2014 particularly in the impoundments. Pump suction dredging was conducted in shallower locations where the water depths were too shallow to float hydraulic dredges. Some sediment traps were dewatered and excavated as was the Ceresco bowl scrap after the impoundment was lowered via the dam notching (Dollhopf and Durno, 2011; Dollhopf et al., 2014).

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Table 2-3—Case Studies of Spilled Oil That Initially Floated Then Sank or Submerged Without Stranding Onshore (Continued)

Spill Name/ Date/ Location	Oil Type/ Volume Spilled/API	Response Summary
T/V *Erika*, December 1999 80 miles off the coast of France	Heavy fuel oil/ 87,000 bbl/ 9.6	The vessel broke in two during severe storms. Most of the oil floated and stranded along 250 miles of shoreline. In one bay, chronic re-oiling of the shoreline led to a search for sunken oil. Borings and diver observations were used to delineate 2.5 acres with sunken oil mixed with sediment. In Phase 1, barge-mounted excavators with screened buckets removed 800 tonnes of material over 10 days from the most heavily contaminated area, working during low tide when water levels and currents were lowest, to minimize impacts to shellfisheries in the bay. In Phase 2, suction dredgers with blade cutters were used to recover less-contaminated sand. Seabed nets with weights were placed up and down current of the dredging areas. The dredged materials were pumped through onshore separation lagoons. The liquid oil separated from the coarse sand and floated, allowing for recovery by skimming. The sand sank and was tested for oil content. If the oil was less than 1000 ppm, the sand was stockpiled on the beach for surf washing; if it was greater than that, it was put back through the settling tanks. Very fine mesh eel nets were used to recover oil during the surf washing. In Phase 2, 5500 tonnes of material were excavated in 1 month and 85 % of the sand was returned to the site (Le Guerroué et al., 2003).
Lake Wabamun, Canada August 2005	No. 6 fuel oil/ 5000 bbl/ 11.9	A train derailment released warm fuel oil that flowed over land then into the freshwater lake, where the oil both floated and sank. Sunken oil was mixed with vegetation and coarse sediment (some sediment uptake occurred while flowing over land) in the form of tarballs 1 in. to 5 in. and logs up to 1 ft wide and 15 ft long. Tarballs refloated or became neutrally buoyant as the water warmed. Sunken oil was mapped using viewing tubes from small boats in shallow water. Other less successful techniques included bottom trawl nets, grab samples, and underwater video (oil too patchy) and weighted snares (oil did not adhere to the snares) (Fingas et al., 2008).
T/V *Katina*, June 1982 North Sea	Heavy fuel oil/ 10,250 bbl/ 10.7	The oil was highly viscous and became submerged below the surface. Seven days later, oil stranded on the shoreline, fouling 38 miles of shoreline (Koops and Huisman, 2002).
T/B *Morris J. Berman*, January 1994 San Juan, Puerto Rico	No. 6 fuel oil/ 190,000 bbl/ 9.5	Some of the oil picked up ~2 % sand in the surf zone and sank in protected areas over a distance of 90 miles both east and west of the grounding site. Sunken oil was visible in the clear water. During the day, as the water warmed, the oil would separate from the sand and float to the surface, re-oiling the shoreline. Heavier oil accumulations were removed by diver-assisted vacuum systems, Archimedes screw pumps (with cutter blades to chop up the large amount of debris), and positive displacement piston pumps. Small dredges using centrifugal vane pumps and rotating dredge cutter heads were used to remove sunken oil from two sheltered lagoons–during pumping into a large swimming pool, the sand separated from the oil, which floated. Divers used snare to remove oil adhered to seagrass. In all, 3450 bbl were recovered (Ploen, 1994; Burns et al., 1995).

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Table 2-4—Case Studies of Spilled Oil That Initially Floated Then Became Submerged and Moved On the Bottom With the Currents, With Little To No Accumulation

Spill Name/ Date/Location	Oil Type/ Volume Spilled /API	Response Summary
M/T *Athos 1*, November 2005 Delaware River across from Philadelphia, Pennsylvania	Bachaquero crude/ 6310 bbl/ 13.6	Occurred when the vessel struck submerged objects while docking. The oil floated but some oil mixed with sand after stranding on sandy tidal flats and became negatively buoyant and transported by riverine and tidal currents. Snares suspended in the water column showed that the submerged oil moved along the bottom. V-SORs were used to look for oil on the bottom at 17 potential accumulation areas downriver and found trace amounts in 2 locations. Sorbent drops and sediment corers were not effective in detecting submerged oil. Submerged oil was tracked downriver for several weeks using snare sentinels. Water intakes along the river from depths of up to 20 ft reported some oil present, and a nuclear power plant shut down as a precaution. Diver-directed pumping was used to remove 20 bbl over 3 days from one area where oil had been injected into the soft sediments during the release. A barge-mounted decanting system used settling and sorbents to treat the effluent prior to discharge back to the river. A sorbent filter fence was deployed down-current during diver-directed removal actions; no oil was collected on the sorbent fence (Michel, 2006).
T/V *Presidente Rivera*, June 1989 Delaware River	No. 6 fuel oil/ 7310 bbl/ 17.4	Occurred in the Delaware River, near Marcus Hook, Pennsylvania. Water temperatures were below the oil's pour point, thus the oil congealed into heavy, tar-like globs with only 10 % visible above the water surface. A fish net was used to recover the floating oil but could not be reused, so clamshell dredges were used. Oil that stranded on sand banks picked up sediment and rolled along the river bottom as evidenced by oiled crabs in crab pots (Wiltshire and Corcoran, 1991).

Table 2-5—Case Studies of Spilled Oil That Sank After Burning or Intense Heating

Spill Name/ Date/ Location	Oil Type/ Volume Spilled /API	Response Summary
T/V *Betelgeuse*, January 1979 Bantry Bay, Ireland	Arabian Light crude oil/ 207,000 bbl/ 36.5	Most of the oil burned following an explosion and fire; 13,800 to 69,000 bbl of burn residue and intensely heated oil formed an asphalt-like material that coated the shoreline or sank, disrupting fishing activity. Divers reported sunken patches in the vicinity of the wreck, and fishermen reported oil-contaminated bottom trawls and scallop dredges up to 17 miles away. Oil leaked intermittently from the wreck for over a year. In late 1980, scallop-dredging boats removed 30 tons of oil over a 20-day period (Grainger et al., 1984).
M/C *Haven*, April 1991 Genoa, Italy	Heavy Iranian crude oil/ 67,000-335,000 bbl sank/ 31	Occurred as a result of explosion and fire. Intense heating of the unburned oil removed 30 % to 40 % of the original components and this residual oil floated below the surface or sank. Video and divers were towed from shore to 60 ft depths to map sunken oil close to shore. The oil became more fluid as water temperatures increased and rose to the surface in stringers, where divers manually removed 200 m^3 of oil (also using a metal clam hook) from dense seagrass beds to depths of 30 ft. In marinas, sunken oil was recovered using vacuum pumps. In 1992 and 1994, trawl and ROV (side scan sonar and sub-bottom profilers) surveys showed that extensive sunken globules and mats occurred in water depths of 325 ft to 1300 ft covering over 55 square miles; trawling was limited by wrecks, ordnance, and debris (Moller, 1992; Martinelli et al., 1995; Amato, 2003).
Honam Jade February 1983 Yosu, South Korea	Heavy Arabian crude oil/ 13,000 bbl/ 27.9	The oil was ignited 3 hours after the spill and burned intensely for 2 hours. The burn residue sank and affected crabs reared in cages. Attempts were made to recover the sunken oil using trawls, with limited success (Moller, 1992).

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Lessons learned from these case studies are summarized in the boxes below.

Lessons Learned about How Oil Sinks

- All of the oils that sank shortly after their release were heavy refined petroleum products (e.g. slurry oil, residual fuel oil, carbon black) or coal tar, and seventeen of the nineteen spills were of oils with an API value below 10.
- In the two cases where the oil had an API value above 10 but portions of the oil still sank, the oil was released into very cold water in winter and refloated as the water temperatures increased the next spring.
- The heavy crude oils spilled in these case studies always floated at first, but some of the oil sank after picking up sediment (mostly sand). These oils were very viscous and sticky and formed thick deposits when they strand onshore. Sand adhered to the oil, rather than the oil penetrating into sand. Only a few percent sand attached to the oil is needed to make it more dense than water.
- Oil heavier than the receiving water that is released into waters with high turbulence will likely disperse into the water column, with little opportunity for recovery. Efforts to find recoverable oil on the bottom in depositional areas downstream have had limited success.
- Oil heavier than the receiving water that is released into areas of weak or no turbulence does not spread much, thus poses the greatest opportunity for detection and removal.
- Viscous oil that mixes with sand after stranding on the beach or in the surf zone tends to form mats in the nearshore subtidal that are very persistent and will require removal to prevent chronic re-oiling of adjacent shorelines.
- When released into turbulent, medium- to high-turbidity waters, oil can mix with suspended sediment and settle to the bottom in low-flow areas as oil-particle aggregates.

Lessons Learned about Sunken Oil Detection, Delineation, and Characterization

- Sunken oil is not likely to be detectable from the air, using visual observations or sensors, unless it occurs in very shallow, clear water.
- Many detection techniques used have been low tech, relying on sorbents suspended in the water column or dragged on the bottom, with little documentation of effectiveness.
- Use of bottom trawl fishing nets (augmented with snares) is not an effective detection method and is subject to hang ups.
- Diver observations are most effective when the sunken oil covers a relatively small area and has not spread. Even with low visibility, divers can locate thick and larger accumulations by feel.
- Bottom sampling is best conducted to confirm that a target is oil or to collect samples; it is not usually effective as a search technique.
- Must be systematic and a statistically relevant sample size and pattern to be of use for detection analysis.
- Sonar systems technically are capable of detection of sunken oil on the surface, and the high coverage rate achievable and ready availability of such equipment are attractive; however, operational experience in the case studies and pilot testing indicates that further tests are needed to refine data analysis techniques to improve data availability and reduce false positives/ negatives.
- Sonar systems are useful to identify depressions on the bottom where oil could accumulate.
- The response community has little experience in selection and use of remote sensing techniques.
- Of the 38 case studies, 9 used sonar systems, 6 underwater cameras or videos, 24 used divers, 11 used sorbents, 7 used observations from the surface, 10 used bottom sampling, and 6 used crab pots/trawls (Table 2-6).

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Lessons Learned about Sunken Oil Recovery

— No "off the shelf" solutions for sunken oil recovery were used on any of these case studies. Ad hoc recovery systems were identified and assembled for every spill response.

— Safety, logistics, and weather play significant roles in the feasibility and success of recovery operations.

— Contaminated water and sediment associated with dredging and pumping are big constraints.

— Sunken oil is often viscous and sticky, presenting pumping and handling challenges.

— Of the 38 case studies 6 used suction dredge, 13 used diver-directed pumping or vacuuming, 11 used mechanical methods, 5 used sorbents/V-SORs, 4 used trawl/net, 8 used manual removal, and 1 used agitate/refloat (Table 2-7).

— It is important to note that often multiple techniques are used during a response, depending on the spill conditions, initially and over time.

Lessons Learned about Waste Stream Management

— Historically, waste stream management systems have been designed ad-hoc since there is not a one-size-fits-all decanting or waste stream management system to address all types of oils, volumes, and environmental conditions.

— A significant issue during sunken oil recovery is handling the potentially large amount of water and sediment that can be collected with the oil.

— Standard phase separation with final contact water filtration has proven effective on sunken oil recovery operations. Pump selection, pumping rate, and baffled phase separation tanks can be modified to improve system efficiency based on oil characteristics and environmental conditions.

— The size of the decanting system will be a function of volume, time, pumping method, and oil characteristics. A series of fractionation tanks was placed onboard barges during the T/V *Athos I* and T/B *DBL 152* recovery operations. A swimming pool and a lined settling pond constructed on the beach were used during the T/B *Morris J. Berman* response and later during the dredging of Blind Pass, Florida in 2000 to recover oil submerged, respectively.

— If any part of the waste stream management system is overwhelmed, sunken oil recovery operations may be delayed or suspended.

— Portable decanting systems should be placed on a stable platform since the oil may remain emulsified if agitated by the sea state.

— Regional and State decanting policies vary. The regional- or State-specific decanting checklist should be completed under the direction of the Unified Command in advance of operations.

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Table 2-6 and Table 2-7 indicate the techniques used for sunken oil detection and recovery in the case studies.

Table 2-6—Sunken Oil Detection Techniques for the Case Studies

Sunken Oil Detection Techniques							
	Sonar System	**Underwater Camera/Video**	**Diver**	**Sorbents/ V-SORs**	**Surface Observations**	**Bottom Sampling**	**Crab pots/ Nets**
T/V *Alvenus*			X				
T/B *Apex 3508*	X		X	X		X	
T/B *Apex 3512*				X		X	
Apex Towing							
M/T *Athos 1*	X		X	X		X	
T/V Betelgeuse			X				X
T/B *Bouchard 155*					X		
T/B *DBL-152*	X	X	X	X			
Deepwater Horizon	X	X	X	X	X	X	
Degussa Eng. Carbons			X	X			
Detroit River			X				
T/V *Eleni V*					X		
T/B *EMC-423*	X		X				
Enbridge Pipeline				X		X	
T/V *Erika*	X		X			X	
T/V *ESSO Puerto Rico*				X			
Florida Mystery Spill			X				
T/V *Gino*	X	X					
M/C *Haven*	X	X	X			X	X
Honam Jade							X
T/V *Katina*					X		
M/V *Kuroshima*			X				
Lebanon		X	X				
Lake Wabamun		X		X	X	X	X
Lake Winona			X				
T/B *MCN-5*			X				
T/B *MM-53*			X				
T/V *Mobiloil*				X		X	X
T/B *Morris J. Berman*			X		X		
T/V *Nisa R3*			X				
T/V *Nissos Amorgos*					X		
T/V *Presidente Rivera*							X
T/V *Provence*				X			
SS *Sansinena*			X				
T/B *SFI 33*			X				
T/V *Thuntank 5*			X				
M/T *Velopoula*	X		X				
T/V *Volgoneft 248*			X			X	

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Table 2-7—Sunken Oil Recovery Techniques for the Case Studies

	Sunken Oil Recovery Techniques						
	Suction Dredge	Diver Directed Pump/Vacuum	Mechanical	Sorbents/ V-SORs	Trawl/ Net	Manual Removal	Agitate/ Refloat
T/V *Alvenus*			X				
T/B *Apex 3508*			X	X			
T/B *Apex 3512*		X					
Apex Towing							
M/T *Athos 1*		X		X			
T/V Betelgeuse					X		
T/B *Bouchard 155*	X						
T/B *DBL-152*		X					
Deepwater Horizon			X			X	
Degussa Eng. Carbons		X	X	X			
Detroit River		X	X				
T/V *Eleni V*							
T/B *EMC-423*			X				
Enbridge Pipeline	X						X
T/V *Erika*	X		X		X		
T/V *ESSO Puerto Rico*		X					
Florida Mystery Spill						X	
T/V *Gino*							
M/C *Haven*		X	X			X	
Honam Jade					X		
T/V *Katina*							
M/V *Kuroshima*						X	
Lebanon						X	
Lake Wabamun	X				X	X	
Lake Winona		X					
T/B *MCN-5*							
T/B *MM-53*			X				
T/V *Mobiloil*				X			
T/B *Morris J. Berman*	X	X		X			
T/V *Nisa R3*						X	
T/V *Nissos Amorgos*							
T/V *Presidente Rivera*			X				
T/V *Provence*							
SS *Sansinena*		X					
T/B *SFI 33*		X					
T/V *Thuntank 5*		X					
M/T *Velopoula*	X	X					
T/V *Volgoneft 248*			X			X	

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3 Techniques for Sunken Oil Detection, Delineation, and Characterization

3.1 General

The following techniques for sunken oil detection, delineation, and characterization are discussed in this section:

1) sonar systems,
2) underwater visualization systems,
3) diver observations,
4) sorbents,
5) laser fluorosensors,
6) visual observations by trained observers,
7) bottom sampling,
8) water-column sampling.

Bottom trawl nets are not discussed because they have not proven effective. At the end of the section for each technique, the advantages and disadvantages are summarized. Some readers may want to refer to these summaries, then select which techniques to read about in more detail based on their need. A glossary of sonar terms is provided in Appendix A.

3.2 Sonar Systems

3.2.1 General

Trials and operational experience in the case studies of oil spills where the oil sank have indicated that further experimentation is required to refine sonar sensors and sonar data analysis techniques for improved data availability and detection rates. Considerable effort has been expended attempting to identify and/or develop sonar systems and software that can provide an oil detection rate >80 % with success reported with modified sonar or software. Sonars tested in past programs (Parthiot et al., 2004; Hansen et al., 2009) were either modified units or standard units with special software. However, none are in a configuration that could be considered readily available. As a result, these sonars will not be considered in this discussion.

Industry-standard sonar systems technically are capable of detection of sunken oil without modification or special software and are commonly available, but require higher operator skill levels and support personnel to provide positive identification of sunken oil as the oil can be found in various forms and shapes and a wide variety of environments.

As noted by Hansen et al. (2009), the immediacy of survey is essential to success in detection of sunken oil, because once the oil remobilizes, detection with any relative success becomes more difficult with passing time. Thus, this section focuses only on industry-standard sonar sensors outfitted with commonly available processing software to provide the field operator with the best available technical guidelines for the detection of the following types of sunken oil: 1) bulk oil on the sea bottom; 2) oil-sediment mats on the sea bottom; and 3) buried bulk or oil-sediment mats. Oil-particle aggregates mixed into sediments are excluded because their detection with sonar systems is not likely.

The following sonar systems are commonly available for lease or hire with competent operators and will be considered for sunken oil detection applications:

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— side scan sonar,

— multibeam echo sounder,

— sub-bottom profiler,

— 3D scanning sonar.

This section is intended to provide the on-site emergency response team with sunken oil detection utilizing sonar systems that are immediately available without development or special modifications. Because oil-spill responders may have less familiarity with sonar systems, a detailed discussion is provided in Appendix B, which provides a complete explanation of the function and application of the different sonar systems.

3.2.2 Side Scan Sonar

Side scan sonar can be used to survey large areas of the bottom of a waterbody in a relatively short time, and the real-time output should provide adequate data quality for the detection of anomalies in the backscatter that may indicate the location of sunken oil without extensive processing. Side scan sonar is commonly utilized in the offshore oil and hydrographic sectors for bottom surveys, thus it is readily available in various operating frequencies as a lease item with a skilled operator.

High-frequency side scan sonars (defined in this document as >350 kilohertz [kHz]) typically have a narrower beam angle and produce higher-resolution images of the bottom and associated artifacts compared to lower frequencies. The selection of high-frequency side scan sonar will have significant impact on the performance of the sonar system in the detection of sunken oil.

Side scan sonar has relatively few environmental limitations imposed by most bottom types, such as sandy, silty/sandy, mud, or organic mud. Sandy and silty/sandy bottoms will produce conditions that facilitate detection of sunken oil on the surface or near surface of the bottom, whereas organic mud bottoms will have reduced backscatter and will potentially mimic a return from fresh sunken oil on the bottom. Determination of bottom type prior to a survey is important for success.

As indicated both in the literature and with anecdotal information, sunken oil can be detected utilizing side scan sonar, as discussed in the case study of the recent T/B *Apex 3580* spill and as seen in Figure 3-1. This detection capability and the high area coverage rates obtainable with side scan sonar provide an effective tool for the operator to both assess the magnitude of the spill for strategic planning purposes as well as target specific areas for near-term recovery. Bottom type, water depth, and operator skill levels will determine the effectiveness of side scan sonar in detection of sunken oil and must be taken into account in any operational situation.

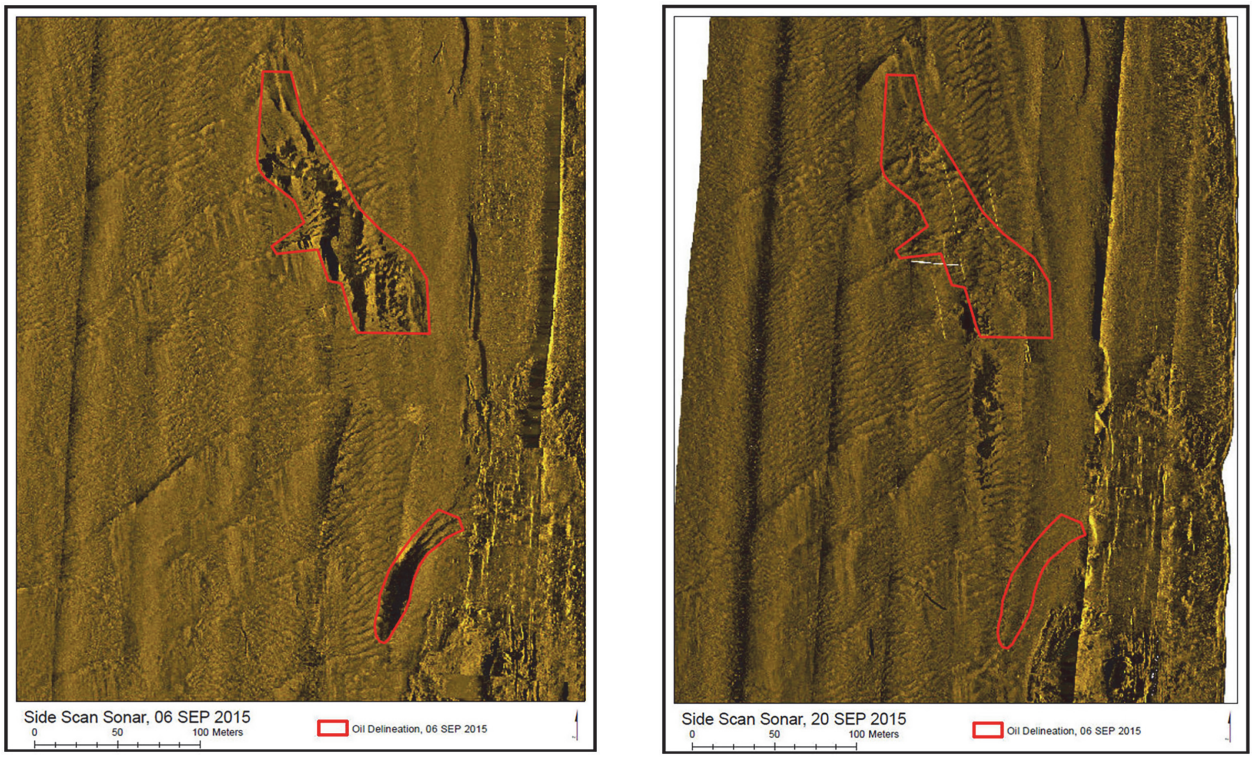
CASE STUDY

T/B *Apex 3508* Spill in the Mississippi River
Use of Side Scan Sonar to Delineate Sunken Oil

On 2 September 2015, a collision occurred between northbound and southbound barges on the Lower Mississippi River near Columbus KY, resulting in a complete breach of the #3 starboard cargo tank on the T/B *Apex 3508*. Approximately 2870 barrels of clarified slurry oil were discharged into the Mississippi River in the vicinity of mile marker 937. A sample of the slurry oil had a specific gravity of 1.14 (API of –7.4) and a viscosity of 160,000 centiStokes (it was almost the consistency of peanut butter), thus the oil was expected to sink as a cohesive mass. No oil was observed on the water surface or on shorelines up to 10 miles downriver from the collision area; an overflight conducted 1 to 2 days after the incident only showed light on-water sheening in isolated locations.

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A technical workgroup was mobilized to identify and determine the extent of any sunken oil on the riverbed, which was mostly sand. An initial side scan sonar survey was conducted by local authorities, utilizing a vessel of opportunity and a consumer quality off the shelf fish finder sonar system operated in the side scan sonar mode at 450 kHz; this preliminary survey indicated areas with anomalously low acoustic backscatter in the vicinity of the collision location. A diver survey and snare/pom-pom drags were subsequently conducted in the same area and confirmed the presence of sunken oil on the river bottom in the anomaly areas. Additional surveys were then conducted with the 450 kHz sonar system to better delineate the bottom anomalies and to identify any additional anomalies; no other anomalies were detected up to 10 km downstream of the incident location. The sunken oil assessment team then developed more detailed assessment plans for the focused operations zone enclosing the side scan sonar anomalies. Geophysical surveys were conducted using a survey vessel with both a commercial quality 445 kHz side scan sonar and multibeam echo sounder, generating high-resolution backscatter, seen in Figure 4-1 as a before and after comparison, and bathymetry that served as a base map for sunken oil recovery planning and operations. The sunken oil occurred in two areas: the northern area (84,500 ft^2) near the collision site and the southern area (8500 ft^2) where the barge was lightered. Both areas of sunken oil were removed using an environmental clamshell dredge. There was some downstream migration of the oil in the northern area, so removal operations were extended there. Side scan sonar surveys were repeated after removal to determine compliance with the cleanup endpoint no more than 10 % observable oil. All treated areas met these endpoints. In all, 2200 cubic yards of solids were removed, and the response ended on 25 September 2015.This response demonstrated how sonar data (both backscatter and bathymetry) can be a valuable tool in a spill where the oil sinks.



Side scan sonar backscatter imagery on 6 September 2015 (left) showing the sunken oil (as black areas of low backscatter) in the two areas delineated; 20 September 2015 (right) after oil removal in the northern area. The southern spread of the sunken oil in the northern area can be seen on this image (USCG).

Figure 3-1—T/B *Apex 3508* Spill of Clarified Slurry Oil

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3.2.3 Multibeam Echo Sounder

Multibeam echo sounders are typically utilized for hydrographic survey with the end data product being a bathymetric map. These units are available in various frequencies and bottom coverage (swath).

Multibeam echo sounders have been employed in other applications such as look-ahead scanning applications and to develop pseudo-side scan sonar data utilizing backscatter from the outer beams. Multibeam echo sounders do not generate classical side scan data because its measurement geometry differs considerably from that of side scan sonar. Multibeam echo sounders in the standard bathymetric configuration are readily available for hire or purchase. Units with specialty software noted as desirable for detection of sunken oil are very limited and available only in prototype formats.

The multibeam echo sounder functions utilizing the backscatter from the bottom so that oil or other material with different backscatter characteristics will clearly show in the data display in varying intensities. The difference in reflectivity or roughness of the bottom and the material of interest is essential in detection of sunken oil. Sampling should precede any sonar operations to determine bottom type. Ground truth sampling is essential to boost the potential for detection of sunken oil, as returns from other bottom objects and conditions can mimic sunken oil.

The value of multibeam echo sounders is not only that they provide some capability to detect sunken oil, but that the device can identify low spots in the bottom where sunken oil is likely to accumulate. The combination of multibeam echo sounder bathymetry with side scan sonar data over the same geographical area can provide the operator with a better opportunity for detection of oil compared to potential detection ability when using either system alone.

3.2.4 Sub-bottom Profiler

The term sub-bottom profiler is broadly utilized to indicate an acoustic device that “looks” directly downward and penetrates into the bottom of a water body to provide a representation of the strata below the sediment surface. As with side scan sonar, there are many frequencies of sub-bottom profiler that produce varying resolution data sets, depending on the results desired. There are essentially two principal types of sub-bottom profilers:

— impulse output pulse (nominally referred to as a “PINGER”),

— CHIRP output pulse (nominally referred to as a “CHIRP”).

Both PINGER and CHIRP sub-bottom profiler systems are commonly available for lease. Combined side scan sonar and sub-bottom profiler systems are available, but are not as common as stand-alone sub-bottom profiler equipment.

Sub-bottom profilers typically will function as designed in sandy or silty/sandy bottom conditions, which produce conditions conducive to bottom penetration and potential detection of buried oil layers. Organic mud bottoms will have reduced penetration due to entrained gases in the decaying organic mud and, in some conditions, there will be no subsurface penetration. Compacted sand bottoms also limit sub-bottom profiler performance, so sampling for bottom type should precede any sonar operations to determine bottom type and assess functionality of a sub-bottom profiler for the area.

Sub bottom profilers may not provide an “image” of buried oil but, when utilized in conjunction with side scan sonar and multibeam echo sounder systems, the effectiveness of the sub-bottom profiler is enhanced as a result of the comparison of observed anomalies from the sub-bottom profiler and the other sonar systems and can provide indications of buried oil for further investigation.

3.2.5 3D scanning sonar

The 3D scanning sonar creates a matrix of multiple beams, both horizontally and vertically, to fully ensonify the area of interest. This capability permits real-time updates of the ensonified area so that the unit can be used to “look” ahead of the survey vessel. The 3D scanning sonar is not widely utilized in the offshore oil or hydrographic sectors, so

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lease or hire potential is limited. The USCG has a number of 3D scanning sonar units that they use for hull and pier inspections, which potentially could be requisitioned in an emergency for use in the detection of sunken oil.

The 3D scanning sonar functions in a similar manner to that of the multibeam echo sounder, utilizing the backscatter from the bottom so that oil or other material with distinctively different backscatter characteristics will clearly show in the data display in varying intensities. The difference in reflectivity or roughness of the bottom and the material of interest is essential in detection of sunken oil. The USCG has tested the 3D scanning sonar; however, as noted in Hanson et al. (2009), additional work is required to ensure that the equipment can provide sunken oil detection for various bottom and oil types. Sampling should precede any sonar operations to determine bottom type. Ground-truth sampling is essential to boost the detection capability for sunken oil, as sunken oil returns can mimic returns from other bottom objects and conditions.

3.2.6 Sonar Systems Summary

The advantages and disadvantages of sonar systems for sunken oil detection include the following.

Advantages	Disadvantages
Side Scan Sonar >350 kHz	
— Rapid area coverage. — Readily available industry. — Good bottom oil detection shown in *DBL-152* spill. — Able to detect oil patch as small as 1 m^2.	— Requires ground-truth for absolute validation of sonar data. — Will not be able to detect buried oil.
Multibeam Echo Sounder >350 kHz	
— Easy to deploy; provides pseudo-imagery of the bottom. — Provides bathymetry maps showing low spots where sunken oil could collect. — Bathy data may be needed to support recovery Ops.	— Resolution is lower than side scan sonar making interpretation/detection of oil difficult.
Sub-bottom Profiler 4 to 24 kHz Chirp	
— Provides potential for detection of oil mats in the shallow sub-bottom region when used in conjunction with side scan sonar and multibeam echo sounders.	— No applicability in detection of sunken oil on the surface. — Data are difficult to interpret due to limitation in resolution of layering in the sub-bottom region.
3D Scanning Sonar	
— 3D mapping and tracking of submerged or subsurface oil. — Real-time observation of sunken oil on the sea bottom for recovery operations. — May be needed for recovery operations.	— Limited availability in the commercial offshore market.

3.3 Underwater Visualization Systems

3.3.1 General

Optical visualization techniques, while not able to provide high area coverage rates, can provide an immediate feedback as to the identity of the bottom material, especially if attached to AUV or ROV platforms that can be deployed in conjunction with surveys conducted with complementary sensors.

Although optical systems have attractive characteristics and can provide needed real-time feedback, these systems have limitations introduced by the medium in which they are operating. In low turbidity situations, optical systems work well with detections being possible at extended ranges of up to 75 ft. However, classification range varies with turbidity, contamination, and oil fouling and, in highly turbid environments, detection ranges can approach 0 ft. Figure 3-2 illustrates the image quality obtainable in low-turbidity situations.

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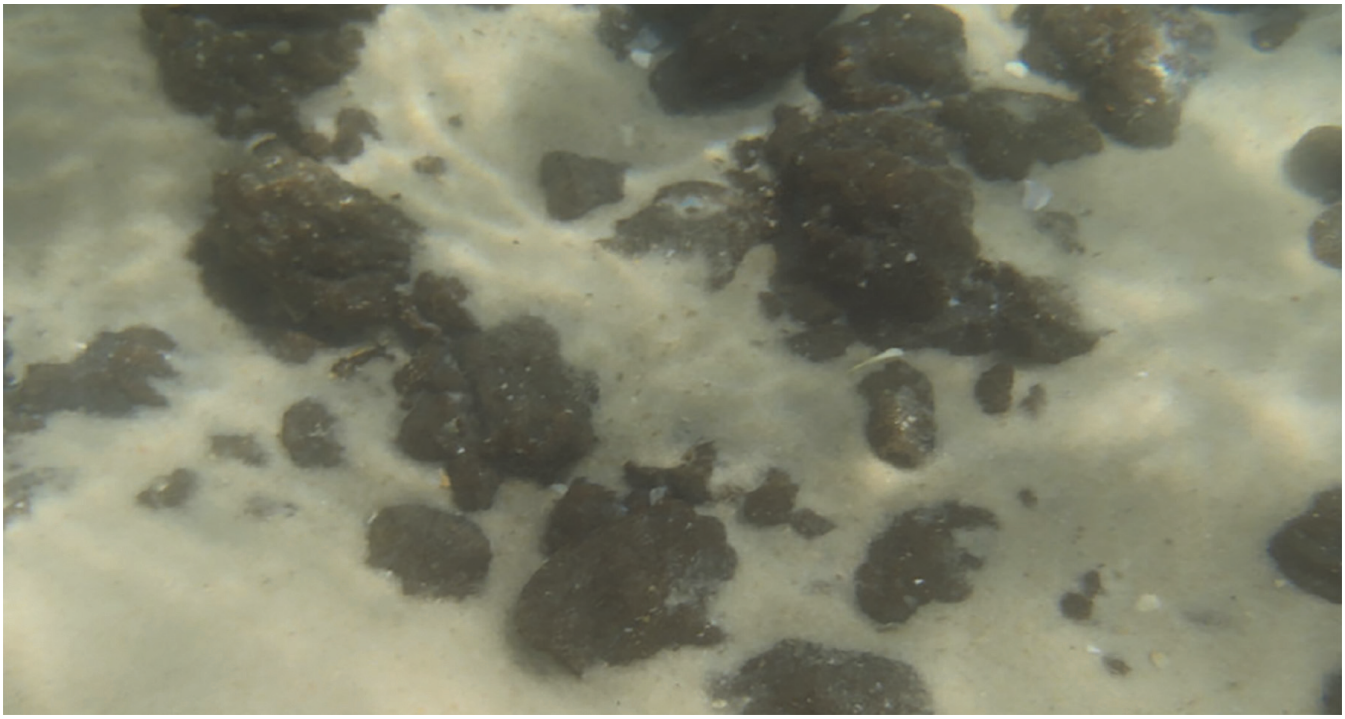


Figure 3-2—Photograph of Partially Buried Oil Mat (*Deepwater Horizon* SCAT Program)

This section is intended to provide the on-site emergency response team with a sunken oil detection capability utilizing visualization systems that are immediately available without development or special modifications. A detailed discussion is provided in Appendix C, which provides a complete explanation of visualization system options, function, and application.

3.3.2 Digital Still Camera

Standard underwater still cameras, equipped with a strobe flash to provide illumination at depth, are available for obtaining high-resolution photographs of the surface of the bottom. High-resolution underwater still cameras are commonly available for hire or lease in the offshore oil or oceanographic sectors, although the increasing capability of video cameras has decreased the popularity of still cameras and could impact availability. Cameras with resolutions of >15 megapixels provide adequate resolution for oil detection applications, although camera resolution in the past decade has increased to 25 megapixels.

Turbidity is the limiting environmental factor in the deployment of optical cameras underwater. Excellent photographic images have been obtained when visibility is 1 ft to 3 ft. In high turbidity conditions, strobe illumination devices must be separated from the camera to suppress backscatter from the flash.

These still cameras can be deployed by divers, in a drop configuration, on a ROV, or on an AUV. Data can be downloaded on deck and displayed or transmitted as desired. Camera resolutions >15 megapixels are necessary, with higher resolutions available.

3.3.3 Video Camera

Standard definition and/or high definition underwater video cameras are commonly available for hire or lease in the offshore oil or oceanographic sectors in conjunction with ROV or AUV platforms. Some cameras are provided with high-intensity light systems, and some light systems are offered as options by related manufacturers. Other video platforms, such as drop systems for point video, can be utilized, but the functionality of ROV and AUV platforms provides significantly better results for such applications as sunken oil detection.

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Turbidity is the limiting environmental factor in the deployment of video cameras underwater. Video data can be obtained successfully in turbid conditions limiting visibility to 1 ft to 3 ft; however, the use of high-intensity lighting sources complicates data collection due to backscatter from particles in the water

Standard-definition or high-definition video photography can provide high-resolution optical ground truth for sunken oil lying on the surface of the bottom. Data can be downloaded on deck to a laptop in real time in the case of the ROV, and after vehicle recovery in the case of an AUV. Data telemetry to shore command posts is possible, dependent upon availability of telemetry systems. Data validation through short survey experimentation is recommended prior to execution of a full survey.

3.3.4 Sediment Profile Imaging (SPI) Camera

The Sediment Profile Imaging (SPI) camera was developed to take photographs of a “slice” of bottom sediment. The SPI camera is a specialty tool and, as a consequence, is not readily available from hire or lease operators in the offshore oil industry. However, SPI equipment is available with skilled operators from geotechnical survey firms on short notice. The maximum penetration of the SPI is 8 in. (20 cm). If the sunken oil is below this depth, it will not be effective. Depending on the oil amount and stickiness, fouling of the lens may occur.

Although the SPI camera was originally designed for deeper water sediment and benthic community analysis, variants of the original design have been created for use in shallow water. Very shallow water operation of the SPI requires two operators to press the device into the bottom as seen in Figure 3-3.

The SPI camera provides a visual representation of the bottom sediments and benthic community. Because of the discrete data sample collection methodology, area coverage rates are low, necessitating development of a sampling strategy for optimum coverage of areas of interest. The operator must be aware that bulk oil may foul the camera lens.

3.3.5 Acoustic Camera

An alternative to optical and laser systems is a very high-frequency and high-resolution imaging sonar, referred to as an “acoustic camera”, sometimes referred to using the product name of “Didson” or “AIRES” (Sound Metrics, 2015). These cameras provide an acoustic image very similar to an optical video system in real time and have the ability to detect contacts of varying specific gravity, such as entrained oil, in the water column. Acoustic cameras are available on Inspection Class ROVs commonly utilized in the offshore oil industry and can be sourced with the ROV for lease or hire from equipment rental companies or survey companies.



Figure 3.3—Example of SPI Deployment in Shallow Water (Germano & Associates, Inc.)

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The value of these acoustic cameras is that the units can function in very high turbidity conditions that would completely defeat an optical camera or video. Consequently, there are few environmental limitations. However, these units are sonars and require ground truth to obtain positive identification of a potential submerged or sunken oil target.

The principal limitation of the acoustic camera is that the unit is a sonar with all associated sonar issues. However, in environmental conditions that limit the application of optical cameras, both still and video, the acoustic camera is a viable alternative. Acoustic cameras provide an imaging capability in environmental situations where turbidity in the water precludes the use of optical cameras.

3.3.6 Underwater Visualization Systems Summary

The advantages and disadvantages of underwater visualization systems include the following.

Advantages	Disadvantages
Digital Still Camera	
— Very high resolution images.	— Discrete images do not provide continuous images of the sea bottom. — Water turbidity limits effectiveness.
Video Camera	
— Provides continuous color or b/w images of the bottom. — Low light b/w cameras facilitate imaging in high turbidity conditions by eliminating requirement for light sources .	— Water turbidity limits effectiveness.
Sediment Profile Imaging Camera	
— Provides digital images of shallow sub-bottom for identification of sunken oil or buried oil layers and benthic communities.	— Fouling of SPI window due to oil in water column or sunken oil on sea bottom. — Samples only a very small area on the bottom.
Acoustic Camera	
— Provides acoustic imaging in very high turbidity water conditions. — Could be deployed at a site to monitor sunken oil behavior over time or during remobilization events such as storms.	— Acoustic images have limited resolution when compared to optical images.

3.4 Diver Observations

Divers have served in both sunken oil observation and recovery roles during numerous historical sunken oil detection and recovery operations discussed in this report (see Table 2-6). Commercial divers have helmet-mounted cameras that provide hands-free video to the surface. In low- to no-visibility conditions, divers can often detect sunken oil “by feel”. Additionally, divers can measure oil thickness and the extent of contamination, whereas remote sensing techniques are often unable to quantify the thickness of oil on the bottom or detect buried oil. Finally, direct communications with the diver allow immediate feedback on bottom conditions and the ability to direct underwater workers to take measurements, oil samples, and other work tasks. Potential operational limitations include limited bottom-time based on depth, the length of the diver’s umbilical may require repositioning the support vessel, and environmental conditions such as high sea states and excessive current that may delay or prevent diving operations. Decontamination, as shown in Figure 3-4, can be a challenge. Section 6.0, entitled “*Diving in Contaminated Water*,” should be referenced to protect the safety and health of the divers assigned to complete this work.

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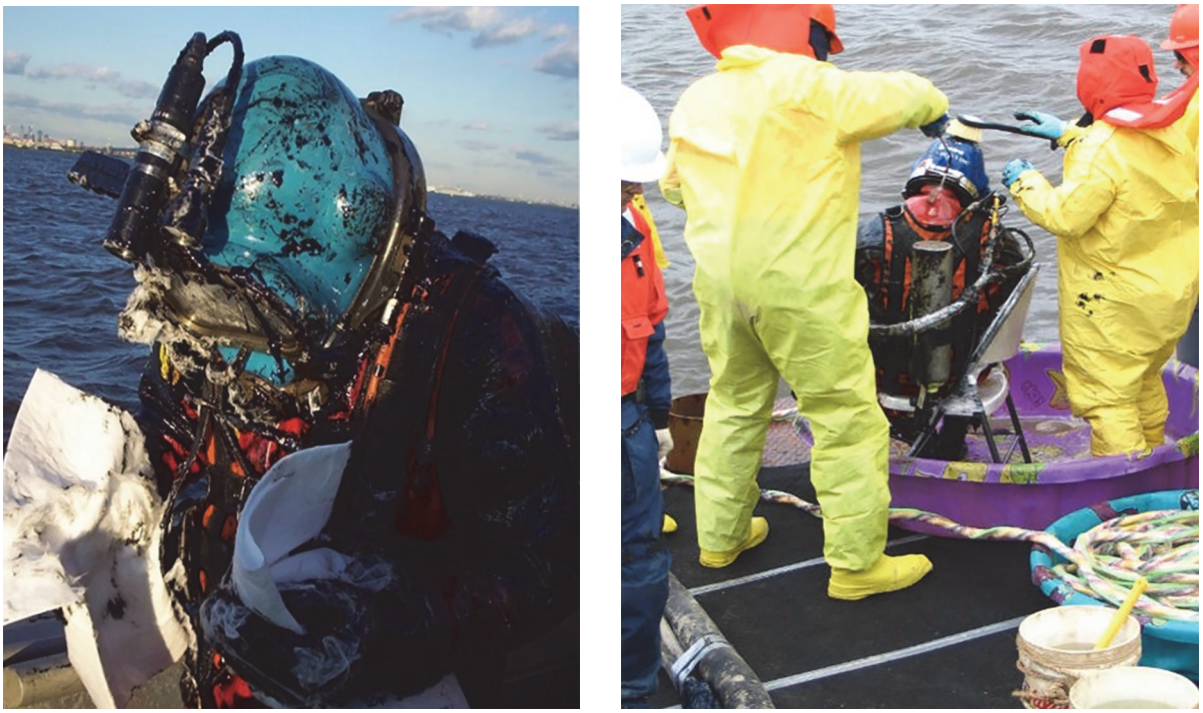


Figure 3-4—Contamination of Divers and the Decontamination Process (Elliott, 2004)

The advantages and disadvantages of diver observations for sunken oil detection include the following.

Advantages	Disadvantages
Diver Observations	
— Proven effective in successfully detecting, mapping, and recovering sunken oil on the majority of documented case studies (reference Table 2-6 and Table 2-7). — Quick turnaround on data; divers provide real-time imagery to the surface, may be directed by the diving supervisor and technical specialists while on the bottom, and can immediately communicate observations to the surface. — Often effective in low to no visibility conditions; divers can feel the oil and changes in bottom topography. — Accurate determination of oil on bottom; can provide verbal and visual description of extent and thickness of oil and spatial variations. — Experienced river divers can conduct detection and recovery operations in high current environments that typically restrict ROV operations or may restrict towed systems due to bottom obstructions. Salvage divers may prevent additional oil outflow by patching the vessel hull or hot-tapping the damaged tank. — Submersibles and one-atmosphere diving suits may be used to increase depths and bottom times. — Low false positives.	— Environmental limitations may include sea state, currents, weather/lightening, water depth, ice/cold water, debris, and dangerous marine life. — Surface-supplied air diving is limited to 190 ft of salt water (fsw) in the US. Mixed gas, saturation systems, and one-atmosphere suits or submersibles may be used to increase bottom time and depth; however, these systems will increase project complexity and cost. — Time limitations based on depth. For example, at 60 fsw an air diver is limited to 60 minutes for no-decompression diving. — Procedures must be implemented and strictly enforced to prevent oil and other contaminants from entering a hyperbaric chamber. Oil contamination is a fire hazard in a hyperbaric chamber. Additionally, oil contamination poses a respiratory hazard for personnel in a hyperbaric chamber. — Coverage rate; the length of the diver's umbilical limits movement away from the dive support vessel. — Contaminated water diving requires special equipment, training, and decontamination procedures. — Diving in high-current rivers and ice/cold water requires special training, additional equipment (such as hot water suits and dry suits), and experienced divers (reference Table 6-5). — Slow; diver movements may be limited by umbilical length and environmental conditions. — Divers must be replaced routinely to remain within no-decompression limitations and work/rest standards.

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3.5 Sorbents

3.5.1 General

Certain types of sorbents (such as oil snare or pompoms) are very effective at adsorbing heavy, viscous oils even under water. Though admittedly low tech, they are often used to detect the presence of sunken oil on the bottom and the movement of sunken oil in the water column, as described in the following sections. White snare (known as “first run” snare and has to be special ordered) is required to improve oil detection. Prior to use of the method, tests should be conducted to confirm that the spilled oil does adhere to the sorbent under water. Spill-specific pictorial guides for oiling degree can be developed to improve consistency among observers and over time.

3.5.2 Towed Sorbent Tactics

Snares are attached to various configurations of chains (heavy = multiple chains attached to a header bar or light = a single chain) and dragged along the bottom at set intervals, then brought to the surface for visual description of the type and degree of oil (Figure 3-5). This tactic is sometimes referred to as Vessel-Submerged Oil Recovery System (V-SORs).



Top Left: After a tow in the Delaware River at the 2005 T/V *Athos 1* spill (USCG).

Top Right: Before deployment at the 2007 M/V *Cosco Busan* spill (USACE).

Bottom: V-SORs “light” at the 2005 T/B *DBL-152* spill (M. Ploen, QualiTech).

Figure 3-5—V-SORs Used to Detect Oil On the Bottom

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