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Oil Sands Products Spill Response

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Oil Sands Products Spill Response

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16. Abstract (MAXIMUM 200 WORDS) U.S. Coast Guard Research and Development Center (RDC) conducted research on response improvements to non-floating oil spills since 2008, when it carried out projects to identify, design, and test new methods for detecting and responding to sunken oil and oil suspended in the water column. RDC began its oil sands products (OSP) Spill Response Project in 2014 with an assessment to determine transportation risks, research and development efforts by other organizations, and potential response gaps with respect to OSP spills. Next, RDC developed a prototype to sample an oil/silt mixture on the bottom of a water body. RDC then evaluated the recovery of weathered OSP in fresh water using a drum skimmer and brush skimmer to determine if any issues related to OSP recovery differed when fresh water was involved. Finally, RDC developed and tested three separate prototypes designed to mitigate the impacts of OSP spilled in moving water in the inland and offshore environments. This report contains results of the RDC research along with information from parallel efforts by other organizations. The report serves as a resource for Federal On-Scene Coordinators in planning for OSP spill responses in both fresh and salt waters.					
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EXECUTIVE SUMMARY

The increase of oil sands production in Canada has been a major contributing factor to the overall growth of crude oil production in North America. Spills of oil sands products (OSP) have occurred in the past, and real world experience demonstrates that they behave differently than conventional crude oil during an incident. In 2010, approximately a million gallons of diluted bitumen (dilbit) flowed into the Kalamazoo River from a damaged pipeline. Over 20 miles of shoreline were affected, making it one of the largest inland spills in U.S. history. The Environmental Protection Agency made the following statement on the overall initial response activities in the Kalamazoo River: “...there exists a great need for ongoing research and development into effective submerged oil containment devices and tactics.”

The USCG Research and Development Center (RDC) began its OSP spill response project in 2014 with an assessment to determine transportation risks, research and development efforts by other organizations, and potential response gaps with respect to OSP spills. Next, RDC conducted a series of research efforts designed to address the gaps identified in the assessment, including:

- Underwater Sediment Sampling Research (January 2017).
- Testing of Oil Sands Products Recovery in Fresh Water (April 2018).
- Mitigation of Oil Moving Along the Waterway Bottom (November 2019).

The results of RDC’s studies contribute to the understanding of response measures for dilbit and other OSP spills. Some of the findings discussed include standard skimmers being effective without special modifications and potential technology solutions for both inland and offshore submerged OSP response based on prototypes tested in this research. However, additional research remains to ensure responders are prepared for spills of these and other medium and heavy oils. In particular, responders still need:

- Better understanding of OSP behavior in various real-world environmental conditions.
- Better approaches for detection, mapping, and mitigation for submerged and sunken oil not only for oil spills in rivers and streams, but for other potential OSP or non-floating oil spills in the nearshore and large lake environments.

Federal On-Scene Coordinators should use this report as a resource for planning OSP and other heavy and sinking oil spill responses in both fresh and salt waters.



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LIST OF ACRONYMS AND ABBREVIATIONS

AMOP	Arctic and Marine Oilspill Program
ASTM	American Society of Testing and Materials
AWB	Access Western Blend
CFD	Computational fluid dynamics
CLB	Cold Lake Blend
CLWB	Cold Lake Winter Blend
CRRC	Coastal Research and Response Center
cSt	Centistokes
DFO	Fisheries and Oceans Canada
Dilbit	Diluted bitumen
ECCC	Environment and Climate Change Canada
ELA	Experimental Lakes Area
EPA	Environmental Protection Agency
FOSC	Federal On-Scene Coordinator
g/cm ³	Grams per cubic centimeter
GLRI	Great Lakes Restoration Initiative
GPS	Global Positioning System
IISD	International Institute for Sustainable Development
IMO	International Maritime Organization
IOSC	International Oil Spill Conference
ISB	In situ burning
No.	Number
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRCan	Natural Resources Canada
NSFCC	National Strike Force Coordination Center
NTSB	National Transportation Safety Board
Ohmsett	National Oil Spill Response Research and Renewable Energy Test Facility
OMA	Oil-mineral aggregate
OSP	Oil sands product(s)
OSRO	Oil Spill Removal Organization
ppt	Parts per thousand
PVC	Polyvinyl chloride

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)



Oil Sands Products Spill Response

R&D	Research and Development
RDC	USCG Research and Development Center
SDS	Safety Data Sheet
Synbit	Bitumen diluted with synthetic crude oil
TPH	Total petroleum hydrocarbons
U.S.	United States
uSCAT	Underwater Seabed Cleanup Assessment Technique
USCG	U.S. Coast Guard



1 INTRODUCTION

The U.S. Coast Guard Research (USCG) and Development Center (RDC) has conducted research on response improvements to non-floating oil spills since 2008, when it carried out projects to identify, design, and test new methods for detecting and responding to sunken oil (on the bottom of a water body) and oil suspended in the water column. With these projects complete, RDC shifted its focus to oil sands product (OSP) spills, which have garnered national attention. With partial funding support from the U.S. Environmental Protection Agency (EPA) through its Great Lakes Restoration Initiative (GLRI) program, RDC sought to advance the science of spill response technologies for moving, sunken oil.

RDC began its OSP Spill Response Project in 2014 with an assessment to determine transportation risks, research and development efforts of other organizations, and potential response gaps with respect to OSP spills. Next, RDC developed a prototype for the purpose of sampling an oil/silt mixture on the bottom of a water body. RDC used the laboratory test results with the prototype to provide recommendations for future efforts addressing operational conditions for use of oil/silt sampling devices. RDC then evaluated the recovery of weathered OSP in fresh water using drum and brush skimmers to determine if any issues related to OSP recovery were different when fresh water was involved instead of salt water. Finally, RDC developed and tested three separate prototypes designed to mitigate the impacts of OSP spilled in the inland and offshore environments.

This report contains RDC's findings, outcomes, summary, and recommendations regarding equipment and tactics for OSP spill response along with information from parallel efforts by other organizations. This information will serve as a reference for Federal On-Scene Coordinators (FOSCs) in making decisions during OSP spill responses in both fresh and salt waters. It may also be useful for response to other heavy and sinking oil spills.

1.1 Objective

The project objective was to identify and/or develop mitigation techniques for OSP spills and provide a resource for oil spill responders and planners.

1.2 Background

In the past decade, the increase of oil sands production in Canada has been a major contributing factor to the overall growth of crude oil production in North America. Oil sands generally consist of extra heavy crude oil or crude bitumen trapped in unconsolidated sandstone along with sand, clay, and water. Bitumen is extremely dense and viscous, with a consistency ranging from that of molasses to peanut butter at room temperature, making extraction difficult. As a result of bitumen's high viscosity and its abundance in landlocked Alberta, the future of oil sands as a reliable energy source is dependent on how it can be transported to distant refineries.

Oil sands can be transported if heated, or if diluted with lighter hydrocarbons or natural gas condensates known as diluents. Diluted bitumen (dilbit), one type of OSP, is typically comprised of 70 percent bitumen and 30 percent diluent. Producers normally transport dilbit by rail or pipeline, although they may also use marine vessels such as barges and coastal tankers. Every transportation method carries with it an inherent risk of spillage. Spills of OSP have occurred in the past, and real-world experience demonstrates that OSPs



behave differently than conventional crude oil during an incident. Scientists and researchers continue to study dilbit's properties as well as its fate and behavior if spilled into the environment.

1.2.1 Current Knowledge of Oil Sands Products Spill Behavior

Diluted bitumens are Alberta oil sands bitumen diluted by either condensate, C4-enhanced condensate (with butane), or synthetic crude oil (called synbit). The properties of the starting bitumens vary widely, as do the diluents, resulting in highly variable products with highly variable behaviors (Fingas, 2015b).

When first released into water, dilbit floats similarly to medium oils, and can be treated as such for the response. As the diluent evaporates, the oil gets denser, eventually reaching a density approximately equal to salt water. This process may take days to weeks, depending on the environmental conditions. In salt water, the weathered dilbit may continue to float and can be treated like other heavy oils. However, like other crude oils, environmental effects such as wind, waves, and water particulates (e.g., silt) may cause the dilbit to become neutrally buoyant or sink, and at that point it must be treated as non-floating oil. The key difference between a dilbit and other crude oils is the shorter weathering timeframe for a dilbit (Polaris, 2013). In fresh water, with lower density than salt water, the weathered dilbit is more likely to eventually sink, and at that point it must be treated as a non-floating oil.

APPENDIX A contains more information about OSP characteristics and spill behavior.

1.2.2 Example of an OSP Incident: 2010 Kalamazoo River Spill

In 2010, approximately 877,000 to one million gallons of dilbit flowed into the Kalamazoo River from a damaged pipeline. Approximately 38 miles of the river's channels, as well as associated backwaters, floodplains, islands, and wetlands were affected, making it one of the largest inland oil spills in U.S. history. Some of the spill behavior and response issues are highlighted in this section. See APPENDIX B and Dollhopf and Kimble (2016) for more details.

The unprecedented scale of the impact and massive quantity of oil released into the Kalamazoo River required the development and implementation of new approaches for detection and recovery. At the onset of cleanup, EPA successfully used conventional recovery techniques, including booms, skimmers, vacuum equipment, and shoreline cleanup processes for the initial floating oil. However, evaporation of the lighter diluent, along with mixing of the oil with sediment during flooded, turbulent river conditions, caused the oil to sink and mostly collect in natural deposition areas in the river. Responders also faced the atypical challenge of trying to mitigate the impacts of moving, sunken oil. Recovery of the oil in the water column (submerged) and on the river bottom (sunken) continued for more than three years after the spill (Dollhopf et al., 2014).

The EPA FOSC and Oil Spill Removal Organizations (OSROs) tried several approaches to recover the submerged and sunken oil with varying degrees of success. Some approaches included the use of air curtains, silt curtains, gabion baskets with snare booms (Figure 1), surface booms with sediment curtain using X-Tex® material, and sedimentation basins. They developed techniques, including poling (Figure 2), to disturb the bottom sediment so responders could raise the oil to the surface for recovery. Ultimately, it was necessary to recover oiled sediment and sludge by conventional methods such as hydraulic dredging (Dollhopf et al., 2014).





Figure 1. Gabion basket with snare booms in the Kalamazoo River during cleanup efforts.
(Dollhopf and Kimble, 2016)



Figure 2. Submerged Oil Task Force Poling Team.
(Dollhopf and Kimble, 2016)

2 SUMMARY OF RELATED RESEARCH EFFORTS

Various organizations have conducted OSP spill response research for almost thirty years. However, some aspects of the research are still in the early stages, especially in the United States. In general, the response community is still working to understand exactly what OSP is (fate and behavior) before it can begin to consider response alternatives. This section summarizes some of the significant laboratory and mesoscale research and identifies current non-RDC research efforts.

2.1 A Study of Fate and Behavior of Diluted Bitumen Oils on Marine Waters

Witt O'Brien's and others used a series of dedicated tanks where they could observe the 10-day behavior of two types of dilbit – Cold Lake Winter Blend (CLWB) and Access Western Blend (AWB) – on brackish water (salinity 20 parts per thousand (ppt)) (Witt O'Brien's et al., 2013). They used wind and wave generating devices to simulate environmental conditions for the study. Neither of the two weathered dilbits sank. Ultimately, researchers reported the behavior of both products proved to be no different than what might be expected of conventional heavy crude oils when exposed to similar conditions (Witt O'Brien's et al., 2013).

For the equipment portion of their study, Witt O'Brien's and others carefully discharged only CLWB dilbit into a series of large rectangular tanks. They staged the tanks outdoors where they would be subject to ambient atmospheric conditions. Researchers uniformly tested and analyzed three brush and drum skimmers for both their ability to recover spilled oil and their recovery efficiency. All skimming devices were able to recover the spilled dilbit at all stages of the 10-day weathering cycle (Witt O'Brien's et al., 2013).

Witt O'Brien's and other researchers also investigated three non-mechanical countermeasures for their ability to mitigate spilled CLWB dilbit under specific conditions. They found that in-situ burning on fresh water was effective for oil that had only weathered for 24 hours or less. Chemical dispersants were marginally effective for up to a 6-hour weathering window. Corexit 9580, a shoreline cleaning agent, proved effective up to a 4-day weathering cycle (Witt O'Brien's et al., 2013).

2.2 Environment Canada's Study of Two Diluted Bitumen Products

Environment Canada (2013) reports early research simulating dilbit products spilled at sea. The Government of Canada executed this work as part of the first phase of a strategy to implement a world class prevention, preparedness, and response regime for oil spills from ships in marine environments.

Researchers studied the behavior of two dilbit products (AWB and Cold Lake Blend (CLB)) under laboratory conditions in three phases. They considered these two products to be representative of products currently being shipped in Canada. First, they measured the properties and composition of the two samples before (fresh) and after (weathered) exposure to environmental conditions. Second, they examined the potential for evaporation, exposure to light, mixing with salt water, and sediments in the salt water to affect whether these dilbit products float or sink in salt water. Finally, they evaluated the effectiveness of two existing spill treating agents meant to disperse spilled oil products. The major results of this effort were:

- Like conventional crude oil, both dilbit products floated on salt water (free of sediment), even after evaporation and exposure to light and mixing with water.



- When fine sediments were suspended in the salt water, high-energy wave action mixed the sediments with the diluted bitumen, causing the mixture to sink or be dispersed as floating tarballs.
- Under conditions simulating breaking waves, where chemical dispersants were proven effective with conventional crude oils, a commercial chemical dispersant (Corexit 9500) had limited effectiveness in dispersing dilbit.
- Application of fine sediments to floating diluted bitumen was not effective in helping to disperse the products.
- The two dilbit products displayed some of the same behaviors as conventional petroleum products (i.e., fuel oils and conventional crude oils), but also significant differences, notably for the rate and extent of evaporation.

2.3 Other Research

The Canadian federal government continues to expand and refine the scope of its research, through Environment and Climate Change Canada (ECCC), Fisheries and Oceans Canada (DFO), and Natural Resources Canada (NRCan). This research primarily deals with fate and effects, particularly on organisms and the shoreline. Research results are generally reported at the annual Canadian Arctic and Marine Oilspill Program (AMOP) conferences and/or the triennial International Oil Spill Conference (IOSC). Brown et al. (2019) provides an update on five years of the Government of Canada's oil spill research. Below is a list of research efforts related to OSP and similar topics that researchers from Canada and elsewhere conducted between 2016 and 2019:

Response Guidance

- Scientific Support Information and Response Guidance for Dilbit Spills Impacting Marine Shorelines (AMOP 2017).
- uSCAT: Underwater Seabed Cleanup Assessment Technique for Sunken Oil – an Approach for Characterizing Seabed Oiling (AMOP 2018).
- Detection and Characterization of Subsurface Oil Using a Calibrated Scientific Echosounder (AMOP 2019).

Alternative Response

- Effectiveness Testing of Chemical Countermeasures and Sorbent Performance on Oil Sands Products (AMOP 2016).
- Physical and Chemically Enhanced Dispersion of Synthetic Bitumen in Fresh and Brackish Waters (AMOP 2019).

Behavior, Fate, and Transport

- Chemical Fate of Photodegraded Diluted Bitumen in Seawater (IOSC 2017).
- Comparative Study on Rate of Biodegradation of Diluted Bitumen and Conventional Oil in Fresh Water (IOSC 2017).
- Evaluation of Oil-Sediment Interactions and the Possibility of Oil Sinking in Marine Environments (IOSC 2017).



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- Mapping the Penetration and Retention Potential of Two Weathered Diluted Bitumen Crude Oils for the Shorelines of Northern British Columbia, Canada (IOSC 2017).
- Meso-scale Studies on the Penetration and Retention of Diluted Bitumen in Different Types of Shorelines (IOSC 2017).
- Movement and Erosion of Alberta Bitumen along the Bottom as a Function of Temperature, Water Velocity, and Salinity (IOSC 2017).
- Potential Dilbit Residence Times on Coarse-sediment Shorelines (AMOP 2017).
- Flow Behavior of Oil: What Makes Diluted Dilbit Different? (AMOP 2018).
- Investigation to Compare the Behavior of Spilled Conventional Crude Oils with Unconventional Oils (Including Diluted Bitumen Products) through Laboratory and Meso-scale Testing (AMOP 2018).
- A Case Study with Enbridge Line 3 Replacement Program (AMOP 2018).
 - Assessing Risks of Crude Oil Spills along a Pipeline.
 - Failure Frequency Assessment of a Pipeline Using Reliability Methods.
 - Assessing the Trajectory and Fate of Crude Oil Spills along a Pipeline to Answer Multiple Questions.
 - A Framework for Evaluating and Comparing the Effects of Spills of Diluted Bitumen and Light Crude Oils.
- Impacts of Partial Upgrading Processes on Diluted Bitumen Characteristics and Behavior in Water (AMOP 2018).
- Predicting the Retention Potential of Diluted Bitumen on Marine Shorelines: The Field Implementation of Diluted Bitumen Experiments (AMOP 2018).
- Evaluation of Alberta Based Oils and Common Degradation Mechanisms by GCxGC (AMOP 2018).
- Access Western Blend (Dilbit) Weathered on Cold Fresh and Marine Salt Waters (AMOP 2019).
- An Estimate of the Sinking Rate of Spilled Diluted Bitumen in Sediment Laden Coastal Waters (AMOP 2019).
- Seasonal Climatic Factors Influence on Monocyclic Aromatics Rate of Release and Decay in Water from Surface Spills of Oil Sands Products (AMOP 2019).

Responders' Health and Safety

- Development of Health and Safety Procedures and Training Materials for Dilbit/Synbit Crude Oil Spills for Environment Canada's Responders (AMOP 2016).

In addition, the International Institute for Sustainable Development (IISD) operates the Experimental Lakes Area (ELA) near Kenora, Ontario, Canada, which encompasses 58 lakes and their watersheds supporting mesoscale water-based research. In November 2017 they announced a three-stage research project to learn more about what oils do in fresh water systems, including the chemical and physical behavior of dilbit in fresh water and how dilbit reacts in fresh water over longer periods. IISD-ELA researchers will also examine the most effective methods of cleaning spilled oil from shorelines (Trans Mountain, 2018). IISD results to date from AMOP 2019 include:

- The BOREAL Project: The Design and Execution of a Controlled Oil Spill Study in a Canadian Fresh Water Lake.



- The BOREAL Project: The Physical Fate and Behavior of Diluted Bitumen Spilled into Fresh Water Limnocorrals.

3 RDC OSP SPILL RESPONSE ASSESSMENT

RDC began its OSP spill response project in 2014 with an assessment to determine transportation risks, research and development efforts by other organizations, and potential response gaps with respect to OSP spills. The scope of this effort was to perform and document a qualitative assessment of potential risk of OSP spills, specifically dilbit, and to identify initial response issues for study. In addition, this report provided recommendations and proposed research tasks. Specific focus areas of this study were:

- Current and potential routes and nodes of transportation, especially in the Great Lakes, Washington State, and on or near navigable waters that are subject to USCG jurisdiction.
- Geographic areas most at risk for an OSP spill, based upon volume of product transported, location of transportation routes and nodes, and infrastructure condition.
- Response issues related to both fresh water and salt water spills in different seasonal weather conditions and the likelihood that dilbit would float, suspend, or sink if spilled.

3.1 RDC Assessment Recommendations

The assessment included the following conclusions and recommendations. See Hansen et al. (2015) for more details.

- Oil Spill Response Plans: The USCG should consider a means for addressing submerged oils that may be present in surface water spills that can be included in Geographic Response and Area Contingency Plans.
- Physical and Chemical Properties and Processes of OSPs: The USCG should work with industry and other U.S. and Canadian agencies to compile sufficient information on the OSP Safety Data Sheet (SDS) that is specific for each blended bitumen product.
- Response Gap for Non-Floating Oils – Dilbit Classification: The USCG should reconsider the classification of dilbit to account for the characteristics of the spilled material after it enters the environment and not just its characteristics prior to its release.
- Response Gap for Non-Floating Oils – Need for Additional FOSC and Responder Information: There are substantial informational needs that should be developed to assist the FOSC in preparing for, and responding to, dilbit spills in nearshore/onshore and offshore geographic environments with regards to the fate and effects of dilbit.
- Response Gap for Non-Floating Oils – Need for Additional Responder Equipment and Tactics: The primary issue is the absence of specific USCG regulatory requirements for the onshore/nearshore or offshore geographic areas for any specific type, specific quantity or specified arrival time frames for any equipment.



3.2 Proposed Research Tasks

The assessment proposed the following research tasks related to technologies for detecting, tracking, containing, and recovering oil spills, especially dilbit spills. See Hansen et al. (2015) for more details.

Modeling and Prediction: Improve the understanding of the chemistry of submerged oil and better predict the fate of the oil and its transport/trajectory through the water column or along the bottom.

Detection and Sampling: Improve the detection of submerged and sunken oil.

Containment: Improve current submerged oil barriers. Evaluate and test different approaches to contain, divert, collect, and improve recovery of oil on the seafloor.

Recovery: Improve sunken oil recovery systems. For example, modify dredges to minimize water and sediment uptake. Researchers could reduce dependence on divers by developing automated/unmanned systems, improving product recovery rates, and expanding operational capabilities/parameters.

4 RDC OSP SPILL RESPONSE DEVELOPMENT EFFORTS

RDC conducted a series of research efforts designed to address some of the gaps identified in the 2015 assessment, including:

- Underwater Sediment Sampling Research (January 2017).
- Testing of Oil Sands Products Recovery in Fresh Water (April 2018).
- Mitigation of Oil Moving Along the Waterway Bottom (November 2019).

4.1 Underwater Sediment Sampling Research

During the Kalamazoo River spill response, responders used poles to agitate the river bottom to determine if oil was present in the sediments based on whether a sheen formed on the water surface. The only reliable method to determine the exact concentration at that time was to obtain a full sediment sample and perform an analysis in a laboratory (Hanson et al., 2017).

RDC initiated the sediment sampling study to design, construct, and test a bench top system to sample an oil/sediment mixture and measure the concentration of total petroleum hydrocarbons (TPH) while in-situ. While this study focused on dilbit and a type of Texas crude oil, RDC desired a sampling process that could also be applied to other types of oils and conditions. As a bench top system, this design does not meet all of the final requirements needed for a fully deployed system, but the concept allowed preliminary evaluation in a laboratory setting.

The research approach was to sample the interstitial water between the grains of sand and attempt to determine the amount of oil in and on the surrounding particles. The report describes the equipment and process followed for the demonstration and includes recommendations for further efforts needed to develop a fieldable system for use in subsequent testing. This system would need to function at depths of up to 100 feet, in currents of up to 0.5 knots, and perform at least five samples per hour during a 12-hour operating window without bringing a sample to the surface. RDC based these performance criteria on experiences during the Deepwater Horizon and Kalamazoo River spills.



Researchers successfully demonstrated the bench top system in the laboratory, measuring TPH concentrations in sediments containing dilbit and Texas Raw Crude oil, based on a mathematical relationship for each type of oil. This relationship does not provide the exact concentration of oil in the sediment but could provide decision-makers with better information on the location of potential oil patches. Due to the unusual hydrophobic nature of dilbit, researchers experienced significant difficulty in preparing the oil/sediment/water mixtures in the laboratory. However, they developed innovative procedures to resolve the issue. More work is needed to: (a) evaluate the usefulness of this type of data; (b) develop a process that addresses the calibration required; and (c) determine the type of environmental conditions and oils for which this can be used.

As RDC had multiple objectives within the Oil Sands Products Spill Response project. Its end goal with the sediment sampling study was to determine the effectiveness of its bench-top device prototype and provide opportunities for organizations within oil and spill response industries to further its work.

4.2 Testing of Oil Sands Products Recovery in Fresh Water with Skimmers

In the past, researchers performed limited recovery tests for response to dilbit in salt and brackish water, but did not perform these tests in fresh water, which may have different outcomes due to the lower density of fresh water. For example, brackish water (20 ppt salinity) skimmer test results on CLWB dilbit from Witt/O'Brian's et al. (2013) included:

- No performance shortcomings observed in the current inventory of recovery equipment available to the participating company.
- Even the more viscous oil did not cause skimmer malfunctions.
- Operational adjustments to compensate for increased dilbit viscosity were no different than field adjustments made to equipment during actual spill events for most types of oils.
- This particular dilbit behaved similarly to any other crude oil that the participating spill response professionals had experienced in the past.

RDC evaluated the recovery of weathered dilbit in fresh water to determine if there were any differences compared to the traditional recovery of floating, heavy oil in salt water (Balsley and Hansen, 2018). The research team collaborated with a transportation company to acquire the appropriate oil (CLWB) and identified a drum skimmer and a brush skimmer to represent the two classes of skimmer commonly found in responders' inventories. The Bureau of Safety and Environmental Enforcement's National Oil Spill Response Research and Renewable Energy Test Facility (Ohmsett) installed a separate test tank adjacent to the main test tank and filled it with fresh water (Figure 3). Ohmsett conducted the test using the American Society of Testing and Materials (ASTM) standard F2709, Standard Test Method for Determining Nameplate Recovery Rate of Stationary Oil Skimmer Systems. Ohmsett personnel weathered the oil to simulate a spill lasting over eight days. The recovery efficiency was never below 70 percent for either skimmer, although the recovery rates varied somewhat due to the skimmer configuration.

The data collected during that evaluation indicated that with care, standard skimmers do not need special modifications to recover dilbit in fresh water, especially in the early stages of a spill while the oil is on the surface. Skimmers need to be monitored closely for rotational speed during the early stages to ensure efficiency. A lower recovery rate may be acceptable for increased efficiency. Responders may need more powerful pumps during the later stages of a spill involving this type of product as the viscosity increases.





Figure 3. Skimmer test with dilbit in Ohmsett's fresh water tank.

4.3 Mitigation of Oil Moving Along the Waterway Bottom

In the FOSC Report on the Kalamazoo River spill, EPA noted that the use of sediment curtains, X-Tex® curtains, gabion baskets, and air curtains all demonstrated some level of effectiveness in containing submerged and sunken oil. EPA also observed that placing equipment in high velocity areas of the Kalamazoo River caused significant scouring of the river bed sediment, resulting in less effective capture of submerged oil. EPA deemed that the surface booms with sediment curtains and the use of X-Tex® material were promising approaches for collecting submerged oil in higher flow velocity areas while air curtain techniques were the least effective. They concluded that there is a great need for ongoing research and development into effective submerged oil containment devices and tactics (Dollhopf and Kimble, 2016).

RDC recognized this need for mitigation of non-floating oil spills in rivers and streams as well as nearshore and large lake environments. They executed a research project that included the development of prototypes to address this need. The RDC OSP Assessment Report (Hansen et al., 2015) noted barriers for this application should function effectively in a range of bottom current conditions, be flexible, possess the ability to be rapidly deployed, and be appropriately adjustable to meet the dimensional requirements of the deployment site. Procedures and capabilities should be in place to enable the responders to track the location and efficiency of the barrier. RDC developed and tested three oil spill response prototypes designed to mitigate the impacts of OSP in the inland and offshore environments. Balsley (2019) contains the details of the prototype development and testing.

4.3.1 Boom-Type Inland Mitigation System

This prototype, tested in the Kalamazoo River, consisted of three separate 25-foot boom-like sections linked together with slide connectors for a total length of 75 feet. Each 25-foot section weighed approximately 500 pounds with the flotation and weights covered with polyvinyl chloride (PVC) material (Figure 4). The system's primary purpose is to divert moving, sunken oil from a faster part of the river towards the shoreline where current velocity is less.

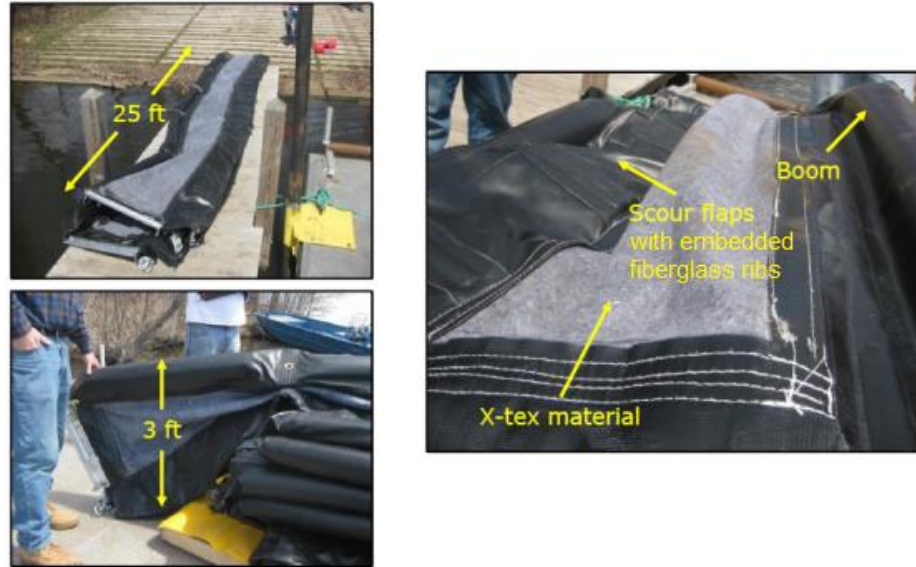


Figure 4. Boom-type inland mitigation system prototype.

Balsley (2019) contains prototype-specific recommendations for a boom-type device, but the following general conclusions can apply for inland operations in restricted areas:

- With limited access for barge platforms or large vessels on smaller tributaries, boom-type systems might need shore deployment and towing to the desired position to overcome a smaller vessel's deck footprint.
- Cleaning a system after use may be challenging with limited deck space, especially if decks become oiled during recovery.
- A sectional boom-type system requires connecting features that prevent oil from flowing past. Irregular bottom features (rocks, obstructions) can impede effective use of a bottom-hugging system.

4.3.2 Deposition-Type Mitigation System

This prototype system (Figure 5), also tested in the Kalamazoo River, was designed to be deployed as part of a long-term cleanup strategy instead of a first response option. It consisted of four sections (27 feet each) connected together for a total length of 108 feet. The purpose of this system is to promote deposition of moving, sunken oil along the length of the system by mimicking naturally occurring bottom features. Figure 6 provides a conceptual configuration of the system deployed in a spill scenario.



Figure 5. Deposition-type system prototype.

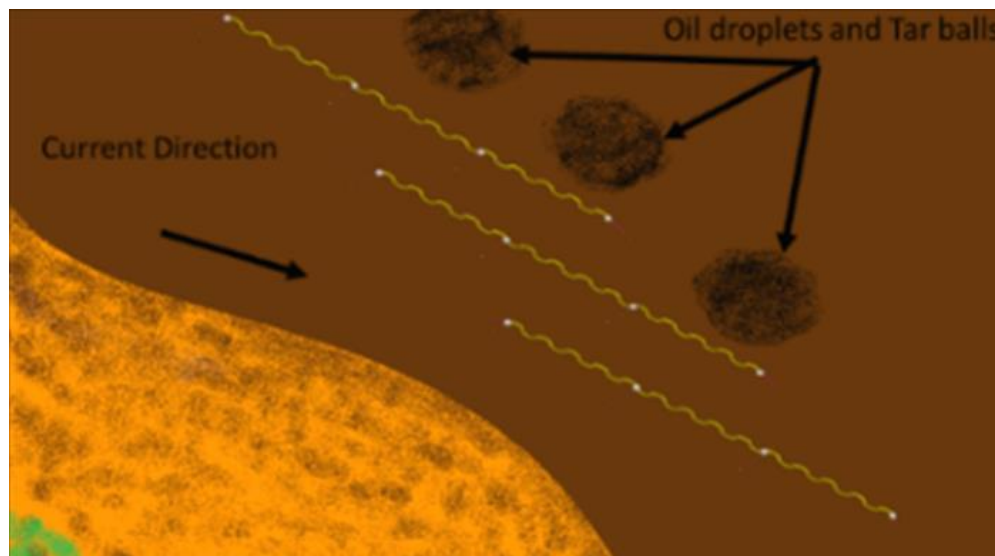


Figure 6. Conceptual configuration of deposition-type system layout in a spill scenario.
(Oates, 2017)

Balsley (2019) contains prototype-specific recommendations for a deposition-type device, but the following general conclusions apply:

- Deploying and recovering a relatively-light system from the bow of a modified 24-ft deck boat can be quick and effective. However, side thruster capability to maximize maneuverability and keeping station for an extended amount of time might enhance operations.
- Key to a successful system is deployment and retrieval with at most three people, two to work directly with the system and one to operate the vessel.
- To maintain position in river currents up to two knots, proper anchor line configuration is paramount, and can allow submerged systems conform to natural features on the river bottom.

However, when laid on top of medium to large cobblestones, such a system may be misaligned. A careful site survey is necessary before deployment.

4.3.3 Offshore Mitigation System

This prototype, designed for offshore mitigation, was made of semi-rigid high-density polyethylene panels covered with PVC. The system was approximately three feet high and was 200 feet in total length (Figure 7). Its primary objective was to collect sunken oil in lower current environments (less than two knots) rather than diverting it to a specific location.



Figure 7. Offshore mitigation system prototype.

RDC tested the system in Lake Huron. Balsley (2019) contains prototype-specific recommendations for a submerged boom-type device, but the following general conclusions apply:

- If a mitigation system requires the use of divers to complete installation, dive platforms should be stable.
- Coast Guard buoy tenders are capable of deploying a submerged-boom system “sideways”. However, it would be difficult to do the same from a vessel of opportunity lacking side thruster capability. For other vessels with ample deck space aft, a stern deployment (and recovery) method would likely work best.
- Using a crane to recover a submerged-boom system may be a practical approach in very low-wind conditions, but alternative methods such as the use of cross-deck winches or boom reels keep the boom sections lower to the deck and out of the wind, for safer recovery.
- Operators need to carefully consider anchor and anchor line arrangements to prevent entanglement and improper setting during deployment. Anchoring options must account for multiple conditions, i.e., heavier anchors for open water, different anchors for different bottom types, different anchor-line scope, etc. Additionally, varied anchoring options might allow use by a wider range of vessels of opportunity.
- The RDC prototype required diver deployment. Any adaptation of this concept should develop deployment and recovery techniques, possibly with remotely operated vehicles to eliminate the need for divers.

4.3.4 Summary

RDC sought to advance the science of response technologies for moving sunken oil with the development and testing of three mitigation systems. After reviewing results and lessons learned, RDC recommended further developmental efforts and testing with oil to determine actual effectiveness of the mitigation systems.

5 RECOMMENDED EQUIPMENT AND TACTICS FOR DETECTION AND SAMPLING OF OIL SANDS PRODUCTS

For a dilbit spill, responders should be prepared to encounter both floating and submerged, or sinking oil. Initially when spilled, dilbit is on the water surface, the detection approach is similar for other floating oil types. An exception in large freshwater systems may occur because heavy oils float lower in the water column and may be more difficult to detect, especially in rough conditions. If a portion of the dilbit becomes submerged through weathering and/or material incorporated into the oil mass, detection may become even more challenging.

Dilbit's mixture of heavy and light components renders it highly susceptible to weathering-induced changes, making it difficult for responders to predict whether and when it will sink. This requires responders to take more samples in a variety of media (e.g., lower in the water column and sediment in the spill area) to track the fate of the oil, compared to other more common oil types that better fit existing predictive models (Winter and Haddad, 2014). This section discusses the detection and sampling of submerged and sunken oil.

5.1 Traditional Heavy Oil Detection and Sampling

When RDC began heavy oil research in 2008, the oil spill response community was using the most direct and simple detection and sampling methods for submerged and sunken oil, such as diver observations and using sorbent arrays. These techniques are slow and labor intensive. RDC's research efforts determined that in some scenarios, it was possible to detect and map stationary oil on the sea floor and river beds using multi-beam sonars and laser fluorometers. If responders use those types of equipment, detailed guidance for use during actual responses will be needed based on accumulated experience.

Underwater acoustic systems have greatly improved in the last few years, making them relatively easy to operate (Michel and Bambach, 2020). Responders can review data in real time to refine a survey pattern on-the-fly. Since the CG created a new classification "Nonfloating Oils" in the OSRO Guidelines on 1 April 2016 (USCG, 2016), many OSROs have incorporated sonar systems and experienced operators (Michel and Bambach, 2020). In addition, Harper and Sergy (2018) describe the development and use of an Underwater Seabed Cleanup Assessment Technique (uSCAT) for sunken oil. The *uSCAT Technical Reference Manual* (Harper et al., 2018) provides a systematic framework for characterizing sunken oil on the seabed of the nearshore coastal environment.

5.2 Sediment-oil Measurement System

Sunken oil may become entrained in the underlying sediments (marine or freshwater) in a process called burial or sedimentation. If disturbed, sunken oil may become re-suspended and enter the water column again, resurface and/or be re-distributed in the subsurface (Lee et al., 2015). As discussed in Section 1.2.2



and APPENDIX B, this happened to some of the oil in the 2010 Kalamazoo River spill as well as many other spills of heavy oil.

To address this issue, RDC developed and successfully demonstrated a bench top system to measure TPH concentrations in sediments containing dilbit and Texas Raw Crude oil, as mentioned in Section 4.1. However, more work is needed to: (a) evaluate the usefulness of this type of data; (b) develop a process that addresses the calibration required; and (c) determine the type of environmental conditions and oils for which this can be used.

6 RECOMMENDED EQUIPMENT AND TACTICS FOR CONTAINMENT AND RECOVERY OF OIL SANDS PRODUCTS

In the initial stages of dilbit spill, responders will need typical surface response equipment and tactics though responders should determine characteristics and makeup of the particular OSP. This information will help stakeholders understand the expected weathering and submergence potential of the released materials. This knowledge would help responders select appropriate recovery tactics and associated equipment (Hansen et al., 2015).

As is the case in any oil spill, response time is critical, and particularly so with OSP. A rapid response means the spilled product has less time to disperse, weather, and potentially become submerged, which ultimately makes the cleanup process easier, more efficient, and more predictable.

6.1 Initial Response

6.1.1 Containment

Research and experience show that after a spill in fresh or salt water, dilbit initially behaves like a medium crude oil and can be treated as such. Responders commonly use barriers to mechanically impede oil spreading and movement. Booms, dams, and weirs are used to contain and concentrate oil on the water surface. Containment challenges with booms include flow relative to the boom (current or towing speeds), turbulence, wave action, oil load in boom, and oil density relative to water. Heavy floating oil can be contained with conventional boom but boom efficiency may decrease as oil weathers to densities near those of the water body (Polaris, 2013).

6.1.2 Recovery

As dilbit weathers, its viscosity increases significantly. However, skimmers designed for more viscous oils, including brush, belt, and other mechanical systems, may continue to effectively recover weathered oil that remains on the water surface. Witt O'Brien's et al. (2013) recommends that spill countermeasures for dilbit in brackish water can proceed with skimming and/or in-situ burning (ISB). They concluded skimmers with interchangeable discs and brushes are best run initially with discs and then after about a few days with brushes.

With care, unmodified standard skimmers can recover dilbit in fresh water, especially in the early stages of a spill, while the dilbit is on the surface (Balsley and Hansen, 2018).

6.1.3 Other Responses

Fieldhouse et al. (2016) studied the effectiveness of different response approaches with OSP including:



- Dispersant testing indicates effectiveness is limited by rheological properties (deformation or flow of matter) in the same manner as other oils; the high proportion of interfacially active asphaltenes and resins in some OSP may further reduce dispersibility, especially as weathering occurs.
- Surface washing agent tests indicate effectiveness is reduced for highly weathered dilbit residues relative to the other OSP and reference oils, attributable to the lower mobility of the bituminous residue compared to other oils that contain a higher proportion of mid-range hydrocarbons.
- Herder testing results suggest that slicks of fresh OSP contract similarly to other oils, with the slick thickness governed primarily by the rheological properties of the oil.
- Solidifier testing shows only a small variance due to the oil type, with performance ties primarily to the solidifier product itself.
- Sorbent testing indicates a general trend toward greater oil uptake with increasing viscosity. However, increased contact time may be necessary to allow for penetration into the sorbent matrix.

Witt O'Brien's et al. (2013) executed mesoscale ISB tests on fresh water, and results showed ISB to be viable on dilbit weathered up to one day. Wave action led to water uptake within the oil matrix and could impede initiation of a burn. Burning freshly spilled dilbit can be an effective countermeasure to complement mechanical response options up to one day after an initial spill, particularly in remote areas or areas that are difficult for responders to access (Witt O'Brien's et al., 2013).

6.2 Submerged and Sunken Oil Response

If the dilbit weathers to the point of submergence, responders must use tactics for response to non-floating oils. The research and response communities continue to work to understand the fate and behavior of dilbit and other OSP during a spill. As noted in other sections of this report, the point of submergence and sinking in any particular spill will depend on the initial qualities of the oil, the type of water body into which it is spilled, the environmental conditions at the time of the spill, and the time lost before remedial operations. The *uSCAT Technical Reference Manual* (Harper et al., 2018) contains specific guidance for responders to assess the risk of submerged and sunken oil and determine its extent.

When the Committee on Marine Transportation of Heavy Oils formed by the National Research Council's (NRC's) Marine Board first investigated response to non-floating oils in 1998, they noted there were limited options available for effective containment and recovery of non-floating oils. For oil dispersed in the water column, even the most promising methods were ineffective, except under ideal conditions (e.g., small spills of emulsified oils in an area of very low current velocity and wave activity). Generally, oil in the water column disperses quickly over large areas/volumes, becoming unavailable for effective recovery. Containment of oil deposited on the seabed has only been feasible where the oil naturally accumulates. In these cases, responders accomplished some recovery with the use of dredging or manual methods such as trawl nets or diver-directed pumping. However, responders need to address the challenge of working with large volumes of water and solids (NRC, 1999).

While USCG and other entities executed some research on response to spills of heavy and non-floating oils since the NRC report, most of the limitations and challenges cited in that report still apply. A specific challenge, such as that encountered in the 2010 Kalamazoo River Spill, involves dealing with non-floating oil in moving water. There has been very little research or experience in this sphere of spill response. A notable exception, in addition to the Kalamazoo River spill, was the tanker *Athos 1* spill resulting in submerged oil in the Delaware River in 2004. During that incident, moving sunken oil threatened utility and industrial water intakes along the river close to the spill site. A nuclear power plant shut down two reactors



for two weeks due to the discovery of oil in sediment below cooling water intakes and scattered pea-sized tar balls in the intake debris screen (USCG NSFCC, 2005).

6.2.1 Mitigation and Containment

The underwater environment poses major complications for oil containment and recovery including poor visibility, difficulty in tracking oil spill movement, and colder temperatures (Hansen et al., 2009). Conventional booms might help to contain oils that are only slightly submerged. However, boom containment for OSP and heavy oils is most effective prior to significant weathering and before any sediment uptake, hence the need to contain the relatively fresh oil. Once oil is easily overwashed or near neutral density compared with that of the water body, alternative forms of containment must be considered, such as allowing the oil to collect in natural or artificial depressions if it does not remain in the water column (Polaris, 2013).

Brown and group performed containment tests on 24-hour weathered dilbit, bitumen, and emulsified dilbits using three barrier systems: conventional boom, fine mesh net, and bubble barrier (Brown et al., 1992). Only the boom and net barriers proved to be partially successful for submerged oil. Boom with mesh skirts provided moderately improved containment but were limited to approximately one knot. Boom losses were greater for bitumen and emulsified dilbit relative to the 24-hour weathered dilbit. As would be expected for any heavy oil (natural or through weathering and/or emulsification), increased current speed and oil density result in less effective containment. The fine mesh tested successfully trapped floating and submerged oil, though some of that oil gradually extruded from the net (Polaris, 2013).

Notwithstanding the general differences between fresh and salt water environments, the general principles of responding to submerged oil spills remain the same for fresh and salt water environments (Usher, 2006).

RDC's previous project on non-floating oil was focused on areas of low current velocities. In this current project, RDC sought to advance the science of response technologies for sunken oil moving in higher water current velocities with the development and testing of three mitigation systems, including:

- An inland mitigation system consisting of barriers anchored to the river bottom. This prototype was designed to deflect moving, sunken oil toward the shoreline, for use in fast waters with a current velocity up to 3 to 4 knots.
- An inland mitigation system, designed to promote deposition of moving, sunken oil along the length of the system and be deployed as part of a long-term cleanup strategy instead of a first response option.
- An offshore barrier attached to a lake bottom designed particularly for lower current environments (less than 2 knots) and for the purpose of collecting oil in a "U-shaped" configuration rather than deflecting it.

After reviewing results and lessons learned, further developmental efforts and testing with oil to determine *actual* effectiveness for all three types of systems is needed. This would refine the design as a response tool with tested tactics before use in an actual OSP spill.

6.2.2 Recovery

The selection of a recovery method for submerged or sunken oil is highly dependent on:

- Specific location and environmental conditions during the spill, especially in inland environments.



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- Characteristics of the oil and its state of weathering and interaction with sediments.
- Availability of equipment, and logistical support for the cleanup operation.
- Potential environmental impacts of implementing these methods, particularly in sensitive benthic habitats.

Based on experience with research and actual spill response, conditions that increase the potential for a successful response to submerged or sunken oil include:

- Shallow water.
- Sheltered conditions (minimal waves, currents, and winds).
- Limited and stationary distribution or extent of oil.
- Nearby staging and decanting facilities.
- Either pumpable oil for vacuum recovery or weathered asphalt-like oils for physical removal.

Once sunken oil is located, the primary methods currently available to recover the oil include divers with vacuum pumps or dredging operations. Historically, submersible pumps have collected very minor amounts of oil compared with the volume released during actual spills. There are inherent dangers to divers when working at significant depths for prolonged periods, or in areas with high current velocity. Submersibles and remotely-operated vehicles (ROVs) can be useful to both detect and collect sunken oil but there are not many OSROs that offer those equipment to specifically detect and collect sunken oil. Successful use of recovery systems will still depend on the ability to locate sunken oil and the availability of oil accumulations in amounts that warrant their removal (Hansen, et al., 2015).

RDC's report on heavy oil spill response (Fitzpatrick et al., 2014), IMO's operational guidelines (IMO, 2014), and NOAA's *Response Guide for Sunken Oil Mats* (Michel and Bambach, 2020) provide more information associated with submerged sunken oil recovery options. However, further research and development work is still needed for responders to become adequately equipped for response to non-floating oil spills in moving water.

7 SUMMARY

Dilbit is Alberta oil sands bitumen diluted by either condensate or synthetic crude oil. The properties of the starting bitumen vary widely, as do the properties of the diluents, resulting in highly variable products with highly variable behaviors (Fingas, 2015a). When paired with the many different environmental conditions and water types that the OSP can be spilled into, there is a wide range of spill scenarios that can exist.

When first released into water, dilbit generally floats similar to medium oils, and can be treated as such for the response. As the diluent evaporates, the oil gets denser, eventually reaching a density approximately equal to salt water. This process may take days to weeks, depending on the environmental conditions. In salt water, the weathered dilbit may continue to float and can be treated like other heavy oils. However, like other crude oils, environmental effects such as wind, waves, and water particulates may cause the dilbit to become neutrally buoyant or sink, and at that point it must be treated as a non-floating oil. The key difference between a dilbit and other crude oils is the shorter weathering timeframe for a dilbit, meaning responders will need to arrive at the location of a dilbit spill quicker than other types of oil spills (Polaris, 2013). In fresh water, the weathered dilbit is more likely to eventually sink, and at that point it must be treated as a non-floating oil.



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A number of entities executed laboratory and mesoscale tests to understand the behavior of spilled dilbit and other OSP. Of particular importance are the conditions under which spilled dilbit may submerge into the water column or sink. For example, studies supported by the Canadian government on the behavior of dilbit spilled in a marine environment concluded the buoyancy behavior of the dilbit products they examined in marine conditions depended most strongly on the presence of medium-to-fine sediment in the water column. Evaporative weathering with evaporative and photo-oxidative weathering in combination all resulted in products that were buoyant in marine conditions. Mixing with water generally increased the density of the products, but all oils tested remained buoyant in seawater even when saturated with water. When mixed with fine- and moderate-sized sediments, however, the fresh to moderately weathered diluted bitumen products sank in salt water (Environment Canada, 2013).

RDC began its OSP spill response project in 2014 with an assessment to determine transportation risks, research and development efforts by other organizations, and potential response gaps with respect to OSP spills. Next, RDC conducted a series of research efforts designed to address the gaps identified in the assessment, including:

- Underwater Sediment Sampling Research (January 2017).
- Testing of Oil Sands Products Recovery in Fresh Water (April 2018).
- Mitigation of Oil Moving Along the Waterway Bottom (November 2019).

The results of RDC's studies contribute to the understanding of response measures for dilbit and other OSP spills. However, researchers need to conduct additional work to ensure responders are prepared for spills of these and other medium and heavy oils. In particular, responders still need:

- Better understanding of OSP behavior in various real-world environmental conditions.
- Better approaches for detection, mapping, and mitigation for submerged and sunken oil not only for oil spills in rivers and streams, but for other potential OSP or non-floating oil spills in the nearshore and large lake environments.

RDC's report on heavy oil spill response (Fitzpatrick et al., 2014), IMO's operational guidelines (IMO, 2014), and NOAA's *Response Guide for Sunken Oil Mats* (Michel and Bambach, 2020) provide additional information for submerged and sunken oil detection and recovery options.



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APPENDIX A. OIL SANDS PRODUCTS PROPERTIES AND BEHAVIOR

Diluted bitumens are Alberta oil sands bitumen diluted by either: condensate, C4-enhanced condensate (with butane), or synthetic crude oil (called a synbit). The properties of the starting bitumens vary widely, as do the diluents, resulting in highly variable products with highly variable behaviors (Fingas, 2015a). Spills of heavy and non-floating oils can have complex behavioral patterns, depending on the density of the oil, the density of the receiving water, and the physical setting of the spill site.

A.1 OSP Physical Characteristics

The density of bitumen depends on the specific reservoir and temperature of the source material. Density, the mass (weight) of a given volume of oil, indicates whether a particular oil will float or sink in water. As the density of fresh water is 1.0 gram per cubic centimeter (g/cm^3) at 15°C, and the density of most oil ranges from 0.7 to 0.99 g/cm^3 , most oils will float on water. The density of most bitumens range from 0.997 to as high as 1.016 g/cm^3 . The density of seawater is 1.03 g/cm^3 , so even heavier oils such as bitumen will usually float on it. Many bitumens that sink in fresh water may initially float in seawater (Fingas, 2015b).

With OPS's varied density range with respect to water density, variations due to temperature or other environmental factors can change the way the product behaves in a spill. The density of oil also changes as a result of weathering processes. For example, as diluents and other lighter molecules evaporate from an OSP, the remaining material becomes denser. Responders are particularly interested in whether an OSP can sink or submerge after weathering, interaction with sediments, or other environmental conditions that may occur (NOAA, 2013).

Bitumens are blended with diluents to meet pipeline export specifications, with dilbit's defined range of density not to exceed 0.94 g/cm^3 at a reference temperature of 15°C. The blend is a single-phase liquid (solution) with its own unique properties. Dilbit crude oil is not bitumen in suspension, in emulsion, or in a two-phase liquid (Witt O'Brien's et al., 2013).

Viscosity is the resistance to flow in a liquid. The lower the viscosity, the more readily the liquid flows. The viscosity of the oil is largely determined by the amount of lighter and heavier fractions that it contains. The greater the percentage of light components such as saturates and the lesser the amount of asphaltenes, the lower the viscosity. As with other physical properties, viscosity is affected by temperature, with a lower temperature giving a higher viscosity. For most oils, the viscosity varies as the logarithm of the temperature, which is a very significant variation. Oils that flow readily at high temperatures can become a slow-moving, viscous mass at low temperatures. In terms of oil spills, viscosity is not directly related to density, but viscosity can affect the oil's behavior. Viscous oils do not spread rapidly, do not penetrate soil as readily, and affect the ability of pumps and skimmers to recover the oil (Fingas, 2015b).

Dilbit and synbit start out at a viscosity of about 300 centistokes (cSt), which is similar to that of light syrup. Once spilled, dilbit eventually returns to the highly viscous and dense properties of the starting bitumen (~1,000,000 cSt) as the lighter components in the spilled material evaporate, which may take from days to weeks. A spilled synbit does not return to the properties of the starting bitumen, but rather weathers to a heavier oil, moderating properties between a weathered synthetic crude and a bitumen. Figure A-1 shows pictures of weathered dilbit's increase in viscosity after about four to nine days of weathering. Most



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bitumens will sink in fresh water but require an extensive weathering period before this occurs (Fingas, 2015b).



Figure A-1. Dilbit after weathering four days (left) and nine days (right).
(Fingas, 2015b)

Researchers may predict behavior change with time for a specific dilbit and/or synbit using laboratory and/or field data (Fingas, 2015b). However, gathering the characteristics to accurately predict or model weathering behavior may be difficult for OSP. The physical properties of crude oil from conventional reservoirs typically change slowly over years, making their behavior easier to model at any given time. In contrast, physical composition of the OSP being transported out of Alberta can vary greatly and is not readily generalized. Not only do the physical properties of bitumen deposits vary across the region, the mixtures entering the transmission lines after being upgraded and or diluted can vary on a weekly basis. Each OSP entering a pipeline differs, based on specifications from the refineries receiving the product (NOAA, 2013).

As an example of weathering behavior prediction, Fingas (2015b) provides data from laboratory and small test tank studies on the weathering of dilbits (Environment Canada, 2013; Witt O'Brien's, 2013). These data show a typical dilbit reaching a density of $\sim 1.0 \text{ g/cm}^3$ after 8 to 9 days of weathering at 15°C (Figure A-2). It would take approximately twice as long to weather at about 0 to 5°C and half as long at temperatures of about 30°C (Fingas, 2015b).



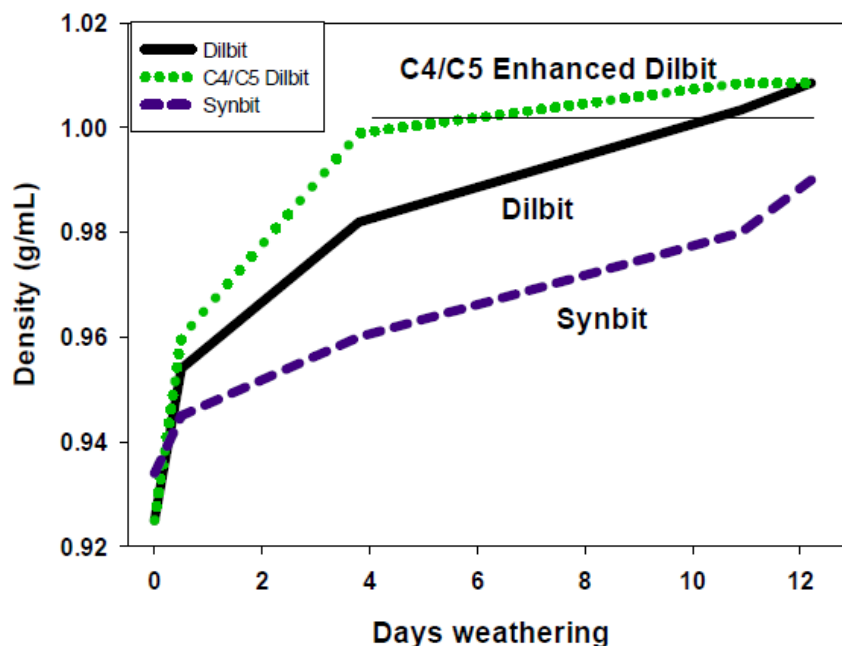


Figure A-2. OSP density as a function of weathering at 15°C.
(Fingas, 2015b).

Other heavy oils typically have minimal light components. Therefore, evaporation occurs differently for dilbit compared to other heavy oils. Environment Canada confirmed this to be the case in its 2013 Technical Report (Environment Canada, 2013). Approximately four to five times as much of the dilbit evaporated compared to intermediate fuel oil (a heavy oil with no diluent), and the evaporation occurred much faster for dilbit than for intermediate fuel oil in their study. Evaporation transports toxic components of the dilbit into the air, creating a short-term exposure hazard for spill responders and assessment scientists at the site of the spill, which was the case at the 2010 Kalamazoo River spill (Dollhopf and Kimble, 2016).

A.2 OSP Spill Response Challenges

The major factors that have a bearing on whether spilled oil, including dilbit, will float, become neutrally buoyant (suspended in the water column), or sink are as follows:

- Density of the oil, which may change with weathering (evaporation) and emulsification.
- Salinity of the water (i.e., density of the water relative to the oil).
- Turbidity of the water (stirring up sediment and breaking oil into smaller droplets).

Oil may submerge through dispersion or emulsification and eventually sink through the water column to become entrained in the underlying sediments (marine or freshwater) in a process called sedimentation. If disturbed, sunken oil may become re-suspended to enter the water column again, resurface and/or be re-distributed in the subsurface (Lee et al., 2015).

When oil mixes with sediment particles, the combinations of sediment and oil, called oil-mineral aggregates (OMAs), can become heavier than water and cause sinking. OMA formation is more likely to occur in the following situations:



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- The oil is in fine droplets;
- There is a large sediment load in the water column; and
- There is a lot of turbulence in the water, which increases the number of smaller oil droplets, stirs up sediment from the bottom, and increases the likelihood of contact between the oil droplets and sediment particles.

OMA sinking is more likely to occur in fresh water than salt or brackish water because of the greater likelihood that the density of the OMA will be higher than the water density.

Given the likelihood of sediment in a fresh water river, stream, or lake, it is possible for the dilbit to form OMAs and sink. This situation would be most likely in a shallower stream with a rapid current velocity, high sediment load, and turbulent waters that stir up the bottom sediment and break the oil into smaller droplets. Once sunk, oil will generally either migrate to a collection point or may become buried in nearshore sediments. Under some conditions, the oil may resurface. Figure A-3 from the *uSCAT Technical Reference Manual* (Harper et al., 2018) illustrates the various ways spilled oil can interact with the environment.

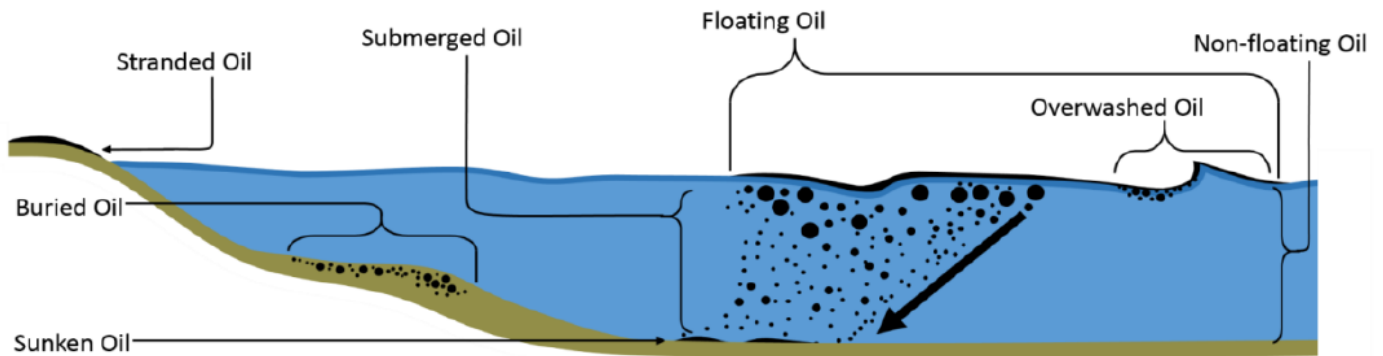


Figure A-3. Spilled oil interactions with the environment.
(Harper et al., 2018).

In salt water, the oil would undergo similar processes, but it is less likely that the oil would sink due to the salinity of the water causing an increase in the density of the water. If oil sinks below the surface of the water, it becomes much harder to detect and recover.

Deposits of sunken oil are challenging to detect, track/map, and recover following an oil spill. Methods of detection and tracking/mapping, using existing techniques, are often inefficient and time consuming, involve labor-intensive searches, and thus contribute to low recovery volumes for these kinds of spills.

Regardless of whether the spilled oil exists as a surface slick or as a deposit at the sediment/water interface, natural physical processes within the water column (surface waves, tidal currents, etc.), evaporation, and dissolution will cause the spilled oil-product to weather and properties to change over time. Submerged oils, however, weather at much slower rates than floating or stranded oil. Higher density oil deposits or tarballs on the seafloor are also affected by bottom current action and the incorporation of sediment grains into the oil matrix. Exposure to near-bottom currents of significant magnitude may result in transport of the oil along the bottom by tidal, river, or storm wave currents and continued incorporation of native ambient sediment grains, as well as widespread dispersion from the original point of origin.



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Submerged and sunken oil may move uncontrolled in the water column due to temperature changes, currents, gain or loss of sediments, and wave action. The result of a heavy oil spill that sinks to the sea floor may therefore cause significant damage to the marine environment, recreational areas, sensitive industrial installations, and property such as boats and docks.

A.3 Summary

When dilbit initially spills into a water body, it generally floats, which is similar behavior to that of medium crude oils, and can be treated as such for the response. As the diluent evaporates, the oil gets denser, eventually reaching a density approximately equal to salt water. This process may take days to weeks, depending on the environmental conditions. In salt water, the weathered dilbit may continue to float and can be treated like other heavy oils. However, like other crude oils, environmental effects such as wind, waves, and water particulates may cause the dilbit to become neutrally buoyant or sink, and at that point it will need to be treated as a non-floating oil. In fresh water, the weathered dilbit will eventually sink, and at that point it will need to be treated as a non-floating oil. APPENDIX C contains the NOAA's dilbit spill response fact sheet (NOAA, 2019).



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APPENDIX B. KALAMAZOO RIVER SPILL SUBMERGED OIL CONTAINMENT AND RECOVERY

The largest and most-documented example of a dilbit spill into fresh water is the 2010 Enbridge pipeline spill into Michigan's Kalamazoo River, which included both Cold Lake Blend and Western Canadian Select crude oil condensate mixtures. According to responders and damage assessment specialists who worked on-scene monitoring and advising the response effort from its early stages, the spill presented unique challenges atypical of traditional crude oil spills. Since oil began to weather as soon as it entered the environment, some of these unique challenges resulted from the specific conditions in which the spill occurred.

However, it is difficult to isolate the role that physical properties of Cold Lake Blend and Western Canadian Select played in determining the fate of the spilled oil. In the EPA, NOAA, and the National Transportation Safety Board (NTSB) reports, responders stated that containment and cleanup efforts included floating, submerged, and sunken oil. Initially, there were surface slicks and a visible sheen of oil on the water, but during the course of the cleanup, responders also found "blobs" of oil moving in the water column as well as sunken oil on the river bottom. Flood conditions, turbidity, and the current velocity and volume of the river at the time of the spill all influenced the behavior of the oil once it was spilled.

Responding to spilled OSP in this kind of dynamic fresh water environment would be particularly challenging especially in warm summer weather, because the lighter diluents would presumably evaporate and leave the heavier components of the product. If these heavy ends were sufficiently dense, and especially if they mixed with sediment, the oil could have submerged or sunk. Beyond the characteristics of the oil, the water temperature, the presence of sediments, and the river current velocity affected oil recovery (NOAA, 2013).

An important issue impeding oil removal efforts during the Kalamazoo River spill was the fast moving water of the river and Talmadge Creek. Recovering oil in fast moving water is difficult, as oil tends to flow under most containment booms and skimmer efficiency is greatly reduced, necessitating more rapid responses further downstream. In these situations, USCG recommends installing underflow dams, overflow dams, sorbent barriers, or a combination of these techniques (NOAA, 2013).

Except where otherwise noted, the information in this Appendix comes from the EPA FOSC Desk Report for the spill – Dollhopf and Kimble (2016).

B.1 Initial Response

Within the first weeks of the response efforts, EPA evaluated the potential for some of the discharged oil (dilbit) to become submerged within the Kalamazoo River system. As the lighter, diluent fractions of the discharged oil volatilized, the density of the oil increased. Additionally, turbulent water conditions resulting from the flood event and recovery operations (e.g., boat traffic, collection activities, etc.) caused the oil to mix with sediments and organic particles, further increasing its density. As a result, the oil submerged and was deposited into the river sediments, and moved through the river system below the surface of the water.

Responders first became aware of submerged oil when personnel from the NOAA Wildlife Section reported stepping out of boats into shallow sediments and producing oil globules and heavy sheen from the disturbed sediments. Subsequently, Enbridge proposed the method of poling to determine if oil was present in and/or on sediment in areas absent of oil sheen and/or globules on the water surface. Responders noted that existing



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structures, such as dams, and natural barriers, such as islands and sand bars, created preferential depositional areas for submerged oil to accumulate within the river system.

During the initial response actions, responders placed various man-made structures (e.g., silt curtains, gabion baskets, and a sediment basin) in the river and along Talmadge Creek in an attempt to contain submerged oil and/or oil-containing sediment from further migration. Like natural structures, these installed structures created preferential depositional areas in the river system. Several subsurface containment structures were installed within the affected portion of Talmadge Creek and the Kalamazoo River, including:

- Underflow dams and hay bale structures at various locations within Talmadge Creek;
- An in-situ stream sediment basin upstream of the confluence of Talmadge Creek with the Kalamazoo River;
- Surface boom with sediment curtain at the confluence of Talmadge Creek with the Kalamazoo River;
- Gabion basket structures containing sorbent snare boom at two locations across portions of the river to contain suspended, oil-containing sediment and submerged oil;
- Surface containment with silt curtain installed at numerous control points along the Kalamazoo River; and
- Surface boom with X-Tex® sediment curtain (oleophilic synthetic filtering material designed to sorb oil while allowing water to pass through) in the neck area between the Morrow Lake Delta and Morrow Lake.

Responders routinely monitored and maintained structures and replaced subsurface containment materials.

B.2 FOOSC Commentary on the Effectiveness of Initial Response Activities

Conventional Containment and Recovery: Within a few weeks from initial discharge, the use of conventional oil spill response strategy, tactics, and equipment (booming, skimming, vacuuming, and excavation) resulted in the recovery of over 760,000 gallons of floating oil or oil soaked into overbank areas of the Talmadge Creek and Kalamazoo River. Thus, while responders immediately recognized that weathering of the dilbit was resulting in its submergence, they also noted that submergence did not happen immediately, and timely application of standard, conventional floating oil recovery principles and methods was very successful.

Early Submerged Oil Containment: At the same time, based on their experience during this response, EPA recognized that submerged oil should be immediately and aggressively contained. Use of sediment curtains, X-Tex® curtains, gabion baskets, and air curtains all demonstrated some level of effectiveness in containing submerged oil early in the response. The gabion basket setup containing sorbent snare boom was one of the most effective methods during early response efforts. EPA learned that the placement of gabion basket structures in areas where flow velocities were less than one foot/second was most effective in the collection of submerged oil. Placing such structures in higher velocity areas resulted in significant scouring of the river bed sediment, resulting in less effective capture of submerged oil. Additionally, the use of closed loop snare within the gabion basket structures resulted in more effective capture of submerged oil particles. Sediment curtains made with X-Tex® material were more effective in absorbing submerged oil than traditional sediment curtain. As with the gabion baskets, placement of X-Tex® sediment curtain in low velocity areas



was crucial to keeping the curtain on the sediment bed. During subsequent stages of the response, EPA recognized that development of methods to deploy X-Tex® sediment curtain in higher flow areas would be beneficial in curtailing further migration of submerged oil in areas such as the Morrow Lake Delta neck. Development of the half-curtain or partial curtain deployment technique proved beneficial in limiting further migration while maintaining the curtain along the river bottom in higher flow velocity areas. Use of the air curtain techniques attempted early in the response seemed to be the least effective of the early submerged oil containment methods that they used.

Responders determined the submerged oil containment concepts of half curtain/boom deployments developed and implemented in 2013 and 2014 to control submerged oil migration in the Morrow Lake Delta were effective and warranted strong consideration for earlier, broader deployment for future discharge events.

B.3 Submerged Oil Assessment

Responders implemented a phased approach to investigate the presence and relative distribution of submerged oil in the Kalamazoo River and Morrow Lake. Initially, they conducted a qualitative assessment to quickly identify areas with the presence of submerged oil, identify depositional areas, prioritize sites based on a relative comparison of affected sites, and obtain information on the depositional/erosional characteristics of the geomorphic settings. They accomplished this through an initial visual assessment followed by in-channel sediment poling. Poling is a method that responders have used in other non-floating oil spill incidents. Determining parameters by which to record observations from poling was essential to ensure that poling results were evaluated and recorded consistently.

Poling involved inserting a graduated metal pole equipped with a disk into the sediment and then recording observations. Observations included 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. Teams recorded visual evidence of oil as it was liberated from the sediment and rose to the water surface. Responders used a uniform set of metrics evaluate the emanating oil and included the number of oil globules and areal sheen production in a one-meter square surrounding the poling location. Teams also documented the Global Positioning System (GPS) coordinates, water surface elevation, and depth of water. Approximately 3,700 discrete points were collected from August 29 through October 29, 2010. Responders amended poling procedures in 2011 to include documentation of water and sediment temperature.

B.4 Submerged Oil Cleanup Recommendations

The EPA FOSC directed Enbridge to identify and test various field techniques that would be effective at liberating submerged oil from river sediments so that it could be recovered. Responders conducted several small-scale field tests, or pilot tests, at known submerged oil locations to determine which oil recovery techniques were most effective. Researchers identified the following techniques from the field test program:

- Hydraulic Flushing: Pressurized river water was used to agitate shallow sediment and liberate submerged oil so that it could be recovered at the water surface using sorbent material.
- Aeration: Pressurized air was injected into shallow sediment to liberate submerged oil so that it could be recovered at the water surface using sorbent material.



- Manual Agitation: River sediment was agitated using manual methods, such as raking, to liberate submerged oil so that it could be recovered at the water surface using sorbent material.
- Dredging: Sediment containing submerged oil was mechanically removed.

B.5 2010 Submerged Oil Recovery

Initial submerged oil recovery consisted of responders aerating submerged oil and/or oil-containing sediment to release the submerged oil to the surface where they recovered it using sorbent material. They also performed conventional dredging to remove oiled-sediment.

Responders installed containment at each oil recovery location to minimize downstream migration of oil and/or oil-containing sediment. They also installed immediate, local containment devices, including hard boom, sorbent boom, or geotextile curtains, for containment of oil brought to the surface. They deployed sorbent boom along the entire shore side perimeter of the work area and along any vegetative areas.

Responders performed sediment agitation using a pond aeration unit with an electric motor and aluminum impeller. Teams used the aeration unit in cells of approximately 50 feet of linear runs from the shoreline to the containment boom. They established oil collection points at areas that had the lowest ecological complexity and that were the most accessible. They directed floating oil to the collection points by leaf blowers for collection by sorbent materials, including pads, mops, and pom-poms. Aeration and collection continued until there was no visible oil present on the water surface.

When the aeration method could not be used due to the water being too deep, responders manually flushed the oil recovery locations with a high-volume, low-pressure water stream; manually raked; mechanically raked; or manually swept.

Responders dredged the sediment with an Amphibex dredge, which integrated a hydraulic cutterhead dredge with a positive-displacement pump. In addition to the Amphibex, responders used two other dredges: smaller dredge (specific area) and a cutterhead dredge (deeper waters).

B.6 2011 Submerged Oil Recovery – Agitation

In June 2011, the EPA FOSC once again directed Enbridge to recover submerged oil, oil sheen, and oil-containing soils and sediments. Responders used sediment agitation techniques to liberate submerged oil from the sediment and bring it to the water surface for recovery. Agitation techniques, or tool box techniques, included manual rakes, handheld tillers, handheld stingers, rotating stingers, vessel-mounted water injectors, vessel-mounted pipe drags, and hydraulic flushing. Responders recovered oil released to the surface using sorbent materials including booms, pads, and snares. They repeated the agitation and recovery process until no oil was visibly released from the area. Prior to implementation, researchers conducted pilot studies for each tool box technique to evaluate its effectiveness.



APPENDIX C. NOAA DILBIT SPILL RESPONSE FACT SHEET



Diluted Bitumen Spills

Definition

Diluted bitumen (Dilbit) products are unconventional crude oils created by mixing bitumen, which is a highly viscous form of petroleum with a density close to 1 g/cm³, with a lighter hydrocarbon (diluent) to meet the minimum requirements for transport in pipelines (viscosity <350 cSt and density <0.94 g/cm³).

Properties

- The final oil is a true mixture; the diluent will not separate out as a liquid, though it will be lost by normal volatilization processes (see ADIOS® oil weathering plots on the next page). Table 1 lists the different types of bitumen products and diluents used to make them.
- Diluted bitumen has greater density, viscosity and adhesion properties, and higher resin and asphaltene content (~50%) than most conventional crude oils.

Environmental Behavior

- In the early part of a spill (several days), the environmental behavior of diluted bitumen will be similar to medium crude oil. The oil will float and spread relatively quickly, thus booming and recovery tactics will be the same as for medium crude oil.
- Diluted bitumen spills are expected to pose air quality concerns similar to medium crude oil spills. However, BTEX concentrations (average of 0.84% by volume) and hydrogen sulfide concentrations (<25 ppm) are lower than many conventional crude oils.
- Diluted bitumen weathers faster than conventional oils due to the rapid loss of low molecular weight hydrocarbons associated with the diluents. As the oil weathers, it becomes very viscous (more viscous than peanut butter) and very sticky, so it can thickly coat and adhere to solid surfaces, vegetation, debris, wildlife, etc. Expect response equipment, Personal Protective Equipment, etc. to become coated with oil that will be difficult to remove.
- The bitumen component of diluted bitumen behaves like a highly weathered oil and undergoes very slow natural degradation, making it persist in the environment. Thus, under certain conditions there may be a need for more aggressive removal of stranded or submerged oil.
- After loss of the light fractions, diluted bitumen has a greater potential to submerge and form aggregates with suspended particulates, especially in freshwater environments with turbulent flow and suspended sediments.
- These oil-particulate aggregates can be heavier than water and sink in low-flow areas, which can be many miles downstream of the release site. Therefore, it may be necessary to develop a sunken oil detection plan to confirm the presence or absence of sunken oil.
- Oil droplets and oil-particulate aggregates that sink can be spontaneously released from the bottom of a waterbody by a process known as ebullition, where anaerobic degradation of organic-rich sediments generates bubbles of methane that carry oil with them as they rise to the surface. This process can increase during warmer water temperatures. Thus, chronic sheening can be a concern in low-flow areas where oil has accumulated on the bottom.
- For spills in rivers, sunken oil-particulate aggregates can become re-suspended during higher flow conditions, migrate downstream, and again accumulate in low-flow areas.



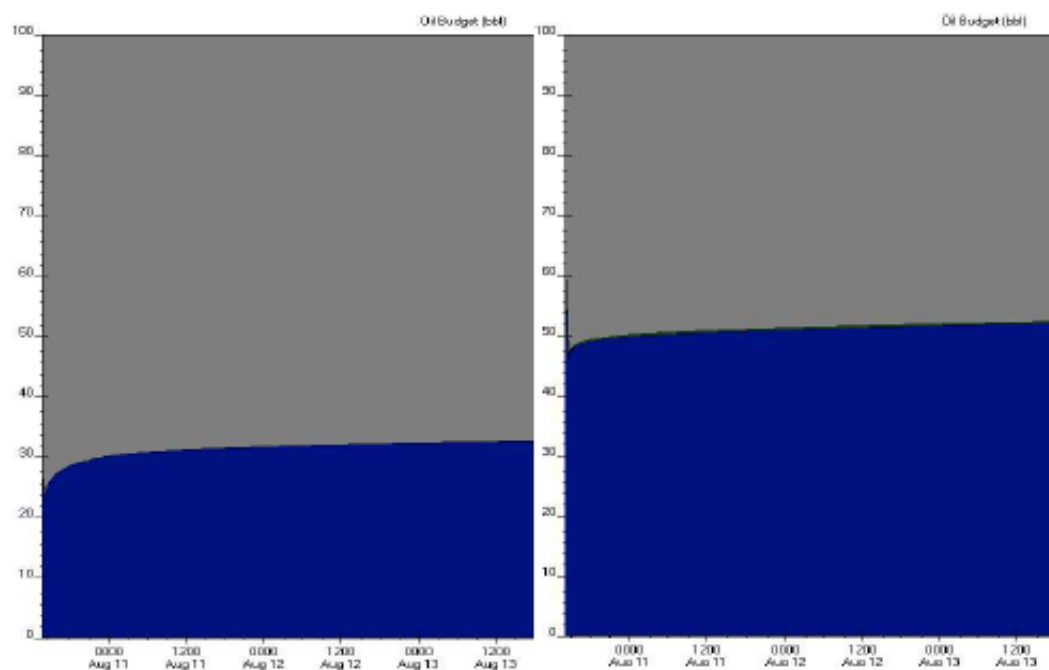
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Environmental Effects

- The greatest hazard of diluted bitumen spills to biological resources is smothering.
- The aquatic toxicity of diluted bitumen varies widely due to variations in the chemical composition of the source bitumen oil and the products used as diluents. However, the aquatic toxicity of diluted bitumen oils is generally similar to that of conventional crude. Chronic toxicity due to residual oil associated with sediments may be of greater concern.
- Early containment and recovery is key to reducing the risks of the oil submerging or sinking in freshwater, as it will lose the diluent by evaporation over time and can then adhere to particulates in the water under turbulent conditions.

Table 1. Different types of bitumen products.

Product	Description
Bitumen, Neatbit	Undiluted extremely heavy oil extracted from oil sands. Must be heated to be shipped.
Diluent	Any light petroleum used to dilute bitumen for transportation by pipeline or rail; can be a condensate, ultralight crude oil, or a light refinery cut such as naphtha.
Synthetic crude	An oil made by partial upgrading or refining of bitumen; used as a diluent in synbit.
Dilbit	Bitumen diluted with ~30% diluent, such as condensate or naphtha, for transportation.
Synbit	Bitumen diluted ~50% with synthetic crude.
Dilsynbit	Bitumen diluted with synthetic crude plus ~15% diluent, usually a condensate.



ADIOS model output for a Cold Lake Blend spill of 100 bbl; winds of 5 knots (left) and 20 knots (right). Blue = evaporated; green = dispersed; grey = remaining. Note the very slight amount of dispersion at 20 knots.

ADIOS (Automated Data Inquiry for Oil Spills) web link: <https://response.restoration.noaa.gov/adios>



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