Sunken Oil Detection and Recovery

API TECHNICAL REPORT 1154-1
FIRST EDITION, FEBRUARY 2016

AMERICAN PETROLEUM INSTITUTE

Special Notes

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

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

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

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

Foreword

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

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

Contents

Figures

Tables

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.

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.

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.

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

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

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).

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

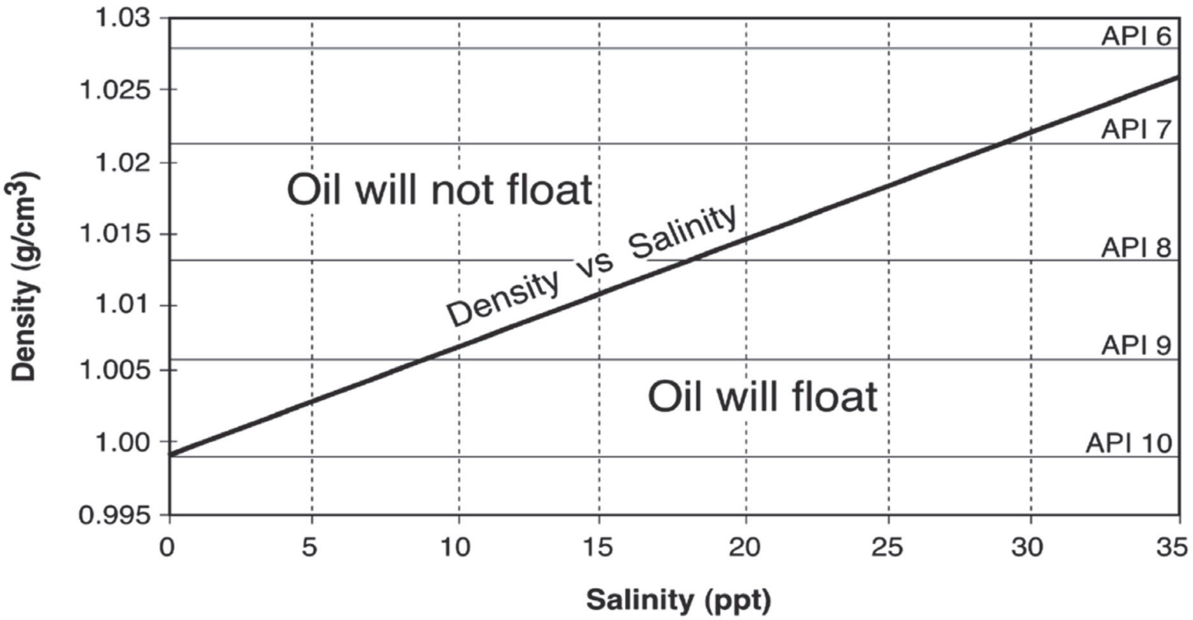
3) Sediment interactions

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.

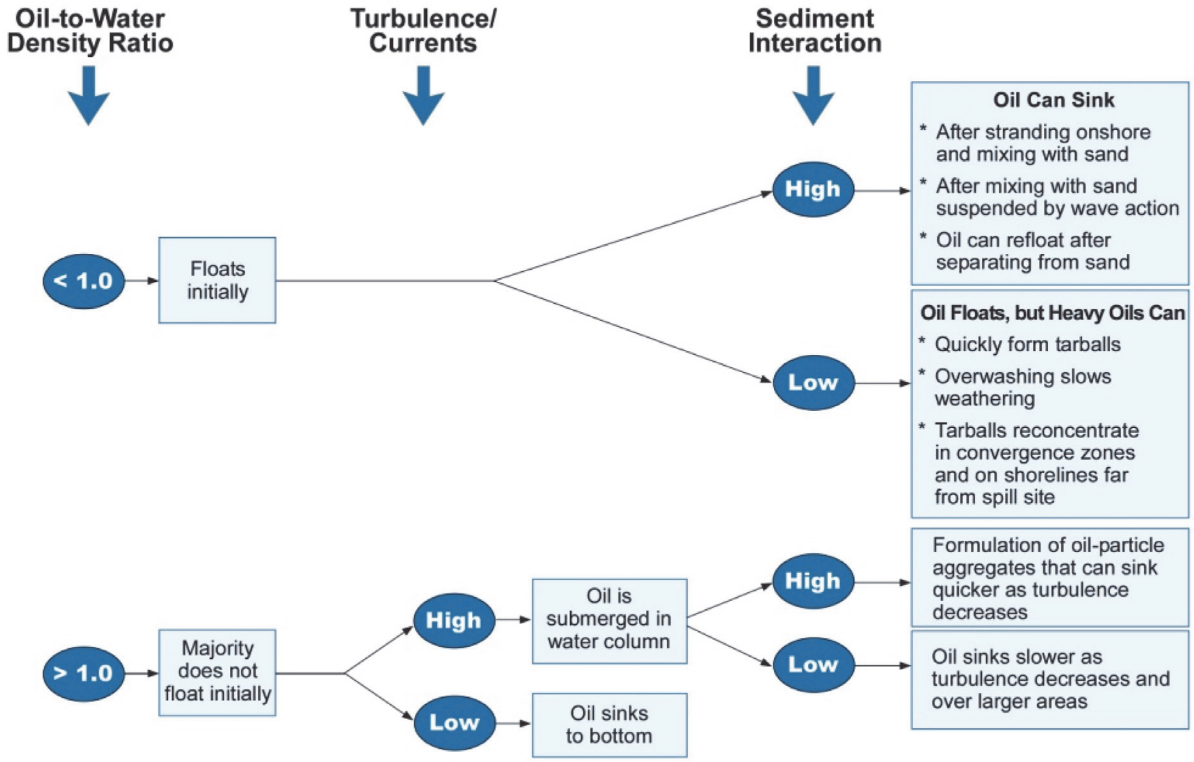
NOTE Specific gravity for API calculations is always determined at 60°F as: API gravity = (141.5/Specific Gravity) – 131.5.

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.



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

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.

— 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).

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).

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).

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.

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).

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).

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).

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).

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).

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.

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	

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**	

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:

- 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.

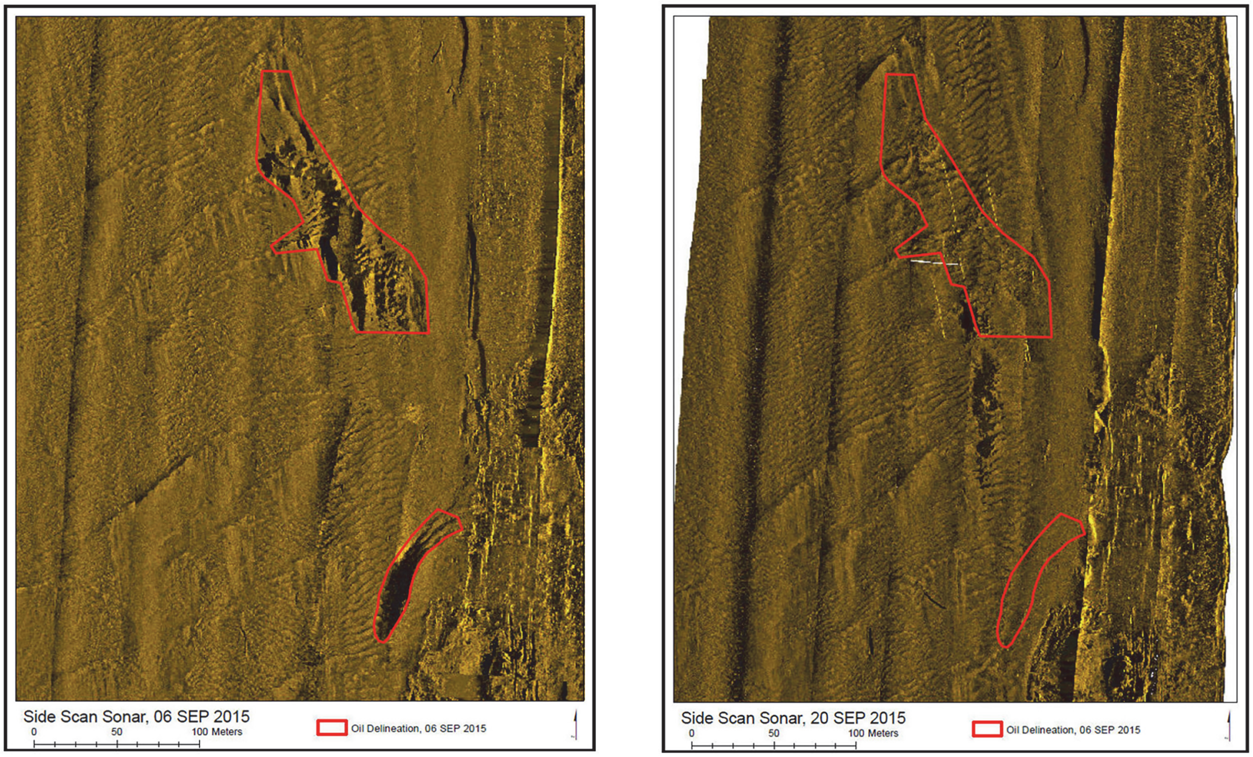
As indicated both in the literature and with anecdotal information, sunken oil can be detected utilizing side scan sonar, as discussed in the case study of the recent T/B *Apex 3580* spill and as seen in Figure 3-1. This detection capability and the high area coverage rates obtainable with side scan 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.

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

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 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.

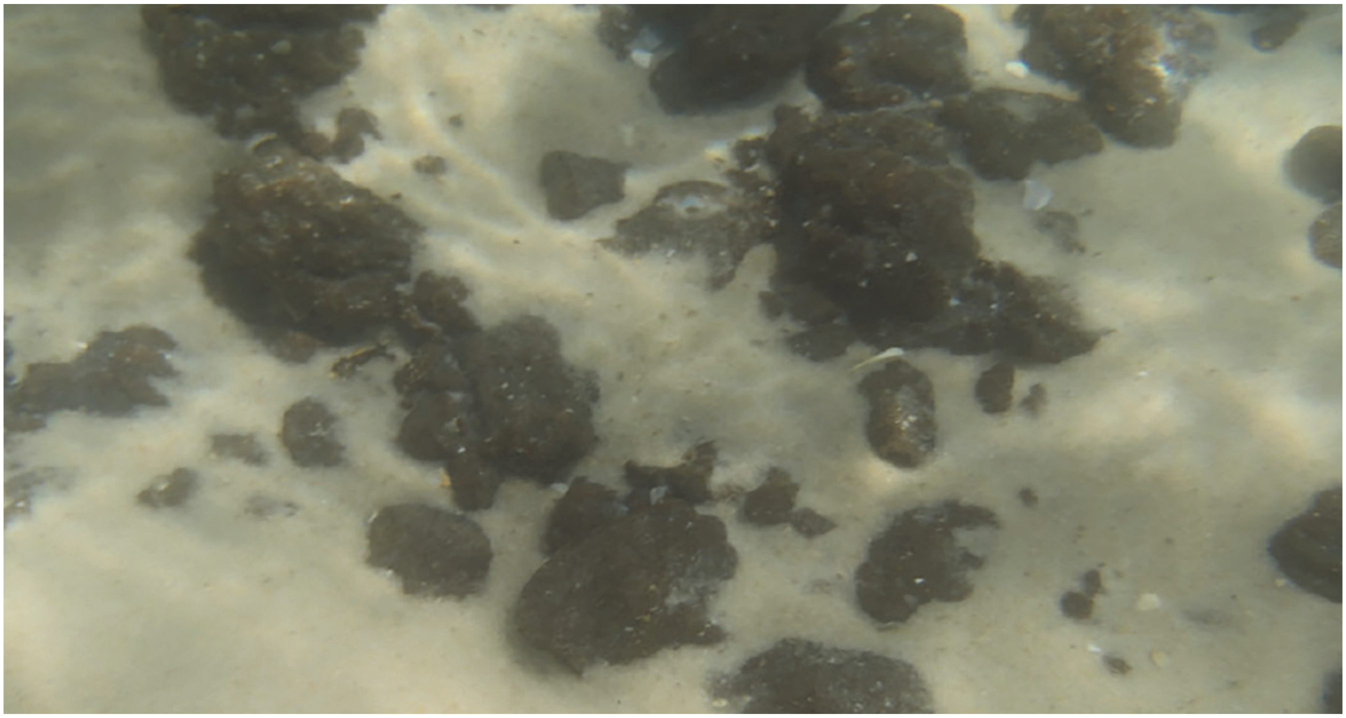


Figure 3-2—Photograph of Partially Buried Oil Mat (*Deepwater Horizon* SCAT Program)

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.

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.)

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.

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.

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

The advantages and disadvantages of towed sorbents for sunken oil detection include the following.

Advantages	Disadvantages
***Towed Sorbents (Heavy)*: Sorbents Attached To Multiple Chains Attached To a Header Bar**	
— Can be towed at up to 5 knots, though usually 3 to 4 knots, thus able to cover a large distance. — Area swept is about 8 ft. — Higher confidence that it maintains bottom contact. — Can vary the length of the trawl to refine spatial extent, to some degree. — Good positioning capability with onboard GPS; can load assigned tracks into the vessel navigation system. — Can be used in vessel traffic lanes.	— Requires larger vessel with crane or A-frame and pulley to deploy/retrieve. — Lots of concern about pipeline and debris snagging. — Cannot determine where along the trawl the oil occurred; no calibration with actual amount of oil on bottom. — Longer transects because of handling difficulty. — Highly dependent on wave conditions.
***Towed Sorbents (Light)*: Sorbents Attached To a Single Chain**	
— Manually deployed so can be used on smaller boats. — Can have very short trawls, if needed. — Can conduct continuous surveys without stopping, towed at 2 to 3 knots.	— Narrow swath (~1 ft) so less information on patchy oil. — Highly dependent on wave conditions. — Concerns about it losing contact with the bottom with wave action. — Cannot determine where along the trawl the oil occurred. — No calibration with actual amount of oil on bottom.

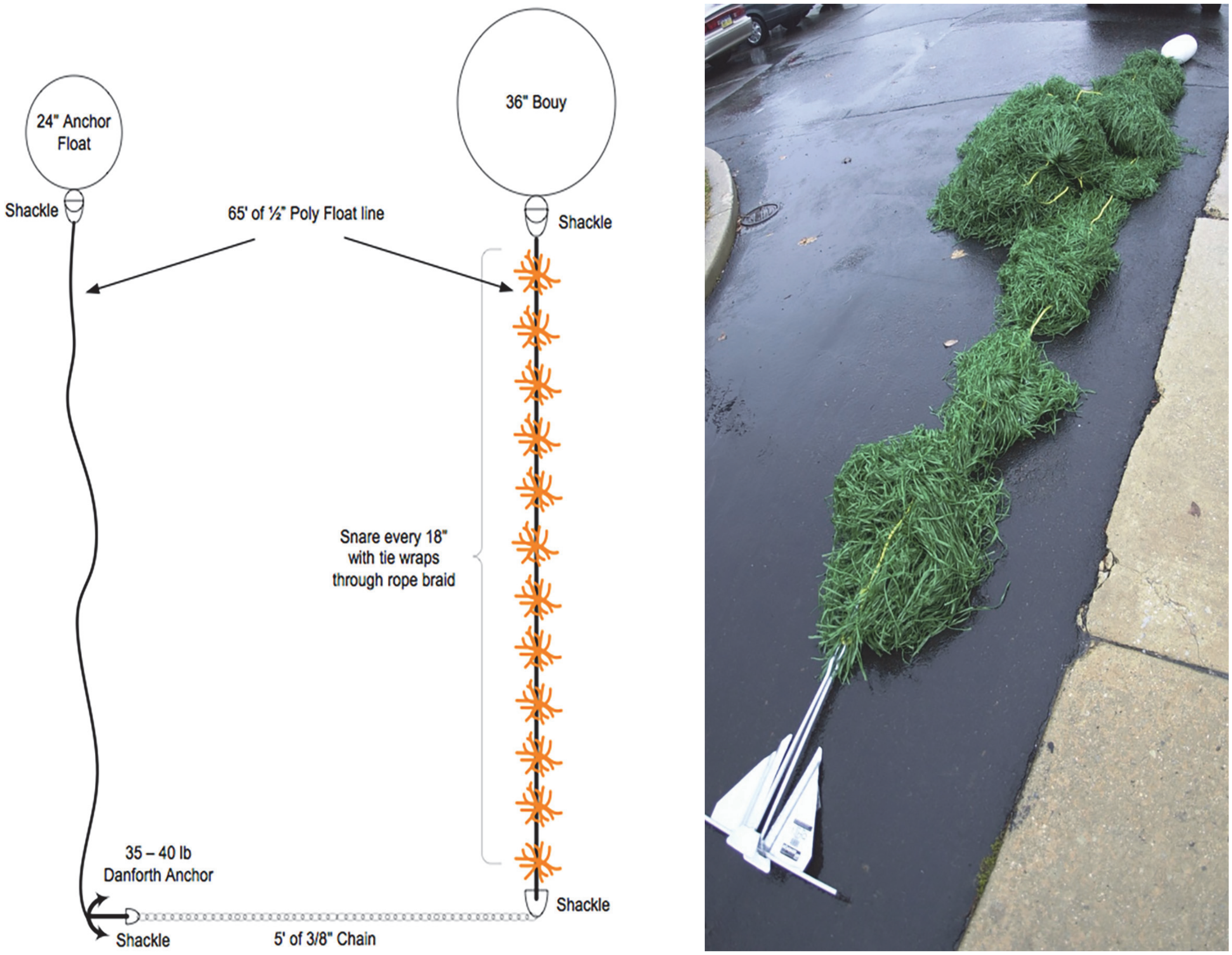
3.5.3 Stationary Sorbent Tactics

Sunken oil can become suspended in the water column during storms, when waves generate turbulence that mobilizes the oil, as occurred during the T/B *DBL-152*. River and tidal currents can also re-suspend sunken oil. Sunken oil could also become mobilized during recovery operations. Therefore, one method to monitor for the spread of the oil in the water column and along the bottom is to deploy stationary sorbents.

Snares are attached to a rope and suspended from the water surface to the bottom (Figure 3-6). Variations include placing the snare in crab/lobster pots or minnow/eel traps either on the bottom or at selected water depths (Figure 3-7). They were deployed in water depths up to 50 ft during the *DBL-152*, though with high loss rates. They would be difficult to use in water depths greater than 100 ft. They can also be configured as a snare fence (in low currents) or a rigid steel frame (in higher currents) (Figure 3-7); however, the efficacy of this type of deployment is not known. The three times that filter fences were deployed, no oil recovery on the sorbent was reported, meaning either: 1) no oil was mobilized; or 2) no oil adhered to the sorbents.

The advantages and disadvantages of stationary sorbents for sunken oil detection are:

Advantages	Disadvantages
Stationary Sorbents – Detection of oil in the Water Column or Along the Bottom	
— Proven to be effective at detecting oil at various depths in the water column and moving along the bottom. — Time-series data very useful to track trends, though requires a lot of data points to be meaningful. — Can be re-deployed as needed as the oil migrates down current.	— Time and labor intensive for deployment, inspection, and replacement. — Can have high loss rates. — No calibration of the efficacy of oil adsorption and it might change over time. — Can not be deployed in active vessel traffic lanes. — Low temporal data on when the oil was mobilized.



Left: Diagram of the design used during the T/B *DBL-152* spill.

Right: Photograph of unit used during the T/V *Athos 1* spill (USCG).

Figure 3-6—Stationary Sorbents

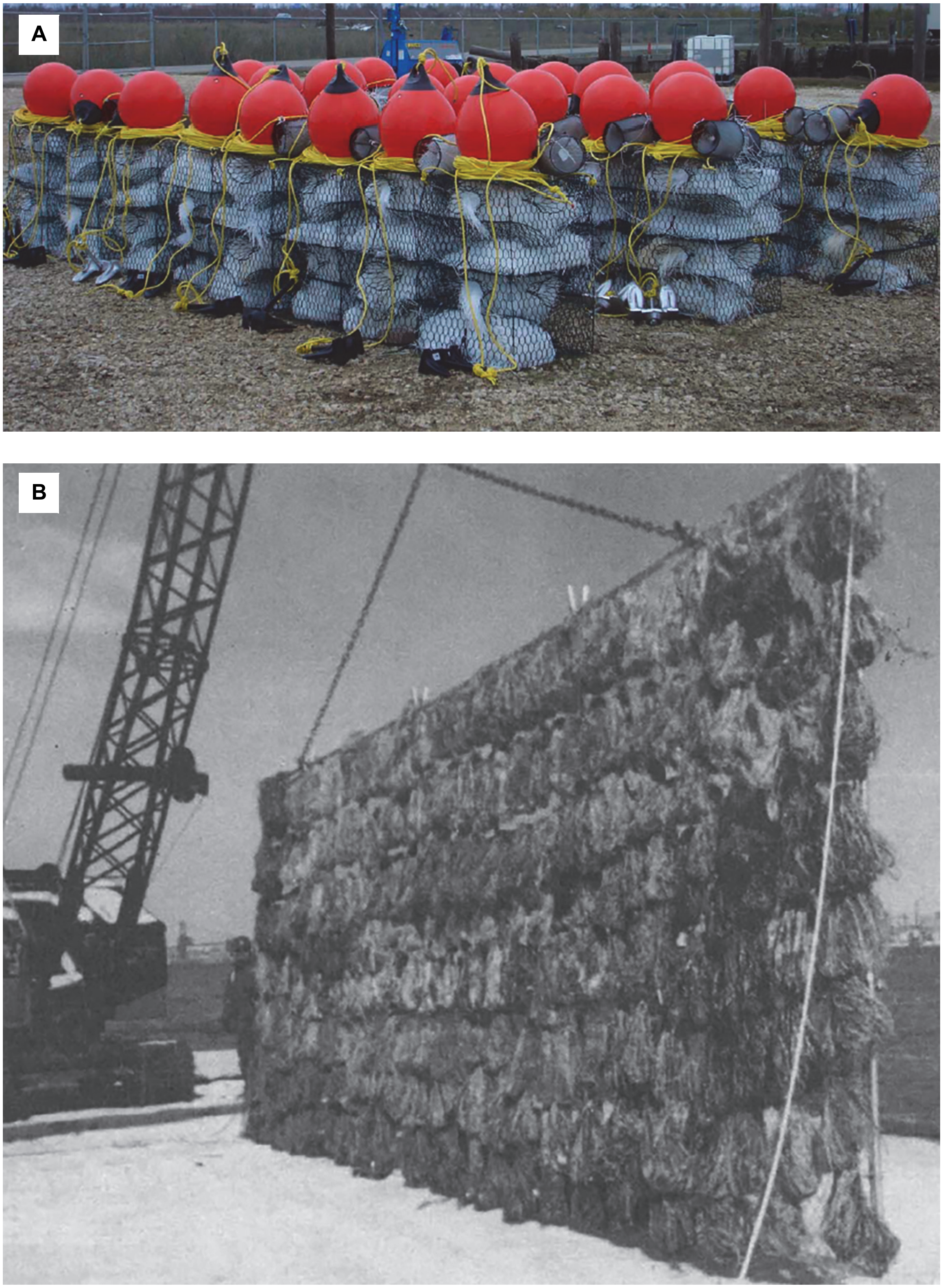
3.6 Visual Observations by Trained Observers from Above the Water Surface

3.6.1 General

Trained observers can be rapidly deployed and integrate a lot of data into information about sunken oil, as long as the oil is visible to the observer. Observations can be from aircraft or from the water surface. Observation by divers is discussed in Section 3.4.

3.6.2 Aerial Observations

In clear, shallow water, trained observers can search for and detect sunken oil accumulations of the sediment surface by aerial observations. The flight path and waypoints of general locations of sunken oil are collected by a GPS receiver and noted on maps or charts. Polarized sunglasses or rotating a polarizing lens on a camera can be used to remove sun glint and improve sunken oil detection. Buried oil cannot be detected with this technique. Natural materials, such as sunken seaweed, seagrass beds, and schools of bait fish, can look like sunken oil; therefore, ground surveys are needed to confirm aerial observations.



Top: Snare-stuff crab pots at the T/B *DBL-152* (M. Ploen, QualiTech).

Bottom: Snare filter fence at the Detroit River spill (Helland et al., 1997; Marine Pollution Control Corp.)

Figure 3-7—Sorbents Used To Detect Oil in the Water Column

3.6.3 Water Surface Observations

In clear, shallow water, where observers can see the bottom using underwater viewers (Figure 3-8), systematic surveys are conducted along predetermined transects. The actual transect and waypoints of sunken oil are collected by GPS. SCAT-type forms are used to record the size, percent cover, or number of oil deposits along the transect. The results are plotted as track lines and spill-specific oiling degree categories that can be used to determine the need for removal.

Figure 3-8—Sunken Oil Detection Using Underwater Viewers at Lake Wabamun (E. Owens, OCC)

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

Advantages	Disadvantages
Visual Observations by Trained Observers	
— Aerial surveys can cover large areas quickly. — Data are collected in real time, rather than having to view video post-collection. — Observers can adjust their survey once sunken oil is located for better detail. — During water surface surveys, it is possible to stop to take samples to confirm an observation as oil and take photographs.	— Only effective in clear, shallow water during daylight hours. — Not effective for buried oil. — Aerial observations will only identify general areas for ground truthing and more detailed assessment. — Aerial observations are not effective for small, patchy accumulations. — Water surface observations collect data along narrow transects so of limited spatial detail. — Even trained observers can make false positive or negative observations.

3.7 Bottom Sampling

3.7.1 General

Sunken oil can be detected using sediment grab or core samplers, wading-depth shovel pits, or agitation methods. Limitations as a stand-alone method include the very small sample area (often 6 in. x 6 in. or less), potential for the oil to be pushed away by the wake of the grab sampler or coring device as it impacts the bottom, labor and time needed to cover even small areas, large resources needed for work in deep water, and sea/weather restrictions. A more likely use of grab samples or coring device is to confirm the presence of oil detected by other means and to collect a sample for chemical and physical characterization. Wading-depth shovel pits are most effective when surveying the nearshore areas in the surf zone. Where sunken oil can be made to refloat by agitation of the bottom sediments, a method called poling can be used.

For all of these methods, if oil is detected, a grid pattern can be used to delineate the sunken oil using grab or core samplers over limited areas or following a statistically based random sampling scheme for larger areas. Each sample location should be documented using GPS.

Past Use: See Table 2-6, which shows past spills where bottom sampling was used to detect sunken oil.

3.7.2 Sediment Grab and Core Samplers

Bottom samples can be collected at almost any depth using the following.

— **Grab samplers**: Consist of a set of jaws that shut when lowered into the surface of the bottom sediment or a bucket that rotates into the sediment when it reaches the bottom. Grab samplers are relatively easy to handle and operate, readily available, moderately priced, and versatile in terms of the range of substrate types they can effectively sample. Their main limitations include sample depth (limited to 4 in. to 12 in.) and ability to penetrate into compacted sediments. However, this type of sampler would be preferred in all cases except where the oil is deeply buried, below the sampling depth of the unit; and

— **Core samplers**: Consist of a tube or box that is driven into the sediment by gravity, pistons, or vibration. Box corers can collect sediments up to 3 ft thick; gravity cores can take undisturbed cores of sediment to depths up to 10 ft in soft sediments; and vibracores can collect samples up to 30 ft in thickness. Most of the time, these samplers have to be deployed using a winch. For most core samplers (except a box corer), the sediment core has to be extruded or the tube cut open to observe the sediments. This type of sampler would best be used where the oil is deeply buried (greater than about 12 in.).

In shallow water, these samplers can be hand deployed; in deeper water, they are deployed from boats using a winch, crane, boom, A-frame, or other support equipment. Sediment cores have been taken in water thousands of feet deep, though working at these depths requires large and specialized systems and highly skilled operators.

3.7.3 Wading-depth Manual Shovel Pits

Operational situations in which other techniques prove to be unworkable due to shallow water depths in the surf zone depth, wading-depth manual techniques using shovels to dig shallow pits may be used for successful detection and delineation of buried oil mats (OSAT III, 2014). This technique was referred to as “Snorkel SCAT” during the *Deepwater Horizon* response because it was performed by Shoreline Cleanup Assessment Technique (SCAT) teams.

Water-resistant GPS portable Wide Area Augmentation System or WAAS-enabled receivers are deployed with each crew for precise positioning of each sample point. Processing and display of sampled data requires manual positioning of each sample, which by necessity requires long data processing times once the field data are checked for accuracy and completeness, then turned into a data manager for manual processing and display. The use of portable radios for near real-time transmission of the results of each sample datum could improve processing times. Figure 3-9 illustrates the final data product and the use of color to aid in the interpretation of the data.

Figure 3-9—Data Reduction and Display Sample for Snorkel SCAT During the *Deepwater Horizon* Response (Deepwater Horizon Unified Command, 2012)

Manual validation techniques are restricted to water depths typically no deeper than shoulder depth as seen in Figure 3-10. Strong currents, surf conditions, wind, and lightning are common safety concerns, with the halt of all operations when conditions exceed established limits. Detection is limited to the depth reached by the shovel, so there can be false negatives if the oil is buried deeper.

The following survey technique is summarized from *SCAT OSAT III* (2013) as applied during the *Deepwater Horizon* oil spill.

A normal "Snorkel SCAT" team has one GPS operator; two shovel technicians; one data recorder; two safety boat crewmen (the safety boat is normally a rigid inflatable boat with motor); and one communications technician. The sample methodology for Snorkel SCAT investigations includes:

— an initial assessment of the shoreline oiling in the surf zone;

— shovel pit transects along the shoreline and inside the first sand bar;

— shovel pit transects outside the first sand bar (surf conditions permitting).

Transects can be located offshore areas of shoreline oil stranding (one indicator of nearshore oil mats) or in areas identified as having a high probability of buried oil by other means. Data are collected along transects that are 30 ft apart, with the sample taken at the top of the swash zone, on the plunge line, then roughly every 15 ft. These grids can be modified based on special instructions or specific shoreline or oiling conditions. A narrow blade shovel has been demonstrated to be best for collecting samples. Two samples are collected from either side of the GPS person, and the highest distribution is recorded. The information recorded on forms for each site includes:

— GPS coordinates of the site;

Top: “Snorkel SCAT Team in the field.

Bottom: Oil mats and residue balls (*Deepwater Horizon* SCAT Program).

Figure 3-10—Wading-depth Manual Shovel Pits to Detect and Delineate Oil Mats During the *Deepwater Horizon* Spill Response

- substrate material;
- surface oiling description (% distribution, oil type);
- subsurface oiling description (% distribution in each interval from the surface, oil type).

In dynamic environments, elevation points would be highly valuable to be able to determine depth of burial over time.

If oil on or below the bottom is observed, then additional shovel pits are taken to delineate the extent of the oil. Depending on the site conditions, the teams can work closely with removal operations, directing the removal to specific locations and confirming completeness of removal actions by repeat shovel pits. However, it is important to note that there can be false negatives if the oil is buried deeper than can be surveyed by digging.

3.7.4 Detection by Poling or Sticking

Where the sunken oil can be made to rise to the surface when the sediments are disturbed, a method referred to as "poling" can be used in shallow water. Poling involved inserting a graduated metal pole equipped with a disk on the end into the sediment (Figure 3-11), agitating the sediments in a standard manner, and recording observations for:

- depth to soft sediment (i.e. first contact with subsurface resistance);
- estimated thickness of soft sediment (determined through additional pushes of the poling device with more force); and
- oil/sheen manifestation on the water surface.

Figure 3-11—Poling to Detect Sunken Oil in the Kalamazoo River (F. Fitzpatrick, USGS)

A spill-specific set of metrics would be developed to describe the type and amount of oil released to the surface, such as the number of oil globules and extent of sheen production in a 1 m^2 surrounding the poling location. Waypoints can be generated according to the survey plan and preloaded onto GPS receivers. Poling can be conducted by boat or by wading in very shallow water.

Where the sunken oil is very viscous, and the water clarity almost nil, a method referred to as "sticking" may be used. Divers insert a pike pole into the bottom and use the differences in penetration and feel to differentiate among hard bedrock, soft sediments, and viscous oil on the bottom. This method has been used during asphalt spills, such as the T/B *MM-53.*

The advantages and disadvantages of bottom sampling for sunken oil detection include the following.

Advantages	Disadvantages
Bottom Sampling	
— Allows collection of samples to confirm the presence of oil, either visually or through chemical analysis. — Can be effective in small areas for rapid delineation of a known patch of oil. — Poling method indicated the relative risk of sheening of sunken oil. — Can detect buried oil and oil thickness.	— Only point sample of a very small area. — Not effective in patchy oiling conditions. — Very slow and labor intensive. — Even slower in deep water, rough sea conditions. — Oil may be buried deeper than the sampler can penetrate into the bottom. — Must use a statistically relevant sampling grid to be useful.

3.8 Laser Fluorosensors

3.8.1 General

Laser fluorosensors detect oil by aiming a laser (a high-energy source of light), usually in the ultraviolet portion of the spectrum, at the oil. The aromatic compounds in petroleum oils absorb this light, become excited, and emit light in the visible portion of the spectrum that has a unique pattern that can be quantified. They are highly sensitive, have few false positives, and can be used during day or night. Historically, laser fluorosensors have been large systems that could only be deployed on large aircraft for detection of surface slicks (Brown, 2011). The USCG tested two prototype systems designed for in-water operations, and they determined that laser fluorosensors had a promising role in the detection of oil underwater (Hanson et al., 2009).

Past Use: Tested during the *Deepwater Horizon.*

3.8.2 Airborne Sensors

The USCG tested three very different laser fluorosensors designed for airborne deployment at the OHMSETT large test tank in 2005. The tests showed that these sensors could detect oil in clear water to depths of 6.5 ft (Fant and Hanson, 2006). However, detection decreases significantly with increased water depth and wave height, and particularly with water turbidity. Also the bright light reflected off the white tanks walls interfered with the laser line scan system.

3.8.3 In-water Sensors

The USCG tested two underwater laser fluorosensors (Laser Line Scan System and Fluorescence Polarization system) in the OHMSETT tank in 2007-2008. Both systems were able to detect sunken oil in test trays; however, each required further development to meet the USCG minimum requirements. The Fluorescence Polarization system was tested during the *Deepwater Horizon* response to detect submerged oil mats and oil suspended in the water column by wave action, in water depths of 3 ft to 33 ft, and did detect oil suspended in the water column (GCIMT, 2010). These systems have a very narrow swath of coverage, cannot detect oil that is buried, and are of limited use in turbid water. The best potential application is to use these sensors in combination with other techniques that cover larger areas to locate possible sunken oil deposits on the surface. The laser fluorosensor can then be used to confirm if the target is oil. The advantages and disadvantages of laser fluorosensors for sunken oil detection include the following.

Advantages	**Disadvantages**
Laser Fluorosensors	
— Highly sensitive to oil. — Generates few false positives once calibrated for the sunken oil. — Can be used during day or night.	— Cannot detect buried oil. — Detection ability decreases with water turbidity, distance from the target, and wave height. — Bright, backscattered light (such as from white sand) may saturate the input. — Only one prototype system available, and the latest model has not been tested.

3.9 Other Techniques

3.9.1 Water-column Sampling

Two types of instruments that detect hydrocarbons in the water column have been tested or used to locate sunken oil deposits: flow-through fluorometers and real-time mass spectrometers. The premise is that the sunken oil will release dissolved hydrocarbon plumes or oil droplets into the overlying water column. The instruments are deployed on an ROV or AUV with an underwater navigation system just above the bottom and continuously measure the hydrocarbon concentration in the water along track lines.

Past Use: *Deepwater Horizon*, tank tests.

The use of fluorometry to detect oil in the water column is a well-established method for monitoring dispersant effectiveness and is used in many other applications. The fluorometer emits ultraviolet (UV) light. When aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and toluene (BTEX) and polyaromatic hydrocarbons (PAHs) absorb the UV light, they emit fluorescent light at a longer wavelength. The intensity of the UV fluorescence light is a function of the amount of aromatic hydrocarbons in the water, and the intensity measured over the range of wavelengths can be used to fingerprint different types of oil and natural materials that also fluoresce. Conmey et al. (2014) tested five submersible fluorometer instruments, and all of them were able to detect oil concentrations down to 300 parts per billion (ppb). Operationally, oil detection is usually indicated by an increase above background intensity.

During the *Deepwater Horizon* response, submersible fluorometers were towed along 410 nautical miles in bays and sounds from Florida to Mississippi in August 2010 to search for recoverable sunken oil, with no detections noted (GCIMT, 2010).

Mass spectrometers are capable of detecting individual hydrocarbons in water at concentrations to less than 1 ppb, and their use and availability have expanded in the last several years, particularly for oil and gas exploration and water quality monitoring. A system consisting of a small mass spectrometer and a UV fluorometer (Camilli et al., 2009) was tested in a small FasTank as part of the USCG program to identify promising techniques of sunken oil detection. A second mass spectrometer system was also tested. Hanson et al. (2009) concluded that plumes of light tracer compounds (methane through butane) did diffuse from the sunken oil sources used in the tests and were detected by the mass spectrometer. However, they questioned how long sunken oil deposits in open water would actually release soluble compounds into the water column, and how these compounds would move away from the sunken oil source, with even low currents. With a small source strength, the equipment has to be deployed very close to the bottom (within a few feet), though bottom-following technologies are available on the latest AUVs. The in-water detection of soluble hydrocarbons by mass spectrometry is a promising approach for searching large areas of the bottom for sunken oil; however, further development is needed to make it operational for emergency response.

Induced polarization is another promising method to detect oil in the water column. This technology is based on the electromagnetic differences between water and oil, which are quite large (Wynn and Fleming, 2012). Further testing is needed to determine its application to sunken oil conditions.

The advantages and disadvantages of water-column sampling for sunken oil detection include the following.

Advantages	Disadvantages
Water-column Sampling	
— Can provide geo-referenced oil locations in real time and at high spatial resolution. — Once oil is detected, the survey can be adapted to sample above potential targets. — Mass spectrometers can determine hydrocarbon composition, allowing differentiation among sources. — Can map gradients of oil levels in the water column, which could be used to identify areas of higher oil accumulations. — Submersible UV fluorometers are readily available and easily deployed and interpreted. — Submersible mass spectrometer technology and availability are improving. — Other sensors can be added to the vehicle to measure other parameters, e.g. salinity, dissolved oxygen, temperature.	— Only works if there are soluble components or small oil droplets in the water column. — The rate of release of soluble oil may decrease to non-detectable levels quickly. — Submersible mass spectrometers require a specially trained team of operators and interpreters.

3.9.2 Satellite Imagery

Satellite imagery is often used to detect oil on the water surface and is a valuable tool for responders. API (2013) has a guide for using remote sensing technology during oil spill responses; however, it only addresses oil on the water surface because:

> *The science of oil spill remote sensing in the marine environment, below the surface of the water, is in the early stages of development. Although technology for subsurface oil detection and tracking exists, it has not been extensively tested or utilized in real-world scenarios.*

Furthermore, most of the technology development using remote sensing for subsurface oil is focused on detection of subsurface oil plumes, rather than sunken oil on the bottom of a waterbody.

3.10 Considerations for Sunken Oil Detection in Rivers and Extreme Cold Conditions

3.10.1 Sunken Oil Detection in Rivers

In rivers, oils that are heavier than water can become suspended in the water column in currents greater than about 0.2 knots. If the oil is liquid, it will form small droplets in the water column; if it is semi-solid, it will form larger masses. Where currents and turbulence slow, the suspended oil will sink to the bottom and coalesce into pools or masses that can be inches thick. Thus, initial surveys for sunken oil in rivers should focus on low-flow areas, such as:

— dredged berths or depressions created by prop scour at port facilities;

— dredged channels or pits;

— in the lee of a grounded vessel or other natural or man-made structures;

— side channels such as oxbows;

— at the mouths of streams entering a river, where there can be deeper areas that are scoured during high-flow events;

- where the river or stream enters an slack waterbody such as a reservoir or pond;
- upstream of locks;
- downstream of point bars;
- areas where the river widens or deepens resulting in reduced current and turbulence.

Responders should be aware that sunken oil can spread into depressions that are “up river” of the release site under low-flow conditions, such as occurred during the Degussa Engineered Carbons spill in the Ohio River in 2008.

Bottom debris in rivers poses particular concerns with sunken oil detection, including the following.

- Interference with the ability of sonar to detect the oil, because the debris protruding above the bottom will provide a stronger return signal and sunken oil trapped below it. Bottom debris is also an entanglement hazard for ROVs and towed systems.
- Diver safety issues; swift current are typically associated with limited to no visibility for the diver. As a result, divers may become entangled in bottom debris and/or the diver umbilical may become fouled. Additionally, particularly during flood and high water events, submerged debris and objects flowing down river in the water column pose a threat to the diver’s safety.
- Snagging when towing V-SORS for detection.
- Cable snag or entanglement when using underwater cameras or ROVs.

Response operations on rivers are challenging because of limited access points for equipment and worker deployment, variable flow rates and water depths, conflicts with navigational use (vessel wakes can pose safety issues and cause equipment to fail), hazards associated with vessel operations, particularly by operators who may not be familiar with the waterbody, and seasonal constraints associated with cold water/ice conditions. Though vessels are commonly used during the initial mobilization for a river spill, so responders can be mobile as the oil spreads downriver, once the oil sinks, it is recommended that spud barges or similar platforms be brought in to provide a safe and stable working base at assessment sites.

In addition to current variations and limitations, entanglement hazards, and low visibility for remotely operated vehicles in riverine environments, salinity should also be considered as it may vary substantially near river mouths, in tidal estuaries, and near outfalls. The resulting variation in water density may affect ROV buoyancy, trim, and accuracy in sonar data (ADCI, 2014).

Diving operations in riverine and other high-current environments are considered hazardous and should only be conducted by professional commercial divers experienced in low-visibility, high-current operations. SCUBA diving should never be permitted in this type of environment. Divers often over estimate personal diving skills while also underestimating the physical force of moving water. Specific hazards when conducting diving operations in riverine systems include the following.

- Entanglement and umbilical fouling on bottom debris.
- Unanticipated changes in current direction and intensity.
- Submerged debris and objects flowing downstream in the water column.
- Entrapment concerns around dikes, dams and jetties. The current around these structures is often strong and unpredictable.
- Lacerations and puncture wounds on bottom debris.
- Moving water increases diver heat loss and may require additional thermal protection.

— Increased physical exertion by the diver may limit bottom time and should be addressed in work/rest considerations in the safety plan.

— Operations are often conducted in remote locations that will require the ability to conduct diver emergency treatment on-site, including placing a decompression chamber at the work site with a diving medical technician (DMT) in attendance.

3.10.2 Sunken Oil Detection in Extreme Cold Conditions

Extreme cold conditions are defined here as when the waterbody is frozen over by ice, air temperatures are below freezing, or thick snow accumulations. These conditions pose unique challenges to responders who are not experienced in spill response under these conditions. Floating oil response during extreme cold conditions is difficult; locating sunken oil under these conditions is even more challenging. Consider the following issues during the detection phase of a sunken oil response during extreme cold conditions.

— Use arctic-grade equipment and supplies such as arctic-grade hoses. Use crank case and battery heaters on combustion engine driven equipment. Diesel fuel and hydraulic and lube oils can gel in extreme cold conditions causing equipment failure.

— Hot houses on work platforms where workers can warm up.

— Additional protective equipment is required for diving operations, such as a dry suit or hot water suit to prevent hyperthermia.

— Equipment and trained personnel to determine ice thickness and load-bearing capacity each day.

— Equipment and trained personnel to cut ice slots for diver access and detection equipment deployment.

AUVs are capable of routine under ice operation, where they can perform largely independent of ice thickness, roughness, and other physical process in a generally quiescent water environment free of the effects of weather that may affect operations on the open-water surface. Sonars, still cameras, and/or video cameras can be deployed on an AUV to survey the bottom for sunken oil. All that is needed is an opening in the ice, which can be created using standard methods for ice slotting. ROVs could be similarly deployed to assess a specific location.

Underwater cameras developed for sport fishermen are readily available and can be used to locate oil on the river bottom during ice conditions. Small holes can be drilled through the ice with a hand or power auger and the camera can be appropriately weighted and lowered down to the river bottom. These small portable cameras come with a small monitor to allow real time viewing.

Diving below the ice and in cold water, defined by NOAA as <37 °F, is considered a hazardous operation and should only be conducted by professional commercial divers with experience in such operations. SCUBA diving should not be permitted. Of note, in 2006, the USCG lost two SCUBA divers that were attempting to conduct a 20-fsw dive in the arctic. The following should be considered when planning to conduct sunken oil detection operations in ice or cold-water conditions.

— Divers should wear appropriate thermal protection based on the water temperature and expected bottom time.

— A dry suit or hot-water suit should be worn to prevent hyperthermia.

— The dry suit or hot-water suit should fit properly; all seals should be inspected and in good condition.

— Severe chilling can result in impaired judgment. As such, the tasks to be performed under water must be simple and clearly defined, and the diver’s condition should be continually monitored.

— Keep the diver hydrated and minimize any additional exercise in cold water to try and stay warm. Exercise will cause the body temperature to fall more rapidly.

- Always abort the dive if the diver is showing even minor symptoms of hypothermia. Minor symptoms include uncontrolled shivering, slurred speech, imbalance, and/or poor judgment. Severe symptoms include loss of shivering, impaired mental status, irregular heartbeat, and/or very shallow pulse or respiration.

- Upon exiting cold water, do the following.

    1) If the diver is wearing a wet suit or hot-water suit, immediately flush the suit with warm water. Doing so will have a comforting, heat-replacing effect.

    2) Get the diver to a dry, warm area as soon as possible.

    3) The diver should remove any wet dress, dry off, and don warm, protective clothing as soon as possible.

    4) Hot, non-alcoholic beverages should be available for the diver.

- A decompression chamber and supplemental first-aid equipment to treat hyperthermia should be on-site during diving operations. 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.

- Topside personnel should wear warm, protective clothing. The dive tender should have a hand on the diver's umbilical at all times, the standby diver should be dressed-out and ready to enter the water, and the supervisor and topside crew should be prepared to take immediate action.

- Plan for diving operations in cold environments to take additional time in comparison to fair weather operations.

The Association of Diving Contractors International recommends the following special precautions for diving equipment when operating in cold environments.

- The moisture in air compressors and air lines must minimized to prevent freezing of the surface-supplied air system, which can cause catastrophic damage or failures.

- The dive crew should consider the use of high-pressure cylinders as an air supply, which generally will contain less moisture than air produced by a low-pressure compressor.

- Topside must continually empty the excess water out of the volume tank to help reduce the amount of moisture in the system.

- Do not allow the diver's umbilical to rest for long periods of time on cold surfaces (barge decks, etc.). Fittings on the umbilical can transfer the temperature from the cold surface and cause the moisture in the diver's umbilical to freeze.

- In water temperatures of 37 °F (3 °C) or less, first-stage regulator on bailouts should be equipped with a proper cold-water setup (environmental kit).

- Extra precautions must be taken to make sure that the bailout cylinders are completely dry inside, that moisture-free air is used, and that the regulator is thoroughly dried prior to use.

- If using a hot-water machine, careful attention must be exercised to monitor the output temperature of the hot-water machine. In extreme cold-water environments, the hot-water machine is classified as life-support equipment. Failure of the system can cause catastrophic results for the diver.

- Failure of the hot-water machine during decompression must be considered during the operation and dive plan.

— Gasoline and diesel engines must be cold-weather modified to prevent engine freeze-up.

— Use proper lubricants in the diver's air compressor.

— Use appropriate cold-temperature lubricants in pre-packed bearings.

— Bring extra batteries for equipment. Cold temperatures can shorten the life of a typical battery.

— A hypothermia-management kit should be considered.

— Extreme caution must be exercised when refueling in dry, cold weather. Static electricity should be "drained off" by grounding the equipment or fuel container (away from vapor openings) with the hand. Static electricity can form in the layers of clothing worn by personnel and can cause a spontaneous discharge of electricity, which can ignite fuels.

— Use funnels with a copper screen to help filter out ice particles and foreign debris.

3.11 Summary of Techniques for Sunken Oil Detection, Delineation, and Characterization

Effective techniques for sunken oil detection, delineation, and characterization vary based on the oil behavior, site conditions, and available resources. Table 3-1 provides a summary of the uses and limitations of sunken oil detection, delineation, and characterization techniques. Table 3-2 provides a matrix to assist in evaluation of detection techniques for specific spill conditions.

Table 3-1—Techniques For Sunken Oil Detection, Delineation, and Characterization

	Sonar Systems	Still, Video, and Acoustic Cameras	Diver Observations
Description	Sonar systems can detect and delineate sunken oil on and in the near sub-bottom areas.	Visualization devices are utilized to validate the presence of sunken oil.	Professional commercial divers can detect, delineate, and collect field data for oil characterization.
Availability of Equipment	Available from offshore oil or oceanographic equipment rental companies. The 3D sonar has limited availability in the commercial sector, but the USCG has a supply that could be made available upon request.	Visualization devices are available from offshore oil or oceanographic rental companies or direct from the manufacturer.	Surface-supplied diving systems with diver comms and video are readily available and required to be on-site within 18 hours for salvage operations. Contaminated-water and cold-water diving equipment may require additional time.
Logistical Needs	Support vessels of sufficient size and sea-keeping capability are required to provide an operational platform for the sonar systems. Different sonar systems have specific platform requirements so care must be taken in platform selection to ensure compatibility.	Visualization systems have definite platform requirements depending on technique selected. Diver-operated video devices have specific diver related logistic requirements as noted for Diver Observations, which must be adhered to.	Diving support vessel/platform; heavy-lift equipment to load compressors, dive control rooms, and other equipment onboard. Emergency transportation to a medical facility with a multi-place decompression chamber. Decompression chamber located on-site as a contingency.
Coverage Rate	Up to 3 square miles/hour using side scan sonar. Other sonar devices have lower coverage rates.	Up to 0.7 square miles/hour in low turbidity water with optics; lower coverage rates in high turbidity.	Low: Due to often limited visibility. Diver rate limited by umbilical length and repositioning of dive platform.
Data Turnaround	Most provide usable data in real or near real time for human analysis. Some require minimal post processing; data should be available by end of the survey.	Depending on the device utilized, data are available in real time or near real time.	Immediate turnaround with diver to surface communications and video capabilities.
Probability of False Positives	After ground truth of preliminary results, low false positive rates are obtainable.	Provides low false positive rates due to the ability of human interpretation of raw optical data.	Low probability since divers can verify observations.

Table 3-1—Techniques For Sunken Oil Detection, Delineation, and Characterization (Continued)

Operational Limitations	Water depth of 10 ft or less establishes an operation limitation on acoustic techniques, although operations in shallower water are possible in certain situations.	Water turbidity limits the functionality of visualization devices with the exception of the acoustic camera that functions in zero visibility with lesser resolution than optical devices.	Surface-supplied air diving is restricted to 190 fsw. Diving operations are limited by depth, bottom time, visibility, currents, and other environmental conditions.
Pros	Sonar systems are easy to use and have a high area coverage rate for fast establishment of sunken oil locations on the bottom.	Visualization techniques and devices provide visual validation of the presence of sunken oil without the requirement for ground truth of images.	Accurate, immediate observations can be conveyed to the surface. If visibility permits, real-time video can be viewed in the dive control house.
Cons	For absolute detection, sonar systems require a ground truth of the detected contact on the bottom to provide positive identification of sunken oil.	Increasing turbidity creates decreasing visibility until the acoustic camera is required which provides images of lesser resolution than optical techniques.	Diving in contaminated water is considered “high-risk”. The limitations above combined with diver decon requirements often result in a relatively high cost and time-consuming operation.
	Towed Sorbents	**Stationary Sorbents**	**Visual Observations by Trained Observers**
Description	Snares attached to chains are dragged on the bottom at set intervals then pulled up to detect oil presence/amount.	Sorbents are suspended in the water column and/or placed in cages on the bottom and inspected at set intervals to detect oil presence.	Observers visually detect and delineate oil on the bottom as seen from aircraft or boats.
Availability of Equipment	Ad hoc systems can be readily constructed. GPS units needed to follow pre-set track lines and record waypoint for intervals.	Ad hoc systems can be readily constructed in most areas, using anchors, floats, snares, and various pots/cages.	Uses readily available equipment.
Logistical Needs	Light tows (1 chain) can be deployed on small boats. Heavy tows (multiple chains with a header bar) require a vessel with a crane or A-frame and pulley to deploy/retrieve the tows.	In shallow water, requires minimal support. In deep water, requires davits or winches to deploy and retrieve them.	Aircraft or boat; GPS units to record locations and geo-reference photos; field computers to record descriptions.
Coverage Rate	Moderate: Can be towed at up to 5 knots but swath width is 1 ft to 8 ft, depending on how many chains are attached.	Low: Only provides point information.	Aerial surveys can cover large areas but in less detail. Boat surveys have low coverage rates.
Data Turnaround	Moderate: Oiling degree can be reported real time for each interval.	Slow: Data only available when the sorbents are retrieved.	Moderate: Field notes and waypoints have to be entered, raw data converted into oiling categories, and maps generated. Likely 24 hour turnaround.
Probability of False Positives	Low: It is easy to detect oil versus other fouling materials.	Low: It is easy to detect oil versus other fouling materials.	High for aerial surveys. Boat surveys have few false positives because samples can be collected to confirm the oil.
Operational Limitations	Standard safety limits for boat operations. No use possible in the surf zone or where snagging on the bottom is of concern. More difficult to deploy/retrieve in >100 ft water depths.	Standard safety limits for boat operations. No use possible in the surf zone or vessel traffic lanes. More difficult to deploy/retrieve in >100 ft water depths.	Can only be used during daylight periods. Standard safety limits for aerial and boat operations, including no surveys possible in the surf zone.
Pros	Effective in low visibility conditions; can be used in vessel traffic lanes; can vary the tow length to refine spatial extent; can be used to confirm removal.	Proven effective at detection of oil moving at various depths in the water column; time-series data are useful to track trends; can be re-deployed as the oil migrates down current.	Aerial surveys can cover large areas quickly and can be adjusted once oil is found to get more detail.

Table 3-1—Techniques For Sunken Oil Detection, Delineation, and Characterization (Continued)

Cons	Do not know where along the tow the oil occurred or how much oil is present (one larger patch or lots of small patches); can not determine duration of bottom contact or efficacy of oil adhesion; labor intensive.	Very time and labor intensive; can have high loss rates; no calibration of the efficacy of oil adsorption and changes over time; can not be deployed in active vessel traffic lanes; low temporal data on when the oil was mobilized during the deployment.	Cannot detect buried oil; effective only in clear water and daylight; aerial surveys require ground truth; boat surveys are slow; not safe for work in surf zone or strong currents.

	Grab or Core Sampler	**Wading-Depth Manual Shovel Pits**	**Laser Fluorosensors**	**Water-Column Sampling**
Description	Point locations are surveyed with sediment grabs or cores to detect and characterize the oil on the bottom,	A narrow blade shovel is used to dig shallow pits underwater, bringing the sediments to the surface to determine presence and character.	Laser is used to excite the aromatic compounds in the oil to emit light with a unique pattern, for oil detection.	Underwater unit (fluorometer and/or mass spectrometer [MS]) is towed above the bottom to detect oil dissolved/ dispersed in the water.
Availability of Equipment	Uses readily available equipment.	Uses readily available equipment.	Only one prototype tested; latest model has not been tested.	Fluorometers are readily available; MSs are not, mostly from academic institutions.
Logistical Needs	In shallow water, requires minimal support. In deep water, requires a winch, A-frame, etc.	Can require a large team, depending on safety issues and access. Requires safety boat/crew at site, boats for access to sites with no land access.	Unit must be towed close to the bottom; could be deployed on ROV as well.	Units are deployed from boats; navigation system used to record location and measurements in 3D.
Coverage Rate	Low: data are collected from point samples of a very small area.	Low: A team might be able to cover several hundred square yards/hour once in the water, depending on access and spacing of pits.	Low; has a very narrow swath width.	High: Data can be recorded every 5-15 seconds.
Data Turnaround	Moderate: Field notes and waypoints have to be entered, raw data converted into oiling categories, and maps generated. Likely 24 hour turnaround.	Rapid to Moderate: If teams are supporting Operations, they can quickly delineate areas for removal and then re-survey to determine complete removal.	Unknown: Data can be visualized in real time. Uncertain time to process the data to generate geo-referenced maps.	Rapid: Intensity contour maps can be generated quickly in the field.
Probability of False Positives	Low: samples can be visually inspected, and samples collected for chemical confirmation.	Low: Teams can be calibrated to consistently identify the oil vs. other materials.	Low, once calibrated for the oil.	Low: the units can be optimized for the spilled oil.
Operational Limitations	Standard safety limits for boat operations. No surveys possible in the surf zone.	Many safety limits. Requires wading water depth, low waves and currents, light wind, no lightning, and warm water.	Detection decreases with water turbidity, distance from the target, and wave height. Bright light can interfere. Water depths accessible by boat.	Standard safety limits for boat operations. No surveys possible in the surf zone. Water currents must be low enough to minimize transport of the plume.
Pros	Samples can be collected for confirmation; can detect buried oil and oil thickness; poling can indicate the relative risk of sheen generation.	May be best option to detect buried oil in the surf zone; can work closely with Operations to achieve rapid removal after delineation of treatment area.	Highly sensitive, few false positives; can be used day or night.	Can map at high spatial resolution and differentiate among oil sources in real time, allowing detailed mapping of targets.
Cons	Slow, labor intensive, not effective for patchy oil; weather and sea limits.	Narrow operational limits, slow coverage rate, and limited to depth of digging.	Cannot detect buried oil; not effective in turbid water; not proven operationally.	Only effective if there is oil in the water; currents can transport the oil away from source; MS requires special teams and gear.

Table 3-2—Matrix to Evaluate Technologies For Detection, Delineation, and Characterization of Sunken Oil

	Sonar Systems	Camera/ Video	Acoustic Camera	Diver Observations	Towed Sorbents	Stationary Sorbents	Visual Observations	Bottom Sampling	Manual Shovel Pits	Laser Fluorosensor	Water Column Sampling
Water Depth (ft)	10 to 1000	10 to 1000	10 to 1000	5 to 190	5 to 100	5 to 100	0 to 30	0 to 1000	0 to 5	10 to 100	5 to >1000
Water Visibility											
— >30 ft	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
— 5 to 30 ft	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟨	🟩
— <5 ft	🟩	🟥	🟩	🟨	🟩	🟩	🟥	🟩	🟩	🟥	🟨
Availability	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨
Substrate Type											
— Sand	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
— Silty sand	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
— Mud	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟩
Bottom Obstruction	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟥	🟩	🟩
Oil Patch Size											
— <0.1 ft^2	🟥	🟩	🟨	🟩	🟨	🟨	🟨	🟥	🟨	🟩	🟨
— 0.1 to 1 ft^2	🟥	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟨	🟩	🟨
— >1 to 10 ft^2	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟨
— >10 ft^2	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟨
Oil Thickness	🟨	🟨	🟥	🟩	🟨	🟥	🟨	🟩	🟩	🟥	🟥
Buried Oil	🟨	🟥	🟥	🟨	🟨	🟥	🟥	🟩	🟩	🟥	🟨
Sensitive Habitat	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟨	🟨	🟩	🟩
False Positives	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩
Coverage Rate	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Data Turnaround	🟩	🟨	🟨	🟩	🟨	🟨	🟩	🟨	🟩	🟨	🟨

NOTE Red = not likely effective; yellow = may be effective; green = most likely effective

4 Techniques for Sunken Oil Containment

As shown in Figure 2-2, oil usually accumulates on the bottom where currents and turbulence are low. However, sunken oil can be remobilized when turbulence increases, such as during higher-flow conditions in rivers and higher-wave conditions in nearshore areas. These remobilization events do not have to be a result of floods or large storms; they can be part of the normal fluctuations in currents and turbulence in the system. Because sunken oil removal can take a long time, there may be a need to attempt to contain the sunken oil and prevent its remobilization and spread during such events.

Techniques for sunken oil containment have been listed in numerous guides on sunken oil response, starting with Castle et al. (2005) and NRC (1999), and include:

- physical barriers such as artificial depressions (e.g. trenching);
- bottom booms;
- sheet piling;
- nets or curtains attached to the bottom and/or suspended from the surface;
- air curtains;
- filter fences or gabion baskets stuffed with sorbents;
- other structures to slow bottom currents and promote deposition of oil and/or oiled sediments in front of the structure for removal by appropriate means.

These techniques have been rarely attempted, and few have been documented as being effective. There are no standard configurations. The 2010 Enbridge Pipeline spill in the Kalamazoo River is the best recent example of the challenges faced when trying to contain sunken oil that is remobilized by increases in turbulence and currents. The FOSC report for the 2010 Enbridge Pipeline spill in the Kalamazoo River (USEPA, 2015) describes the efforts to prevent the spread of diluted bitumen-particle aggregates along the river and into impoundments. Early methods used included silt curtains, surface boom with X-Tex sediment curtain (oleophilic synthetic filtering material designed to sorb oil while allowing water to pass), gabion baskets (Figure 4-1), and air curtains.

In 2012 through 2014, the goal was to prevent the spread of oiled sediments through various sediment-trapping methods. During the summer of 2012 and 2013, X-Tex curtains were set on the bottom where the river entered into a large impoundment (Figure 4-2), to trap and concentrate oiled sediments before they spread into the lake. There was a gap between the bottom curtain and the floating boom to allow water to pass. These bottom curtains were placed at an angle to the flow of the river currents to increase settling of the oil-particle aggregates (Fitzpatrick et al., 2015). Oiled sediments accumulated behind the curtain and were removed later by dredging prior to removal of the system during winter months. The gabion baskets were judged to be the most effective at removing oil from the water column; the half-curtain or partial-curtain deployments were judged to be very effective at trapping oiled sediments; air curtains were judged to be least effective.

Methods were also designed to increase the passive deposition of oiled sediments in natural depositional areas throughout the river system such as side channels, backwaters, smaller impoundments, and oxbow lakes. Trees and coir log booms were placed on the bottom to increase sediment accumulation at 25 locations along the river. Sediment accumulation was monitored using sediment-trap cylinders, changes in bathymetry, and poling. When appropriate, the accumulated sediments were removed by dredging or excavation, in some cases, multiple times.

Western Canada Spill Services conducted two field trials to evaluate the use of fine-mesh fishnets and a subsurface containment fence to contain sunken oil. They concluded that there were not effective containment techniques for spills of this nature.

Figure 4-1—Gabion Baskets in the Kalamazoo River at the Enbridge Pipeline Spill (USEPA)

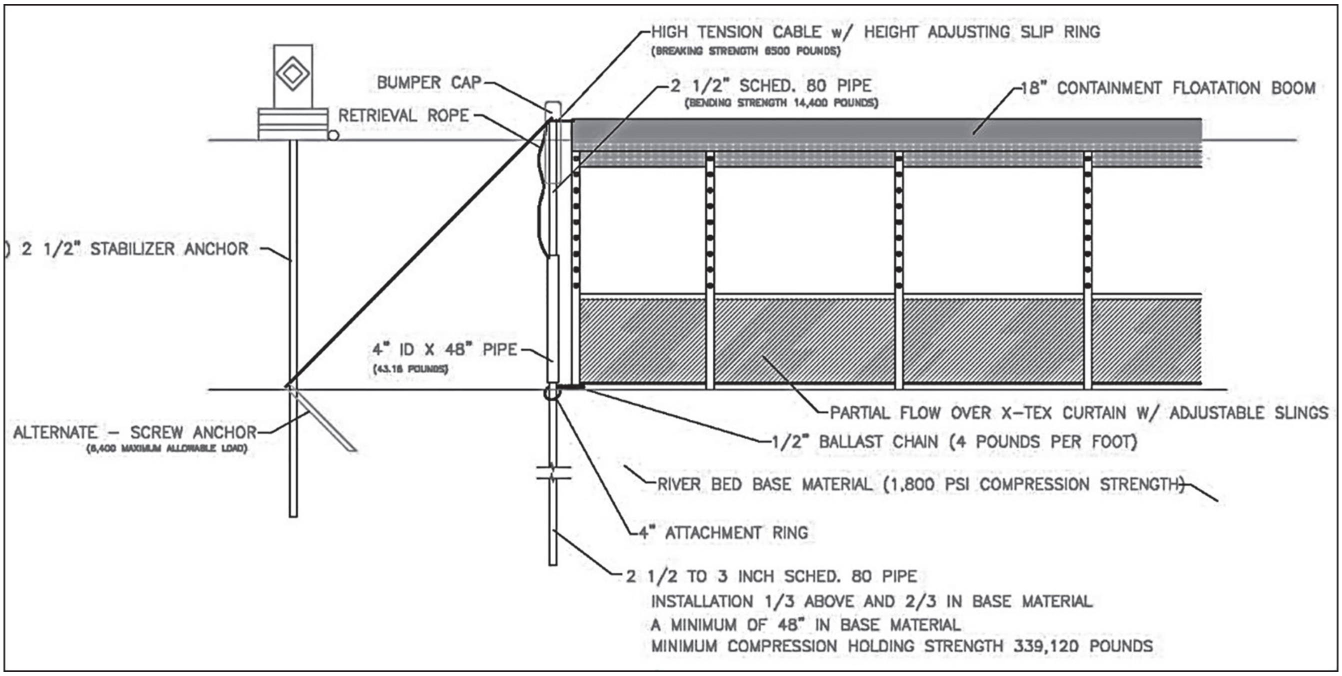


Figure 4-2—Containment System Used To Trap Oil-contaminated Sediment Transported in the Kalamazoo River from Entering Lake Morrow at the Enbridge Pipeline spill (USEPA)

The advantages and disadvantages of those sunken oil containment techniques that have shown to be effective include the following.

Advantages	Disadvantages
Filter Fences or Gabion Baskets filled with Sorbents	
— Constructed of readily available materials. — Effective at removal of oil droplets in the water column. — Can be deployed at and just below the surface or on the bottom, depending on water depth and where the oil is moving in the water column or along the bottom. — Closed-loop snare may be more effective.	— If currents are >1 foot/second, there can be scouring of the bottom in front of the baskets and less effective oil recovery. — Not feasible to deploy in high-flow areas. — Can completely fail and be swept downstream if flows suddenly increase. — Can only filter the entire water flow in small streams.
Sediment Curtains	
— Curtains constructed of hydrophilic materials can sorb oil as well as slow the flow and increase sedimentation. — Half-curtains or partial currents can be deployed at angles to the flow in moderate-flow areas to slow currents and increase deposition of oiled sediments.	— Full curtains are only effective in low-flow areas, where the curtain can maintain contact with the bottom, where risk of oil mobilization is also low. — Requires measurement of current speeds at surface and/or bottom and knowledge of hydraulics for proper design. — Can interfere with navigation.
Air Curtains	
— Does not interfere with navigation. — Could help bring oil in the water column to the surface.	— Only effective in very low-flow areas, where risk of oil mobilization is also low.
Enhanced Passive Sediment Accumulation	
— Builds on natural processes and uses natural materials that can be left in place. — Does not interfere with navigation.	— Restricted to areas of natural accumulation, which may be sensitive or high-public use areas such as impoundments. — Requires dredging or excavation to remove the accumulated sediment. — Need a good understanding of seasonal flow patterns so sudden floods don’t flush the oiled sediments out.

The Enbridge Pipeline spill demonstrated that containment of oil and oiled sediments on the bottom in riverine systems is very difficult, is highly dependent on site-specific conditions, and must often be redesigned as conditions change. The design, testing, and evaluation of sunken oil containment techniques are recommended in Section 9 on Research & Development.

5 Techniques for Sunken Oil Recovery

5.1 General

Various techniques for recovering sunken oil have been used and developed over the years with varying degrees of success. The low frequency of these events, vast geographical distribution, and differing scenarios all contribute to the slow pace of advancement in solutions for sunken oil recovery. Limited information is available regarding best practices or industry standards for sunken oil recovery, requiring responders to assemble low-tech or ad hoc systems designed for other tasks and adapting them to sunken oil recovery. The recovery techniques discussed in the next sections include:

- suction dredge,
- diver-directed pumping and vacuuming,
- mechanical removal,
- sorbent/V-SORs,
- trawls and nets,
- manual removal,
- agitation/refloat.

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.

5.2 Suction Dredge

Dredging is a well-developed process of removing sediments and debris from the bottom of lakes, rivers, harbors, and other waterbodies. Dredging can be accomplished mechanically using a clamshell dredge, excavator, or hydraulically using pumps to remove and transport the sediments and debris. This section addresses the latter; Section 5.3 addresses mechanical removal. Hydraulic dredging is accomplished by transporting sediments and solids in water. Dredge pumps are high-volume centrifugal pumps designed to handle and pass solids.

Past Use: See Table 2-7.

There are several manufacturers of small dredges, and several contractors that have dredges and offer dredging services. Past experience has shown that these systems can be effective at recovering sunken oil with little or no modification. During the response to the T/B *Morris J. Berman* incident in Puerto Rico, a small suction dredge with a cutter/auger head (Figure 5-1) was used effectively to recover small amounts of sunken oil in two sheltered lagoons (Burns et al., 1995). The portable dredge was effective due in part to the shallow depths of the two lagoons as these types of dredges can only reach depths of about 15 ft and because an abandoned stadium with swimming pools was located adjacent to the lagoons which offered an adequate means of storage and treatment of recovered oil, water, and sand. The cutter/auger head attachment aids in breaking up and transporting bottom sediments to the centrifugal submersible pump. The pump transports the mixture of water, sediment, and oil via a discharge hose or pipe. Booster pump(s) can be placed in line when pumping long distances.

While this method works well for small concentrations of sunken oil scattered on the bottom or mixed in layers of sediment, it is not an ideal way to pump larger concentrations of viscous sunken oil due to the pump limitations. Dredge pumps rely on the movement of water to carry sediments. Increased amounts of viscous oil will clog dredge pumps or “starve” them causing them to cavitate. A suction dredge similar to the one used in Puerto Rico, with a cutter/auger head, was used to dredge areas with oiled sediments after the Enbridge Pipeline spill in parts of the Kalamazoo River and Morrow Lake (Figure 5-2). A large waste-handling area had to be established utilizing geotubes and water catchments to address dewatering, water treatment, and solids handling (Figure 5-3). In both of these case studies, dredging was used to recover vast amounts of water and sediment with relatively small amounts of sunken oil. This method can be very effective in removing the sunken oil, but the logistical effort involved with handling the large amounts of recovered sediments and water should be carefully considered.

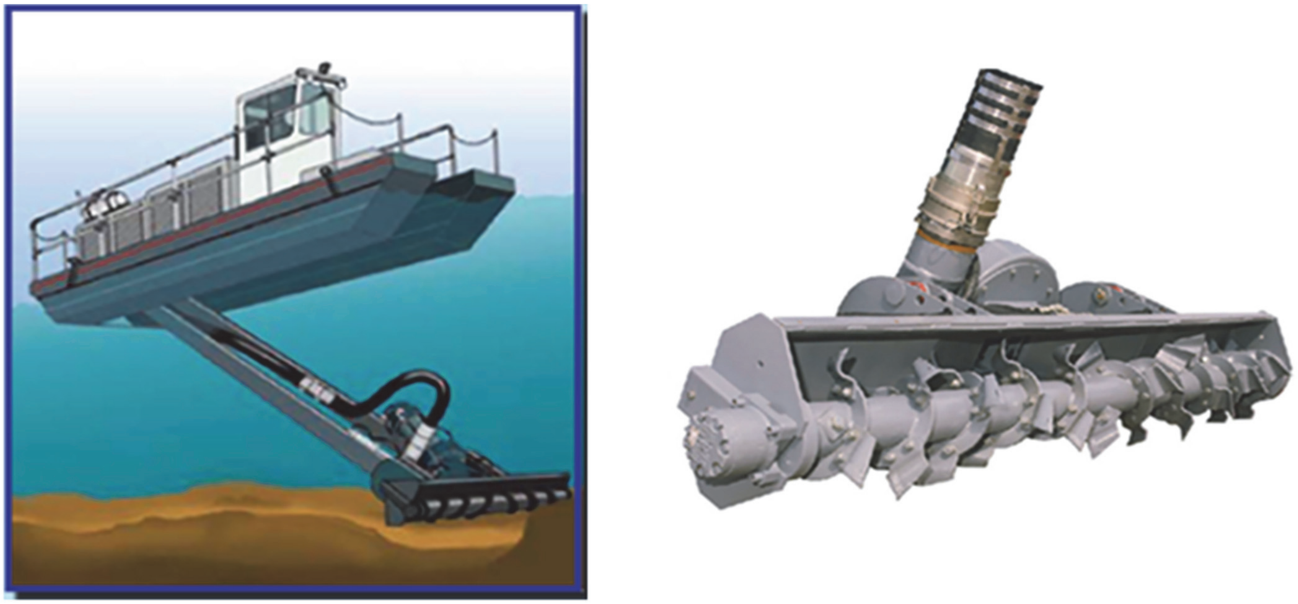


Figure 5-1—Portable Suction Dredge with Cutter/auger Head Similar to the One Used in the T/B *Morris J. Berman* Response (SRS Crisafulli, Inc., Glendive, Montana)

Figure 5-2—Amphibious Suction Dredge Used On the Enbridge Pipeline Response in the Kalamazoo River (www.enbridge.com)

Figure 5-3—Area for Dewatering, Solids Handling, and Water Treatment During Dredging Operations in the Kalamazoo River (www.enbridge.com)

The advantages and disadvantages for dredging for sunken oil recovery include the following.

Advantages	Disadvantages
Suction Dredge with Cutter/Auger Head Attachment	
— Common piece of equipment, readily available, easy to transport. — Little to no modifications required for sunken oil recovery. — Can cover large areas quickly with 5 ft to 8 ft swath width. — Ability to pump/transport great distances. — Ability to pass large solids, i.e. rocks and debris. — Self-propelled or guide-cable operation. — Adjustable “cut” depth allowing the removal of ±1 in. to several inches in one pass. — Can track and document progress with GPS. — Low manpower requirement to operate. — Amphibious models can operate from 0 ft to 20 ft depth for small units and up to 40 ft for large units.	— Generates large amounts of water and sediment requiring dewatering, handling of solids, and water treatment. — Only suitable for protected waters. — Non-discriminate recovery, cannot tell the difference between oil and water/sediment. — High rpm pump has the potential to create issues with turbulence that results in oil emulsification and shearing. — Not allowed to work in areas with pipelines, cables, or other obstructions.

As part of a USCG Research and Development program (Fitzpatrick et al., 2013) Oil Stop developed the Oil Stop Bottom Oil Recovery System (OSBORS). Based on the same proven technology as conventional dredging, the OSBORS adapts conventional dredging technology to the unique conditions involved with sunken oil recovery. Oil Stop developed a Sub-Dredge and a smaller version Ninja Mini-Dredge neither of which underwent testing at OHMSETT as part of the USCG R&D effort due to their relatively large size. Testing of the recovery pump was achieved at OHMSETT with a system mounted on an excavator. Oil Stop continues to work with this technology and successfully deployed the Ninja Mini-Dredge recovering contaminated sediment on a project in Mexico. The Sub-Dredge and Ninja Mini-Dredge would not have the same depth restrictions as conventional dredging due to the “crawler” design, which allows it to operate autonomously from a vessel. As with suction dredging, a lot of associated water and sediment would be generated in conjunction with the OSBORS technology.

5.3 Diver-Directed Pumping and Vacuuming

Diver-directed pumping and vacuuming of sunken oil have proven to be a very effective method of recovering sunken oil and offers the opportunity to reduce the amount of sediment and water recovered as compared to suction dredging. Of the 38 case studies examined, 13 successfully used diver-directed pumping and/or vacuuming. For this report, pumping refers to the use of a centrifugal or positive-displacement type pump at or below the water surface with a diver-directed suction hose. Vacuuming refers to a vacuum truck or unit above the water surface either on shore or on a vessel/barge that creates a vacuum and divers directing the hose attached to the vacuum. While vacuum trucks and portable vacuum units are available, they are restricted as the average vacuum pump is rated to lift or “pull” water about 21 ft at sea level. Vacuum systems experience a decrease in effectiveness as their height above water level increases and as hose length increases. Figure 5-4 and Figure 5-5 illustrate these systems.

Pump selection plays a significant role in the success of sunken oil recovery operations. High-capacity centrifugal pumps have the ability to move large amounts of liquid, but do not work well on higher viscosity liquids. The high rpm rates associated with these pumps cause shearing and emulsification of recovered oil, making it more difficult to separate oil and water. Positive-displacement pumps work well on higher viscosity liquids but at much lower volumes. Positive-displacement pumps, by nature of their design, are much less likely to emulsify or shear recovered oil, making oil/water separation much easier. Nozzle and stinger selection for sunken oil recovery can also impact the success of the operation.

Left: Positive displacement Archimedes screw pump.

Right: Centrifugal pump (M. Ploen, QualiTech).

Figure 5-4—"Rock Box" Mounted on Standard Pumps to Capture Larger Solids in the Box Rather Than Go Through the Pump

Figure 5-5—Portable Vacuum Transfer Unit (VTU) Mounted on a Portable Barge During the 1993 T/B *Bouchard 155* Incident (NOAA)

Ad hoc nozzles and stingers have been fabricated and used on several of the case studies; however, very little information exists regarding the advantages and disadvantages of different designs. Stinger designs varied in materials from steel, aluminum, and PVC pipe in varying lengths with and without diver-operated shut off valves and with different angles cut at the end of the stinger. Nozzle designs vary in construction material (steel and aluminum) with varying widths and angle in relation to the hose. Some nozzles were designed with steam fittings allowing the use of steam or hot water at the point of recovery to aid in reducing viscosity.

As part of a USCG Research and Development program (Fitzpatrick et al., 2013) Marine Pollution Control and Alion developed and tested technology for use recovering sunken oil. The Alion Seagoing Adaptable Heavy Oil Recovery System (Sea Horse) addresses detection with commercially available high-resolution sonar and 3-D positioning incorporated into a ROV platform. The recovery phase incorporates a commercially available pump mounted to a sled that is controlled by ROVs. Alion has not carried out any further development or testing of this system since the completion of the USCG contract.

Marine Pollution Control (MPC) developed a manned submarine that can operate at depths up to 200 feet with increased bottom time compared to divers. The submersible unit houses a pilot and one operator in a spherical acrylic cabin, providing excellent visibility in all directions. Only the pumping apparatus could be tested at OHMSETT due to the size of the submersible, but the system was successfully demonstrated in the Rouge River adjacent to MPC's facility recovering red clay balls that simulated oil.

Both the "Sea Horse" and "Manned Submarine" have the potential to recover sunken oil at greater depths and with extended bottom time as compared to commercial divers using essentially the same proven techniques associated with diver directed pumping. Positive-displacement pumps can be placed in-line during recovery operations to aid in the pumping of vicious oil or when pumping long distances. This is a proven effective method, and the operators must be familiar with the operation of these pumps and in particular should never "dead head" a positive-displacement pump (pump against a closed valve or a downstream pump that is not operating). Always refer to the manufacturer's operation manual before placing a pump in service.

Past Use: See Table 2-7

In the late 1990s, after responding to three incidents involving highly viscous oils the USCG National Strike Force along with the U.S. Navy Supervisor of Salvage and various representatives from oil spill response companies assembled an informal workgroup to study and test viscous oil pumping. The Canadian Coast Guard joined the workgroup in 2002 that formed the Joint Viscous Oil Pumping System workgroup. The workgroup concluded that annular water injection (AWI*)* is an effective way to move heavy viscous products (Drieu et al., 2003).

The AWI is a device that is mounted inline in front of a pump at the suction end or at the discharge side of the pump (Figure 5-6). Water injected into the flange forms a "sleeve" of water around the stream of viscous oil, providing lubrication between the oil and the discharge hose and resulting in less friction and lower discharge pressures. While none of the case studies examined for this report utilized AWI for sunken oil recovery, it has been identified as a successful method of transporting viscous oil and should be evaluated for usefulness during sunken oil responses.

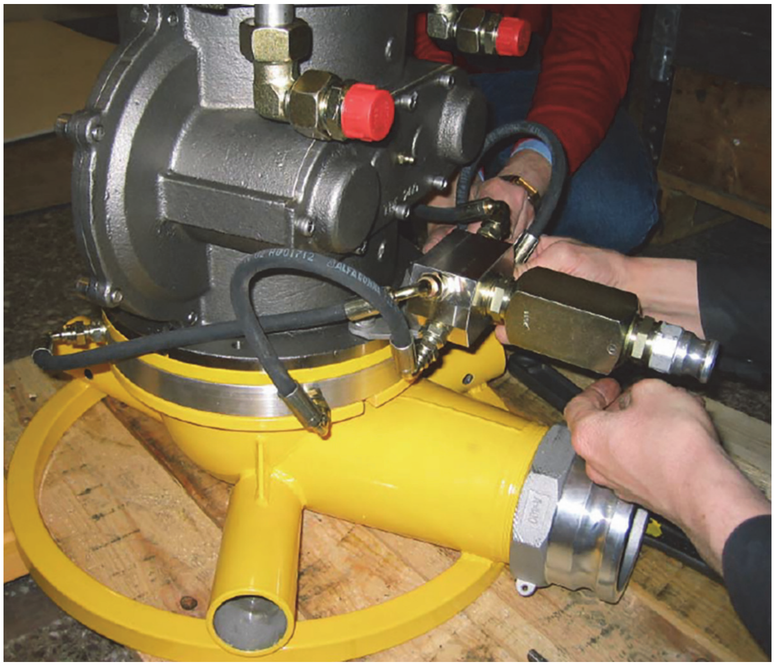


Figure 5-6—Annular Water-injection Flange Mounted on an Archimedean Screw Pump (FOILEX Engineering AB)

The advantages and disadvantages of diver-directed operations for sunken oil recovery include the following.

Advantages	Disadvantages
Diver-directed Vacuuming	
— Vacuum trucks readily available. — Portable Vacuum Transfer Units (VTUs), while not as prolific as vacuum trucks, are available. — Ability to regulate flow. — Minimal mixing of recovered fluids and solids. — Ability to pass some solids (i.e. rocks and debris). — Can handle high viscosity. — Selective recovery provided diver has visibility.	— Rapid loss of effectiveness due to hose distance. — Large, heavy units. — Requires larger vessel or barge if unprotected water. — Small coverage area.
Diver-directed Pumping with Centrifugal Pump	
— Lightweight and portable. — Can pump long distances. — High head pressure, can pump several hundred feet up. — Easily modified to protect from rocks with a “rock box”. — Ability to regulate flow. — Selective recovery provided diver has visibility. — Can introduce steam or hot water to reduce viscosity. — Ability to pass some solids (i.e. rocks and debris).	— Not readily available; must locate from dive or dredge contractor, some oil spill response organizations. — Generates large amounts of water and sediment requiring dewatering, handling of solids, and water treatment. — High rpm pump has the potential to create issues with turbulence, emulsification, and shearing. — Cannot handle viscous oil other than small amounts moved in large amounts of water. — Small coverage area.
Diver-directed Pumping with Positive Displacement Pump	
— Lightweight and portable; Can pump long distances. — High head pressure, can pump several hundred feet up. — Easily modified to protect from rocks with “rock box”. — Ability to regulate flow. — Selective recovery provided diver has visibility. — Can introduce steam or hot water to reduce viscosity. — Ability to pass some solids (i.e. rocks and debris). — Low rpm thus minimal mixing of recovered fluids and solids, reducing the potential issues associated with turbulence, emulsification, and shearing. — Can handle very high viscosity oils. — Can adapt water-injection flange for viscous oil pumping.	— Not readily available; must locate from dive or dredge contractor, some oil spill response organizations. — Lower recovery rates than centrifugal pumps. — Small coverage rates.

The use of divers to detect and recover sunken oil has historically proven highly effective. As in all response operations, worker safety should be the overriding priority. Thorough dive and safety planning, using Table 6-1 to Table 6-5, combined with a fully equipped professional commercial diving crew that is trained and experienced in contaminated water operations, is always required. Additionally, the *Association of Diving Contractors International Consensus Standards*, Section 5.38, should be referenced for contaminated water diving best practices. The following lessons learned are provided in effort to improve future operations.

- SCUBA diving is not recommended for diving in oil-contaminated water. Divers should be fully protected from the contaminated water by dry suits with mating helmet, boots, and gloves.

- To expedite decontamination procedures and protect diving life-support equipment, use of disposable Tyvek® over-suits and gloves is recommended. Additionally, diving helmets can be taped and umbilicals covered with protective sleeves to minimize oil contamination. Note, no effort should be made to make the protective outer suit water-tight since this could create air pockets negatively affecting diver buoyancy.

- When diving in areas with floating oil, bubbler systems have been effectively used to create a relatively clean entry/exit point to minimize oiling of the diver on the surface.

- Air compressor intakes must be located upwind and outside hazardous atmospheres. On-site atmospheric monitoring should be conducted by qualified personnel during diving operations.

- Divers should approach sunken oil from an up-current position, if at all possible. Tidal fluctuations should also be considered when planning diving operations.

- Dive crew manning levels should be increased well beyond regulatory minimums to ensure adequate personnel for emergency and decontamination procedures.
- Work-rest standards should be outlined in the dive safety plan and strictly adhered to during operations.
- A third-party safety officer experienced in contaminated diving operations should be assigned to conduct a safety audit prior to commencing operations.
- Any breach of personal protective equipment while diving in a contaminated water environment should result in termination of the dive to limit exposure.
- Diving operations should typically be planned as “no-decompression” diving operations given the potential of cross-contaminating decompression chambers. Dives should also be scheduled to require no in-water decompression to limit the diver’s exposure time. If needed, however, dive times may be extended using NITROX, as on the T/B *DBL 152* sunken oil recovery, or other mixed-gas diving systems. Additionally, one atmosphere suits and submersibles should be considered for diving beyond the limitations of surface-supplied systems and when extended bottom times are required. Note: these one-atmosphere systems have yet to be proven in actual sunken oil detection and recovery operations.

When conducting surface decompression operations, decontamination and diver undress procedures within the 5-minute time constraint should be exercised and proven prior to exceeding no-decompression limits.

5.4 Mechanical Removal

5.4.1 General

Mechanical removal involves physically removing sunken oil with an excavator, clamshell dredge, environmental dredge bucket, or other machinery used to grab, scoop, or pick up sunken oil. This method, when properly employed, is very well suited for recovery of solid or semi-solid sunken oil as the oil can be physically recovered with little associated water.

Past Use: See Table 2-7.

5.4.2 Excavator

Excavators come in a variety of sizes and configurations, ranging from compact “mini” excavators to much larger and long-reach units. They are readily available for lease or from construction contractors. They can be equipped with different sized buckets, with or without a “thumb” to assist in grabbing sunken oil. Additionally, there are amphibious models also known as “marsh buggy” excavators. Excavators (Figure 5-7) have been used effectively to recover sunken oil at the shoreline by reaching out into the water and scooping or grabbing sunken oil. They have also been used from the deck of a vessel or barge further from shore.

Left: Working from a barge (www.ultratrex.com.my).

Right: Amphibious or “marsh buggy” (www.wetlandequipment.com).

Figure 5-7—Excavators

5.4.3 Grab or Clamshell Dredge

Mechanical grab or clamshell dredges are readily available, though they are not as prolific as excavators. They incorporate two halves, like a clam, that are open when the device is dropped to the bottom that close as the dredge is lifted taking a bite out of the bottom sediment. They do not have a good seal, allowing liquid to leak from them as it is raised. Traditionally, they have been operated as an attachment to a crane. This technique is very effective at removing large amounts of bottom material. Coverage accuracy is increased with the aid of a GPS. During the response to the T/B *MM-53* incident in the Ohio River, a clamshell dredge was used to recover 333 bbls of asphalt (Howard and Laisure, 2008). This method proved to be a very effective way to recover the asphalt with little or no associated water or sediment (Figure 5-8). While well suited for recovery of semi-solid sunken oil, they are not as ideally suited for more fluid sunken oils, as the oil can be remobilized during the recovery process by physically being pushed or moved by the dredge and or draining out of the dredge while being lifted.

Figure 5-8—Mechanical Dredge Bucket Removing Asphalt During the T/B *MM-53* (USCG)

5.4.4 Environmental Dredge Bucket

Environmental dredge buckets operate in principal the same as a mechanical clamshell dredge operated from a crane and, in recent years, have been adapted to be used successfully at the end of an excavator. They are commonly used to remove contaminated sediments and can reduce the amount of associated water recovered. They incorporate a liquid-tight seal that reduces the amount of loss from the bucket as it is being raised (Figure 5-9). Environmental dredge buckets are better suited for recovering liquid or fluid sunken oil as they reduce the amount of liquid escaping the dredge bucket. Coverage accuracy is increased with the use of a GPS. Figure 5-10 shows how the removal progress can be documented using a GPS attached to the bucket.

Left: Used from crane during the T/B *Apex 3508* response (NOAA).

Right: Attached to excavator (www.cashmandredging.com).

Figure 5-9—Environmental Dredge Buckets

The advantages and disadvantages of mechanical removal operations for sunken oil recovery include the following.

Advantages	Disadvantages
Excavator	
— Readily available in varying sizes. — Can work from shore for nearshore work. — Can work from vessel or barge. — Amphibious models available though not as prevalent. — Can scoop sunken oil with bucket. — Easy addition of a thumb attachment for recovering solid or semi-solid sunken oil. — No issues with rocks or debris. — Can track progress with geo-referenced data.	— Limited to ±20 ft of water. — Difficult to be selective, resulting in additional sediments. — Difficult to manage liquid flowing from bucket during lift. — Large, heavy units. — Requires larger vessel or barge if unprotected water. — Small coverage area.
Grab or Clamshell Dredge	
— Readily available from dredge and construction contractors. — Can work from shore for nearshore work. — Can work from vessel or barge. — No issues with rocks or debris. — Can track progress with geo-referenced data.	— Requires logistical support to store and transport recovered sunken oil and sediment (hopper barge). — Generates large amounts sediment requiring dewatering, handling of solids, and water treatment. — Liquids not contained, allowing leakage during recovery. — Small coverage area.
Environmental Clamshell Dredge	
— Available from dredge, construction. and environmental engineering contractors. — Can work from shore for nearshore work. — Can work from vessel or barge. — No issues with rocks or debris. — Water-tight seal greatly reduces liquid leakage during recovery operations. — Can track progress with geo-referenced data.	— Not as prevalent as conventional clamshell. — Small coverage area.

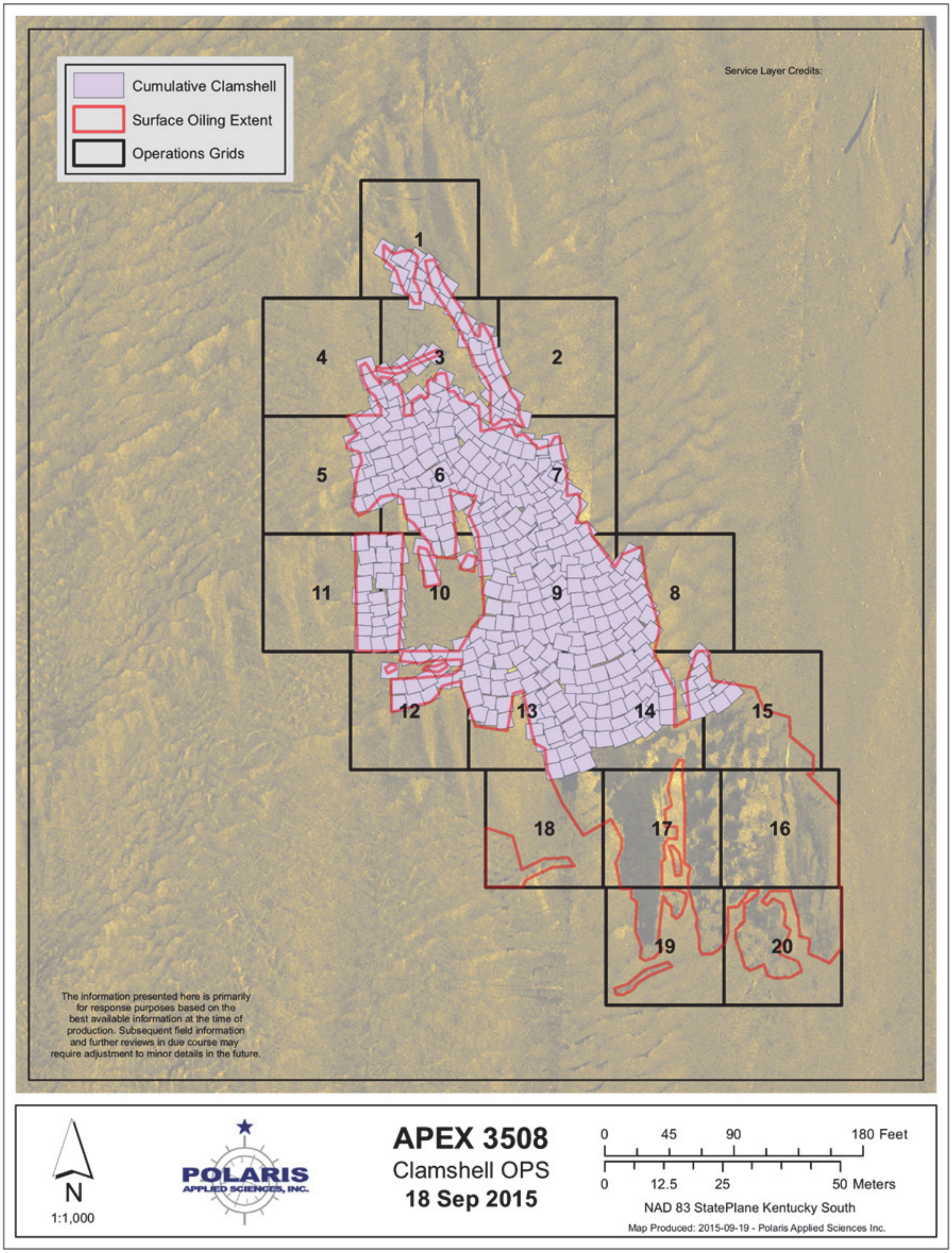


Figure 5-10—Tracking the Progress of Sunken Oil Removal During the T/B *Apex 3508* Spill of Clarified Slurry Oil in the Mississippi River in September 2015 (USCG)

5.5 Sorbents/V-SORs

Sorbents are attached to chains or other materials and dragged on the bottom to recover liquid oil. This recovery technique is most appropriate when the oil occurs in sporadic, trace amounts, where other removal techniques would generate large amounts of water and/or sediments that would require treatment. It could be used after gross oil removal was achieved using other techniques, as a final pass to remove any residual oil. This method could also be used to document removal to cleanup endpoints, such as no more than trace amounts of oil adhered to the sorbents. Use of white, “first run” snares is preferred, to improve oil detection.

Past Use: See Table 2-7

The advantages and disadvantages of sorbents for sunken oil recovery include the following.

Advantages	Disadvantages
Sorbents/V-SORS	
— Can be used in active vessel traffic lanes. — Track lines can be recorded with the vessel’s GPS to provide actual survey lines. — Could detect both pooled and mobile oil moving above the bottom, but won’t differentiate between them. — Relatively efficient in that large areas could be surveyed. — Readily available; can be sized for the task. — Low tech; easy to train crews. — Can vary the length of the trawl to refine spatial extent.	— Time and labor intensive for deployment, inspection, and replacement. — Susceptible to snagging on the bottom. — Cannot determine where along the trawl the oil occurred. — Difficult to calibrate the effectiveness of oil recovery. — In deeper water, requires a vessel with a boom/pulley and adequate deck space on the stern for handling, inspection, and replacement. — Best suited for recovery of small amounts of oil.

5.6 Trawls and Nets

Trawls or nets of different mesh sizes can be towed to recover viscous oil floating suspended in the water column. Though not tested, nets may be dragged on the bottom to recover viscous sunken oil, or placed down current on the bottom to passively recover sunken oil mobilized off the bottom by currents.

Past Use: See Table 2-7

Commercial trawls and fishing nets have been used with limited success during sunken oil incidents. One year after the spill, escallop-dredging boats were successful in recovering 30 tons of sunken oil from the T/V *Betelgeuse* incident (Grainger et al., 1981). Commercial shrimp and fishing nets have been used successfully to recover viscous oil at or near the surface. During the response to the T/V *Presidente Rivera* a commercial fishing net was used to contain and recover viscous oil at/just below the surface. Though successful this operation was suspended as the net was fouled and could not be re-used (Wiltshire et al., 1991). Responders have attached sorbents to trawl nets to increase oil retention, or added a liner to the cod end of shrimp nets to serve as a quick-release storage bag. Nets have been used with some success to recover submerged oils just below the surface that were too viscous for recovery by skimmers (Clark et al., 1997).

Sunken oil has been observed during past responses moving along the bottom with currents (T/V *Athos 1*, T/B *Morris J. Berman,* T/B *DBL 152,* Degusa Engineered Carbons*).* Netting deployed at the bottom could intercept the movement and potentially hold the oil in under weak currents, but this tactic has not been proven. No evidence of the successful use of nets for containing sunken oil was found in any of the case studies examined. Ad-hoc bottom nets were assembled for testing during the response to the T/B *DBL 1*52 spill, but the oil spread before they could be deployed.

There have been several tank tests to determine the effectiveness of nets to recover viscous oils that might apply to sunken oil recovery with nets. Delvigne (1987) tested nets of varying sized openings in a test flume to develop equations to predict leakage rates based on oil viscosity, water velocity, and net type. Brown and Goodman (1989) conducted 60 tests in a tank to evaluate the ability of towed nylon nets with mesh sizes of 1, 1.9, and 5 mm to collect floating Cold Lake diluted bitumen, finding that there was no leakage with the smallest mesh size at tow speeds up to 0.6 knots; at this speed, the medium mesh size leaked at what they considered to be an acceptable rate. They also found that it was not possible to clean the nets. Meshes with 0.25 in^2 to 1 in^2 openings tested by Cooper et al. (2007) did not contain heavy oil with a viscosity of 1000 centistokes at current speeds of 0.8-0.9 knots. The many disadvantages of nets and trawls as a sunken oil *recovery* technique include the following.

Advantages	Disadvantages
Towed Nets or Trawls	
— Readily available in areas with commercial fisheries. — Experienced operators (fisherman) with vessels capable of effectively towing.	— Difficult to specify size of net openings, have to use what is available. — Leakage of oil through net may occur and hard to monitor. — Cannot be cleaned and returned for intended purpose, thus most likely will be a one-time use. — Will require support to handle and dispose of oiled nets. — May have issues with debris. — May snag on rocks or obstructions.

5.7 Manual Removal

Manual removal is achieved by physically picking the viscous oil up by hand or with hand tools (i.e. shovels, rakes, pitch forks, bags, and hand nets; Figure 5-11) in relatively shallow water, or by the same means using divers in deeper water. Manual removal is a slow and labor-intensive method of sunken oil removal; however, with good visibility this method allows selective recovery with minimal recovered water or sediments.

Past Use: See Table 2-7.

Left: Recovery of sunken oil with nets (Bernard Fichaut, University of Brest).

Right: Diver placing sunken oil in a bag (Mohamed Elsarji, Bahr Loubnan NGO).

Figure 5-11—Manual Recovery

The advantages and disadvantages of manual methods for sunken oil recovery include the following.

Advantages	Disadvantages
Manual Recovery Shallow Water	
— Low tech, only requires labor force and hand tools. — Selective recovery, limiting co-collection of water and sediment.	— Slow and labor intensive. — Requires proper PPE. — Restricted to shallow water <5 ft. — Waves and currents will limit operations. — Requires relatively good water clarity for visibility. — Severe weather will suspend operations.
Manual Recovery with Divers	
— Relatively low tech, requires divers and hand tools. — Selective recovery, limiting co-collection of water and sediment.	— Slow and labor intensive. — May require extensive logistical support if based off vessel or barge. — Requires contaminated-water dive gear. — Requires proper decontamination of dive gear. — Requires relatively good water clarity for visibility. — Severe weather will suspend operations.

5.8 Agitation/Refloat

This method involves agitating sunken oil on the bottom, to get it to float to the surface, either because it is adhered to the sediments and agitation breaks it free allowing it to float, or because the source of agitation allows tiny air bubbles to attach to the sunken oil allowing it to float to the surface. Either of these scenarios result in getting the oil to the surface where it can be recovered with conventional oil spill response methods such as skimming or sorbents. The agitation can be achieved by injection of water using stingers or water wands, injection of air using pond aerators, manual disturbance using rakes, or similar methods. This technique might also be used to flush oiled sediments from locations with poor access to depositional areas with better access and containment, for eventual removal (USEPA, 2015).

Prior Use: Enbridge Pipeline.

During the response to the Enbridge Pipeline incident in the Kalamazoo River, sediment flushing (using river water), sediment raking, and/or aeration to liberate the submerged oil and float it to the surface was used extensively (Figure 5-12) (Dollhopf and Durno, 2011; Dollhopf et al., 2014). During agitation/refloat operations, care must be taken to contain the oil once it reaches the surface. This can be accomplished with conventional oil containment boom and or sorbent boom creating cells or at least placed down current and or down wind. Conventional leaf blowers and airboats have been used successfully to herd surface oil, and these methods have proven useful when recovering sunken oil once it has surfaced.

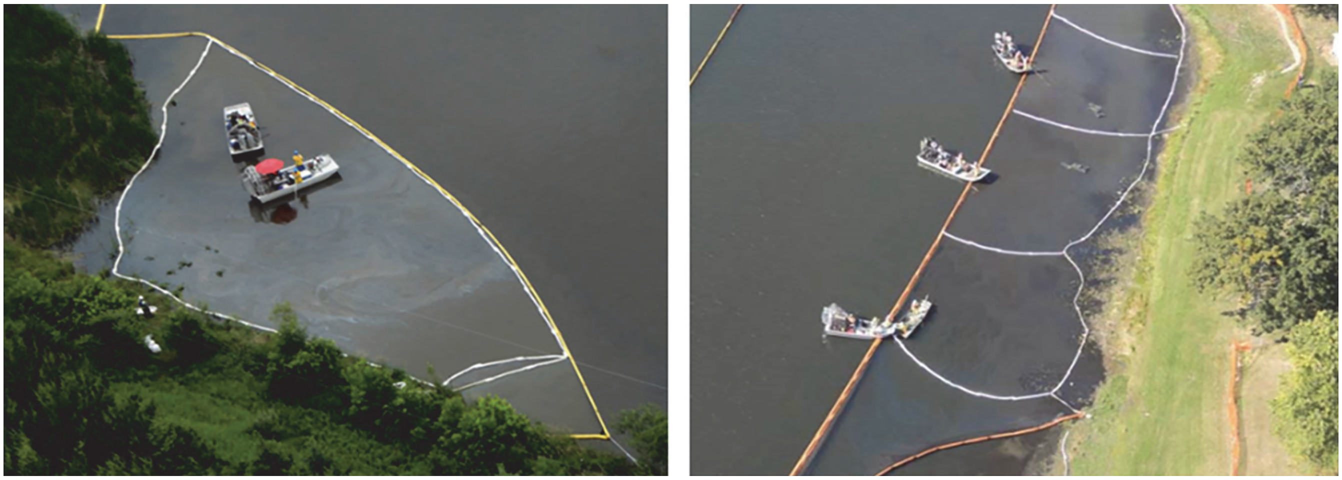


Figure 5-12—Agitation of Sediments in the Kalamazoo River Liberating Sunken Oil to Float to the Surface for Recovery (USEPA)

Because of the risk that some of the liberated oil will remain suspended in the water column and settle back to the bottom down current, this technique is best considered where the oil can be contained and recovered. Agitation could also cause mixing of the oil deeper into the sediments, to the depth to which the sediments are disturbed. Thus, it is recommended that field tests be conducted to determine the efficacy of this method prior to full-scale application.

The advantages and disadvantages of agitation and refloat for sunken oil recovery include the following.

Advantages	Disadvantages
Agitation/Refloat	
— Off the shelf items such as pumps and rakes can be used. — Aerators designed for waste water treatment or fish ponds can be modified for sunken oil recovery. — Selective recovery limiting associated recovered water and sediment.	— Slow and labor intensive. — Small coverage area. — Restricted to shallow water <8 feet and relatively low water velocity. — Suspended oil can remain mixed with the sediments and resettle to the bottom after agitation. — Mixes remaining oil deeper into the sediments. — Only effective with liquid oils that are loosely adhered to the sediment and will re-float when separated from the sediment, and where complete containment of the resuspended oil is possible. — Generates high turbidity that can spread downstream.

5.9 Considerations for Sunken Oil Recovery in Rivers and Extreme Cold Conditions

5.9.1 Sunken Oil Recovery in Rivers

Response operations on rivers are challenging because of limited access points for equipment and worker deployment, variable flow rates and water depths, conflicts with navigational use (vessel wakes can pose safety issues and cause equipment to fail), hazards associated with vessel operations, particularly by operators who may not be familiar with the waterbody, and seasonal constraints associated with cold water/ice conditions. Though vessels are commonly used during the initial mobilization for a river spill, so responders can be mobile as the oil spreads downriver, once the oil sinks, it is recommended that spud barges or similar platforms be brought in to provide a safe and stable working base at recovery sites.

Bottom debris in rivers poses particular concerns with sunken oil recovery, including the following.

— Vacuum/pumping systems may need to include blades for chopping debris prior to transport in hoses to the surface.

— May only be able to use mechanical removal methods if the debris is large or too varied to use vacuum/pumping systems.

— Wastewater systems on deck may require special designs to handle the debris.

— Diver safety issues, particularly in areas of low visibility.

Diving operations in river and high-current environments are considered hazardous and should only be conducted by professional commercial divers experienced in low-visibility, high-current operations. SCUBA diving should never be permitted in this type of environment. Divers often over estimate personal diving skills while also underestimating the physical force of moving water. Specific hazards when conducting diving operations in riverine systems include the following:

— entanglement and umbilical fouling on bottom debris;

- unanticipated changes in current direction and intensity;
- submerged debris and objects flowing downstream in the water column;
- entrapment concerns around dikes, dams and jetties; the current around these structures is often strong and unpredictable;
- lacerations and puncture wounds on bottom debris;
- moving water increases diver heat loss and may require additional thermal protection;
- increased physical exertion by the diver may limit bottom time and should be addressed in work/rest considerations in the safety plan;
- operations are often conducted in remote locations that will require the ability to conduct diver emergency treatment on-site, including placing a decompression chamber at the work site with a diving medical technician in attendance.

5.9.2 Sunken Oil Recovery in Extreme Cold Conditions

Extreme cold conditions are defined here as when the waterbody is frozen over by ice, air temperatures are below freezing, or thick snow accumulations. These conditions pose unique challenges to responders who are not experienced in spill response under these conditions. Floating oil response during extreme cold conditions are difficult; recovering sunken oil under these conditions is even more challenging. Issues to be considered when preparing for the recovery phase of a sunken oil response during extreme cold conditions include the following.

- Use arctic-grade equipment and supplies, such as arctic grade hoses. Use crank-case and battery heaters on combustion engine driven equipment. Oil can gel in extreme cold conditions causing equipment failures.
- Hot houses on work platforms where workers can warm up.
- Additional protective equipment is required for diving operations, such as a dry suit or hot water suit to prevent hyperthermia.
- Equipment and trained personnel to determine ice thickness and load-bearing capacity each day.
- Equipment and trained personnel to cut ice slots for diver access and recovery equipment deployment.
- The oil will likely be more viscous, requiring viscous oil pumping systems, steam injection at the nozzle.
- Wastewater systems on deck will require heating units to keep water from freezing and to reduce oil viscosity prior to pumping.

Diving below the ice and in cold water, defined by NOAA as <37 °F, is considered a hazardous operation and should only be conducted by professional commercial divers with experience in such operations. SCUBA diving should not be permitted. Of note, in 2006, the USCG lost two SCUBA divers that were attempting to conduct a 20-fsw dive in the arctic. The following should be considered when planning to conduct sunken oil detection operations in ice or cold-water conditions.

- Divers should wear appropriate thermal protection based on the water temperature and expected bottom time.
- A dry suit or hot-water suit should be worn to prevent hyperthermia.
- The dry suit or hot-water suit should fit properly. All seals should be inspected and in good condition.

— Severe chilling can result in impaired judgment. As such, the tasks to be performed under water must be simple and clearly defined, and the diver's condition should be continually monitored.

— Keep the diver hydrated and minimize any additional exercise in cold water to try and stay warm. Exercise will cause the body temperature to fall more rapidly.

— Always abort the dive if the diver is showing even minor symptoms of hypothermia. Minor symptoms include uncontrolled shivering, slurred speech, imbalance, and/or poor judgment. Severe symptoms include loss of shivering, impaired mental status, irregular heartbeat, and/or very shallow pulse or respiration.

— Upon exiting cold water, do the following.

1) If the diver is wearing a wet suit or hot-water suit, immediately flush the suit with warm water. Doing so will have a comforting, heat-replacing effect.

2) Get the diver to a dry, warm area as soon as possible.

3) The diver should remove any wet dress, dry off, and don warm, protective clothing as soon as possible.

4) Hot, non-alcoholic beverages should be available for the diver.

— A decompression chamber and supplemental first-aid equipment to treat hyperthermia should be on-site during diving operations.

— Topside personnel should wear warm, protective clothing. The dive tender should have a hand on the diver's umbilical at all times, the standby diver should be dressed-out and ready to enter the water, and the supervisor and topside crew should be prepared to take immediate action.

— Plan for diving operations in cold environments to take additional time in comparison to fair weather operations.

The Association of Diving Contractors International recommends the following special precautions for diving equipment when operating in cold environments.

— The moisture in air compressors and air lines must minimized to prevent freezing of the surface-supplied air system, which can cause catastrophic damage or failures.

— The dive crew should consider the use of high-pressure cylinders as an air supply, which generally will contain less moisture than air produced by a low-pressure compressor.

— Topside must continually empty the excess water out of the volume tank to help reduce the amount of moisture in the system.

— Do not allow the diver's umbilical to rest for long periods of time on cold surfaces (barge decks, etc.). Fittings on the umbilical can transfer the temperature from the cold surface and cause the moisture in the diver's umbilical to freeze.

— In water temperatures of 37 °F (3 °C) or less, first-stage regulator on bailouts should be equipped with a proper cold-water setup (environmental kit).

— Extra precautions must be taken to make sure that the bailout cylinders are completely dry inside, that moisture-free air is used, and that the regulator is thoroughly dried prior to use.

— If using a hot-water machine, careful attention must be exercised to monitor the output temperature of the hot-water machine. In extreme cold-water environments, the hot-water machine is classified as life-support equipment. Failure of the system can cause catastrophic results for the diver.

- Failure of the hot-water machine during decompression must be considered during the operation and dive plan.
- Gasoline and diesel engines must be modified for cold weather to prevent engine freeze-up.
- Use proper lubricants in the diver's air compressor.
- Use appropriate cold-temperature lubricants in pre-packed bearings.
- Bring extra batteries for equipment. Cold temperatures can shorten the life of a typical battery.
- A hypothermia-management kit should be considered.
- Extreme caution must be exercised when refueling in dry, cold weather. Static electricity should be "drained off" by grounding the equipment or fuel container (away from vapor openings) with the hand. Static electricity can form in the layers of clothing worn by personnel and can cause a spontaneous discharge of electricity, which can ignite fuels.
- When using a funnel, use a copper screen to help filter out ice particles and foreign debris.

5.10 Summary of Techniques for Sunken Oil Recovery

Effective techniques for sunken oil recovery vary based on the oil behavior, site conditions, and available resources. Table 5-1 provides a summary of the uses and limitations of sunken oil recovery techniques. Table 5-2 provides a matrix to assist in evaluation of recovery techniques for specific spill conditions.

Table 5-1—Techniques for Sunken Oil Recovery

	Suction Dredge	Diver-Directed Pumping and Vacuuming	Mechanical Removal
Description	Commercially available suction dredge used to recover sunken oil and associated sediments and water. Some models incorporate cutter heads for use in removing sediments.	Divers manually direct a nozzle or stinger at the suction end of a hose to recover sunken oil. System can be based on a vacuum system or pump system utilizing a centrifugal or positive displacement pump.	Mechanical removal involves physically removing sunken oil with an excavator, clamshell dredge, environmental dredge bucket, or other machinery used to grab, scoop, or pick up sunken oil. Works well for solid or semi-solid sunken oil.
Equipment Availability	Small and medium-sized dredges are commercially available and can be used for sunken oil recovery with little or no modification to depths of 20 ft for small units and 40 ft for larger units.	Requires specialized contaminated water diving gear and capable divers, which are available from reputable commercial diving firms. Pumping equipment is readily available for ad-hoc systems. Requires some experience to assemble a functional set up.	Excavators and clamshell dredges are readily available. Environmental dredge buckets are not as available.
Logistical Needs	Requires the need to handle large quantities of sediments and water associated with recovery.	Contaminated water capable commercial divers, proper diver decon, oil/water/sediment separation and storage.	Platform or barge to work from and hopper barge or suitable storage for recovered sunken oil and associated water and sediment.
Operational Limitations	Smaller units work in depths up to 20 ft, larger units can go as deep as 40 ft. Suited for protected waters only.	Vacuum systems can only lift about 28 ft total. Pumps can push long distances and from great depths.	Excavators are limited to ±20-ft depth. Clamshell and environmental clamshell dredge can work in deeper depths. All can be operated from shore or from large vessel or barge.

Table 5-1—Techniques for Sunken Oil Recovery (Continued)

Optimal Conditions	Protected water, relatively shallow, small concentrations of sunken oil.	Larger concentrations “pooled” on the bottom in less than 100-ft depth with good visibility and little to no current.	Viscous or solidified oils in shallow or protected water.
Pros	Effective way to recover small concentrations of sunken oil mixed throughout sediments.	Selective recovery, diver can distinguish between sediment and oil limiting the recovery of associated sediment and water.	Effective way to recover solidified oil with little associated water.
Cons	Generates large amounts of associated water and sediments. Requires sophisticated oil water separation, and treatment/ disposal of oiled sediments and water.	Vacuum systems effectiveness decreases with hose length, centrifugal pumps tend to emulsify and shear oil, complicating separation after recovery; positive displacement pumps recover at slower rates.	Requires geo-referenced program to control accuracy. Can end up with large amounts of associated sediments. Disturbs bottom, so may be restricted in sensitive benthic habitats.
	Sorbents/V-SORs	**Manual Removal**	**Agitation/Refloat**
Description	Sorbent material such as oil snare or pom poms are weighted or attached to a pipe/chain and dragged along the bottom allowing sunken oil to adhere to oleophilic material.	Hand and hand tools are used to pick up viscous oil on the bottom. Can be conducted in shallow water by wading; in deeper water, divers in gear appropriate for contaminated water place the oil into bags or nets that are lifted to the surface.	Bottom sediments are agitated by physical disturbance or air injection to refloat the oil for recovery using skimmers or sorbents. Can be conducted from boats or by wading in shallow water.
Logistical Needs	Small V-SORs systems can be worked from smaller vessels; large V-SORs systems require larger vessel or platform.	For wading depths working from shore, need shoreline access, trafficable substrate, hand tools, and standard waste handling facilities. For diving depths, will need all logistics for contaminated water diving as well as waste handling and management.	May need sediment curtains or other containment methods to prevent oil migration down current. Other needs are standard: boats, pumps, booms, sorbents, etc.
Operational Limitations	While effective at any depth, accuracy and bottom contact suffer as water depth increases.	For wading depths, safety will drive wave, wind, rain, and lightning restrictions. Diving may be limited by depth and environmental conditions.	Limited to shallow water <8 ft, low-flow conditions, and standard limitations for on-water operations.
Optimal Conditions	Small or trace amounts of oil distributed along the bottom in less than 50 ft of water with little or no current.	Shallow water, good visibility, low currents, viscous oil that can be readily removed by hand.	Static water conditions, fresh oil that will be more easily liberated, and areas with good containment/ recovery access.
Pros	Required materials are readily available. No associated recovered water or sediments.	Individual pieces of oil can be removed. Selective recovery, limiting co-collection of water and sediment. Can be low-tech, except where diving logistics are complicated.	May be the only alternative to dredging or excavation of oiled sediments. Does not require sediment or water handling and treatment.
Cons	Low recovery volumes, oiled solid waste generated for disposal. Placement accuracy decreases as water depth increases. Must contact oil/bottom.	Slow and labor intensive. Requires relatively good water clarity for visibility. Diving may require extensive logistical support if work is offshore on vessel or barge. Will require contaminated water diving gear and decontamination of divers and gear. Severe weather will suspend operations.	Liberated oil may suspend in the water column and settle back to the bottom, with potential to spread down current. Can mix the oil deeper into the sediments during agitation.

Table 5-2—Matrix to Evaluate Technologies for Sunken Oil Recovery

🟥 Red = not likely effective; 🟨 yellow = may be effective; 🟩 green = most likely effective

	Suction Dredge	Diver-Directed Vacuuming	Diver-Directed Pumping	Excavator	Grab/Clamshell Dredge	Environmental Clamshell	Sorbents/V-SORS	Trawls and Nets	Manual Removal Shallow Water	Manual Removal with Divers	Agitation/Refloat
Water Depth (ft)											
— <5 ft	🟨	🟥	🟥	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩
— 5 to 40 ft	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟥	🟩	🟨
— 40 to 80 ft	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟨	🟥	🟨	🟥
— >80 ft	🟥	🟩	🟩	🟥	🟩	🟩	🟨	🟨	🟥	🟥	🟥
Water Visibility											
— >5 ft	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩
— <5 ft	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩
Water Current											
— <1 (kt)	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
— 1 to 2 kt	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
— >2 kt	🟨	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨
Wave Height (ft)											
— <2 ft	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩
— >2 ft	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟩	🟨
Availability	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟩	🟩
Oil Pumpability											
— Fluid	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟥	🟥	🟥	🟨
— Not fluid	🟥	🟥	🟨	🟩	🟩	🟩	🟥	🟨	🟩	🟩	🟥

Table 5-2—Matrix to Evaluate Technologies for Sunken Oil Recovery (Continued)

Red = not likely effective; yellow = may be effective; green = most likely effective

	Suction Dredge	Diver-Directed Vacuuming	Diver-Directed Pumping	Excavator	Grab/Clamshell Dredge	Environmental Clamshell	Sorbents/V-SORS	Trawls and Nets	Manual Removal Shallow Water	Manual Removal with Divers	Agitation/Refloat
Oil Distribution (%)											
— <10 %	🟩	🟩	🟩	🟨	🟥	🟨	🟩	🟨	🟩	🟩	🟩
— 10 to 50 %	🟨	🟩	🟩	🟩	🟨	🟩	🟨	🟥	🟨	🟨	🟩
— >50 %	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩
Oil Patch Size											
— < 0.1 ft^2	🟥	🟩	🟨	🟨	🟨	🟩	🟨	🟥	🟨	🟨	🟩
— 0.1 to 1 ft^2	🟥	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟩
— > 1 to 10 ft^2	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩
— > 10 ft^2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩
Substrate Type											
— Sandy	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩
— Muddy	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟥
Bottom Obstructions	🟥	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟨	🟨	🟨
Buried Oil	🟩	🟨	🟨	🟩	🟩	🟩	🟥	🟥	🟨	🟨	🟩
Sensitive Habitat	🟥	🟩	🟩	🟨	🟥	🟨	🟨	🟨	🟩	🟩	🟥
Removal Rate*	🟩	🟨	🟨	🟩	🟩	🟩	🟥	🟨	🟨	🟥	🟥
Waste Generation**	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Environmental Impact**	🟥	🟩	🟩	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟨
Cost **	🟥	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟩

* Classified as rapid, medium, or slow.

** Classified as low, medium, or high.

6 Diving in Oil Contaminated Water

6.1 Regulatory Requirements

Commercial divers often play a critical role in the success of sunken oil detection, delineation, characterization, and recovery operations. The USCG notes that commercial divers are “necessary in areas inaccessible or inappropriate for dredging because of environmental concerns” (Burns, 1995; Ross, 1994). Additionally, divers can operate in low to zero visibility, unlike an ROV that is limited by visibility and prone to entanglement (USEPA, 1985), and they can collect samples of the sunken oil.

Human health and safety are always the highest priority during sunken oil spill response operations. The *National Contingency Plan* (40 *CFR* 300) requires that all response operations, including diving operations, adhere to the requirements, standards, and regulations of the Occupational Safety and Health Administration (OSHA). In general, OSHA diving standards (29 *CFR* 1910.401-441) apply to all commercial diving operations that take place in U.S. waters. The USCG also has commercial diving regulations (46 *CFR* 197) that apply to diving from a certificated vessel and on the U.S. Outer Continental Shelf. When diving in contaminated waters, commercial divers must also meet the requirements of the *Hazardous Waste Operations and Emergency Response* (HAZWOPER) standards of 29 CFR 1910.120. The Association of Diving Contractors International (ADCI, 2014) and the International Marine Contractors Association (IMCA, 2004) have published comprehensive standards on commercial diving operations, including specific guidance on contaminated water diving. USEPA (1985; 2010), U.S. Navy (2008), and NOAA (2010) have also published recommended guidance on diving in contaminated water.

Table 6-1 through Table 6-4 summarize selected U.S. commercial diving regulatory requirements. The regulations should be consulted for additional or revised requirements. In general, a commercial diving operation inspection consists of three categories: 1) personnel, 2) operations, and 3) equipment. OSHA and USCG regulations are similar in scope; however, additional requirements apply when conducting operations from vessels that require a USCG certificate of inspection. These tables are not a comprehensive regulatory analysis. They are intended to provide an indicator of substantial non-compliance with the mandatory health and safety requirements for commercial divers. They also provide supporting documentation to shut down a commercial diving operation for safety concerns (Elliott, 2005). For additional information on diver life support systems, please refer to the *ADCI Consensus Standards*, Section 6.0, entitled “Life Support Equipment: Requirements, Maintenance and Testing”.

Table 6-1—Selected Regulatory Requirements for Commercial Diving Personnel

Requirement	OSHA Regulation	USCG Regulation	Additional Comments
Dive team members must be qualified to conduct assigned tasks.	29 *CFR* 1910.410 (a) 29 *CFR* 1910.120	46 *CFR* 197.404 46 *CFR* 197.410	ADCI and IMCA issue certification cards. At least one qualified and designated dive supervisor should manage operations on-site. Divers should also provide proof of HAZWOPER training before commencing diving operations.
All dive team members must have current CPR and first-aid certifications.	29 *CFR* 1910.410		
A qualified dive crew consisting of a designated, non-diving supervisor, diver, standby diver, tenders, and support personnel.	29 *CFR* 1910.410 (b)	46 *CFR* 197.432	The industry standard for offshore operations is a minimum of five-members. The diving supervisor must not serve in a dual role as both supervisor and diver. A standby diver must be dressed out with helmet standing by on-line ready to dive.
An experienced, designated person-in-charge is on-scene and supervising the operation.	29 *CFR* 1910.410 (c)	46 *CFR* 197.208 46 *CFR* 197.210 46 *CFR* 197.402 46 *CFR* 197.404	Under OSHA, the person-in-charge is the qualified diving supervisor. For diving operations on an inspected vessel, under USCG, the person-in-charge and the diving supervisor are separate individuals, and both must be designated in writing.

Table 6-2—Selected Regulatory Requirements for Commercial Diving Operations

Requirement	OSHA Regulation	USCG Regulation	Additional Comments
A Safe Practices Manual or Operations Manual must be available on-site.	29 *CFR* 1910.420	46 *CFR* 197.420	OSHA regulations require a Safe Practices Manual that describes the diving activities, while USCG regulations require an Operations Manual that meets the requirements of the Safe Practices Manual. In particular, response personnel should review emergency procedures, emergency phone numbers, and the directions to the nearest decompression chamber and hospital. For contaminated water diving, a more specific safety plan that addresses the specific contaminant and protective equipment should be available.
The divers must have a plan to obtain emergency assistance, specifically, a two-way communications system.	29 *CFR* 1910.421(b)	46 *CFR* 197.420 46 *CFR* 197.314 (b)	If a decompression chamber is not on site, ensure that divers know the location and contact numbers of the nearest facility and hospital. Most importantly, the divers must have the capability to quickly reach emergency services. On-site Diving Medical Technician (DMT) is recommended.
First-aid equipment, including a hand-held resuscitator, must be located on site.	29 *CFR* 1910.421(c) 29 *CFR* 1910.423	46 *CFR* 197.314 46 *CFR* 197.432	For dives deeper than 100 fsw (feet of sea water) or dives outside the no-decompression limits, an operating decompression chamber and supply of breathing gas sufficient to treat for decompression sickness must be located on-site. The chamber must be within five minutes of the dive station.
The Diving Supervisor must conduct a pre-dive safety briefing and inspect equipment.	29 *CFR* 1910.421(f)	46 *CFR* 197.410	All members of the dive team must attend. Key personnel of the ship or facility should also attend.
A warning signal (dive flag) must be displayed.	29 *CFR* 1910.421(h)	*COLREGS*, Rule 27	The warning signal must be a rigid replica of the international code “A” flag at least one meter in height.
The person-in-charge and the diving supervisor must maintain a dive log.	29 *CFR* 1910.440	46 *CFR* 197.480	The log should contain the date, time, and location of the start and completion of dive operations; underwater and surface conditions; name of diving supervisor; and general nature of the work performed.

Table 6-3—Selected Regulatory Requirements for Surface-supplied Air Diving

Requirement	**OSHA Regulation**	**USCG Regulation**	**Additional Comments**
Surface-supplied air diving must be conducted at a depth of 190 fsw or less.	29 *CFR* 1910.425 (b)	46 *CFR* 197.432	Dives of 30-minutes or less may be conducted to depths of 220 fsw.
Each diver must be continuously tended.	29 *CFR* 1910.425 (c)	46 *CFR* 197.432 (c)	
Divers must carry a reserve breathing gas supply	29 *CFR* 1910.425 (c) (4) (iii)	46 *CFR* 197.432 (e)	USCG and ADCI recommend bailout bottles for all commercial diving operations, regardless of depth.
An operating decompression chamber must be on-site for any dive outside the no-decompression limits or greater than 100 fsw.	29 *CFR* 1910.425 (b)	46 *CFR* 197.432 (e) (2)	Note USCG regulations require a decompression chamber on-site for dive operations >130 fsw or outside the no-decompression limits. The more conservative OSHA limitation of 100 fsw should be applied. A decompression chamber is recommended on-site for remote locations regardless of diving depth.

Table 6-4—Selected Regulatory Requirements for Commercial Diving Equipment

Requirement	OSHA Regulation	USCG Regulation	Additional Comments
Air compressors used to supply air to the diver must be equipped with a volume tank with a check valve on the inlet side, a pressure gauge, a relief valve, and a drain valve.	29 *CFR* 1910.430 (b)	46 *CFR* 197.310	
Air intakes for air compressors must be located away from areas containing exhaust fumes or other hazardous materials.	29 *CFR* 1910.430 (b)	46 *CFR* 197.310 (b)	Air intakes should be located upwind from any hazardous atmospheres. Continuous on-site air monitoring is recommended to prevent the compression of hazardous atmospheres.
The output of the air compressor systems must be tested for air purity every six months and after every repair or modification. An analysis certificate stating the serial number of the compressor and the results of the air test should be available at the dive location.	29 *CFR* 1910.430 (b)	46 *CFR* 197.450 46 *CFR* 197.340	The diving supervisor must provide laboratory results or maintenance records for air quality dated within the previous six months. Compressed air used for breathing mixtures must be 20 % to 22 % oxygen by volume, have no objectionable odor, and have no more than 1000 ppm carbon dioxide, 20 ppm carbon monoxide, 5 mg/cubic meter of solid and liquid particulates including oil, and 25 ppm hydrocarbons.
Surface-supplied helmets and masks must have a non-return valve, exhaust valve, and two-way voice communications system.	29 *CFR* 1910.430 (h)	46 *CFR* 197.322 (a)	
Breathing gas supply hoses must have a working pressure at least equal to the working pressure of the total breathing system, have a bursting pressure at least equal to four times the working pressure, and be tested at least annually to 1.5 times their working pressure.	29 *CFR* 1910.430 (c)	46 *CFR* 197.312	Ensure the breathing supply line has been pressure tested to 1.5 MAWP within the past year. Additionally, ensure all connectors are made of corrosion-resistant material, the umbilical is marked in 10-foot increments from the diver to 100 fsw, and is constructed of kink-resistant material.
A depth gauge is required for every diver.	29 *CFR* 1910.430 (g)	46 *CFR* 197.318	OSHA and USCG regulations require a depth gauge that can be read on the surface for surface-supplied diving operations.
A diving ladder or stage must be provided to assist entry and exit.	29 *CFR* 1910.425	46 *CFR* 197.320 46 *CFR* 197.432	
A diving bell must be used for divers with an in-water decompression time greater than 120 minutes, except when heavy gear is worn or diving is conducted in physically confining spaces	29 *CFR* 1910.425	46 *CFR* 197.432	In-water decompression is not recommended for contaminated water diving to limit the diver exposure time.
A diver's safety harness, with a positive buckling device capable of distributing the pulling force of the umbilical, is required for surface-supplied divers.	29 *CFR* 1910.430 (j)	46 *CFR* 197.324	The harness should be certified by the manufacturer, have an overall breaking strength on no less than 2000 pounds, and be capable of lifting an unconscious diver and all equipment safely from the water.

Table 6-4—Selected Regulatory Requirements for Commercial Diving Equipment (Continued)

Requirement	OSHA Regulation	USCG Regulation	Additional Comments
When weights are worn, the belt or assembly should be equipped with a quick release.	29 *CFR* 1910.430 (j)		
Decompression chambers, or "pressure vessels for human occupancy" (PVHO) must be properly equipped and maintained. 1. PVHO must be stamped ASME PVHO-1 or have documentation of USCG approval. 2. PVHO piping must have a shut-off valve within 1-foot of every pressure boundary penetration. 3. The PVHO must have a: a) pressure relief device; b) two-way communications between compartments and to the outside; c) a pressure gauge in each compartment; d) view ports; e) enough illumination to allow occupants to read gauges; f) a means of extinguishing an interior fire; and g) a means of overriding interior breathing and pressure-supply controls.	29 *CFR* 1910.430 (f)	46 *CFR* 197.328 46 *CFR* 197.462	Records must show that the chamber has been examined for mechanical damage or deterioration on an annual basis. Additionally, the pressure vessel and associated piping must be pressure tested every three years. During surface decompression operations, incomplete decontamination of divers may contaminate divers and present a fire hazard (USN, 2008). 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.

6.2 Contaminated Water Diving Checklist

Table 6-5 provides an overview of contaminated water diving procedures. Please note SCUBA diving is not considered acceptable for diving in oil-contaminated water as there is a risk of oil or toxic chemical ingestion. While SCUBA divers were utilized in past sunken oil response operations, such as the T/B *Morris J. Berman* and T/V *Erika* response operations, the *NOAA Diving Manual* states "standard SCUBA gear offers inadequate protection to divers operating in contaminated water environments" (NOAA, 2010). The USN (2008) notes that diving with a standard SCUBA ensemble provides very little protection to a diver. ADCI, IMCA, and the USN recommend complete protection of the diver. For "petroleum fuels, lubricating oils and industrial chemicals," ADCI specifically recommends a "helmeted surface-supplied diver with mated non-porous dry suit with attached boots, gloves and a return line exhaust or double exhaust valve system" (ADCI, 2014). In sum, diving equipment designed to eliminate any exposure to the water should be considered when diving in waters containing petroleum fuel or lubricating oils (Barsky, 1999).

Table 6-5—Contaminated Water Diving Safety Checklist

Action	Sources	Comments
Conduct a Hazard Evaluation. a) If contaminant is unknown, conduct a sampling study before diving. b) Determine degree and extent of contamination. c) Determine duration of potential exposure to the contaminant. d) Determine environmental exposure due to geographic location (thermal conditions, depth, current speed, and weather forecast). e) Establish three zones of contamination based on sampling study: i. Support, “Cold”, or “Clean” Zone, ii. Contamination Reduction Zone (CRZ), iii. Exclusion, “High Contamination” or Hot Zone.	ADCI, IMCA, USN, NOAA, EPA, OSHA	Diving operations should not be permitted until the pollutant has been characterized and a hazard evaluation is complete. Standard SCUBA gear does not provide adequate protection in contaminated water environments. Diving operations should cease if there is any suspected breach in the watertight integrity of the surface-supplied diving system.
Place commercial divers and topside personnel that could be potentially exposed on an approved Medical Monitoring Program.	OSHA, NOAA, EPA	Ensure both divers and support personnel are on a medical monitoring program that includes a baseline examination and annual physical examinations.
Assign a site safety officer and prepare a site-specific safety plan.	OSHA, EPA	
Choose and test commercial diving equipment that will prevent contact with contaminated water: a) Every piece of diving equipment, including umbilical and connectors, must be compatible with the contaminants. b) Diving system materials must be of matching durability. c) Conduct a diving system leak test before diving. d) Consider using a positive pressure diving system to limit exposure. e) Review diving equipment durability, material permeation rate, and potential break-through time. NOTE Personal protective equipment is only as strong as its weakest point. Evaluate, inspect, and test diving suit seam construction, potential breach points, and exhaust valves or through-suit penetrations.	ADCI, IMCA, USN, NOAA, EPA, OSHA	SCUBA diving gear and band-masks are not recommended. NOAA recommends using the “suit-under-suit” concept or the traditional surface-supplied helmet diving system with encapsulated diving suit. The ADCI, IMCA, and USEPA recommend a helmeted surface-supplied diver with a return-line exhaust system and a mating dry suit with attached boots and gloves. Equipment used in contaminated water must be maintained, repaired, and replaced more frequently than equipment used in unpolluted environments.
Manufacturers use the National Fire Protection Association (NFPA) *Standard for Vapor Protective Suits for Hazardous Chemical Emergencies* and the American Society for Testing and Materials (ASTM) *Standard Guide for Chemicals to Evaluate Protective Clothing Materials* to develop test formats (Trelleborg, 2001).		Air compressors must be located in a clean atmosphere or divers should use bottled air compressed in a clean atmosphere.

Table 6-5—Contaminated Water Diving Safety Checklist (Continued)

Action	Sources	Comments
Ensure divers and topside personnel are trained to conduct contaminated water diving. Specifically, diving personnel should have the following training or experience: a) decontamination procedures; b) dry suit diving (donning/doffing and emergency procedures); c) leak testing procedures; d) maintenance, repair, and proper use of contaminated water diving systems; e) sampling procedures; f) emergency procedures; g) HAZWOPER Training (plus annual refresher).	ADCI, IMCA, USN, NOAA, EPA, OSHA	Training should be based on the duties and function to be performed by each member of the contaminated water diving team, surface support personnel, and decontamination teams.
Backup team or standby divers must be equipped and trained to the same standard as the entry team.	ADCI, IMCA, USN, NOAA, EPA, OSHA	The backup or standby diver must have equipment that equals or exceeds that of the diver in the water. If the diving mode is surface-supplied, the standby diver's umbilical must be at least 50 ft longer than that of the diver in the water (Barsky, 1999).
A decontamination system must be set up and manned by trained responders. a) Procedures must be in place to remove the specific contaminant from the surface of the diver, diving system, equipment, the environment, and property. b) There should be a system in place to measure the effectiveness of the decontamination procedures.	ADCI, IMCA, USN, NOAA, EPA, OSHA	The majority of hazardous materials response injuries are caused by improper decontamination procedures.
A disposal plan for contaminated equipment and decontamination wastes must be reviewed and approved by the Incident Commander.	OSHA, EPA	Wastes should be contained and properly disposed in accordance with federal, state, and local regulations.
Maintain comprehensive records: a) medical surveillance records; b) a detailed description of exposures to hazardous substances; c) complaints following exposures to hazardous substances; d) training records; e) a complete log of response actions; f) equipment maintenance records.	ADCI, IMCA, NOAA, EPA, OSHA	

Safety officers should review the requirements and checklists in Table 6-1 to Table 6-4 with the diving supervisor or designated person-in-charge before commencing diving operations. Additionally, the Association of *Diving Contractors International Consensus Standards*, Section 5.38, should be referenced for contaminated water diving best practices. If the commercial diving contractor wishes to deviate from the regulatory requirements, the contractor must submit a "variance request" in writing to USCG Headquarters via the local USCG Sector Office. A copy of all approved variances must be available at the dive location or aboard the dive support vessel before commencing diving operations.

Note that commercial divers may also use mixed-gas and saturation diving systems to extended bottom times at depth. These operations require the use of diving bells and decompression chambers with a sufficient supply of the appropriate mixed breathing gas on-site for decompression and emergency treatment. Oversight of mixed-gas diving operations and saturation diving operations is beyond the scope of this report. The regulations covering these operations include 46 *CFR* 197.434 and 29 *CFR* 1910.426, with more comprehensive standards published by the USN (2008), ADCI (2014), and IMCA (2004).

Note, one atmosphere suits and submersibles may allow divers to safely go deeper, extend bottom times and alleviate decompression requirements (Elliott and DeVilbiss, 2014). However, due to their high cost and limited availability, these systems have yet to be effectively used during sunken oil detection and recovery operations.

When diving operations are conducted in contaminated water or in an area where there is a substantial threat of discharge of oil or hazardous materials, the checklist in Table 5.5 should be reviewed to protect the health and safety of the divers.

According to the EPA, equipment problems in contaminated water are caused primarily by petroleum products (USEPA, 1985). Divers exposed to petroleum constituents often experience equipment failure and deterioration. For example, Purser and Kunz (1985) provide a case study where a diver was exposed to elevated levels of benzene, where "The benzene weakened the rubber straps on his helmet and his neck, face and head were well exposed to the benzene mixture for a few seconds." The diver was later hospitalized due to his brief exposure. This case study is another example of why the diver should not be permitted to use standard SCUBA diving equipment but rather be required to wear surface-supplied equipment with dry suits mated to the helmet, gloves, and boots.

7 Waste Stream Management

7.1 Waste Stream Management Options

7.1.1 General

Managing the oil, water, silt, sediment, and debris waste stream collected during sunken oil response operations is often complex given the multiple variables involved, including oil characteristics, temperature, volumes, recovery system, and pumping method and pumping rates. Unfortunately, there is not a one-size-fits-all decanting or waste stream management system to address all types of oils and environmental conditions. Historically, waste stream management systems have been designed ad-hoc following the discovery of a sunken oil incident and tailored to the specific conditions encountered throughout the operation. As such, adaptability and variability can be expected in the development of a waste stream management system for sunken oil recovery.

One of the major issues is handling the potentially large amount of water and silt/sediment that can be collected with the oil. Decanting tank systems were effectively used on the 1996 Detroit River coal tar spill and 2004 T/V *Athos I* Delaware River spill of Bachaquero crude oil, among others. A similar system was also used on the T/B *DBL 152* slurry oil spill; however, the volume of oil and water mixture could not be decanted fast enough to support the recovery rate, given the narrow weather windows and limited time permitted at the offshore worksites. Ultimately, the waste stream was collected in a barge for later treatment and disposal onshore.

In general, the sunken oil waste stream management system is divided into multiple phases, from solid and liquid separation to final filtration or "polishing." Each of these phases is discussed below.

7.1.2 Solids Separation

The first waste stream management phase is typically separating the solids such as with a settling tank with baffles. Specific attention should be paid to the type of tank(s) utilized for purpose, as they should have appropriate draw points at the top and bottom, and potentially at other points, to effectively separate and remove the various waste streams. The oil's behavior will ultimately dictate the positioning of the draw points. Transfer equipment must be made available on-site to connect to any of these multiple draw points, including pumps that can effectively handle heavy, viscous oils potentially laden with solid content.

A lamella clarifier tank that is designed to remove particulates from liquids may also be used. Lamella tanks contain inclined plates that provide a large effective settling area within a small footprint. The inlet stream is stilled upon entry into the clarifier, and solid particles begin to settle on the plates and accumulate in collection hoppers at the bottom of the unit. The sludge is then removed at the bottom of these tanks, and the clarified liquid exits the unit at the top by weir. Floating oil may be simultaneously skimmed off the top of the tank.

7.1.3 Liquid Separation

The second waste stream management phase is typically additional liquid separation. It should be noted the oil may either sink or float. For example, the recovered sunken slurry oil from the T/B *DBL 152* floated upon discharge into the decanting tank. Sunken oil from the T/B *Morris J. Berman* refloated as temperatures increased during the day. As such, liquid separation may be facilitated by heating, either naturally or applied heat. Diffused air flotation (DAF) is another method to facilitate the separation of the oil and water. Dissolved air is released under pressure into the flotation tank. The released air forms tiny bubbles that adhere to the suspended matter causing it to float to the surface of the water where it may then be removed by a skimming device.

Of note, the oil may remain emulsified if agitated. This has occurred historically when waste management systems are placed on floating platforms. If possible, the waste treatment system should be placed on a stable platform such as a spud barge or jack-up rig. Additionally, pumping methodologies should be selected that minimize agitation.

Centrifuge and “voraxial” separator systems were tested during the *Deepwater Horizon* incident and earlier oil spills. Various centrifuge systems have been designed to physically separate oil and water. As the waste stream enters a voraxial separator, an impeller creates a cyclonic flow that forces the heavier liquid outside the stream, while the lighter liquid is drawn inward to form a central core. At the exit of the separation chamber, the separated streams are collected. The water may be discharged upon testing or require additional filtration. Note, sand, carbon, and solidifying polymers have all been used during this “polishing” phase. These systems have proven effective in industrial processes where the waste stream is consistent; however, given the often inconsistent waste stream input encountered during sunken oil spill recovery operations, the throughput may also be inconsistent complicating waste stream management.

Electrocoagulation systems that use electrons to treat waste streams have proven effective in drinking water and wastewater management systems. Depending on the nature of the sunken oil and waste stream, these systems may be used as either a primary or polishing waste stream treatment. For example, these systems have proven effective in separating emulsions. However, to date, these systems have not been applied to sunken oil recovery operations.

7.1.4 Final Polishing

Regional oil spill decanting policies vary with most States requiring the final wastewater stream to be discharged into a designated “response area.” Prior to discharge, the water stream may be discharged through a final media filtration tank to complete the waste stream treatment process. Standard sorbent materials with a large surface area, for example, have been placed in “polishing” tanks to collect residual hydrocarbons. Polymers, have also proven effective in collecting residual oil. Note, supplemental analytical verification of the discharge may be required as part of a particular State permitting process.

System throughput and efficiency are based on variables such as oil characteristics, emulsion, and temperature, among others. The key is to match the waste stream management capacity with the recovery rates. Buist et al. (2005) note there is an “optimum time” at which separated water should be discharged, or decanted, from the temporary storage device. This optimum time maximizes the amount of water that can be removed from the container, minimizes the oil content of the discharged water, and minimizes the time that storage is “out of service.” Pump selection, pumping flow rate, and system design (e.g. multiple phase separation tanks) can be adjusted to optimize efficiency given a specific oil type and environmental condition. The addition of chemical agents, such as emulsion breakers or demulsifiers, can expedite the oil/water separation process. Buist et al. (2003) found that, while the addition of demulsifiers to a waste treatment system improved oil/water separation, the concentration of the demulsifier and total oil concentration in the decanted water increased. Given the environmental trade-offs, emulsion breakers and demulsifiers have not been used in sunken oil recovery operations to date and are not recommended during decanting at sea. Demulsifiers may be considered prior to discharge at a receiving facility to improve offloading efficiency. Table 7-1 provides a summary of these waste stream treatment options.

Table 7-1—Options for Treatment of Waste Streams From Sunken Oil Recovery Operations

Process Phase	Description	Comments
Phase separation	Solid separation	Baffled/gravity settling tank
		Lamella clarifier
	Liquid Phase separation	Heat or air may be applied
		Diffused air flotation
	Oil skimmer	
Centrifuge	Physical separation	
Voraxial separator	Cyclonic separation	
Electrocoagulation	Electrical/electron separation	
Media filtration	Sorbent material	
	Polymers	
	Nanomaterials	
Emulsion breakers	Demulsifier to improve oil-water separation	Consider environmental trade-offs
Storage	Regulatory approved tank vessels	Sufficient capacity to store pumping discharge

7.2 Waste Stream Management Lessons Learned

Based on the case studies and technology review, the following lessons learned are provided.

- Standard phase separation with final water filtration has proven effective on sunken oil recovery operations. Pump selection, pumping rate, and phase separation tanks can be modified to improve system efficiency. Centrifuge and voraxial separation require additional research and applications on actual sunken oil recovery operations to document recommended use and effectiveness.

- All waste management system tanks should be inspected prior to operation to ensure no residual contamination is present.

- The use of tanks with baffles will reduce the free surface effect, speed up oil/water separation, and prevent re-mixing.

— If any part of the waste stream management system is overwhelmed, response operations may be suspended or delayed until sufficient capacity becomes available.

— Agitation of the system, through vessel movement or pumping, can result in oil emulsions that hinder effective separation and delay waste stream processing. Waste stream management systems should be placed on a stable platform such as a spud barge or jack-up rig. Pumping systems should be regulated to minimize agitation. Additionally, contingency plans should identify receiving vessels with sufficient capacity to store pumping discharge.

— Regional decanting policies vary. For example, many States permit direct decanting of oil into a boomed area on-site while others require media filtration or "polishing" of the effluent with analysis of the outflow. Periodic or continuous analysis of effluent may also be a requirement of a discharge permit. The decision when to decant may also be dependent on whether or not sensitive resources could be affected by the discharged oil concentration (Buist et al., 2003).

— The state or regional specific decanting checklist should be completed under the direction of the Unified Command in advance of operations. In the absence of state or regional checklists, IPIECA (2013) provides a pro-forma decanting authorization form.

8 Government Agency Regulations to be Considered

8.1 State Historic Preservation Officer (SHPO)

During the response to an oil spill emergency, which is a federal undertaking, the Federal On Scene Coordinator (FOSC) is required to consider historic properties during emergency response planning and operations. The federal undertaking for an emergency spill response includes all activities related to the response, not the spilled material itself. The USCG is the lead federal agency for coastal spills; the USEPA is the lead agency for inland spills.

The FOSC must determine whether the response activities could affect historic properties. Historic properties are properties that are included in the National Register of Historic Places or that meet the criteria for the National Register. If the activity could affect historic properties in State waters, the FOSC must identify the appropriate State Historic Preservation Officer (SHPO) to consult with during the process. Sunken oil detection and removal activities have the potential to affect submerged historic properties such as shipwrecks, thus consultation with the SHPO will be required if there is any bottom disturbance activity. Table 8-1 summarizes the consultation requirements and process, as outlined in the *1997 Programmatic Agreement on Protection of Historic Properties/Cultural Resources during Emergency Response under the National Oil and Hazardous Substances Pollution Contingency Plan.* [1]

Table 8-1—Consultation Requirements with The SHPO for Sunken Oil Detection and Recovery

Regulation	Resource of Concern	Potential Requirements	Process
National Historic Preservation Act, Section 106	Submerged cultural and historic sites such as shipwrecks	May include: 1) use of a marine archaeologist to identify known and potential sites and set buffers (type-specific) to avoid them; 2) training of monitors in identification of artifacts; 3) a plan for how to address unanticipated discoveries during detection and removal operations; and 4) implementation of remote sensing surveys (magnetometer, side scan sonar) to identify potential historic sites when working in high-sensitivity areas.	Contact the SHPO as early as possible to start the consultation process. The objective is to seek ways to avoid, minimize, or mitigate any potential adverse effects on cultural resources.

---

[1] Advisory Council on Historic Preservation (1997). Available at: http://www.achp.gov/NCP-PA.html.

8.2 Federal Government Agencies

8.2.1 Permits

The U.S. Army Corps of Engineers has issued Nationwide Permit 20 that covers *Response Operations for Oil and Hazardous Substances*. Nationwide Permit 20 applies to activities conducted in response to a discharge or release of oil and hazardous substances that are subject to the National Oil and Hazardous Substances Pollution Contingency Plan including containment, cleanup, and mitigation efforts, provided that the activities are done under either:

- The Spill Control and Countermeasure Plan required by 40 *CFR* 112.3;
- The direction or oversight of the FOSC designated by 40 *CFR* part 300; or
- Any approved existing state, regional or local contingency plan provided that the Regional Response Team concurs with the proposed response efforts.

Sunken oil detection and recovery operations, conducted as part of the Unified Command and in compliance with any applicable requirements such as the Nationwide Permit General Conditions, would be covered under this permit.

If the sunken oil is located within a national marine sanctuary, a permit from the Office of National Marine Sanctuaries may be required. Any activity on federal or tribal land that may impact archaeological resources requires a permit from under the Archaeological Resources Protection Act. The term “archaeological resource” is defined by statute and regulations, and there are some exceptions to the permit requirements. This permit is issued by the federal agency having jurisdiction: Bureau of Land Management, National Park Service, U.S. Forest Service, Department of Defense, or U.S. Army Corps of Engineers. For tribal lands, the Bureau of Indian Affairs issues the permit.

8.2.2 Consultations

The FOSC may be required to consult with the National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (USFWS), and the National Park Service (NPS) during sunken oil detection and removal actions under various Federal acts. There are consultation requirements for:

- Section 7 of the Endangered Species Act (ESA),
- Essential Fish Habitat (EFH) under the Magnuson Stevens Fisheries Conservation and Management Act,
- Section 106 of the National Historic Preservation Act (NHPA).

The Marine Mammal Protection Act does not require consultation, but it does prohibit “taking” of marine mammals, which is defined as to harass, hunt, capture, kill, or collect, or attempt to harass, hunt, capture, kill, or collect. Of particular concern is the use of sonar; depending on the frequencies used and the source level of the system, there may be agency concerns about acoustic impacts to marine mammals.

The 2001 Memorandum of Agreement outlines the process for Emergency Consultation during a spill response under Section 7 of the ESA between the FOSC and the federal agencies as follows (a similar process is followed for EFH consultations):

- Notification will occur as agreed in the Area Contingency Plan (ACP).
- Spill response activities that may affect listed species/habitat require emergency consultation.
- The ACP, and/or agreed upon references cited in the ACP, will form the basis for immediate guidance on response actions.

— Emergency consultation will be accomplished by including USFWS and/or NMFS in the Incident Command System organization established by the FOSC. These representatives will provide timely recommendations to eliminate/minimize impacts to listed species/habitat. Often, the agencies will prepare Best Management Practices to be followed during response actions.

— The emergency will continue until removal operations are complete in accordance with 40 *CFR* 300.320(b). The FOSC will continue emergency consultation until the case is closed.

Since the *Deepwater Horizon* spill, there has been increased awareness of the importance of consultation requirements under ESA and EFH by the FOSC for response activities. Because there have been few responses where sunken oil detection and recovery activities were conducted, the potential for response actions to affect these species and habitats is not well understood. Thus, it is recommended that the Regional Response Teams include tactics for sunken oil detection and recovery in regional response plans, so that potential impacts can be discussed and addressed during the planning phase.

8.3 Tribal Governments

There is a requirement to consult with Tribal governments when the proposed action may impact their environmental and cultural resources. There may be a Tribal Historic Preservation Officer (THPO) who deals with preservation of tribal cultural resources, similar to the SHPO. The SHPO or Historic Properties Specialist within the Unified Command will be able to assist in determining if tribal lands or Traditional Cultural Property could be affected by the response, triggering the need for consultation with Tribal government authorities.

9 Research and Development Recommendations

The following research and development projects are recommended to improve sunken oil detection, containment, and recovery.

1) Proven Techniques for Sunken Oil Containment:

There are no proven techniques for containment of sunken oil on the bottom, to prevent further spreading prior to recovery. Few of the suggested techniques have been attempted and few have been shown to be effective. In most cases, sunken oil occurs in areas of low bottom currents. In offshore locations, the oil can be mobilized during periods of high wave events where turbulence from the orbital motion of the passing wave stirs the bottom. The oil can become suspended in the water column, such as occurred during the T/B *DBL-152* (Barker, 2014). In rivers and streams, sunken oil and oil-contaminated sediments can be remobilized during higher flow conditions. Studies are needed to determine the conditions under which these containment techniques might be effective using oils of various viscosities and densities.

2) Oil Spill Simulants for Field Tests of Sunken Oil Detection Methods:

There is a need for oil spill simulants to improve sunken oil detection methods. Efforts are underway in Alaska (though with a national focus) to promote a national policy and process for identifying and permitting the use of oil spill simulants (DeCola et al., 2014). Simulants for sunken and submerged oil are included in their needs assessment. This effort should be supported.

3) Real-world Testing of Bulk Sunken Oil Detection Methods using Sonar Systems:

Considerable research has been conducted into the effectiveness of remote sensing of sunken oil utilizing facilities such as dry docks and test tanks that can be used to emulate bottom conditions (Hanson et al., 2009; Parthiot et al., 2004). These facilities impose significant operational restrictions on test and evaluation programs due to the limited depth and distance from the prepared sunken oil samples. These programs represent the only controlled experimentation for detection oil and, while they have provided further insight and experience with the detection of sunken oil, they do not understandably represent actual operational conditions.

The successful function of the sonar systems discussed in this document remains to be validated through testing in a range of actual operational conditions. Controlled validation of sonar equipment in an actual operating environment will provide the response community with heightened confidence in equipment function and expanded tactical recommendations for application of that equipment. It must be accepted that such controlled testing with oil may be difficult, if not impossible to execute under federal permitting restrictions. Furthermore, objective evaluation of sonar performance during a spill emergency is limited in feasibility due to the nature of the emergency. Given these restrictions, one approach is to use various oils contained in a leak-proof, thin bladder or bag where the oil thickness can be controlled. These units could be placed on the surface and buried in different types of sediment types. Initial testing should be conducted in a large tank such as OHMSETT, to verify that the container does not interfere with the sonar and to determine the most appropriate type of container material to best represent the expected surface characteristics of sunken oil so that the sonar response is not an artifact of the material.

Once the test conditions are confirmed in tank studies, field studies would be conducted in representative substrate types, including sand, silty sand, and mud. The contained oil units would be: 1) placed on the surface and 2) buried below the surface at various depths and by different sediment types.

4) Effectiveness of Laser Fluorsensors to Detect Oil in Bottom Sediments:

Very few of the techniques discussed in this report are effective at detection of sunken oil in the form of oil-particle aggregates mixed into bottom sediments, such as occurred in the Kalamazoo River after the Enbridge Pipeline spill of diluted bitumen. Laser fluorosensers are very sensitive to the presence of oil, and they can be deployed underwater. A study should be designed to determine the sensitivity of laser fluorosensors to this type of sunken oil.

5) Optimization of Optimization of Nozzle and Stinger Designs to Minimize Water and Sediment Removal During Vacuuming and Pumping Operations:

Different ad-hoc designs of stingers and nozzles have been used on several past responses where diver assisted vacuum/pumping was utilized but very little information exists as to the advantages and disadvantages of different designs. Steam or hot water has been used to help reduce the viscosity of heavy oil but little information exists related to the effectiveness. Prototype designs could be tested at varying depths with varying viscosity oil or oil stimulant. Tests can be performed with stingers and nozzles fabricated from different materials to determine optimal length, shape, weight, etc. Tests can be performed with shut-off valves mounted at the stinger and/or nozzle to determine operator preference under different scenarios.

6) Design and Best Operating Conditions for the Performance of Towed Sorbents for Oil Uptake:

Though low-tech, towed sorbents have a useful role in sunken oil detection and inspection post-treatment. Various configurations have been built during response emergencies; however, there are no data on which to evaluate their performance in terms of maintaining contact with the bottom or oil uptake performance. Questions that need to be addressed include the following.

a) What is the best design to maximize contact with the bottom, considering the tradeoffs between smaller “light” designs with a single chain and the larger, multi-chain designs?

b) What is the appropriate tow speed under different currents and bottom types to maintain contact with the bottom for each design?

c) What design will best allow the towed arrangement to slide over obstacles without snagging?

d) Should the design incorporate a plow or scoop shape that will assist in forcing it downward while being towed to increase/optimize bottom contact?

Various prototype designs could be field tested in real-world setting, using an underwater video camera attached to the frame holding the sorbents to document performance. There is added benefit from the effort to design such a video monitoring system, in that it could be used during actual spills to document performance of towed sorbents. Field teams could monitor the bottom contact rate and revise the tow as needed to maintain contact to improve oil detection capabilities.

7) Evaluate the Performance of Wastewater Treatment Systems for Effluents Typical in Content and Variability from Sunken Oil Pumping, Vacuum, and Dredging Operations:

As noted previously in this report, waste stream management systems have historically been designed ad-hoc following the discovery of a submerged oil incident and then modified throughout the operation to address the specific conditions encountered, such oil type, temperature, depth and volume, among others. Since decanting and waste stream management may ultimately be the limiting factor in the success of a sunken oil recovery operation, there is a need to better evaluate system components in an effort to design a commercial off-the-shelf “plug and play” treatment system to improve response times and sunken oil recovery capabilities. In addition, advancements in waste stream treatment, such as centrifuge, voraxial separators, and eletrocogulation, should be tested regarding applications to sunken oil recovery.

In addition to the above research and development recommendations, the following items are offered to further advance sunken oil detection and recovery efficiency and effectiveness.

— Despite the time-critical nature of marine casualty operations clearly articulated in the NCP, and lessons learned from historical case studies, ship owners and operators are often reluctant to immediately deploy salvage assets to prevent ship casualties from deteriorating. Additionally, USCG FOSCs are often not trained and experienced in salvage and sunken oil recovery operations. This is evident in the recent regulatory mandates and the need for guidance on vessel response plan activations, authorities, and best practices (USCG, 2013). Ship owners, operators, management companies, qualified individuals, and regulatory officials should seek formalized training in salvage operations to gain a better working knowledge of the tools and systems available to quickly respond to a vessel in distress.

— The U.S. SMFF regulations should be amended to apply to vessels carrying Group V, non-floating oils. Additionally, the depth to recover oil outlined in the regulations should be extended well beyond the 150-ft parameter found within the definition of subsurface product removal. Revising the subsurface product removal response timeframes from 72 to 84 hours to more stringent timelines will encourage the continued development of more off-the-shelf systems to immediately address sunken oil detection and recovery needs.

10 Literature Cited and Suggested Readings

[1] Advisory Council on Historic Preservation. 1997. *Programmatic Agreement on Protection of Historic Properties During Emergency Response Under the National Oil and Hazardous Substance Pollution Contingency Plan*. Advisory Council on Historic Preservation, National Conference of State Historic Preservation Officers, U.S. Environmental Protection Agency, U.S. Department of the Interior, U.S. Department of Transportation, Coast Guard, National Park Service, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, U.S. Department of Energy, U.S. Department of Defense, and U.S. Department of Agriculture.

[2] Alejandro, A.C. and J.L Buri. 1987. *M/V Alvenus*: Anatomy of a major oil spill. In: Proceedings of the 1987 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 27-32.

[3] Amato, E., A. Ausili, A. Giannì, and M. Vacchi. 2002. Sunken oil residues in a bathyal system. In: Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response, International Maritime Organization, London, UK, pp. 178-188.

[4] Amato, E. 2003. An Environmental Restoration Programme 12 years after the Haven wreck. Les Journees d'information du CEDRE. 17 pp. Available at: http://www.cedre.fr/en/publication/information-day/2003/8amato_gb.pdf

[5] American Petroleum Institute (API). 2013. Remote Sensing in Support of Oil Spill Response Planning Guidance. API Technical Report 1144. Washington, DC. 32 pp. + appendices.

[6] Ansell, D.V., B. Dicks, C.C. Guenette, T.M. Moller, R.S. Santner, and I.C. White. 2001. A review of the problems posed by spills of heavy fuel oils. In: Proceedings of the 2001 International Oil Spill Conference. American Petroleum Institute, Washington, DC, 16 pp.

[7] ASMA, 2007. ASMA (Analyses of Survey, modelling and remote sensing techniques for Monitoring and Assessment of environmental impacts of submerged oil during oil spill accidents). Final report by CEDRE, Geographic Resource Analysis and Science Ltd. (GRAS) and DHI Water & Environment to the EU, 5 pp + appendices.

[8] Association of Diving Contractors International (ADCI). 2014. International Consensus Standards for Commercial Diving and Underwater Operations. 6th Edition, Change 1. 330 pp. Available at: http://www.underwatermagazine.com/pdf/ADCI_CS_Rev6.1.pdf.

[9] Barker, C.H. 2014. Subsurface oil and waves in the coastal zone. In: Proceedings of the 2014 International Oil Spill Conference, American Petroleum Institute, Washington, DC, Poster. Available at: http://ioscproceedings.org/doi/pdf/10.7901/2169-3358-2014-1-300025.1.

[10] Barsky, S.M. 1999. Diving in High-Risk Environments, 3rd Edition. Hammerhead Press, Santa Barbara, CA, 197 pp.

[11] Blackman, R.A.A. and J. Law. 1980. The *ELENI V* oil spill: fate and effects of the oil over the first twelve months. Part I: Oil in waters and sediments. *Marine Pollution Bulletin* 11:199-204.

[12] Brown, C.E. 2011. Laser Fluorsensors. In: Fingas, M. (ed.). *Oil Spill Science and Technology*. Elesevier, pp. 171-182.

[13] Brown, H., E.H. Owens, and M. Green. 1997. Submerged and sunken oil: Behaviour, response options, feasibility, and expectations. In: Proceedings of the 21st Arctic and Marine Oil Spill Program, Technical Seminar, pp. 135-146.

[14] Brown, H., and R.H. Goodman. 1987. The recovery of spilled heavy oil with fish netting. In: Proceedings of the 1989 International Oil Spill Conference. American Petroleum Institute, Washington DC, pp. 123-126.

[15] Buist, I., S. Potter, A. Lewis, A. Guarino, D. Devitis, B. Smith, B., and J. Lane. 2003. Decanting tests at OHMSETT with and without emulsion breakers. In: Proceedings of the 2003 International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp. 827-831.

[16] Buist, I., A. Lewis, A. Guarino, and J. Mullin. 2005. Examining the fate of emulsion breakers used for decanting. In: Proceedings of the 2005 International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp. 171-175.

[17] Burns, G.H., S. Kelly, C.A. Benson, T. Eason, B. Benggio, J. Michel, and M. Ploen. 1995. Recovery of submerged oil at San Juan, Puerto Rico 1994. In: Proceedings of the 1987 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 551-557.

[18] Camilli, R., B. Bingham, C.M. Reddy, R.K. Nelson, and A.N. Duryea. 2009. Method for rapid localization of seafloor petroleum contamination using concurrent mass spectrometry and acoustic positioning. *Marine Pollution Bulletin 58*:1505-1513.

[19] Clark, T., B. Stong, and B. Benson. 1997. Recovery of tarmats using commercial shrimping boats during the *Buffalo 292* spill. In: Proceedings of the 1997 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 41-49.

[20] Conmy, R.N., P.G. Coble, J. Farr, A.M. Wood, R. Parsons, K. Lee, S. Pegau, I. Walsh, C. Koch, M. I. Abercrombie, M.S. Miles, M.R. Lewis, S. Ryan, B. Robinson, T. King, and J. Lacoste. 2014. Submersible optical sensors exposed to chemically-dispersed crude oil: wave tank simulations for improved oil spill monitoring. In: Proceedings of the 2014 International Oil Spill Conference. American Petroleum Institute, Washington, DC, p. 300156.

[21] Cooper, D., D. Velicogna, and C.E. Brown. 2007. Heavy oil booming. In: Proceedings of the 13th AMOP Technical Seminar, Edmonton, Canada, pp. 343-354.

[22] Coastal Response Research Center. 2007. Submerged Oil–State of the Practice and Research Needs. Prepared by the Coastal Response Research Center, Durham, New Hampshire. 29 pp. + appendix.

[23] Davin, J.J. and J.A. Witte 1997. CLEVECO underwater oil recovery: removing a 50-year-old threat. In: Proceedings of the 1997 International Oil Spill Conference, Washington, DC, pp. 783-788.

[24] DeCola, E.G. T.L. Robertson, J. Robida, B. House, and W.S. Pegau. 2014. Oil spill simulants workshop process and outcomes. In: Proceedings of the 2014 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 102-113.

[25] Delvigne, G.A.L. 1987. Netting of viscous oils. In: Proceedings of the 1987 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 115-122.

[26] Dicks, B., D.V. Ansell, C.C. Guenette, T.M. Moller, R.S. Santner, and I.C. White. 2001. A review of the problems posed by spills of heavy fuel oils. In: Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response, International Maritime Organization, London, UK, pp. 26-36.

[27] Dollhopf, R. and M. Durno. 2011. Kalamazoo River\Enbridge Pipeline Spill 2010. In: Proceedings of the 2011 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 422-428.

[28] Dollhopf, R., F.A. Fitzpatrick, J.W. Kimble, D.M. Capone, T.P. Graan, R.B. Zelt, and R. Johnson. 2014. Response to heavy, non-floating oil spilled in a Great Lakes river environment: A multiple-lines-of-evidence approach for submerged oil assessment and recovery. In: Proceedings of the 2014 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 434-448.

[29] Drieu, M., R. MacKay, F. Hvidbak, P.Nourse, and D. Cooper. 2003. Latest update of tests and improvements to Coast Guard Viscous Oil Pumping System (VOPS). In: Proceedings of the 2003 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 447-452.

[30] *Environment Canada*, *Fisheries and Oceans Canada*, and *Natural Resources Canada*, 2013. *Properties, Composition and Marine Spill Behaviour, Fate and Transport of Two Diluted Bitumen Products from the Canadian Oil Sands*, 85 pp. Available at: http://www.ec.gc.ca/Publications/default.asp?lang=En&xml= D6AB8B67-73F5-48B6-B3D1-AAE1B06FF9A2.

[31] Elliott, J. and DeVilbiss, D. 2014. Advancements in underwater oil detection and recovery techniques. In: Proceedings of the 2014 International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp 2037-2052.

[32] Elliott, J. 2005. An analysis of underwater oil recovery techniques. In: Proceedings of the 2005 International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp 883-893.

[33] Fant, J.W. and K.A. Hansen. 2006. U.S. Coast Guard laser fluorosensor testing. In: Proceedings of the Twenty-ninth Arctic Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, ON, pp. 951-964.

[34] Fingas M., B. Hollebone, and B. Fieldhouse. 2006. The density behaviour of heavy oils in freshwater: The example of Lake Wabamun spill. Presentation and paper for the 2006 Freshwater Spill Symposium, Portland, OR.

[35] Fitzpatrick, M. and P.A. Tebeau. 2013. Detection of Oil in Water Column: Sensor Design. Report No. CG-D-05-13. U.S. Coast Guard Research and Development Center, Groton, CT, 30 pp + appendices.

[36] Fitzpatrick, M., P.A. Tebeau, and K.A. Hanson. 2013. Development of Bottom Oil Recovery Systems - Final Project Report. Report No. CG-D-09-13, U.S. Coast Guard Research and Development Center, Groton, CT, 35 pp + appendices. Available at: http://www.uscg.mil/iccopr/files/Development%20of%20Bottom%20 Oil%20Recovery%20Systems%20-%20Final%20Project%20Report.pdf

[37] Fitzpatrick, F.A., M.C. Boufadel. R. Johnson, K. Lee. T.P. Graan, A.C. Bejarano, Z. Zhu, D. Waterman, D.M. Capone, E. Hayter, S. Hamilton, T. Dekker, M.H. Garcia, and J.S. Hassan. 2015. Oil-Particle Interactions and Submergence from Crude Oil Spills in Marine and Freshwater Environments—Review of the Science and Future Science Needs. U.S. Geological Survey Open-File Report 2015-1076. 33 pp. http://dx.doi.org/10.3133/ofr20151076.

[38] Fremling, C.R. 1981. Impacts of a spill of No. 6 fuel oil on Lake Winona. In: Proceedings of the 1981 Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 419-421.

[39] Grainger, R.J.R., C.B. Duggan, D. Minchin, and D. O'Sullivan. 1984. Investigations in Bantry Bay following the Betelgeuse oil tanker disaster. Irish Fisheries Investigations 27B: 1-24.

[40] Gulf Coast IMT. 2010. Summary of Subsurface Oil Assessment Projects conducted by Mobile Incident Command Post. Deepwater Horizon Unified Incident Command Gulf Coast Incident Management Team December 23, 2010, 37 pp.

[41] Hansen, K.A., M. Fitzpatrick, P.R. Herring, and M. VanHaverbeke. 2009. Heavy Oil Detection (Prototypes). Report CG-D-08-09, U.S. Coast Guard Research and Development Center, Groton, CT, 42 pp + appendices.

[42] Hansen, K.A., L. Guidroz, B. Hazel, M. Fitzpatrick, and G.W. Johnson. 2014. Sunken oil recovery system recommendations. In: Proceedings of the 2014 International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp. 2014-2023.

[43] Helland, R.C., B.L. Smith, W.E. Hazel, III, M. Popa, and D.J. McCarthy. 1997. Underwater recovery of submerged oil during a cold weather response. In: Proceedings of the 1997 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 765-772.

[44] Howard, D.A. and D.L. Laisure, 2008. Asphalt Barge MM52 and the Ohio River. In: Proceedings of the 2008 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 957-962.

[45] Hutchison, J.H., and B.L. Simonsen. 1979. Cleanup operations after the 1976 SS *Sansinena* explosion: an industrial perspective. In: Proceedings of the 1979 Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 429-433.

[46] International Marine Contractors Association (IMCA). 2004. *Diving in Contaminated Waters*. IMCA D 021 Rev. 1 November 2004.

[47] International Maritime Organization. 1985. *Code of Safety for Diving Systems*. International Maritime Organization, London.

[48] International Maritime Organization. 2002. Proceedings of the 3rd R&D Forum on High-density Oil Spill Response. London, UK. 485 pp.

[49] International Maritime Organization. 2012. Operational guidelines on sunken and submerged oil assessment and removal techniques. OPRC-HNS/TG 14/3/6, London, UK. 79 pp.

[50] International Petroleum Industry Environmental Conservation Association (IPIECA). 2013. The use of decanting during offshore oil spill recovery operations, Final Report. Oil Spill Response Joint Industry Project. IPIECA, London, 7 pp.

[51] Kane, D.A. 2003. Recovery of submerged oil from an Alaska lake. In: Proceedings of the 2003 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 713-718.

[52] Kaperick, J.A. 1995. Oil beneath the water surface and review of current available literature on Group V oils: An annotated bibliography. Report HMRAD 95-8. National Oceanic and Atmospheric Administration, Hazardous Materials Response and Assessment Division, Seattle, WA, 34 pp.

[53] Kennedy, D.M. and B.J. Baca (eds.) 1984. Fate and effects of the *Mobiloil* spill in the Columbia River. Seattle: Ocean Assessments Division, National Oceanic and Atmospheric Administration, 99 pp.

[54] Koops, W. and S. Huisman. 2002. Let the oil wash ashore—In case of heavy oil spills. In: Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response, International Maritime Organization, London, UK, pp. 237-246.

[55] Le Guerroue, P., E. Poupon, F.X. Merlin, and G. Cariou. 2003. Recovery of sunken and buried oil in coastal water during the Erika spill. In: Proceedings of the 2003 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 551-558.

[56] Martin, C.A., G.S. Mauseth, and R.D. Suggs. 2003. Underwater cleanup assessment program during the M/V Kuroshima incident, April 1998. In: Proceedings of the 2003 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 1275-1278.

[57] Martinelli, M., A. Luise, E. Tromellini, T.C. Sauer, J.M. Neff, and G.S. Douglas. 1995. The M/C Haven oil spill: environmental assessment of pathways and resource injury. In: Proceedings of the 1995 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 679-685.

[58] Michel, J. 2006. Assessment and Recovery of Submerged Oil: Current State Analysis. U.S. Coast Guard, Research & Development Center, Groton, CT, 36 pp.

[59] Michel, J. and J.A. Galt, 1995. Conditions under which floating slicks can sink in marine settings. In: Proceedings of the 1995 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 573-576.

[60] Moller, T.H. 1992. Recent experience of oil sinking. In: Proceedings of the 15th AMOP Technical Seminar, Edmonton, Canada, pp. 11-14.

[61] Moller, T.H. 1998. Summary of the *T/V Nissos Amorgos* oil spill. Unpublished document distributed at the NRC Workshop on Nonfloating Oil Spills, on 20 August 1998. International Tanker Owners Pollution Federation Limited. London, England, 1 p.

[62] Moller, T.H. 2002. Recovery of sunken oil in the Sea of Marmara. In: Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response, International Maritime Organization, London, UK, pp. 337-345.

[63] National Oceanic and Atmospheric Administration (NOAA). 2010. NOAA Diving Manual: Diving for Science and Technology, 4th Edition. Best Publishing Company, Palm Beach Gardens, FL.

[64] National Research Council. 1999. Nonfloating Oil Spills: Risk and Response. National Academy Press, Washington, D.C. 75pp.

[65] Occupational Safety and Health Administration (OSHA). 2011. OSHA Instruction, Directive Number: CPL 02-00-151, Subject: 29 *CFR* Part 1910, Subpart T—*Commercial Diving Operations*, Effective June 13, 2011.

[66] Occupational Safety and Health Administration (OSHA). *Commercial Diving Regulations* (29 *CFR* 1910 Subpart T).

[67] Occupational Safety and Health Administration (OSHA). 2001. *Training Marine Oil Spill Response Workers Under OSHA's Hazardous Waste Operations and Emergency Response Standards*. OSHA 3172.

[68] Operational Science Advisory Team (OSAT-3). 2013. Summary Report: Investigation of Recurring Residual Oil in Discrete Shoreline Areas and Other Indicators in the Eastern Area of Responsibility. Report to the Federal On-Scene Coordinator, Deepwater Horizon. Available at: http://www.restorethegulf.gov/release/2014/01/15/operational-science-advisory-team-report-iii.

[69] OSAT III. 2013. Appendix B. Snorkel SCAT Methodologies and Standard Operating Procedures. In: *Investigation of Recurring Residual Oil in Discrete Shoreline Areas in the Eastern Area of Responsibility*. Operational Science Advisory Team (OSAT-3) Deepwater Horizon Unified Command, New Orleans, LA.

[70] Park, W.C. 1985. Response to the *Mobiloil* spill incident. In: Proceedings of the 1985 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 335-340.

[71] Ploen, M. 1995. Submerged oil recovery. Second International Oil Spill Research and Development Forum. International Maritime Organization, London, UK, pp. 165-173.

[72] Pfeifer, C., E. Brzozowski, R. Markarian, and R. Redman. 2008. Long-term monitoring of submerged oil in the Gulf of Mexico following the T/B *DBL 152* incident. In: Proceedings of the 2008 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp 275-278.

[73] Popa, M. 2009. Case Study #1: CSO barge. Presentation at the Liquid Asphalt Releases in Aquatic Environments Workshop, 21 October 2009. Coastal Response Research Center, University of New Hampshire. Available at: https://crrc.unh.edu/workshop/crrc/response-liquid-asphalt-releases-aquatic-environments.

[74] Purser, P.E. and H.S. Kunz. 1985. Prologue to diving in polluted waters. In: Proceedings of IEEE/MTS Oceans' 85 Conference, Searle Consortium, Ltd.

[75] Redman, R., C. Pfeifer, E. Brzozowski, and R. Markarian. 2008. A comparison of methods for locating, tracking, and quantifying submerged oil used during the T/B *DBL 152* incident. In: Proceedings of the 2008 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 255-259.

[76] Ross, R.G. 1994. Federal On-Scene Coordinator's Report for the Tank Barge *Morris J. Berman* Spill, San Juan, Puerto Rico, January 7, 1994; *Submerged Oil Recovery Operations*. U.S. Coast Guard Marine Safety Office San Juan.

[77] SL Ross Environmental Research Ltd. 2013. Meso-scale weathering of Cold Lake bitumen/condensate blend. ENG JRP Exhibit #B193-2, Ottawa, Ontario, 27 p.

[78] Rymell, M. 2009. RP595, Sunken and submerged oils—behavior and response. A Report for the Maritime and Coastguard Agency, BMT Cordah Limited. 146 pp.

[79] Stantec Consulting Ltd. 2012. Summary of clean up and effects of the 2007 spill of oil from the Trans Mountain Pipeline to Burrard Inlet. Available at: www.transmountain.com/uploads/pages/1374960812-2012-Summary-2007-Spill-Clean-Up---Effects-REV2.pdf.

[80] TRB (Transportation Research Board). 2013. Effects of Diluted Bitumen on Crude Oil Transmission Pipelines: TRB Special Report 311. National Academies Press, Washington, DC, 112 pp.

[81] Trelleborg Viking. 2001. *Diving in Contaminated Water*, Third Edition, Chemical and Biological Tests of Viking Drysuits and Accessories. Portsmouth, New Hampshire.

[82] U.S. Coast Guard. 2008. *Commercial Diving Regulations* (46 . 197 Subpart B).

[83] U.S. Coast Guard. 2013, Marine Safety Manual Volume II, COMDTINST 16000.7B. Available at: http://www.uscg.mil/directives/cim/16000-16999/CIM_16000_7B.pdf.

[84] U.S. Coast Guard. 2014. *Navigation Rules and Regulations. Department of Homeland Security*. Available at: http://www.navcen.uscg.gov/pdf/navRules/CG_NRHB_20141118.pdf

[85] U.S. Environmental Protection Agency. 1985. *Interim Protocol for Diving Operations in Contaminated Water*. U.S. EPA Office of Research and Development, Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio. EPA/600/2-85/130.

[86] U.S. Environmental Protection Agency. 2010. *Diving Safety Manual;* Revision 1.2, Office of Administration and Resources Management, Safety, Health and Environmental Management Division, Washington, DC.

[87] U.S. Environmental Protection Agency. 2015 (in prep). Federal On-Scene Coordinator Report for the Enbridge Pipeline Spill.

[88] U.S. Navy. 2008. *Guidance on Diving in Contaminated Waters*, SS521-AJ-PRO-010, Rev 1. Naval Sea Systems Command, Washington, DC. Available at: http://www.supsalv.org/pdf/Contaminated%20Water%20Div%20Man.pdf.

[89] Weems, L.H., I. Byron, D.W. Oge, J. O'Brien, and R. Lanier. 1997. Recovery of LAPIO from the bottom of the lower Mississippi River. In: Proceedings of the 1997 Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 773-776.

[90] Wiltshire, G.A. and L. Corcoran. 1991. Response to the Presidente Rivera major oil spill, Delaware River. In: Proceedings of the 1991 International Oil Spill Conference. American Petroleum Institute, Washington, DC, pp. 253-261.

[91] Wynn, J.C. and J.A. Fleming. 2012. Seawater capacitance—a promising proxy for mapping and characterizing drifting hydrocarbon plumes in the deep ocean. Ocean Science 8:1099-1104.

[92] Yaroch, G.N., and G.A. Reiter. 1989. The tank barge *MCN-5*: lessons in salvage and response guidelines. In: Proceedings of the 1898 Oil Spill Conference. American Petroleum Institute, Washington, D.C., pp. 87-90.

Annex A
(informative)

Glossary of Sonar Terms

Absorption: The absorption of sound by the material. This characteristics is important since should be sound be absorbed, there will be no reflected backscatter.

Backscatter: The scattering of sound back to the transducer/s caused by roughness of the seafloor as seen in Figure A.1. Scattering differs from reflection because: (1) scattering results in the incident acoustic energy being redirected over a wide angular sector, (2) reflection is the result of acoustic energy being directed according to rule of angle-in equals angle-out.

Bathymetry: The measurement and utilization of both the peaks and deeps of the seafloor beneath the echo sounder transducer to faithfully represent the three-dimensional shape of the sea bed, typically done with a multibeam echo sounder.

Dead Zone: Also referred to as Nadir Dead Zone, describes an area directly beneath the side scan sonar where the data are spatially under sampled (compressed) and cannot be truly be represented in map-mode scrolling display or in a large geo-registered mosaic image.

Ensonification: A term used to indicate sound coverage of a seafloor area by the sonar beam.

Footprint: The term “footprint” is used to indicate the area that has been ensonified on the seafloor.

Grazing Angle: The grazing angle is the angle that the acoustic beam hits the object or material, typically the seafloor as shown in Figure A.1. The grazing angle is significant because as the grazing angle become shallower, the reflected sound decreases. It is also important because in side scan sonar geometry the cross track grazing angle is typically low over the majority of the swath, but in multibeam echo sounder the grazing angle is typically high over the majority of the swath.

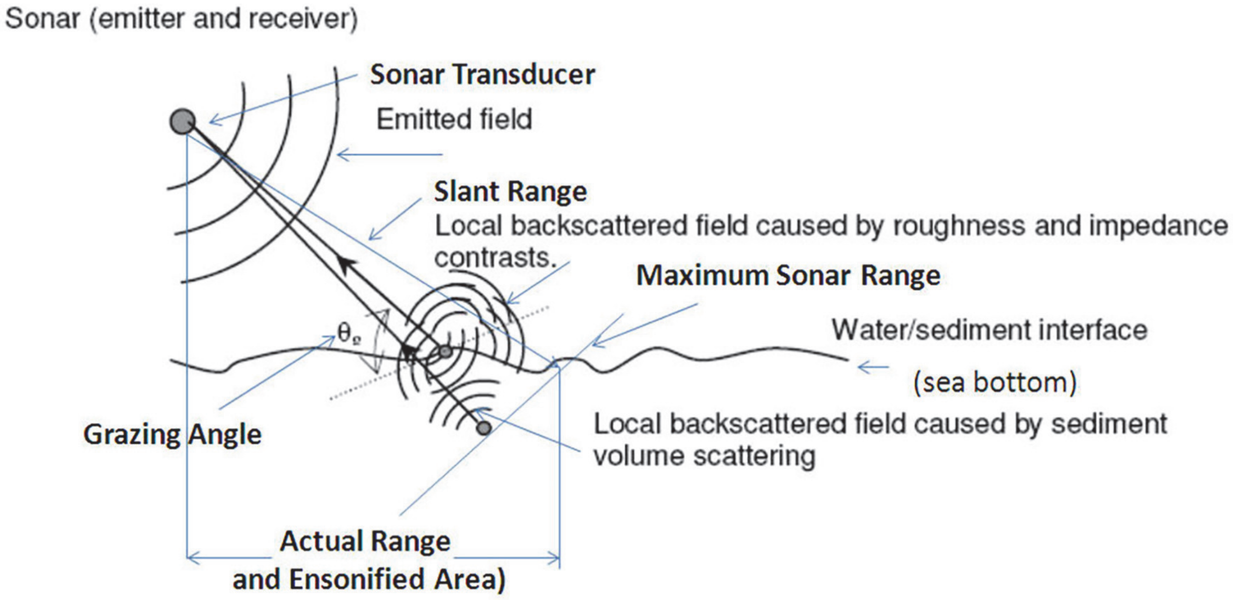


Figure A.1—Function of Side Scan Sonar Utilizing Backscatter (Hansen et al., 2009), Modified to Show Additional Sonar Terms

Impedance: Acoustic impedance of a material is the product of the material density and sound speed in that material. Detection/recognition of layered changes in acoustic impedance is the essence of sub sea bottom.

Lane Spacing: The distance between tracks utilized for a survey. With side scan sonar, there is a region of unusable data beneath the sonar so that the lane spacing for side scan sonar is less than the range of the sonar to allow for coverage of the "dead" zone with an active beam on the return path.

Mow the Lawn Survey: This terminology, while technically vague, provides an excellent description of the standard area survey with acoustic devices. As one would execute with a lawn mower, the sonar is moved or towed up and down parallel courses at the proper lane spacing for providing a minimum of 100 % bottom coverage. In most instances, some overlap is required to allow for navigational errors and to cover the compressed nadir dead zone directly beneath the sonar where data quality is low and not usable. The amount of overlap is dependent upon the survey requirements. As an example, a rapid area assessment can be executed with no overlap to facilitate rapid completion of the survey.

Multibeam Echo Sounder: Sonar system that creates multiple individual echo sounder beams, typically in a cross-track fan shape, and utilizes acoustic beam steering techniques to measure the depth of the bottom of the waterbody beneath the transducer across a defined swath. See Figure A.2.

Nadir Dead Zone: See Dead Zone.

Pseudo-Data Fusion: True data fusion merges all data sets into a usable final data set, while pseudo-data fusion, when used in this context, implies data presentation of different data sets in a format conducive to an operator making an evaluation by reviewing each data set.

Range—Operating Range: Sonar system range typically referred to is the distance from the sonar transducer in a circular arc as seen in Figure A.1 and is selected on the sonar operating console. With side scan sonar, the range refers to the distance from the sonar transducer to one side, typically to the bottom. Side scan sonar swath width is the total bottom coverage for port and starboard sides as seen in Figure A.3.

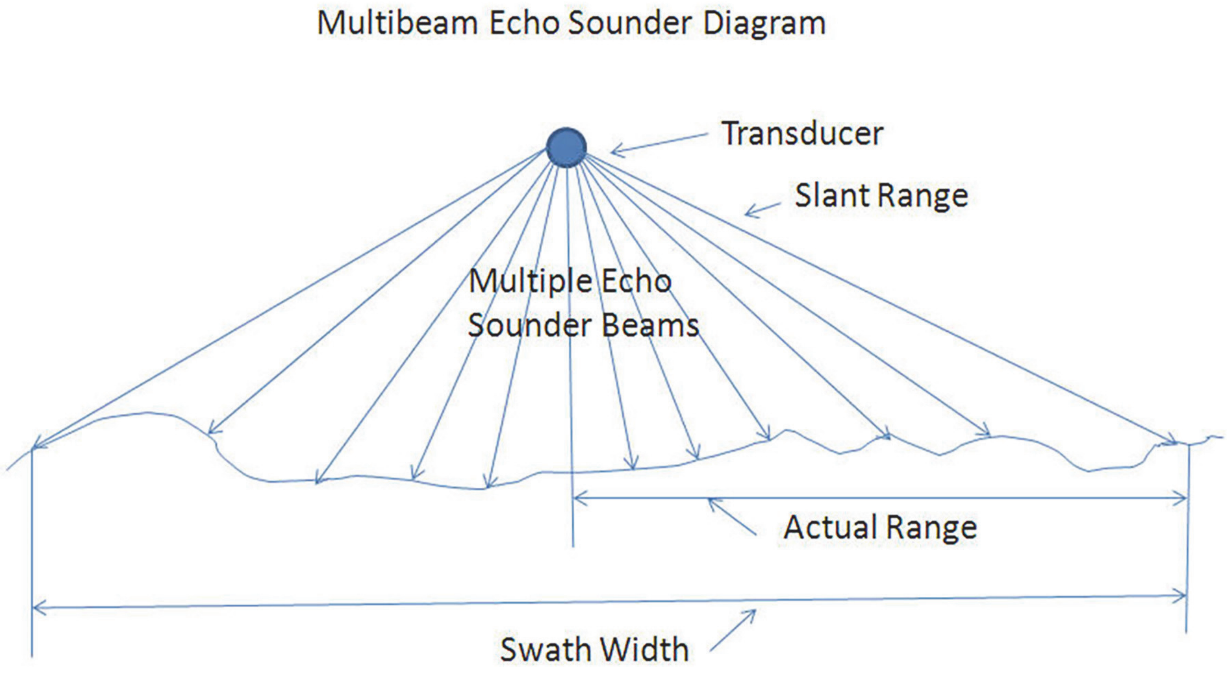


Figure A.2—Multibeam Echo Sounder Diagram

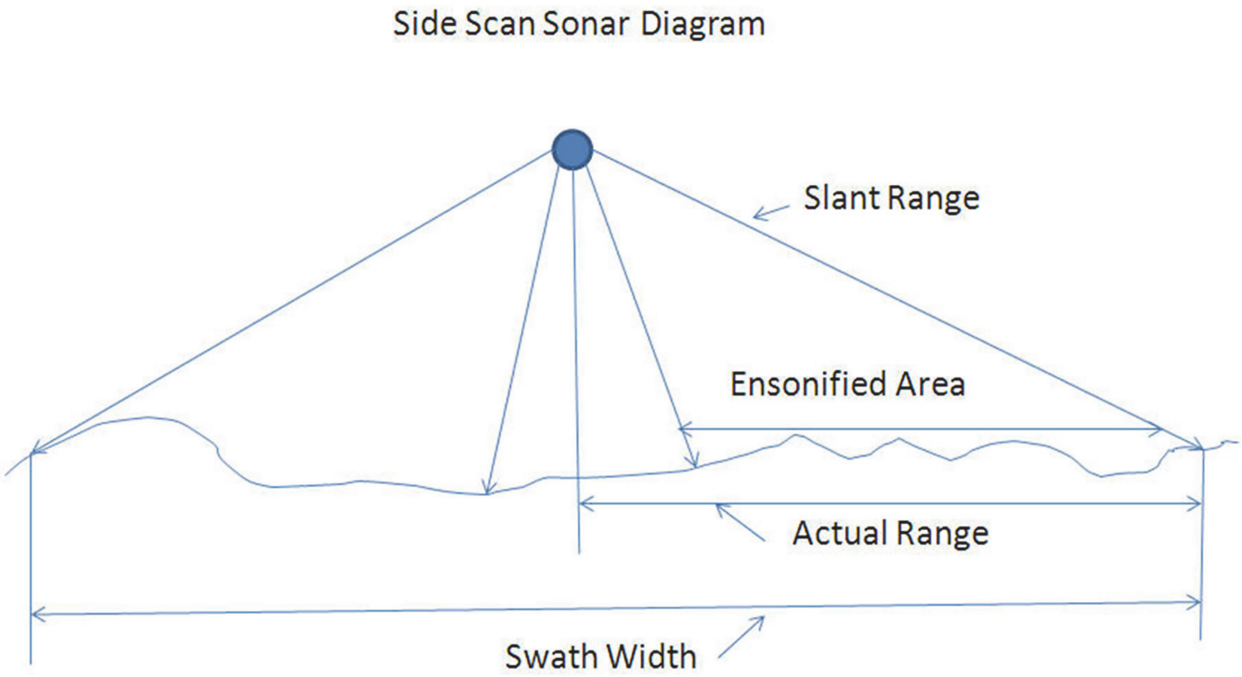


Figure A.3—Side Scan Sonar Diagram

Range—Slant Range: The direct distance from the sonar transducer to the bottom. In most instances, the maximum slant range is the same as the "operating range" In the case of side scan sonar, the sonar transducer is towed approximately 10 % of the sonar's operating range scale above the bottom, and the slant range is the distance from the transducer to the bottom or object of interest.

Range—Actual Range: The projected distance across the bottom from beneath the transducer to the intersection of the slant range with the bottom as seen in Figure A.3.

Reflectivity: The characteristic of an object, sea bottom or sub sea bottom to reflect the sound back to the transducers as seen in Figure A.1. In the case of slick mud and/or bulk oil on the bottom, there is minimal reflection of sound. Reflection differs from scattering because: 1) reflection is the result of acoustic energy being directed according to rule of angle-in equals angle-out, and 2) scattering results in the incident acoustic energy being redirected over a wide angular sector.

Resolution—Sonar Resolution: There are many different terms for sonar resolution, but typically this term refers to the size of the footprint on the bottom with smaller footprint being higher in resolution. High frequency sonars have smaller (better resolution) footprints

Side Scan Sonar: Sometimes also referred to as SLS (side looking sonar) is a sonar system that "looks" out to each side (port and starboard of the track line) at a 10 to 20 degree downward angle from horizontal to provide a high resolution image of the bottom and objects on the bottom.

Side Scan Sonar—Pulsed: the transducer is "hit" with a short electronically generated constant frequency tone burst.

Side Scan Sonar—Chirp: Chirp side scan sonar was the successor to pulsed technology and utilizes an electronically generated signal that is swept in frequency, producing a "chirp" type signal. Advanced processing is utilized with the chirp signal to reduce environmental noise and produce a superior signal.

Sonar Mosaic: Software is commonly available which “laces” sonar bottom coverage swaths into a geo-referenced map of the bottom. While these mosaics can be useful in providing decision makers with sufficient data to make informed decisions, immediate interpretation of the sonar data by a trained operator prior to processing into a mosaic is a recommended way to ensure rapid response to suspected oil mats.

Sub-bottom Profiler: An acoustic system that transmits low frequency acoustic energy directly down into the bottom of a waterbody to determine the layering and consistency of the bottom. See Figure A.4.

Sub-bottom Profiler—Pinger: As described with side scan sonar, the pulsed sub-bottom profiler signal is created either by an electronic discharge into the transducer or by a constant frequency tone input to the transducer to make the transducer “ring” at its resonance frequency. These units are commonly referred to as “Pingers” or a “Pinger Sub Bottom Profiler” and represent the older generation technology.

Sub-bottom Profiler—Direct Chirp: The newer generation technology utilized in sub-bottom profiler systems utilize an electronically generated, frequency swept signal, or Chirp, which sweeps over a range of frequencies from low to high, typically 4 to 24 kHz, and is referred to as a “Chirp Sub-bottom Profiler.” Advanced digital processing techniques are utilized to suppress noise and extract the desired high-resolution signal.

Sub-bottom Profiler—Parametric Chirp: A generation of sub-bottom profiler systems that utilize a parametrically generated, frequency swept signal, or Chirp, Advanced digital processing techniques are utilized to suppress noise and extract the desired high- resolution. The Parametric Chirp employs high levels of acoustic energy and the nonlinear acoustic properties of sea water to generate its pulse of low frequency energy. This technique results in a narrow beam width, which can improve the spatial resolution, compared to Direct Chirp.

Sub-bottom Strata: The sub-bottom area of a waterbody consists of layers of different density material, and the use of a sub-bottom profiler permits evaluation of such layering acoustically, as seen in Figure A.4.

Waterfall Display: Most sonar systems provide a real-time display of sonar data in a format which writes the newest line of acoustic data at the top of a CRT or similar screen, while stepping all past lines down the screen, making it appear to the operator that the bottom is moving down the screen.

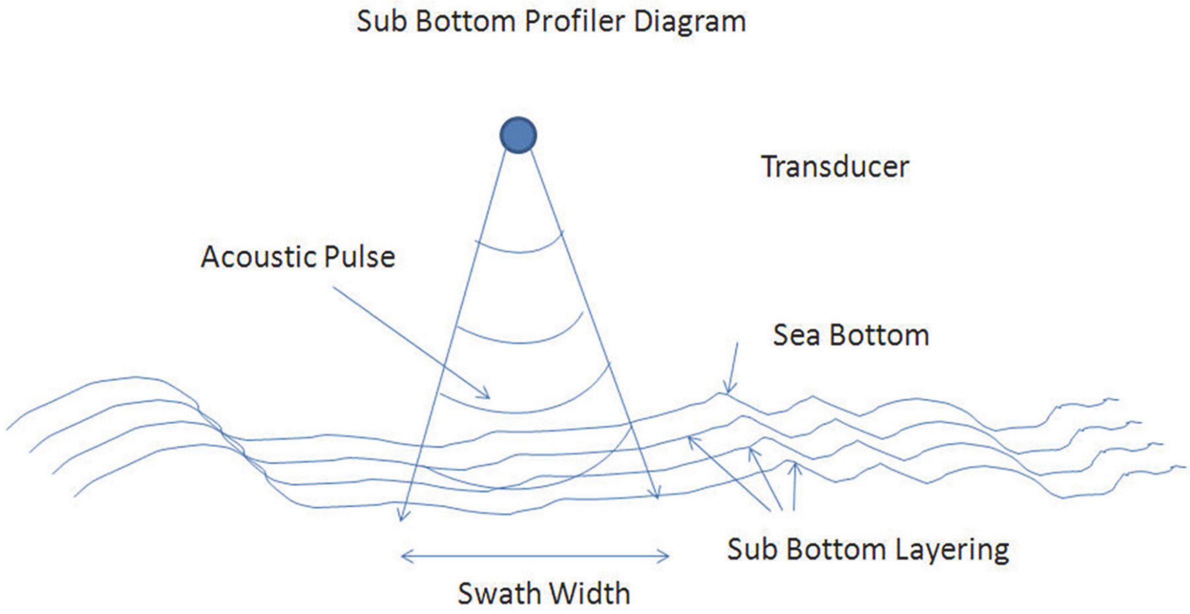


Figure A.4—Sub-bottom Profiler Diagram

Annex B
(informative)

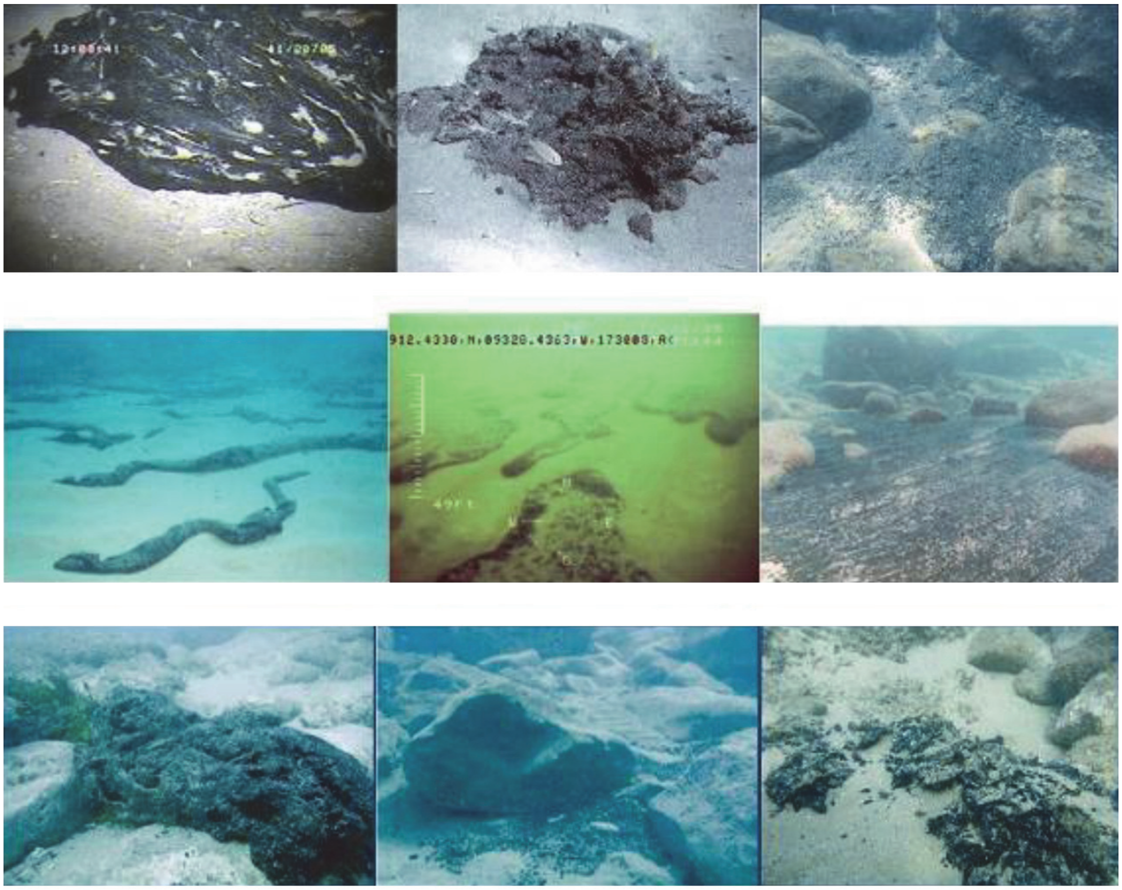
Application of Sonar Systems for Detection of Sunken Oil

B.1 Introduction

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, as seen in Figure B-1, each of which produces its particular modification of the backscatter from that of the pre-spill sea bed.

Even though those various shapes should facilitate the detection of the sunken oil, they can actually complicate interpretation of the backscatter data and therefore introduce long processing times in an effort to increase the potential for detecting a backscatter anomaly and confidently associating any such anomalies with the presence of oil. In any situation, the combination of bottom environment and oil conditions will necessitate the ground truth of the contacts to provide feedback to the sonar operator to facilitate their evaluation of backscatter anomalies.

As noted, this report is intended to provide the on-site emergency response team with an understanding of the function and application sonar systems that are immediately available without development or special and their application in the detection of sunken oil. Because oil-spill responders may have less familiarity with sonar systems than other systems, a detailed discussion in provided in the following sections.



(Photo credits: ICRAM, ARPAT, Guarda Costiera survey of costs of Lebanon, Coastal Response Research Center.)

Figure B.1—Sunken Oil Can Be Found In a Variety of Forms

The following sections provide a discussion of sonar systems with an explanation of the advantages and limitations of each system with consideration of the technical characteristics of the specific equipment. In addition, there is a discussion of the ready availability of such equipment for immediate application. Technical terms utilized in this section are explained in Appendix A.

Sonar systems have evolved to a level where operation of the equipment is not complicated, and these systems can be operated by technical personal with minimal training. However, operation of any sonar system for optimum results will require an operator who is skilled in the operation and interpretation of the sonar output. Therefore, it is essential that any sonar system utilized for sunken oil detection be provided with a skilled operator, who can not only plan and conduct the survey, but who can provide immediate interpretation of the sonar data without extensive data processing.

B.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 sector for bottom surveys, thus it is readily available in various operating frequencies as a lease item with a skilled operator.

Function, Processing, and Display: Acoustic systems function by transmitting a pulse of acoustic energy followed by detection of acoustic energy that has been scattered back toward the sonar due to bottom roughness and impedance contrasts, as can be seen in Figure B.2. The amplitude of such backscattered energy is a function not only of bottom roughness, but also the incidence angle, size, and shape of sonar's footprint on the bottom, and the frequency of the sonar.

Initially, when bulk oil covers the sea bottom, it effectively reduces the roughness of the bottom and therefore produces little backscatter and, as a result, will be appear on the side scan sonar record as a "white" area (lack of backscatter signal) as shown in Figure B.3, from the T/B *DBL-152*. Of special note, this sonar was operated with a copper tone color pallet where lower signals are presented as white and the display moves toward copper as the signal strength increases. Care must be taken concerning the color pallet when making an interpretation as in other operational scenarios; the sonar may be operated with a color pallet where lower signals are presented as dark.

After the oil has interacted with the local sediment and created an oil/sediment mat, there will be detectable changes in backscatter as a result of the backscatter differentiation between a sunken oil/sediment mix and the bottom material. This effect can be seen in Figure B.4 in which a side scan sonar is utilized to detect the oil/sediment mat created under controlled conditions.

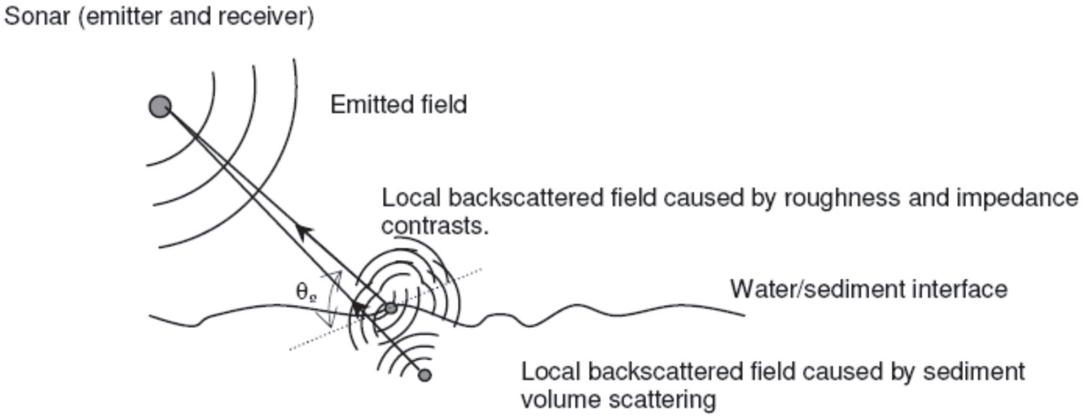
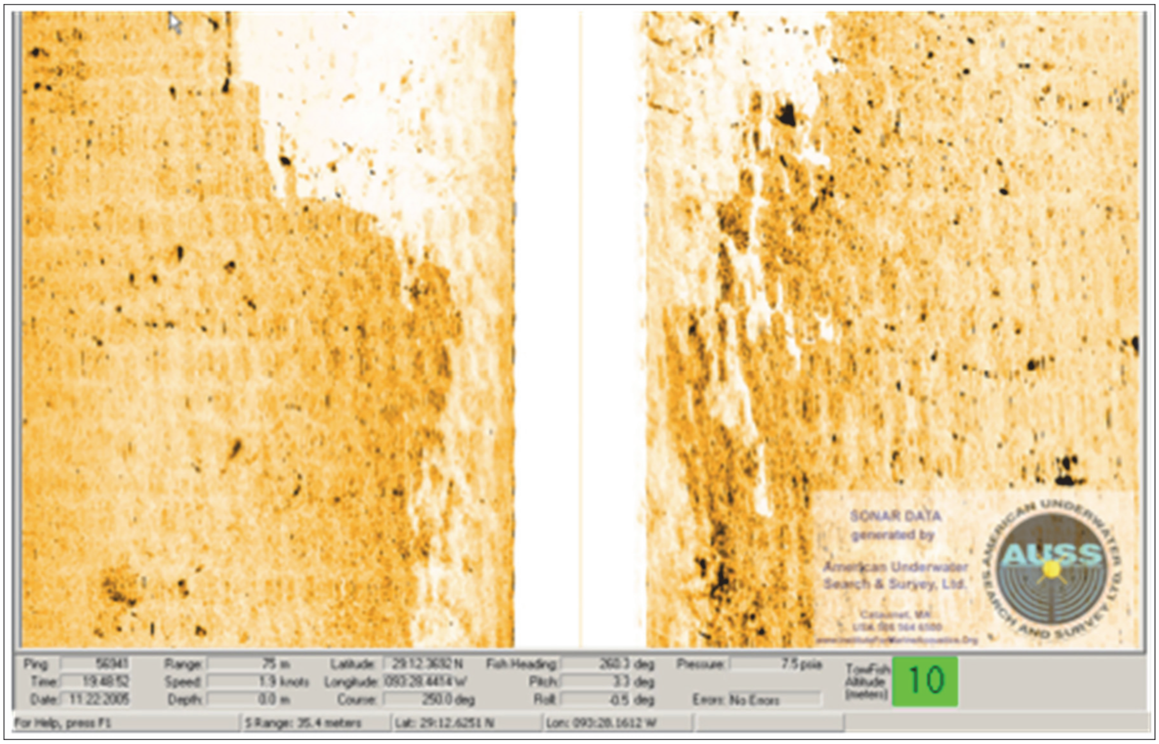


Figure B.2—Function of Side Scan Sonar Utilizing Backscatter (Hansen et al., 2009)



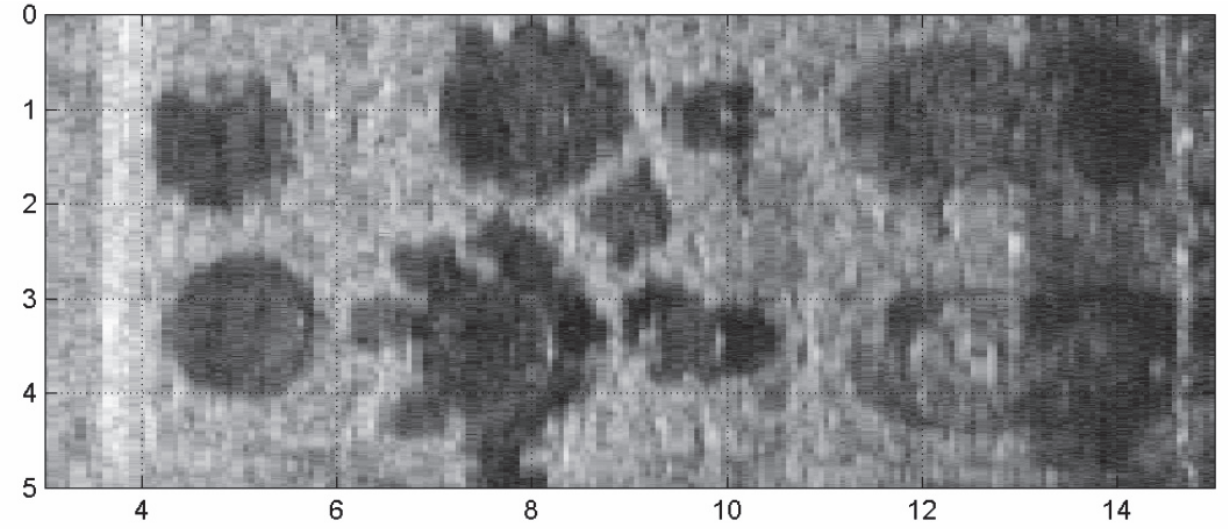
Ping: 56941
Time: 19:48:52
Date: 11:22:2005
Range: 75 m
Speed: 1.9 knots
Depth: 0.0 m
Latitude: 29:12.3692 N
Longitude: 093:28.4414 W
Course: 250.0 deg
Fish Heading: 260.3 deg
Pitch: 3.3 deg
Roll: -0.5 deg
Pressure: 7.5 psia
Errors: No Errors
TowFish Altitude (meters): 10
For Help, press F1
S Range: 35.4 meters
Lat: 29:12.6251 N
Lon: 093:28.1612 W

Figure B.3—Side Scan Sonar Record from the T/B *DBL-152* Incident Showing "White" Areas of Bulk Oil on the Sonar Record (Michel, 2008)

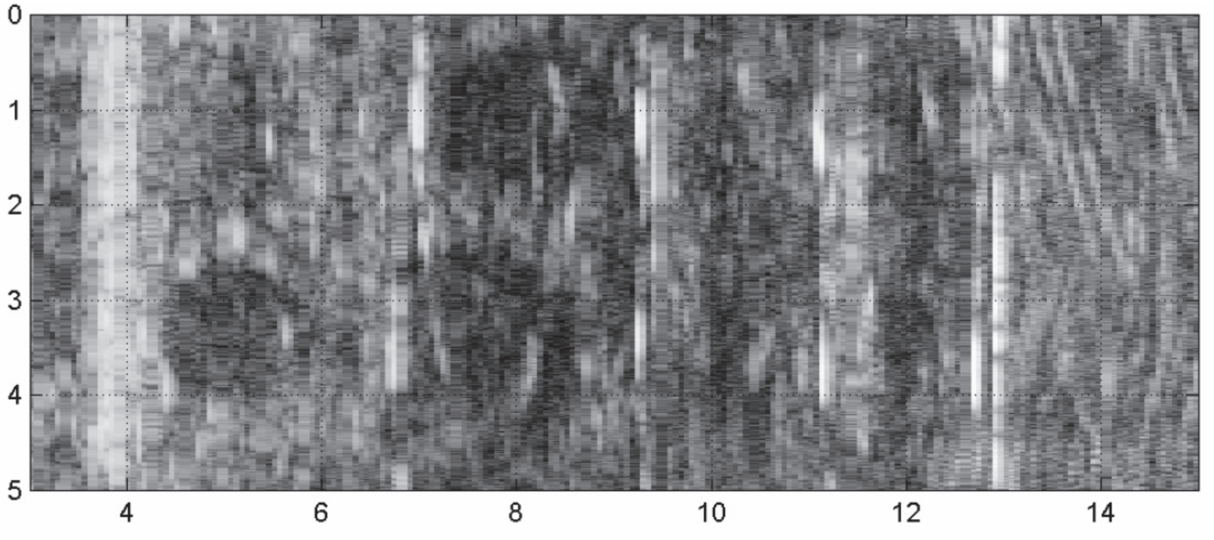
High-frequency side scan sonars (defined in this report as >350 kilohertz [kHz]) typically have a narrower beam angle and produce higher-resolution images of the bottom and associated artifacts. The selection of high-frequency side scan sonar will have significant impact on the performance of the sonar system in the detection of sunken oil. It can be seen in Figure B.4 that the 400 kHz frequency of the dual-frequency, single-beam side scan sonar clearly delineated the oil patches, while the lower frequency 100 kHz produced a less clear image of the oil patches. The changes in relative backscatter levels with frequency indicate a change in the effective roughness of the oil patches as the acoustic frequency changes. The effective roughness of a specific bottom tends to increase as the acoustic frequency increases and consequently the amplitude of backscatter from that bottom tends to increase as the acoustic frequency increases. The implication is that high-frequency side scan sonar may provide better detection performance for sunken oil.

Side scan sonar data are directly readable as "raw" (slant range) imagery created by the sonar that is displayed as a single swath of data, typically on a scrolling video display. Experienced sonar operators prefer this format of data because, although there are errors associated with side scan sonar inherent with this type of presentation, these errors are understandable and manageable. Software does exist to display the sonar data from the current survey line in map-mode on a scrolling video display such that the position of a pixel in the sonar image is relative to the survey track line, rather than indicating the slant range from the sonar to the sea bed. However, such software can introduce errors that may confuse interpretation of the scrolling video display. In addition, near real-time software exists that not only provides the conversion from display in slant range to display in map-mode, but also merges the map-mode data from multiple side scan sonar survey tracks into a large geo-registered mosaic image for strategic or tactical planning purposes.

Field Results: During the 2004 T/V *Athos 1* incident, side scan sonar operating at 100 kHz was utilized to search for the obstruction(s) that caused the damage to the tanker, but also in an effort to delineate any sunken oil. The oil did not actually sink; rather it was suspended above the bottom, and the sonar operators reported that they found artifacts in the sonar data that they believed to be suspended oil, but there was no validation of these observations.



400 kHz side scan sonar data results from sunken oil patches in tank tests.



100 kHz side scan sonar data results from sunken oil patches in tank tests.

Figure B.4—Comparison of 100 kHz and 400 kHz Side Scan Sonar Data (Parthiot et al., 2004)

The side scan sonar record for the T/B *DBL-152* incident seen in Figure B.3 clearly shows the "white" area associated with sunken oil. In discussions with personnel participating in the side scan sonar operations for this incident, they indicated that oil on the bottom was easily detected, down in size to as small as 1 m^2 (John Fish, pers. comm., 2015). Side scan sonar was also effectively used one year after the M/C *Haven* spill and during the 2015 T/B *Apex 3508* spill.

Tactics: Most systems can be leased or hired in a towed configuration or, for shallow-water operation, can be towed at short scope or deployed from a pole mount on a small boat. The towed configuration permits adjustment of the height of the towed sonar transducer (towfish) at the optimum height above the bottom, which is typically 10 % of the selected operating range (slant range) of the sonar. As an example, the optimum height above bottom for a 100-m range (200 m swath) would be 10 m.

Performance is independent of water depth, except in shallow water (less than 20 % of the operating range) where the sonar towfish is positioned at $^1/_2$ of the water depth. Operations in 2 m of water depth with the sonar towfish at half the distance between the surface and the bottom (1 m above the bottom) will produce acceptable sonar records, but with reduced range performance.

Survey Technique: The standard "mow the lawn" survey with swath overlap is effective for determining the overall extent of the sunken oil. For detailed assessment of specific areas, a detailed survey can be conducted which consists of two passes over an area of interest with the second pass executed at 90 degrees to the first pass. These orthogonal passes provide 200 % coverage, but also exploit directionally specific acoustic backscatter characteristics for a more complete understanding of the bottom contact.

For rapid tactical assessment of the extent of bulk oil on the sea bottom, an experienced operator can provide the geographic bounds of the sunken oil in real time as the data are produced by the side scan sonar. Common industry-available software can produce a sonar mosaic in near real time, so that a mosaic presentation of an entire area of interest can be available almost by the end of the survey.

Ground truthing of bottom contacts by divers, bottom sampling, remotely operated vehicles (ROVs), or autonomous underwater vehicle (AUVs) is essential to boost the potential of detection of sunken oil, as various bottom objects and conditions can mimic returns for bulk oil or oil-sediment mats.

Area Coverage Rate: Side scan sonar can function at low grazing angles (angle to the bottom) and as a consequence can cover large areas of the sea bottom in water depths as shallow as 2 m with the sonar towfish 1 m above the bottom. Range performance will degrade in water depths of less than 10 % of selected range, and operations will have to be assessed at time of survey for maximum range performance vs. water depth.

Figure B.5 provides general guidelines for area coverage rate as a function of range and speed over the bottom, based on a sonar towfish height above the bottom at optimum 10 % of slant range with a nadir dead zone (see note) assumed to be 15 % of actual range versus normal 5 %. The maximum slant range possible will be 100 m (200 m swath), while lane spacing selected will permit 5 % overlap of the nadir dead zone.

NOTE Describes an area directly beneath the side scan sonar where the data are spatially under sampled (compressed) and cannot be truly be represented in map-mode scrolling display or in a large geo-registered mosaic image.

Side Scan Sonar Summary: Sunken oil can be detected utilizing side scan sonar, not only in controlled test situations, but also in field applications, as seen in the T/B *DBL-152* and T/B *APEX 3508* incidents. 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.

B.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 in the standard bathymetric configuration are readily available for hire or purchase in the offshore oil or hydrographic sectors. Units with specialty software noted as desirable for detection of sunken oil are very limited and available only in prototype formats.

Function, Processing, and Display: The multibeam echo sounder forms a number of acoustic beams in a cross-track fan-shaped pattern under the transducer and typically utilizes each beam for an echo sounder-like bathymetry measurement. In some instances, the fan beams are utilized for backscatter measurements that are utilized for creation of a pseudo-side scan sonar image. These multibeam echo sounders are available in single frequency or dual frequency to provide operational flexibility. The data from each of the individual beams are processed and displayed on an operator-selectable visual display, typically in a waterfall format.

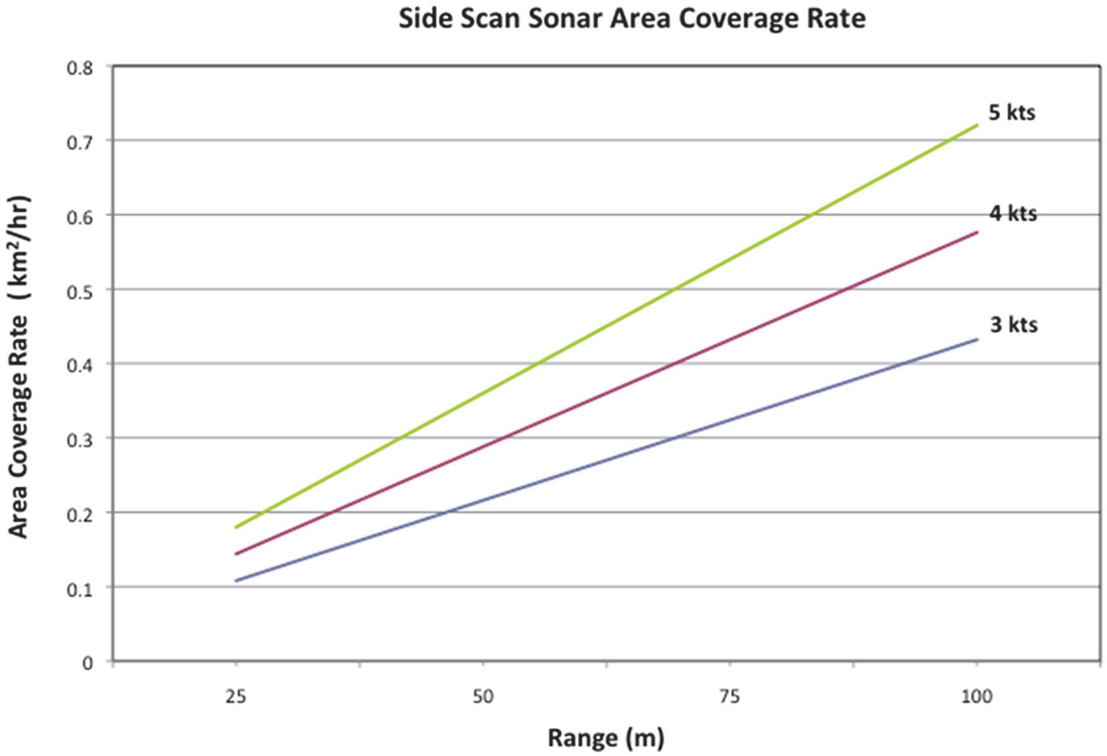


Figure B.5—Side Scan Sonar Area Coverage Rate for Different Tow Speeds and Ranges

Tank Test Results: A multibeam echo sounder tested at OHMSETT showed that a trained operator could visually detect sunken oil in trays on a sandy substrate with approximately an 80 % certainty utilizing the existing processing and display software (Hanson et al., 2009). However, it was noted that a more robust solution is required to facilitate operator recognition of potential oil areas. A Phase II effort to develop processing software produced functional software that required significant post-processing time.

Tactics: Multibeam echo sounders are mounted in the hull or on a pole mounted, thus they can operate in depths of water without difficulties normally associated with towed applications of side scan sonar. There is no optimum height above the bottom for operation of a multi beam echo sounder, although swath wide decreases with decreasing height above the bottom. Detection performance is less than side scan sonar. However, past operational experience has shown that sunken oil will migrate to low spots in the sea bottom, and multibeam echo sounder data provide clear delineation of these low spots and valuable insight into potential areas for accumulation of sunken oil.

The bottom coverage capabilities of multi beam echo sounders are sensitive to speed over the bottom and repetition (ping) rate, so for optimum performance, ship speed, and the sonar range scale should be coordinated/selected to provide as many pings on the bottom as possible. Performance experimentation is encouraged.

Survey Technique: The standard “mow the lawn” survey is effective for determining the overall extent of the sunken oil. For detailed assessment of specific areas, a detailed survey can be conducted which consists of two passes over an area of interest with the second pass executed at 90 degrees to the first pass. These orthogonal passes provide 200 % coverage, but also exploit directionally specific acoustic backscatter characteristics for a more complete understanding of the bottom contact.

For rapid tactical assessment of the extent of oil on the bottom, an experienced operator should be able to provide the geographic bounds of the spill in near real time. Common industry available software can produce a sonar mosaic in near real time, so that a mosaic presentation of an entire area of interest can be available almost by the end of the survey.

Area Coverage Rate: Figure B.6 provides general guidelines for area coverage rate as a function of range and speed over the bottom. In this chart, it is assumed that the included angle of ensonification is 120 degrees (60 degrees on either side of nadir) and that the speed is between 3 and 5 knots, while lane spacing selected will permit 5 % overlap of swaths. Swath widths may vary from calculated, depending on environmental conditions, so operational experimentation is encouraged.

Multibeam Echo Sounders Summary: Multibeam echo sounders in an industry-standard configuration have been tested in controlled conditions and have been shown to detect sunken oil patches on the surface in coarse sand with detections possible from real-time data. No trials have been conducted in other bottom types, and care must be taken in application to establish bottom material so as to better understand the detection capability of the unit. Software variations have been experimented to enhance detection, but extend post-processing times. High frequencies >375 kHz, as with side scan sonar, appear to do better detecting sunken oil patches than lower frequency.

It must be noted that the value of application of a multibeam echo sounders is that not only does the system provide some capability to detect sunken oil, but also that the device can identify low spots in the bottom where sunken oil is likely to accumulate. The combination of multibeam echo sounder bathymetry data sets with other acoustic sensors enhances the potential for sunken oil detection and is encouraged.

B.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”).

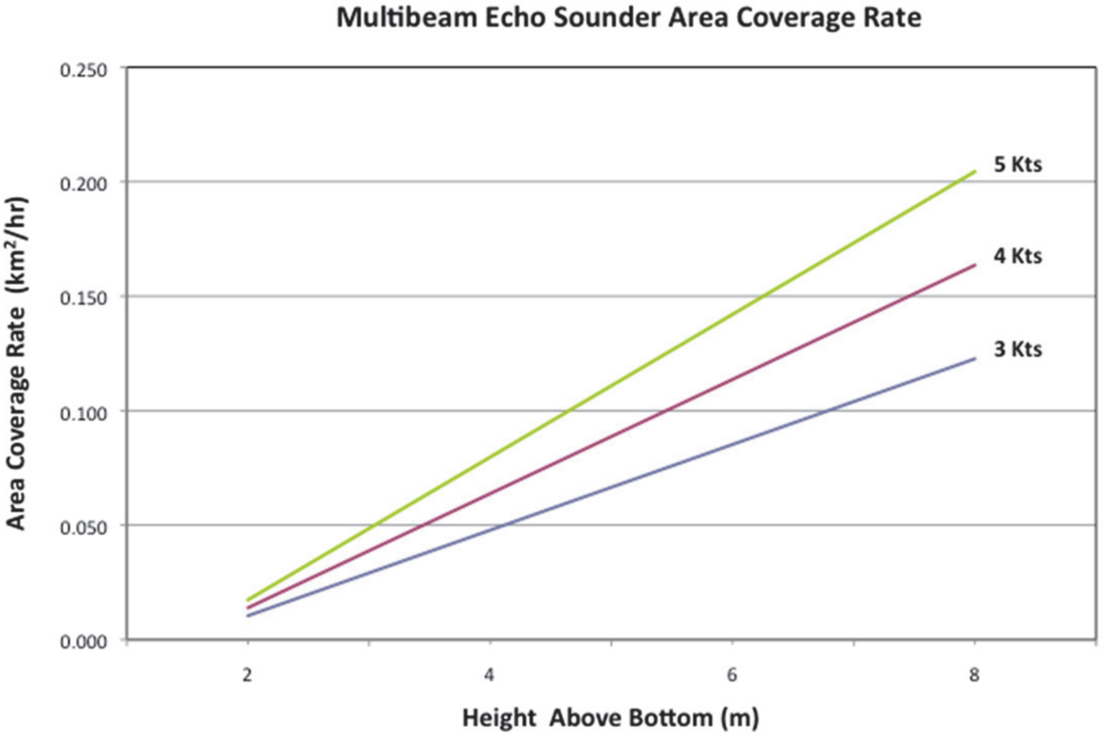


Figure B.6—Multibeam Echo Sounder Area Coverage Rate Based On Speed and Height Above Bottom

Both PINGER and CHIRP sub-bottom profiler systems are commonly available for lease in the offshore oil business. Combined side scan sonar and sub-bottom profiler systems are available, but are not as common as stand-alone sub-bottom profiler equipment. High-frequency sub-bottom profilers, as utilized in trials during the *Deepwater Horizon* response (Gulf Coast IMT Operations Section, 2011), are not common to the offshore oil industry and as a result, are not addressed in this document. The detection of sunken oil is a unique application of this equipment, so it is necessary for the user to be sensitive to the equipment specification and limitations of a sub-bottom profiler for this application.

There are two classes of CHIRP, one directly generates the low frequencies that are capable of penetrating the bottom and the other generates the low frequencies parametrically. The important difference between the two methods of generating the low frequencies is the beam width of the pulse of transmitted low frequency acoustic energy. The difference in beam width imparts a difference in the horizontal spatial extent of an oil patch that can be detected. Parametric and direct CHIRP sub-bottom profiler systems, with or without an operator, are commonly available for lease in the offshore oil business.

Function, Processing, and Display: A CHIRP sub-bottom profiler has an acoustic output pulse that is created by electronically exciting the transducer over a frequency range, typically 4 to 24 kHz. As a result, this swept frequency transmission can produce better definition of the shallow sub-bottom strata layering.

Optimum sub-bottom profiler performance can be anticipated in silty/sandy sediments, while bottoms comprised of organic mud can completely defeat sub-bottom profiler equipment due to the high gas content in the mud. An assessment of the bottom type must be made prior to selection of a sub-bottom profiler survey to determine the suitability for application of sub-bottom profilers. Ground-truth sampling is essential to boost the potential for detection of sunken oil, as sunken oil returns, as noted, can mimic returns from other bottom objects and conditions.

Surveys using both CHIRP sub-bottom profiler and high frequency side scan sonar would be desirable, as the combined unit would provide co-registered data sets over the same bottom, thereby increasing situational understanding. This data set is not fused, but is presented on a single sonar record typically side-by-side and geographically co-registered in position. Correlation of bottom surface expression with sub-bottom profiler data can yield significant understanding of the situation.

Field/Trial Results: The Gulf Coast IMT Operations Section (2011) reported that a combined side scan sonar and sub-bottom profiler system demonstrated that it could detect sunken oil, both on the surface and just below the bottom. The report did note that improvements are needed for real-time readability and better data turnaround times. Co-registered side scan sonar and sub-bottom profiler and presentation of that data without further processing would facilitate faster turnaround times by elimination of the need for data compilation and registration and improve data field applicability.

It is also instructive to note that the sub-bottom profiler that was utilized during the *Deepwater Horizon* trials was a PINGER type system operating at the relatively high frequency of 122 kHz for a sub-bottom profiler, and the implication was that the equipment was able to detect submerged oil mats under a layer of clean sand. However, the “acoustic drop-outs” noted in the report could have been associated with sunken oil on the bottom, not buried in the sub-bottom. A system consisting of two single-beam sonar transducers (200 kHz and 420 kHz) was tested for sub-bottom penetration with limited success, implying that frequencies higher than normal sub-bottom profiler operating frequencies of 1 to 24 kHz are not usable for sub-bottom applications. However the system tested was successful in classifying different types of material on the surface of the bottom, including oil as a different kind of material, indicating usefulness for sunken oil detection.

Area Coverage Rate: The sub-bottom profiler typically utilizes a beam angle of <60 degrees and, as a consequence, suffers from low area coverage rates in shallow water. Figure B.7 provides area coverage rates for a typical sub-bottom profiler. As a consequence, the sub-bottom profiler should be utilized for localized exploration of the sub-bottom region of the sea bottom.

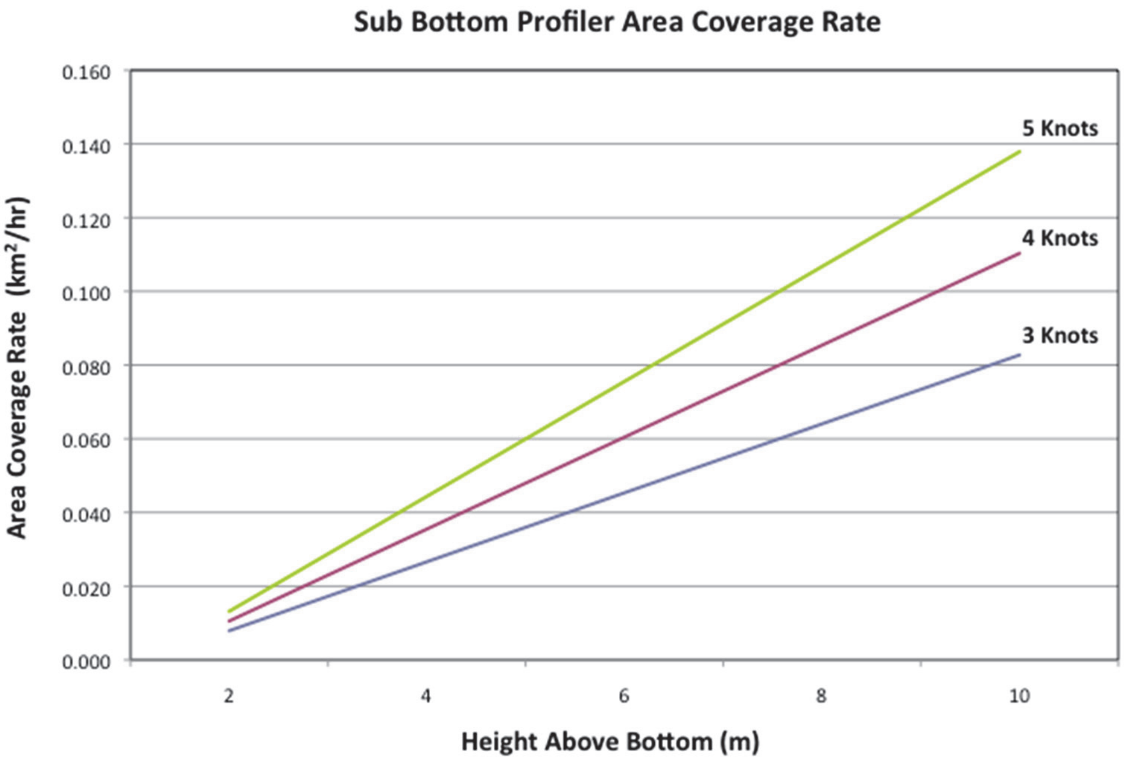


Figure B.7—Sub-bottom Profiler Area Coverage Rate Based On Speed and Height Above Bottom

Sub-bottom Profiler Summary: Common offshore sub-bottom profiler systems can potentially provide indications of buried oil in sandy sediments through identification of sub-bottom anomalies. Sub bottom profilers will 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. It must be noted that sub-bottom profilers will be limited in function in bottoms composed of organic mud or compacted sand so an assessment of the bottom type must be made prior to the decision to deploy a sub-bottom profiler.

B.5 3D Scanning Sonar

The 3D scanning sonar ensonifies the area of interest on the bottom with a matrix of multiple beams, both horizontally and vertically. This capability permits real-time updates so that the unit can be used to “look” at the area of interest on the bottom. The 3D scanning sonar is not widely utilized in the offshore oil or hydrographic sectors, so lease or hire potential is limited.

Function, Processing, and Display: The 3D scanning sonar utilized in the OHMSETT trials conducted by Hanson et al. (2009) operates at 375 kHz and is the system that the USCG is evaluating for other applications. The unit generates an acoustic matrix of 128 beams by 128 beams in a 50 deg by 50 deg grid. The range resolution of a standard unit is 4 cm. It uses return signal strength to differentiate between rocks, bottom, and oil. The trials were conducted against oil patches on coarse sand, and the ability of the sonar to detect oil on the bottom is related to bottom sediment type. The difference in reflectivity or roughness of the bottom and the material of interest is essential in detection of sunken oil.

The data are displayed instantaneously so that the image on the screen is displayed in real time, and the sonar can be used to position a vessel, ROV, or diver when reacquiring a contact of interest. Underwater Inspection System (UIS) software is available for the 3D scanning sonar, which provides a processed image of the bottom and contacts. This software functions more efficiently if the types of bottom and oil can be analyzed separately, and the intensity returns be utilized in a database to differentiate between the bottom and oil contacts. The UIS software can create bottom mosaics on the fly, and it uses averaging in geo-referenced cells to improve signal to noise, said to improve performance significantly.

Field/Trial Results: The USCG tested a 3D scanning sonar under controlled conditions using oil patches on coarse sandy sediment at OHMSETT, showing the capability of the system to detect the oil patches. However, it was recommended that an analysis be conducted on various bottom and oil types and their respective acoustic returns be factored into the software to improve detection performance. Hanson et al. (2009) noted that the 3D scanning sonar can identify heavy oil on the bottom with an 80 % certainty, but additional work is required to determine its performance under different conditions.

3D Scanning Sonar Summary: The USCG has demonstrated viability of the use of 3D scanning sonar, for the detection of sunken oil as noted in Hanson et al. (2009). Lease or hire availability is limited as the equipment is not commonly used in the offshore or hydrographic sectors, but the USCG has a number of units that could be made available through proper channels.

Annex C
(informative)

Underwater Visualization Systems

C.1 Introduction

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 25 m. However, classification range varies with turbidity, contamination, and oil fouling and, in highly turbid environments, detection ranges can approach 0 m.

There have been systems developed utilizing different techniques, such as ultra high-frequency sonar, specified as “acoustic cameras”, which provide an operational capability in low visibility water, and performance is promising. In addition, the real-time transmission of “video data” from optical and other visualization systems to decision makers in onshore command centers is essential for evaluation and response for sunken oil recovery operations. Any delay in the evaluation and deployment of oil recovery systems can defeat the recovery operation. Real-time transmission of ground-truth visualization data can shorten that decision time and improve sunken oil recovery.

Operation of any visualization system for optimum results will require an operator trained and skilled in the operation of, and interpretation of images produced by the specific device. Therefore, it is essential that any underwater visualization system be provided with a trained and skilled operator who can plan and conduct the survey in conjunction with the sonar or other system operator, as well as provide immediate ground truth of the sonar or other data for on-site coordination of both system operations.

C.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 and sub-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 will provide adequate resolution for oil detection applications, although camera resolution in the past decade has increased to 25 megapixels.

Function, Processing, and Display: Still cameras can be triggered by an external trigger from an operator for an ROV or autonomously in the case of an AUV. The typical mode of operation is to select a trigger period on the camera suitable for the application and let the camera run at the prescribed trigger rate, based on the anticipated speed over the bottom of the vehicle so that the desired percentage of coverage can be obtained. Alternatively, the camera can be mounted on a drop frame so that the camera is dropped to the bottom, and photographs are obtained at a specific location.

In all configurations, these still cameras store the image data in solid-state memory in the camera, and those images can be downloaded to a computer through a USB port for visualization and transmission. No processing should be required for the raw image; however, further processing of selected images may be desired utilizing standard image-enhancement software.

Field Results: Many applications of still photography have demonstrated that high-resolution images of oil on the bottom can be obtained utilizing a drop configuration, or deployed on an ROV or AUV.

Environmental Limitations: Turbidity is the limiting environmental factor in the deployment of optical cameras underwater. Excellent photographic images have been obtained when visibility is 0.5 m to 1 m. In high turbidity conditions, strobe illumination devices must be separated from the camera to suppress backscatter from the flash.

Survey Techniques: Digital still cameras can be deployed utilizing diver handheld mode, camera drop systems, ROVs, and AUVs. If operated in a continuous mode as the camera is transited over the bottom, the images can be merged utilizing mosaic software to form a mosaic. However, because of the discrete image capture capability of the still camera, the principal application of the unit is for site inspection and/or validation of contacts. Therefore, the still camera is not recommended for a classic “mow the lawn” type of survey as the primary tool.

One recommended application is to deploy still cameras on the same platform of a sonar system to validate sonar contacts. The side scan sonar collects sonar data while the still camera is triggered at a selected interval to collect optical images for validation of sonar contacts. Geo-referencing of all data sets collected is essential for satisfactory data interpretation.

Figure C.1 provides the swath width of the camera based on the field of view of the lens. Use of this figure will provide a basis for sonar contact validation.

Digital Still Camera Summary: Still photography can provide high-resolution optical ground truth data for sunken oil visible on the bottom. 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. As a consequence of the ability of the digital still camera to provide discrete, very high-resolution images, the unit should be utilized for validation for specific contacts of interest, rather than general survey applications. AUV deployment of digital cameras in conjunction with a side scan sonar “mow the lawn” survey of an area provides ground truthing for side scan sonar contacts simultaneously with collection of the sonar data.

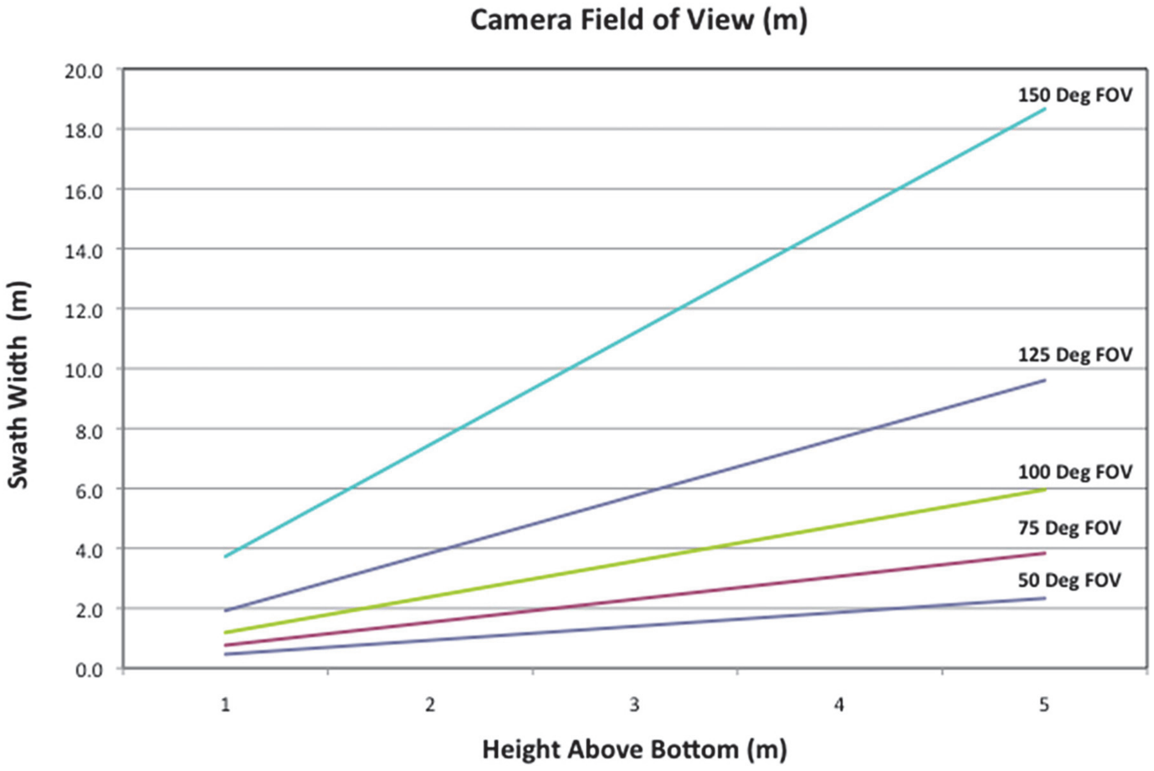


Figure C.1—Digital Still Camera Swath Width vs. Field Of View (FOV)

C.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.

Many applications of video photography have demonstrated that High Definition video data sets of the bottom can be obtained utilizing an ROV and/or an AUV. 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. For ROV use, the use of “turnkey” video acquisition systems, trained (and experienced) personnel, and software suites are highly recommended and can assist in accelerating tactical and strategic decisions for tracking and removal of sunken oil.

Function, Processing, and Display: Black and white video cameras are good in areas of poor visibility, as the sediments tend to scatter the light and make a color camera give a bright image. These black and white video cameras are typically installed on ROVs and are known as the Silicon Intensified Target or “SIT” cameras. This low-light video camera can be used in situations where the ROV lights can be kept low to avoid backscatter from suspended particles. This avoidance of optical backscatter will allow the maximum depth of field. The problem with the SIT camera, however, is it is of a lower resolution. Select the video camera type as a function of water visibility.

For ROV video acquisition, while video is being recorded, an appropriate (not cluttered) “text overlay” should be recorded on top of the video data. This should include at a minimum, date, time, Easting/ Northing (position coordinates if possible), ROV heading, water depth and altitude, and a short description of dive or prospect/area being surveyed. This overlay capability, interfacing, and integration can come as part of the turnkey video acquisition system. Overlays can be spaced on the display to maximize viewing of the subject matter and may have translucency adjusted to maintain the overlay data as background, maintaining the video as primary imagery.

In an AUV application, the vehicle autonomy is programmed to operate the camera at the appropriate settings and geographic locations prior to launch of the AUV. No control can be exercised by the operator over video camera functions during the operational period of the AUV. In the case of the ROV, data can be telemetered in real time, whereas in the case of the AUV, the data can only be telemetered after vehicle recovery and data download.

In both operational scenarios, the video data can be uploaded to a telemetry system for transmission to an onshore facility. The larger offshore vessels of the oil industry will typically carry available bandwidth; however, mid- to small-sized vessels may require installation of a dedicated Internet system. Still screen-shots as well as video snippets of any objects or footage of interest may also be acquired at will and stored separately to the main video. These smaller snippets also make it easier to send to shore bases as they are much smaller and require less Internet transmission bandwidth. Cleaning, editing, and post-processing software is available for viewing enhancement of the video data, but typically with an associated processing delay.

Field Results: Video cameras, both color and black and white, have been utilized for identification of sunken oil on the surface in many applications. Recorded video data have been utilized for oil quantity assessments as well as validation of sonar data.

Environmental Limitations: As with still cameras, 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 0.5 m to 1 m; however, the use of high-intensity lighting sources complicates data collection due to backscatter from particles in the water. Separation of light source and camera facilitates data collection and, in some instances, sophisticated light/camera techniques have improved data collection in turbid water. Alternately, low-light black and white cameras can be used without an external light source with good results as there is no particle backscatter.

Survey Technique: Underwater video cameras are ubiquitously installed on ROVs and AUVs. The ROV-mounted units are primarily controlled over the vehicle umbilical cable to the ROV. This link is typically fire-optic or twisted-wire pairs for data telemetry of video and other data in the case of the ROV. Collection of bottom data using video cameras deployed on an ROV is possible, but not practically feasible due to the basic control limitations on an ROV, which preclude easily and closely following a set track. An ROV is better utilized for site-specific inspection of the bottom for sunken oil.

In contrast, an AUV, as a consequence of the nature of the navigation control of the vehicle, is an ideal platform for surveying an area using controlled track line spacing. The principal disadvantage of an AUV video camera deployment is that review of the video data are only possible after completion of the survey, recovery of the data, and viewing that data on a deck computer. In some AUV applications, small low-resolution data “snippets” can be acoustically uploaded to the surface ship to validate function of the video system and the vehicle, provided the vessel’s acoustic receiver is within range of the AUV during its dive. A short duration survey with the AUV and review of the short data set is recommended for data quality validation prior to committing the AUV to a full area survey.

Towed camera sleds, both those towed above the bottom and on the bottom, are also an option for deployment of video camera systems, although bottom-towed camera sleds are susceptible to fouling on bottom obstructions and should only be utilized after a side scan sonar survey of the bottom locates all obstructions. Although height above the bottom is considerably more difficult to control, maintenance of the survey track line is facilitated as a consequence of the use of the towing vessel’s GPS or similar navigation system and real-time video is available for near real-time review. There are towed systems that have the ability to automatically maintain height above bottom, but the availability of these is limited in the offshore industry, thus making rent or hire problematic.

Area Coverage Rate: Area coverage by video camera is limited by the height above the bottom and field of view angle (Figure C.2) with significant limitations imposed by water turbidity. In clear water, usable video data can be obtained at heights of 10 m to 15 m above the bottom; however, in highly turbid water, height above the bottom can be down to less than 1 m.

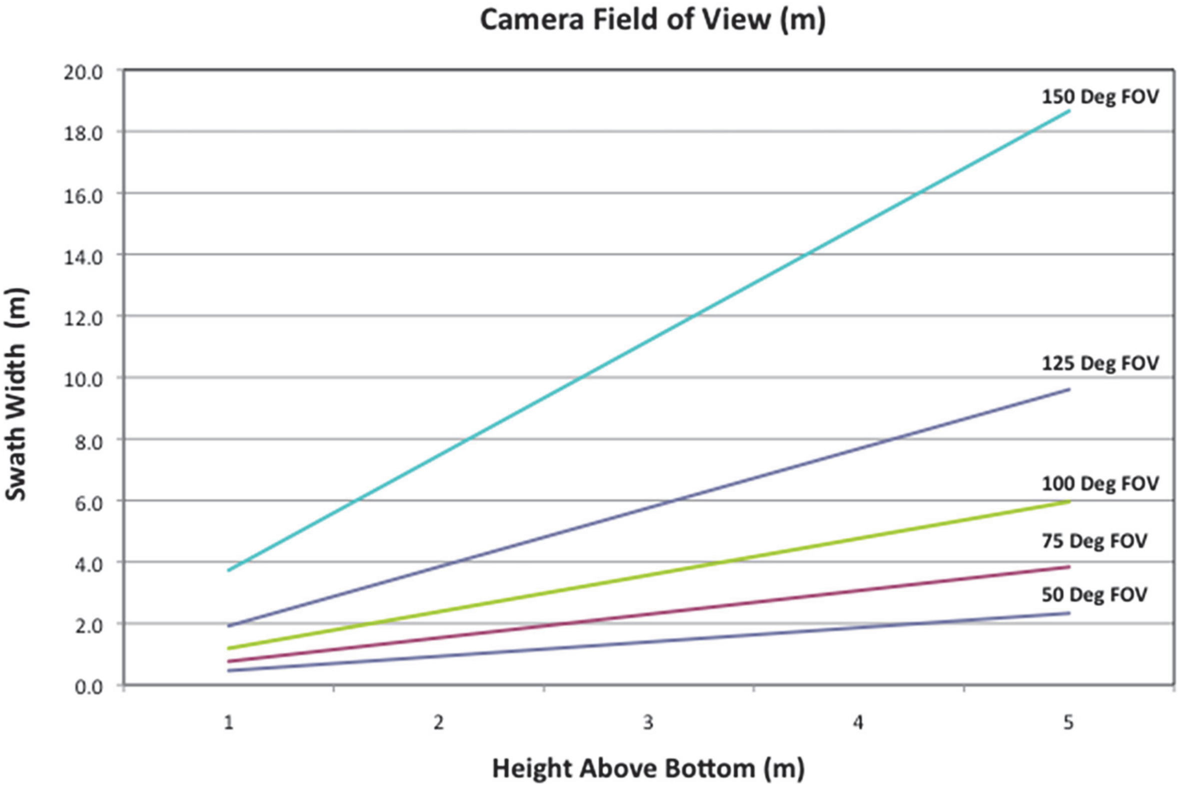


Figure C.2—Video Camera Swath Width vs. Height Above Bottom and Field of View

Video Camera Summary: 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.

Video cameras can be deployed on a ROV, an AUV, or a camera sled (towed body) depending on the availability of the platform. ROV deployment, while attractive due to the ability of the operator to position the ROV, introduces turbidity issues due to thruster turbulence. Other forms of deployment position the camera ahead of any turbidity inducing turbulence and are preferred.

C.4 Sediment Profile Imaging (SPI) Camera

The Sediment Profile Imaging (SPI) camera was developed to take photographs of a “slice” of bottom sediment, up to a maximum of 8 in. (20 cm) in depth. 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.

Function, Processing, and Display: The SPI camera system consists of a wedge-shaped prism outfitted with a high-resolution, 25 megapixel still camera with a mechanism for pressing the wedge-shaped prism into the bottom sediments. This wedge-shaped prism functions in a manner like an inverted periscope with a clear lens and a 45-degree mirror that reflects the image onto the still camera mounted above the mirror. There is strobe lighting inside the wedge that provides light for the photograph. Figure C.3 shows a complete SPI on a deep-water sampling frame. Note the wiper for cleaning the lens of water column fouling as the SPI is pressed into the sea bottom. Limited skill is required for use as the unit is optically calibrated for maximum resolution photography, and operation of the camera and strobe are automatic.

Images can be downloaded from the SPI camera directly to a laptop or desktop computer via a USB cable and are available for viewing utilizing the software provided by the camera manufacturer. A ruggedized laptop, or a tablet with USB port, can be utilized in the field for review of data and adjustment of the survey plan.

Though not standard equipment, the SPI can be fitted with two “Plan View” underwater cameras mounted on the SPI frame that are triggered at the same time as the SPI camera. All cameras are geo-references with image annotation so that the plan view camera data can be co-registered with the SPI camera data. This configuration could be used to detect both surface and buried oil at a location.

Field Results: The SPI has been utilized in numerous sedimentation studies, often to assess biological communities, sediment grain size and quality, redox boundaries, sedimentation rates, etc. It was used to monitor the deposition of oiled sediments at selected deepwater sites surrounding the Macondo-252 well.

Survey Technique: The SPI was originally developed for deployment using a winch in deeper water from a support vessel in the configuration seen in Figure C.3. When the SPI hits the bottom, the hoisting cable is slacked and the wedge prism is driven into the bottom, transecting the water/sediment interface. A trigger fires the strobe and camera or cameras, if plan view cameras are fitted, for photographic documentation of the sediment. Figure C.4 illustrates a photographic cycle, which is initiated by lifting the SPI sufficiently high above the bottom to provide penetration of the bottom when dropped.

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.

Area Coverage Rate: Data sampling with the SPI camera is a discrete function that requires selection of transects and sample intervals for optimum data collection. As a result, area coverage rates will be a function of environmental

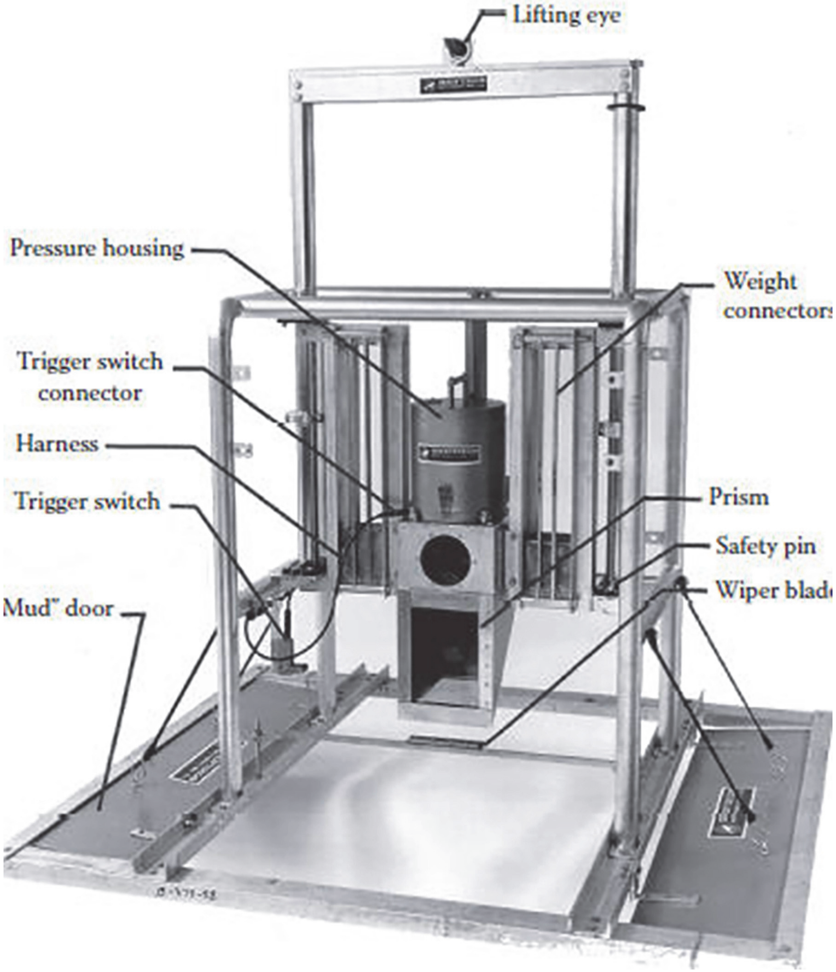


Figure C.3—SPI Deep-water (Standard) Configuration (Germano & Associates, Inc.)

conditions (e.g. distance from shore, water depth, sea state, water currents) and will be under the control of the crew chief and operational guidelines for the survey.

SPI Camera Summary: The SPI camera provides a visual representation of the bottom sediments and benthic community up to 8 in. below the sediment surface at each data sample point. 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. Data are immediately available upon downloading to a ruggedized laptop or tablet with a USB port in the field and can be utilized for field alterations of sampling strategies. It is not known how bulk oil might foul the camera lens. Photographs of the oil on and below the shallow surface are valuable for communications with stakeholders and operations teams. Photographs can also provide information on benthic communities present in the area.

C.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.

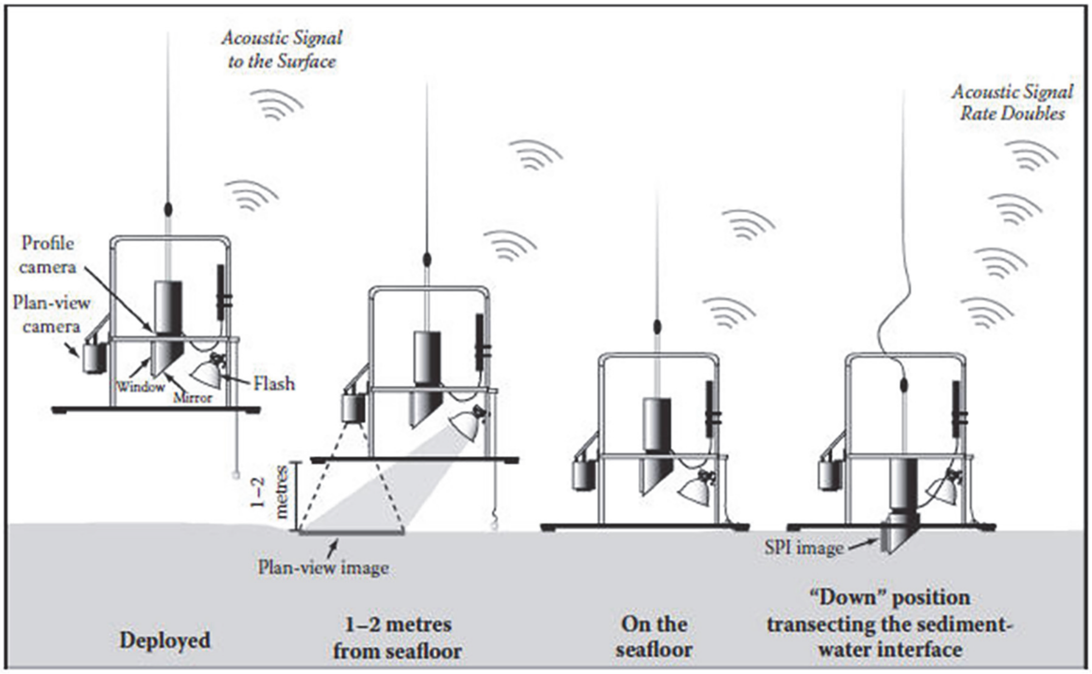
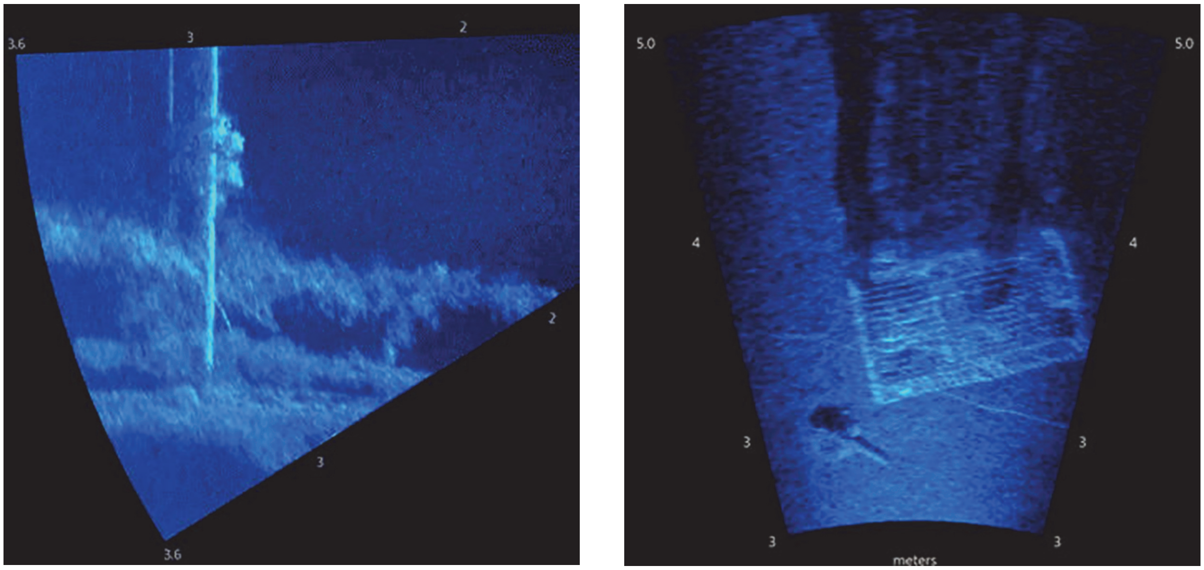


Figure C.4—Deploying a SPI Fitted with Plan View Cameras (Germano & Associates, Inc.)

Function, Processing, and Display: A typical acoustic camera functions in a manner similar to the 3D sonar but at a much higher frequency, forming multiple acoustic beams horizontally and vertically to provide complete pseudo-optical coverage of the field of view in real time. The principal difference in image quality is inherent in operating frequency of the acoustic camera, which operates at between 1.8 to 3 MHz, or approximately 10 times the frequency of the 3D sonar. The result of utilizing the very high frequency is the ability to obtain a very detailed sonar image in the field of view. The image produced by these acoustic cameras is very optical-like and is displayed in real time on a lap top screen. There is no further processing required for analysis. Figure C.5 shows the images produced by an acoustic camera.



Left: Acoustic camera image of a leak from vertical pipe with sea grass in background.

Right: A sea ray lower left near a lobster pot (Sound Metrics Corporation).

Figure C.5—Images Produced by an Acoustic Camera

Many turnkey ROV video solutions discussed in the video camera section can be interfaced to these acoustic cameras after the data are brought topside and output as component video data, as well as recorded into the ROV video acquisition system itself for later analysis and rapid event retrieval. It must be emphasized that, even though the images obtained from an acoustic camera appear as if taken with an optical camera, the images obtained are acoustic images and must be interpreted as acoustic images.

Field Results: This type of acoustic camera has been in service in the offshore industry for over ten years with very positive results. There have been no field applications of the acoustic camera for the detection of sunken oil, but the very high frequency of the acoustic cameras (at >1500 kHz) should produce higher quality images of sunken oil in a similar manner to those demonstrated in trials and field applications of side scan sonar and 3D sonar.

Survey Technique: Applications of acoustic cameras are deployed in a similar manner to optical cameras with one exception, in that acoustic cameras function more effectively if the camera is aimed so that the field of view is at an angle from the acoustic camera, instead of directly downward, as an optical camera might be aimed.

ROVs are not good survey platforms due to the difficulty in maintaining a constant heading and speed over the bottom. AUVs are better for survey applications. However, in most instances, acoustic cameras are too large for installation in commonly available AUVs. It is recommended that ROVs outfitted with acoustic cameras are not utilized for standard survey, but are utilized for inspection of discrete contacts.

One possible use might be to deploy an acoustic camera at a site to acquire images at a set interval to document sunken oil behavior over time and during specific events, such as during storms. The images could provide information on how sunken oil is remobilized.

Area Coverage Rate: Acoustic cameras, by the nature of their ultra-high operating frequency, have limited operating range typically 5 m in normal conditions and, with a field of view of nominally 30 degrees, area coverage rates are low. Area coverage rates are shown in Figure C.6.

Acoustic Camera Summary: Acoustic cameras available on Inspection Class ROVs and are commonly available in the offshore oil industry. The principal limitation 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. Optical cameras, because of the significantly higher resolution should be utilized in all situations where possible.

Table C.1 provides an equipment selection guide categorized by visibility conditions with equipment recommendation based on the optimization of selection criteria. In the absence of the recommended equipment, field application of equipment listed as potential options should be based on ready availability of equipment and deployment mechanism.

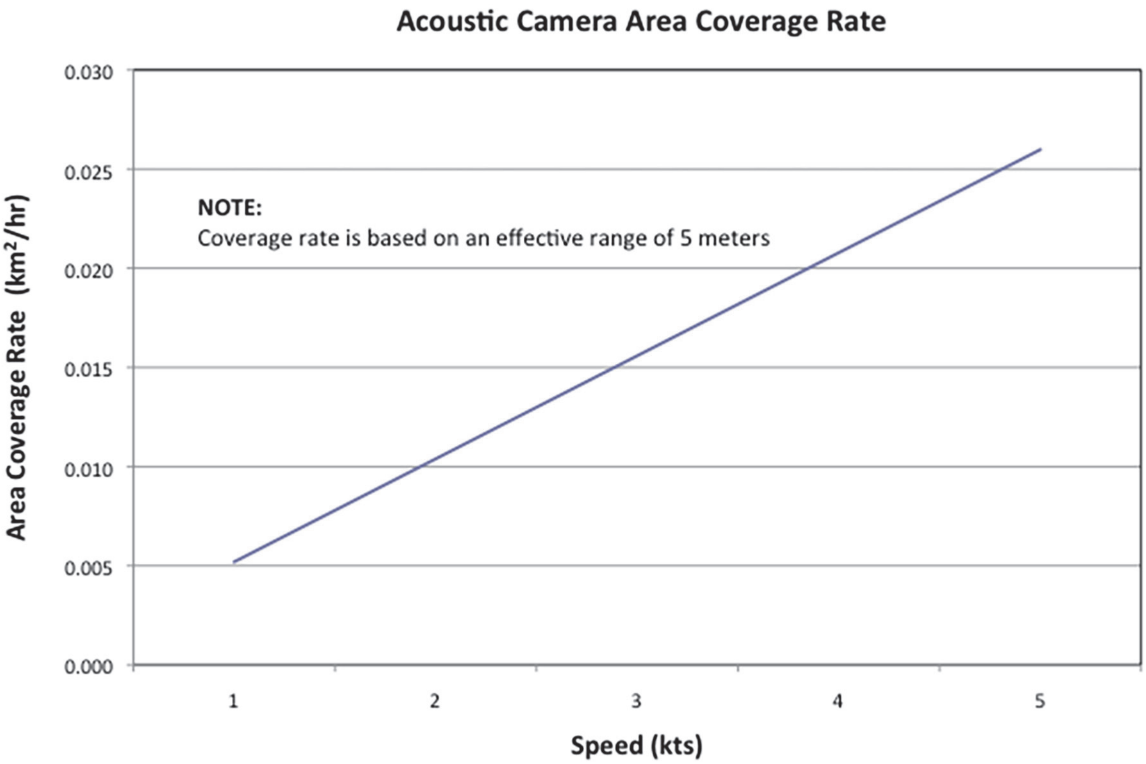


Figure C.6—Acoustic Camera Coverage Rates

Table C-1—Selection Guide for Underwater Visualization Equipment for Sunken Oil Surveys

Water Depth/ Visibility Conditions	Oil Condition	Options for Equipment	Potential for Success*	Recommended Equipment	Recommended Deployment Platform
Water Depth >3 m Visibility >2 m	Bulk Oil or Oil Mat on bottom	Color Still Camera/Video B/W Low Light Video SPI Camera	9 9 5	Color Video	Remotely Operated Vehicle
	Buried Oil	Color Still Camera/Video B/W Low Light Video SPI Camera	1 1 5	SPI Camera	Survey Boat with Deployment Winch
Water Depth >3 m Visibility 0 m to 2 m	Bulk Oil or Oil Mat on bottom	Color Still Camera/Video B/W Low Light Video SPI Camera	7 7 5	B/W Low Light Video	Remotely Operated Vehicle
	Buried Oil	Color Still Camera/Video B/W Low Light Video SPI Camera	1 1 5	SPI Camera	Survey Boat with Deployment Winch
Water Depth <3 m Visibility >2 m	Bulk Oil or Oil Mat on bottom	Color Still Camera/Video B/W Low Light Video SPI Camera	7 7 5	B/W Low Light Video	Handheld Deployment
	Buried Oil	Color Still Camera/Video B/W Low Light Video SPI Camera Acoustic Camera	1 1 5 1	SPI Camera	Handheld Deployment
Water Depth <3 m Visibility 0 to 2 m	Bulk Oil or Oil Mat on bottom	Color Still Camera/Video B/W Low Light Video SPI Camera Acoustic Camera	1 1 5 8	Acoustic Camera	Handheld Deployment
	Buried Oil	Color Still Camera/Video B/W Low Light Video SPI Camera Acoustic Camera	1 1 5 1	SPI Camera	Handheld Deployment
Water Depth <3 m Visibility 0 m	Bulk Oil or Oil Mat on bottom	Color Still Camera/Video B/W Low Light Video SPI Camera Acoustic Camera	1 1 5 8	Acoustic Camera	Handheld Deployment
	Buried Oil	Color Still Camera/Video B/W Low Light Video SPI Camera Acoustic Camera	1 1 5 1	SPI Camera	Handheld Deployment

* Relative ranking with 10 = highest potential and 1 = lowest potential for successful detection of sunken oil.

AMERICAN PETROLEUM INSTITUTE

1220 L Street, NW
Washington, DC 20005-4070
USA

202-682-8000

Additional copies are available online at www.api.org/pubs

Phone Orders:	1-800-854-7179	(Toll-free in the U.S. and Canada)
	303-397-7956	(Local and International)
Fax Orders:	303-397-2740	

Information about API publications, programs and services is available on the web at www.api.org.