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Mitigation of Oil in Water Column: Mitigation Prototype Tests

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16. Abstract (MAXIMUM 200 WORDS)
The U.S. Coast Guard Research and Development Center (RDC) undertook a Research and Development (R&D) effort to identify and develop technologies or techniques that can mitigate the impacts of oil in the water column on the surrounding environment through containment, diversion, or removal of the submerged oil. It was a part of a larger effort in the CG R&D program to develop countermeasures and cleanup technologies for a range of oil spills. This report summarizes the results of Phase II-B (Prototype Development and Demonstration). This phase of the project involved demonstrating two mitigation approaches at the National Oil Spill Response Research and Renewable Energy Test Facility (Ohmsett) in Leonardo, New Jersey for their feasibility and performance.

Argonne National Laboratory (ANL) developed a method to treat polyurethane foam, a commonly used material, to adsorb submerged oil. Prior to use, the foam undergoes a series of chemical processes in order to render it oleophilic and thus more susceptible to adsorbing and retaining oil droplets and dissolved oil in the water column. Dynaflow, Inc. developed a microbubble flotation system, capable of being towed behind a vessel that is designed to remove neutrally buoyant oil droplets from the water column using microbubble injection with DYNASWIRL® bubble generators. Both systems show some promise for mitigation of oil in the water column but need further development before they can be recommended for field testing.

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EXECUTIVE SUMMARY

The U.S. Coast Guard (CG) Research and Development Center (RDC) undertook a Research and Development (R&D) effort to identify and develop a system that can mitigate the impacts of oil in the water column on the surrounding environment through containment, diversion, or removal of the submerged oil. It was a part of a larger effort in the CG R&D program to develop countermeasures and cleanup technologies for oil spills in a range of scenarios.

The first phase of the project focused on detection systems. The second phase of the project focused on mitigation. The RDC tested two potential technologies for mitigating oil suspended in the water column at the National Oil Spill Response Research and Renewable Energy Test Facility in Leonardo, New Jersey; operated under contract by MAR (MD), LLC. The first technology was chemically treated polyurethane foam developed by Argonne National Laboratory (ANL) for the purpose of subsurface oil collection. The foam was altered to be oleophilic and reusable after wringing each volume of collected oil. The RDC conducted testing of this polyurethane foam prototype using a suspended lattice frame containing pads of the treated material, which was towed through a subsurface oil plume to simulate a real world encounter scenario. The test setup included the sorbent array frame, oil channeling walls, and a custom distribution manifold to create consistent and controlled oil encounters with careful measurements recorded after each collection.

The second technology was a system of microbubble generators developed by Dynaflow, Inc. to lift neutrally buoyant oil droplets from the water column to the surface where they can be extracted by conventional oil recovery devices. By creating microbubbles over a range of diameters (10 to 150 microns), the system was designed to induce multiple physical interactions which increase the rate at which oil surfaces. Fine bubbles attach to neutrally buoyant oil droplets while larger ones lift the fine microbubbles and oil droplets to the surface. A prototype system consisting of ten bubble generators was tested by operating in a full depth containment area within the Ohmsett main tank. At specified time intervals, the surfaced oil was collected for measurement and compared with results obtained during unassisted surfaced oil tests.

Both systems show some promise for mitigation of oil in the water column but need further development before they can be recommended for field testing. The ANL treated foam picked up a much smaller percentage of oil compared to water in the Ohmsett tests than it did in the laboratory. Several factors that may have caused this issue have been identified but overall, ANL would need to develop a more realistic field setup that allows for a better oil encounter rate, efficient sorbent wringing, and safe oil handling. Dynaflow's microbubble flotation system also did not perform as well at Ohmsett as it did in the laboratory. Results did not show any significant differences between baseline and actual test recovery numbers. Dynaflow has suggested steps for full-scale system development to address the potential reasons for this performance.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ALD	Atomic layer deposition
ANL	Argonne National Laboratory
ANS	Alaska North Slope
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BAA	Broad Agency Announcement
BS&W	Bottom solids and water
BSEE	Bureau of Safety and Environmental Enforcement
C	Celsius
CG	U.S. Coast Guard
cm	Centimeter (10^{-2} meters)
CONOPS	Concept of Operations
CRRC	Coastal Research and Response Center
ft	Foot or feet
g	Gram(s)
gpm	Gallons per minute
HOOPS	Hoover Offshore Oil Pipeline System
hp	Horsepower
kt	Knot(s)
L	Liter(s)
L/min	Liter(s) per minute
LISST	Laser In-Situ Scattering and Transmissometry
µm	Micrometer(s) or micron(s) (10^{-6} meters)
m	Meter(s)
mL	Milliliter(s) (10^{-3} liters)
mm	Millimeter(s) (10^{-3} meters)
nm	Nanometer(s) (10^{-9} meters)
No.	Number
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
Ohmsett	National Oil Spill Response Research and Renewable Energy Test Facility
OPA 90	Oil Pollution Act of 1990
OSAT	Operational Science Advisory Team
PI	Polyimide
ppt	Parts per thousand
psi	Pounds per square inch
PU	Polyurethane
PVC	Polyvinyl chloride
R&D	Research and Development
RDC	CG Research and Development Center

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

U	Untreated
UAC	Unified Area Command
USCG	United States Coast Guard
V-SORS	Vessel-Submerged Oil Recovery System
VFD	Variable frequency drive

1 INTRODUCTION

A challenge that the U.S. Coast Guard (CG or USCG) faces in many oil spills, including the Deepwater Horizon oil spill response in 2010, is the inability to determine the location of subsurface oil plumes in near-real time, which inhibits timely decisions to protect the environment, water-intakes, and commercial facilities. Other issues that negatively impact response efforts include poor visibility in deep water, difficulty in tracking oil movements in fast-moving currents, and an inability to discover very low levels of oil or dispersed oil at all depths. From 2011 to 2017, the CG Research and Development Center (RDC) worked to close these gaps by advancing the technology for detecting and mitigating subsurface oil in near-shore and river environments. Subsurface or submerged oil is defined as neutrally buoyant oil (with or without sediment particles attached) suspended in the water column.

Phase I of the Detection and Mitigation of Oil in the Water Column project focused on detection of the suspended oil. In 2013, two prototype detection systems were demonstrated at the National Oil Spill Response Research and Renewable Energy Test Facility (Ohmsett) in Leonardo, New Jersey for their feasibility and performance. Both systems are portable, can be deployed easily by one or two persons, and are commercially available. See Fitzpatrick et al. (2014) for details on the detection system development and testing.

During Phase II of the project the RDC focus shifted to mitigation. This portion of the project built on the efforts and lessons learned during the RDC's work in Phase I as well as those learned during the Deepwater Horizon response. Once submerged oil in the near-shore or river environments has been encountered, the next step is to make the decision of whether an active approach is necessary to remove the oil or mitigate the subsurface plume's impacts on the environment, water intakes, and commercial facilities. Currently there is no well-established technology, technique, or strategy to prevent the detected submerged oil from having further adverse impacts on the environment or manmade structures.

1.1 Objective

During Phase II, the RDC undertook a Research and Development (R&D) effort to identify and develop a system that could mitigate the impacts of oil in the water column on the surrounding environment through containment, diversion, or removal of the submerged oil. It was a part of a larger effort in the CG R&D program to develop countermeasures and cleanup technologies for a range of oil spills.

The Deepwater Horizon wellhead released large quantities of submerged oil that remained below the water surface and presented numerous challenges to oil spill responders. However, the scope of this project is limited to near-shore environments up to a depth of 200 feet (ft) (61 meters (m)), which is where the majority of oil spills in the nation's waterways occur.

The RDC solicited contractors through a Broad Agency Announcement (BAA) to develop a proof-of-concept of their mitigation systems. White papers and subsequent proposals needed to demonstrate the technical and scientific basis of their approaches as well as their feasibility. Four contractors responded with descriptions of their mitigation systems and their planned developmental activities. Two were selected for further work. Balsley et al. (2016) summarized the results of Phase II-A (Concept Development) efforts, which included the concept development of a technology, technique, or strategy that could mitigate the impacts of a subsurface oil plume. This report summarizes the results of Phase II-B (Prototype Development and Demonstration).

1.2 Background

The Oil Pollution Act of 1990 (OPA 90) requires that Federal agencies conduct a coordinated research program, in cooperation with academic institutions and private industry, to improve the nation's capability to detect, monitor, and conduct countermeasures, cleanup, and remediation operations to respond to accidental oil spills. Responding to oil spills on the water surface is often a difficult task with recovery rates generally averaging about 20 percent or less of the oil spilled. Responding to spills of submerged oil is far more complex due to the problems associated with operating in an underwater environment where oil is constantly spreading and dispersing in three-dimensions, visibility is limited, and deploying divers is dangerous. Recovery equipment must be far more robust and complex than that used on the surface. However, a number of recent spills involving heavier oils that sank below the surface, as well as the subsurface oil encountered in the Deepwater Horizon spill, underscore the need for improving technology for subsurface oil spill response. Subsurface oil can be either suspended in the water column or sunken to the sea floor or river bottom. The RDC first investigated detection and recovery of sunken oil. Results of this research can be found in Hansen et al. (2009) and Fitzpatrick and Tebeau (2013).

The RDC then investigated detection and mitigation of oil suspended in the water column, also known as submerged oil. A summary of the problems and technologies associated with submerged oil is provided below. Balsley et al. (2016) contains additional information about mitigation of oil in the water column. See National Research Council (NRC) (1999), Michel (2006), American Petroleum Institute (API) (2016a), and API (2016b) for additional information.

1.2.1 Oil in the Water Column

Spilled oil can be suspended in the water column in roughly four distinct scenarios. The physical and chemical properties of oil resulting from these scenarios can be very different and change with time.

- Heavy oil from a surface spill that tends to sink under certain conditions, and is generally called suspended oil while it is in the water column and sunken oil when it has reached the sea floor or river bottom.
- Oil rising to the surface from a subsea blowout.
- Fine droplets of oil resulting from chemical dispersants being applied to either a surface spill or subsea blowout or due to natural dispersion.
- Fast current water that can move oil and sediment quickly and not permit the oil to surface or sink to the bottom.

As described by the NRC (1999) and Michel (2006), each of the above scenarios presents its own challenges depending on the location and condition of the oil. The scope of this current effort does not include chemically dispersed oil.

1.2.2 Mitigation Techniques

The selection of mitigation techniques for oil in the water column is highly dependent on the specific location and environmental conditions during the oil spill, the characteristics of the oil and its state of weathering and interaction with sediments, the availability of equipment, and logistical support for the cleanup operation. Further complications include the difficulty in detecting and tracking the oil from the surface in real time and the constant movement and dispersion of the oil in three dimensions. In addition, the potential environmental impacts of implementing these methods, particularly in sensitive benthic habitats, must be considered.

The effectiveness of mitigation technologies is heavily dependent on the condition of the oil suspended in the water column. Most of the technologies recommended in the literature and used in past spills apply to larger fragments of very viscous oil (often termed globules, tarballs, or pancakes). The technologies recommended for mitigation of heavy and/or viscous oil are listed below. Further details of these technologies can be found in Balsley et al. (2016).

1.2.2.1 *Technologies Used for the Mitigation of Suspended Oil Droplets*

Oil droplets can be suspended in the water column if their size and composition render them neutrally buoyant, or environmental conditions keep droplets below the surface that would normally rise due to their buoyancy. Following the *SS Arrow* spill of Bunker C oil, researchers found that oil particles in the water column ranged from 5 to 2,000 microns (µm) for months following the spill (Forrester, 1971).

While there is no readily available information in the literature about mitigation of suspended oil droplets in actual spills, mitigation technologies that may apply include deep draft oil booms, silt curtains (for larger droplets, depending on the design of the curtain), sorbents, and pneumatic barriers (or bubblers).

Deep draft oil booms. Under certain conditions, booms with deep drafts may contain some of the suspended oil. A deep draft would be considered greater than about 4 ft (1.2 m). In general, deep draft oil booms are successful for water column oil containment only when the oil remains in the upper water column, the currents are low, and the waves are small (NRC, 1999).

Silt Curtains. Silt curtains, which are normally used to control the transport of suspended sediment during dredging operations, are typically restricted to water depths of 10-20 ft (3-6 m) and are deployed so that the bottom of the curtain does not extend to the seabed (NRC, 1999).

Sorbents. Sorbent materials in the form of pom-poms, snare nets, and the Vessel-Submerged Oil Recovery System (V-SORS) are often used for detection of submerged oil. They are also recommended as recovery technologies in some situations, primarily for viscous oil (Michel, 2006).

Pneumatic Barriers. Pneumatic barriers, also known as bubblers, involve injecting air at the seabed and forming a bubble plume that rises to the surface. They were originally designed to collect and/or divert oil at the surface. Pneumatic barriers have also been considered for protecting sensitive structures such as seawater intakes and marinas against oil suspended in the water column, and one was used at the Lake Wabamun spill at one of the power plant water intake canals (Fingas, 2011), but little data are available for assessing their performance. Their optimal application is in confined areas in shallow water (less than approximately 6.5 ft (2 m)) (Chapman, 2012).

1.2.2.2 *Technologies Used for the Mitigation of Submerged Viscous Oil*

In addition to the silt curtains, sorbents, and bubblers described above, the NRC (1999) recommended the following methods for potential mitigation of heavy oil suspended in the water column.

Nets and Trawls. Midwater trawls and nets may be used for containing heavy oil in certain conditions. The performance of these systems depends on the viscosity of the oil and being able to locate and concentrate the oil. In addition to containing dispersed oil, nets and trawls can also be used as collection devices (Brown and Goodman, 1987; Delvigne, 1987; Cooper, et al., 2007), and are often combined with sorbents for this purpose. Some disadvantages of nets and trawls are they are labor intensive, slow to deploy, and can fail from excess accumulation of heavy oil and debris.

Manual Removal. The manual removal of oil, one of the most widely used recovery methods for viscous oil, involves divers or boat-based personnel using dip nets or seines to collect oil, which is temporarily stored in bags or containers. The biggest disadvantages of manual removal are the large manpower and logistical requirements, potential danger for responders, slow rates of recovery, strong dependency on favorable weather conditions, and the potential for the oil to be transported while it is being recovered.

1.3 Approach

1.3.1 Contracting Approach

The RDC developed technical capabilities that a technology for mitigation of oil in the water column should maximize/minimize and included them in a BAA that was released in October 2014. The scope of the BAA included Phase II-A (Concept Development) and a Government Option for Phase II-B (Prototype Development and Demonstration). The Government Option allowed the Government to make a decision at the conclusion of Phase II-A whether or not to move ahead into the next phase depending on a number of factors, including feasibility of technical approach, importance to agency programs, and fund availability.

1.3.2 Performance/Capability Requirements

The BAA required the contractor to develop a design concept for an oil mitigation system prototype. It also further specified that the design concept should maximize/minimize or demonstrate as many of the following capabilities as possible (they are ranked in order of importance):

1. Extent of oil mitigation or removal rates and quantities;
2. Types of oil mitigated (e.g., droplets, tarballs, dissolved oil);
3. Minimization of environmental impacts with a focus on wildlife and plant life;
4. Effective limits in terms of depth of oil and deployment;
5. Effective limits in terms of environmental conditions such as current, wave height, winds, day/night, inclement weather, etc.;
6. Ease of use to include deployability and recovery of equipment;
7. Transportability;
8. Operability in fresh/seawater;
9. Ability to observe and monitor subsurface oil collection;
10. Reusability; and
11. Safety to personnel deploying and recovering.

1.4 Phase II-A Summary

The RDC received four responses and selected two submissions for Phase II-A proof-of-concept development and preliminary testing. See Balsley et al. (2016) for more details on the Phase II-A Concept Development. The selected contractors and their projects chosen were:

- Argonne National Laboratory's Adsorbent Foam.
- Dynaflow Inc.'s Microbubble Flotation System.

Argonne National Laboratory (ANL) chose to use polyurethane foam, a commonly used material for many general purposes, as the material of choice to adsorb submerged oil. Prior to use, the foam undergoes a series of chemical processes in order to render it oleophilic and thus more susceptible to adsorbing and retaining oil droplets and dissolved oil in the water column.

Dynaflow, Inc. developed a mitigation system that utilizes a number of microbubble generators to be placed beneath a submerged oil plume in order to allow air bubbles of differing sizes to adhere and lift oil droplets in the water column to the surface where they can be removed by traditional oil recovery methods.

2 PHASE II-B PREPARATION

2.1 Planning

The RDC worked with the Bureau of Safety and Environmental Enforcement (BSEE), Ohmsett, and the contractors to develop the test plans. The two different mitigation approaches required different setups. Prior to the tests, Ohmsett staff conducted preliminary nozzle testing in their high bay tank to determine the optimum nozzle size and pump pressure to create appropriate oil plumes for the two tests. The Dynaflow test required a long duration of residence time for oil in the water column. Residence time was not as critical for Argonne since their test method allowed for their system to encounter the plume in a relatively short time after oil release.

2.2 Preliminary Nozzle Testing

To achieve the best possible oil plume conditions, Ohmsett staff performed a series of tests quantifying flow rate, oil droplet particle size, and oil plume concentration versus time. Ohmsett staff assembled a 688-gallon modular test tank and refilled it with salt water from the main tank for each test. They modified and assembled a portable high pressure pump system with a new spray wand for testing several combinations of Hoover Offshore Oil Pipeline System (HOOPS) blend crude and diesel fuel with varying nozzle sizes. Oil was released into the test area while droplet size distribution and concentration data were recorded using a Laser In-Situ Scattering and Transmissometry (LISST)-100x instrument (Figure 1).

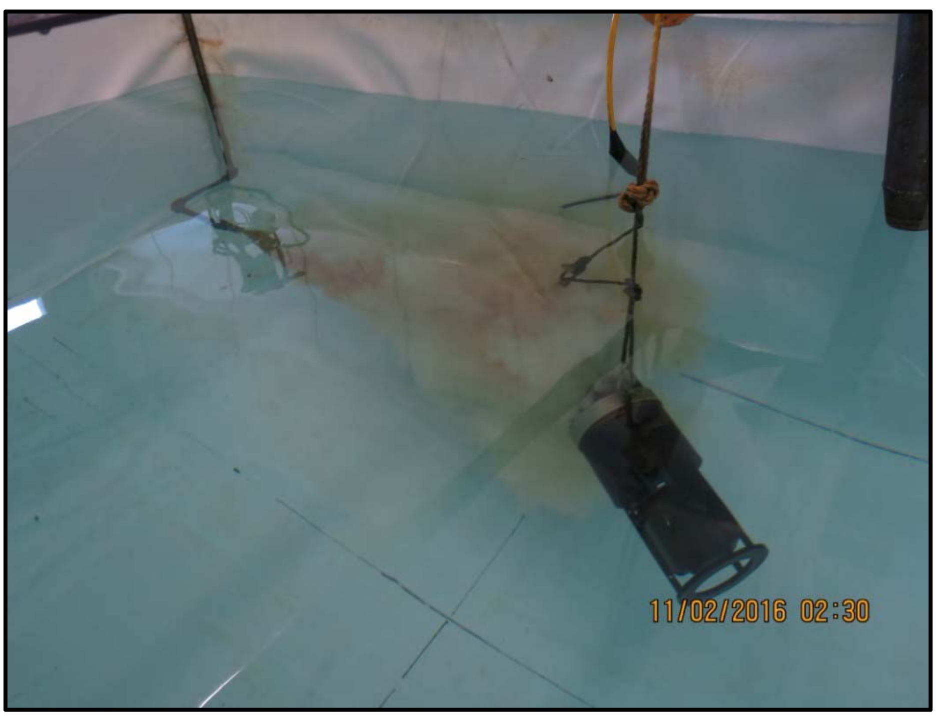

Figure 1. Preliminary nozzle testing.

Ohmsett staff determined flow rates by measuring the volume of oil released into the test area and dividing by the elapsed release time. They performed a total of twelve tests. They used the data gathered during these tests to select the nozzle size, quantity, and orientation for the actual tests.

After Tests 1-8, Ohmsett staff qualitatively determined that the residence time of oil droplets was not sufficient based on the rapid accumulation of dispensed oil on the surface. They performed Tests 9-12 in two steps. They first dispensed approximately 0.25 gallons and acquired LISST measurements. Earlier experiments showed that higher concentrations would exceed the LISST operational range. In the second step they dispensed a total volume of 1.65 gallons, which was equivalent to a concentration of 0.15%, a parameter defined for the actual tests. Sixty minutes after creating the oil plume, they collected and measured the volume of oil that surfaced. They used this volume to calculate the reported percentage remaining in the water column. In an effort to achieve longer durations of the plume, Ohmsett staff explored the introduction of a small current in the test area (using a sump pump), which created enough circulation to keep droplets suspended in the oil column for a longer period of time.

Based on this preliminary work, Ohmsett staff chose Spraying Systems Inc. #6 (0.042-inch sized diameter) nozzle for the Argonne testing. The method planned for the Dynaflow testing required rapid dispensing of the oil plume, which the #6 nozzle was also well suited for due to its higher flow rate.

3 PHASE II-B TESTING

3.1 Argonne National Laboratory Adsorbent Foam

3.1.1 System Description

ANL developed a method to use polyurethane foam, a commonly used material, to adsorb submerged oil. Prior to use, the foam undergoes a series of chemical processes in order to render it oleophilic and thus more susceptible to adsorbing and retaining oil droplets and dissolved oil from the water column. Details of the treatment process can be found in Balsley et al. (2016).

3.1.2 Summary of Phase II-A Efforts

During Phase II-A experiments, ANL used three different types of oil: silicone oil, vacuum pump oil, and Anadarko crude. ANL conducted experiments testing the performance of treated foams with distilled water and at room temperature (~ 23 degrees Celsius (C)). To determine the recovery capacity, ANL followed American Society for Testing and Materials (ASTM) F726-12, Standard Test Method for Sorbent Performance of Adsorbents (Darling, 2016). It describes the performance of adsorbents in removing non-emulsified oils and other floating, immiscible liquids from the water surface. The ASTM standard involves several minutes of exposure to oil or water in each experiment. However, ANL did not use the minimum foam mass of 4 grams as specified in the standard, which would have required larger cube dimensions and made it more difficult to experiment within a laboratory setting. Since ANL obtained results from testing with a small foam mass, the RDC notes that the performance of a larger foam size may be skewed since an exact linear relationship may not be followed when the foam is scaled up in size. The RDC also notes ASTM F726-12 applies to floating oil and results may be different for oil suspended in the water column.

The functionalized foam adsorbed approximately 28 grams (g) of Anadarko crude per gram of the foam (g/g) compared to 8 g of the same oil per gram of the foam when untreated foam is used. The functionalized foam tested with vacuum pump oil shows the best result, adsorbing 34 g/g while untreated foam with the same oil adsorbed 4 g/g. Figure 2 shows the results of the ASTM F726-12 tests to determine adsorption capacity of water and various oils for untreated and functionalized foams.

ANL conducted experiments to determine the reusability of their functionalized foam. Figure 3 shows absorption capacity of the foam for vacuum pump oil following six cycles of compression and readsorption.

Oil mitigation techniques must be able to operate in both fresh and salt water. Although ANL conducted most of their Phase II-A tests with distilled water, they performed some experiments with salt water using simulated seawater (Instant Ocean Salt Mix). As can be seen in Figure 4, salinity had a pronounced influence with increased water uptake relative to the oil. The cause of this difference was not clear and continues to be a topic of further study for ANL.

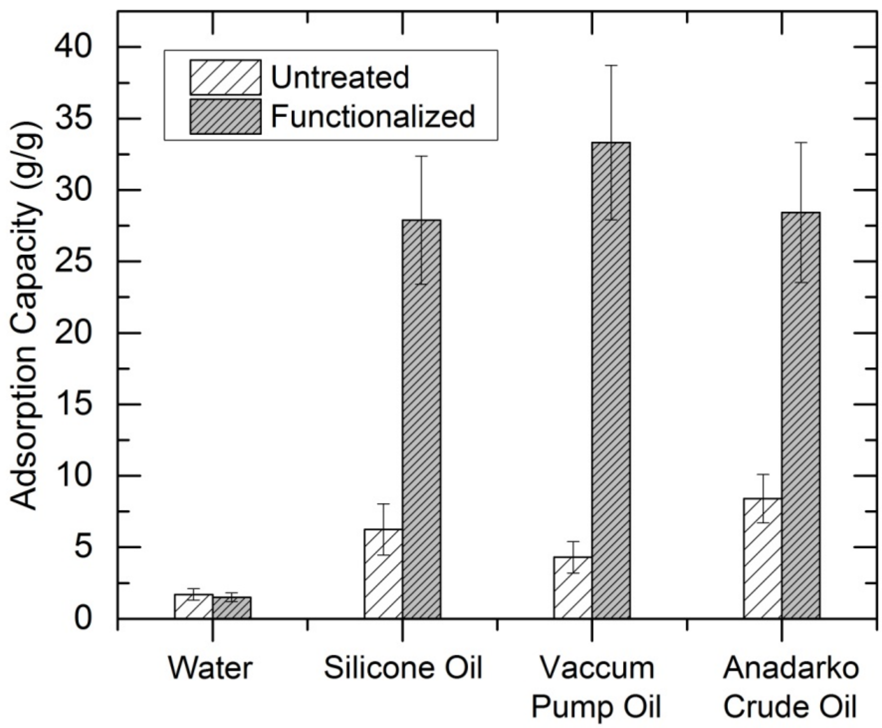

Figure 2. Results of adsorption capacity for untreated and functionalized foams.

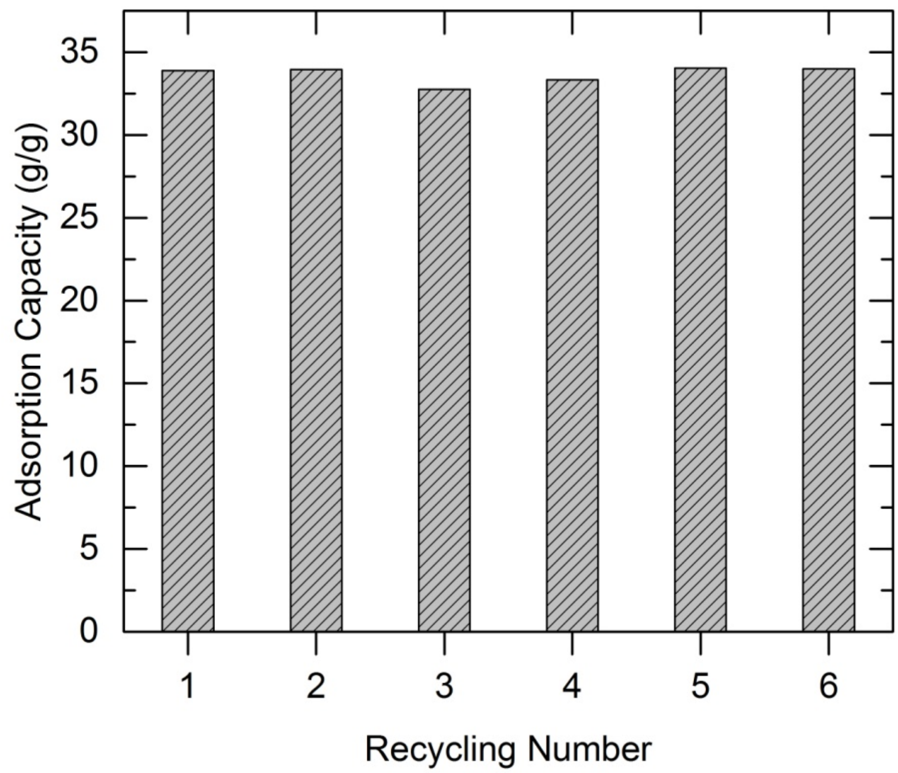

Figure 3. ANL reusability results using vacuum pump oil.

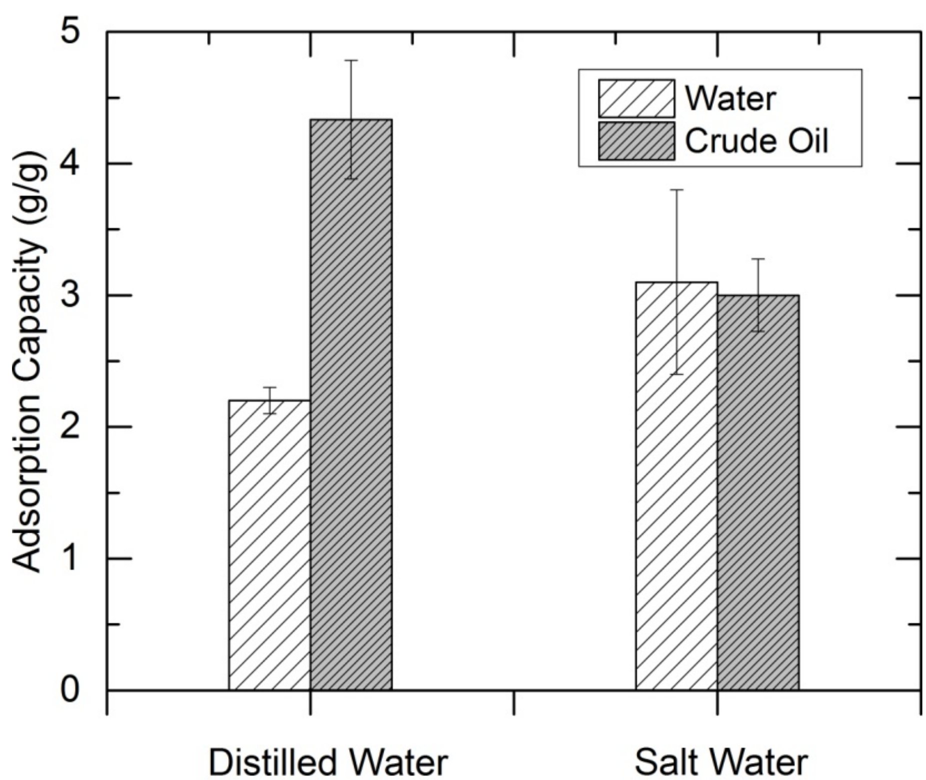

Figure 4. ANL salinity results.

In the course of Phase II-A of the project, ANL also explored polyimide foams because they have different chemical, thermal, and mechanical properties than polyurethane, some of which are advantageous and some disadvantageous for this application. Polyimide foams have an advantage of stability at higher temperatures. In the ANL lab tests, treated polyimide foams performed similarly to treated polyurethane foams in initial oil uptake, which is not surprising since the interfacial functionalization process should result in virtually identical oleophilicity and hydrophobicity regardless of the substrate material. However, ANL found the mechanical properties of polyimide to be inferior to those of polyurethane. Unlike polyurethane, polyimide foams did not recover quickly from compression; rather, they remained deformed for an extended time after having oil squeezed from them. This feature hinders the reusability of the foam.

3.1.3 Phase II-B Laboratory Testing

ANL conducted a number of developments and laboratory tests during Phase II-B prior to the prototype test at Ohmsett. They included but are not limited to:

- Thorough testing of temperature and salinity effects.
- Testing of limits to movement through water for oil-laden foams.
- Atomic layer deposition (ALD) silanization experiments and comparison with liquid process.
- Optimization of foam functionalization process for crude oil absorption.

3.1.3.1 Thorough Testing of Temperature and Salinity Effects

ANL conducted temperature and salinity tests using the functionalization process optimized during Phase II-A of the project. Initial tests were conducted using olive oil. Small sections of foam were tested through eleven adsorption cycles with olive oil floating on deionized water and salt water in small containers. The foam in salt water required additional cycles to adsorb all of the olive oil when compared to that in deionized water. At each cycle, a certain amount of water was adsorbed along with the oil but the selectivity (ratio of adsorbed oil to water) was slightly decreased in the case of salt water, as was seen in the Phase II-A testing. This has important implications for actual recovery operations because responders have a finite volume of collection tanks; the least amount of water should be collected in order to maximize tank volumes for oil.

Olive oil adsorption tests were also conducted with colder water temperatures to simulate Arctic conditions (4° C). The performance was only slightly less in the colder temperature.

3.1.3.2 Testing of Limits to Movement through Water for Oil-laden Foams

ANL designed a small-scale system for obtaining uniform motion of foam through water using the propeller of a modified mixer with varying rotation speed. This system was used to measure the ability of oil-laden foam to withstand motion through water without loss of the oil. Oil desorption was clearly evident, but it was difficult to measure the exact amount.

3.1.3.3 ALD Silanization Experiments

ANL designed studies to determine the feasibility of applying ALD using a vapor-phase silanization process as a potential replacement for the liquid-phase silanization process established during Phase II-A. ANL explored utilizing vapor-phase silanization because of the possibility that it may increase the efficiency of the manufacturing process when the foam is treated on a large-scale basis. This work included selecting molecular precursors that (1) have functional groups likely to bind covalently to the oxide-modified foam,

(2) have tail groups anticipated to exhibit good oleophilicity and hydrophobicity, and (3) exhibit sufficient vapor pressure to produce working partial pressures in the reaction chamber.

For unknown reasons, the vapor-phase deposition of the silane agent significantly reduced the selectivity of oil with respect to water. Namely, ANL found that the vapor-phase treated foams had a significant propensity to adsorb water. ANL did not explore this route further and returned to the original liquid-phase silanization process.

3.1.3.4 Optimization of Foam Functionalization Process for Crude Oil Adsorption

ANL installed a new reactor that was able to functionalize four strands of foam approximately 1 m long simultaneously rather than a single strand at a time. With the bigger reactor, it needed to conduct additional optimization tests to account for changes in flow of precursor gases throughout the reactor volume. All segments of the large foam block were functionalized, but there was a slight gradient along the reactor length. ANL was able to optimize the process to minimize the gradient.

3.1.4 Test Overview

In order to test the foam's performance in Ohmsett's main tank, ANL prepared sufficient quantities of treated foam to fill in 24-inch square panels. One-cubic-inch pieces of the foam were secured within parallel sewn pockets of nylon mesh with grommets serving as attachment points on the top and bottom. The tops of each foam pad were secured to a steel lattice frame with sixteen positions available in a 4×4 array although only 14 panels were used. Figure 5 shows the array of panels being lowered into the frame with a close-up of four of the panels containing the foam pads. Notice the extra space between the panels, which allows the oil plume to pass through without contact. The bottoms of the foam pads were not attached to the frame, but were weighted using steel bars that allowed the individual pads to pivot outwards in a controlled fashion with increasing water flow while also counteracting the natural buoyancy of the foam. This array was mounted to the auxiliary bridge at the Ohmsett main tank and held rigidly in place during testing.

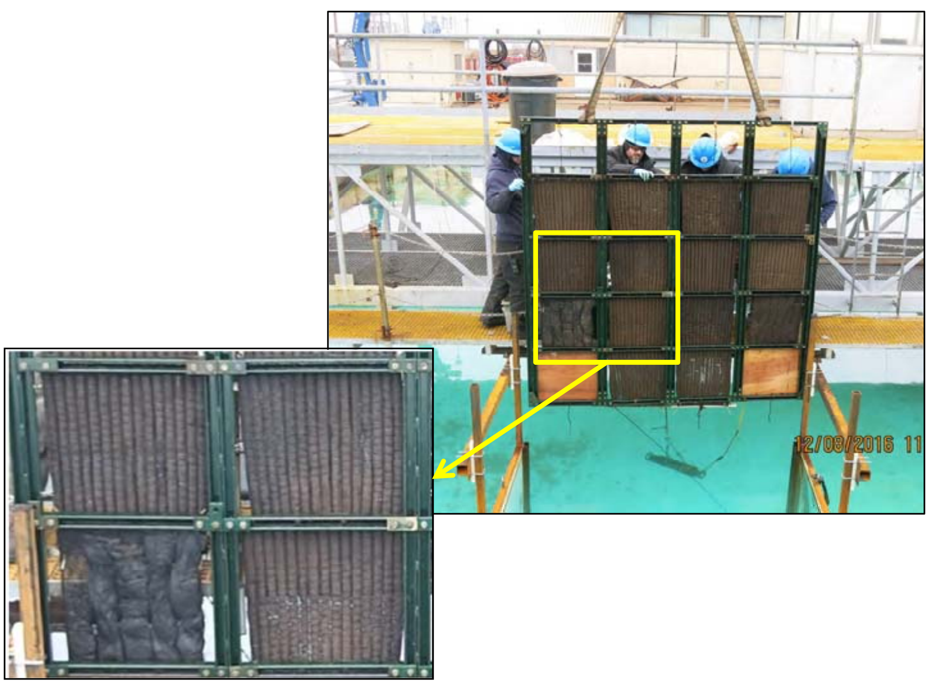

Figure 5. Test frame with sorbent panel array.

ANL's test required an open channel test area within the main tank. Ohmsett staff created the channel with two beams mounted to the auxiliary bridge and parallel to one another approximately 8 ft (2.4 m) apart to accommodate ANL's lattice frame (Figure 6). They attached the frame to the main bridge crane, which could lift the frame directly upward. This setup allowed Ohmsett personnel standing on the auxiliary bridge to remove the mesh bags from behind at the end of each test. Baseline tests provided insight for the appropriate distance between the oil plume distribution manifold and the lattice frame.

Figure 6. ANL test area.

Ohmsett staff used underwater cameras to collect photographic and video data during the tests. They placed the cameras in strategic locations for the most optimal views of the mitigation technology during operation. The LISST equipment was mounted on the auxiliary bridge and positioned behind ANL's lattice frame. Ohmsett staff intended to collect concentration data in the "clean" region of the water column (after the frame passed through) throughout the tests to determine the foam's effectiveness at adsorbing fuel/oil. However, the amount of oil in this region generally exceeded the LISST operational range.

Before each test run, Ohmsett staff used LISST to confirm the background concentration of the clean water to determine if the test could proceed. As soon as oil flow began, the auxiliary and main bridges along with ANL's lattice frame transited south at a predetermined speed. The top row of foam pads attached to the frame was placed approximately one foot below the water surface to ensure that they did not recover oil on the water surface during the sweep through the submerged fuel/oil plume.

Ohmsett staff designed the tests to allow for maximum contact between the foam and the submerged oil. With 14 foam pads, ANL estimated the maximum adsorption capacity to be approximately 10.7 gallons of oil. Thus 12 gallons were regularly dispensed into the main tank for each test. Once the full amount of the oil was dispensed, the flow and subsequent recovery operation ceased. For some of the tests, the frame continued to pass through a body of clean water at the same speed for an extra 30 seconds after it passed through the last of the oil plume. This additional sweep helped to determine if the foam experienced any oil leaching.

At the end of each test run, Ohmsett staff removed the foam pads from the steel frame and placed them into labeled storage bins. They then took the bins into their machine shop area for the wringing process to collect the recovered fluid. ANL personnel squeezed the oil and water out of the foam with a hand wringer system in a secondary containment area for spill prevention (Figure 7).

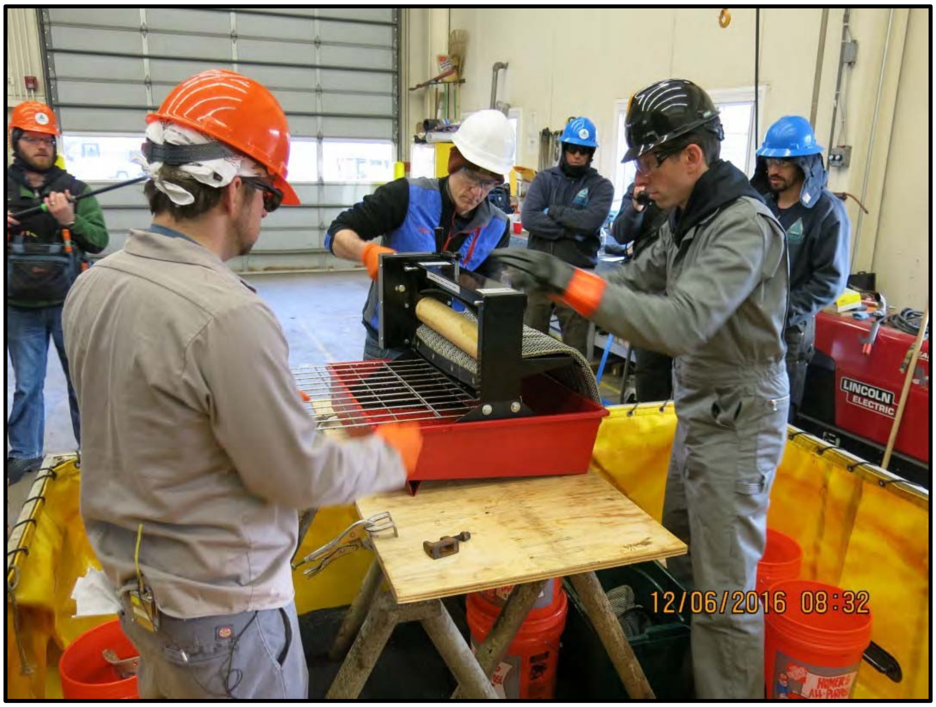

Figure 7. Oil sorbent pad wringer.

Ohmsett staff collected all fluid removed from the foam pads for measurement. They measured each volume in a graduated cylinder for total water volume followed by decant and sampling. Volumes measured included free drip water and loose oil collected from each storage bin, wrung oil, and wrung water for each pad or pad type. They performed bottom solids and water (BS&W) analyses only if there was sufficient volume to do so.

Ohmsett staff then reattached the foam pads to the lattice frame for the next test run, which started just south of the location where the previous run ended. This ensured that the next test occurred in a clean area each time because the filtration system forces the current in the main tank to continuously move north.

3.1.5 Test Results and Discussion

The Ohmsett tests focused on the investigation of three types of sorbent materials: treated polyurethane (PU) foam, treated polyimide (PI) foam, and commercial PIG® socks. Test personnel conducted the first half of the tests with just the PU foam pads and an untreated (U) polyurethane foam pad in row 2 for comparison. Later tests included the PI foam and PIG® socks. ANL tested the PI foam in the laboratory in Phase II-A. The PIG® foam was not tested in the lab. ANL obtained it from a commercial vendor specifically to use for comparison in the Ohmsett tests.

The tests consisted of twelve runs, with each run varying one or more of the following parameters: type of oil (HOOPS, diesel, or Alaska North Slope (ANS) crude), bridge speed, volume of oil, number of nozzles, spacing between the two bridges, types of sorbents in the array, and whether or not the array was dragged for an extra 30 seconds after oil dispensing ceased. After each test, the pads were removed from the array and allowed to drain for varying periods of time. During the draining period, virtually no oil was observed to shed from the foam. In an operational setting, the water dripping from the foam as it is extracted from the water would be returned to the body of water, thereby reducing the need to store that additional volume of fluid.

After the pads were drained of this free water, ANL personnel ran them twice through a compression wringer to expunge sorbed fluid (both oil and water). Ohmsett personnel allowed the collected fluid to settle for a preliminary measurement of oil and water volumes. They subsequently centrifuged the fractions to separate out any residual oil in the water or residual water in the oil. Table 1 contains a summary of one of the results – Oil to Total Fluid Recovery Percentage – sorted by row number and sorbent type. Test 11 had technical difficulties and is not included. More result details can be found in APPENDIX A.1.

Table 1. Summary results of ANL Ohmsett tests.

Test #	Oil	Speed (knots)	Oil to Total Fluid Recovery Percentage (%) by Row								Comment
			Row 1 PU	Row 2 PU	Row 3 PU	Row 4 PU	Row 3 PIG	Row 3 PI	U	PU-AVG	
8	HOOPS	0.1	6.4	13.0	18.5	13.0			1.2	12.8	
9	HOOPS	0.1-0.12	7.8	9.6	9.8	6.9			0.7	8.5	post drag
10	HOOPS	0.12	18.4	22.4	13.1	8.1			0.0	15.5	
12	HOOPS	0.2	14.7	6.2	9.7	14.5			1.9	11.3	post drag
13	HOOPS	0.2	18.0	18.8	16.9	11.9			0.6	16.4	
14	HOOPS	0.2	21.3	20.6		1.2	32.5	31.7	1.6	14.4	
15	Diesel	0.2	22.7	11.6		7.0	9.1	3.0	1.1	13.8	
16	ANS	0.2	19.6	22.3	25.5	30.0	20.0	6.1	0.8	24.4	
17	ANS	0.2	31.2	23.5	19.3	22.0	7.7	8.3	1.9	24.0	
18	ANS	0.1	9.6	8.6	9.9	12.0	8.0	12.0	1.6	10.0	
19	ANS	0.1	4.6	4.8	10.9	7.4	6.3	4.9	1.2	7.0	post drag

The last 6 runs (Tests 14-19) included other sorbents in row 3. Table 2 shows the results from row 3 of the lattice for these test runs. Volumes are given in milliliters (mL) except for the total volume distributed, which is given in gallons.

Table 2. Sample results of ANL Ohmsett tests for Row 3.

Test #	Sample	# Pads	Total Fluid Volume Wrung (mL)	Volume Water Wrung (mL)	Volume Oil Wrung (mL)	Oil to Total Fluid Recovery Percentage (%)	Total Volume Distributed (gallons)
14 HOOPS	PIG	1	420	270	150	32.5	12.7
	PI	3	3,425	2,240	1,185	31.7	
15 Diesel	PIG	1	220	200	20	9.1	12.2
	PI	3	2,325	2,245	80	3.0	
16 ANS	PU	2	840	550	290	25.5	8.7
	PIG	1	250	200	50	20.0	
	PI	1	900	845	55	6.1	
17 ANS	PU	2	940	710	230	19.3	14.0
	PIG	1	130	120	10	7.7	
	PI	1	5	100	100	8.3	
18 ANS	PU	2	760	685	75	9.9	11.7
	PIG	1	125	115	10	8.0	
	PI	1	830	730	100	12.0	
19 ANS	PU	2	825	735	90	10.9	12.7
	PIG	1	160	150	10	6.3	
	PI	1	810	770	40	4.9	

There are few obvious trends in the data, making it difficult to draw solid conclusions. General observations based on the results include:

- The recovery percentage for ANS was better than for HOOPS (except for Tests 18 and 19).
- Runs that include post-test drag had lower percentages of oil recovery. It is likely some of the oil leached off the foam into the clean water. In Test 9, Ohmsett personnel noted the system was either shedding oil from the pads or dragging some of the oil from the plume.
- Comparison of the treated PU to the other sorbents contains mixed results.
- Reusing the PU from one test to the next did not appear to degrade its performance while the recovery numbers for PIG® and PI foams dropped after the first use.

The total amount of oil recovered was less than expected based on the laboratory tests. As noted earlier, the laboratory tests used floating oil as opposed to oil droplets in the water column. In addition, laboratory results indicated the foam exhibited less selectivity with salt water, which was used at Ohmsett. This could account for some of the differences in the recovery numbers from the laboratory and Ohmsett.

During the tests, Ohmsett personnel used qualitative observations to make spacing adjustments such that the plume reached a uniform distribution across the sorbent pad array while minimizing oil lost outward of the guidance channel. In addition to spacing distance, nozzle positions were adjusted laterally and vertically as required to improve oil encounter. Nozzle spacing width, release angle, and nozzle quantity changes are noted on the included Daily Test Logs (MAR, LTD (2017a)). Even with this attention to the nozzles, test personnel were concerned that the test setup did not always allow the oil to have sufficient contact with the foam. This was likely due to the design of the frame, which allowed oil to go through and around the panels, as seen in Figure 8. It is also possible the frame acted similar to a flat plate when the oil encountered it. Table 3 shows the percentage of oil recovered in each of the tests assuming almost half of the oil (45%) is lost through and around the frame. Even with this much oil loss accounted for, the recovery numbers are very low, less than 10% in all but one test.

Figure 8. Example of oil plume around and behind the frame.

Table 3. Percentage oil recovered results.

Test #	Oil Type	Oil Volume Distributed (gallons)	Oil Volume Distributed (mL)	Estimated Oil Volume Actually Encountered (mL)	Total Oil Volume Collected (mL)	Percent Oil Collected
8	HOOPS	5.4	20,441	10,221	1,306	12.8%
9	HOOPS	12.0	45,425	22,712	737	3.2%
10	HOOPS	12.1	45,803	22,902	1,169	5.1%
12	HOOPS	12.6	47,696	23,848	683	2.9%
13	HOOPS	12.0	45,425	22,712	946	4.2%
14	HOOPS	12.7	48,075	24,037	1,839	7.7%
15	Diesel	12.2	46,182	23,091	584	2.5%
16	ANS	8.7	32,933	16,467	1,294	7.9%
17	ANS	14.0	52,996	26,498	1,197	4.5%
18	ANS	11.7	44,289	22,145	524	2.4%
19	ANS	12.7	48,075	24,037	348	1.4%

It should be noted that treated PU foams, which ANL produced for the tests, were not used on all 14 panels within the lattice frame for each test run. One panel was dedicated to using untreated PU to differentiate between the foam's adsorption capacity between treated and untreated foam. Tests 14 to 19 utilized PIG® and PI foams on Row 3 of the lattice frame to show comparisons between PU and different foams. Despite this, there was little oil uptake compared to the amount of water that the foam picked up. Test personnel also noted that the frame appeared to push a portion of the oil ahead rather than having it flow through. Figure 9 shows an example of this, which was captured approximately 6 minutes into Test 18.

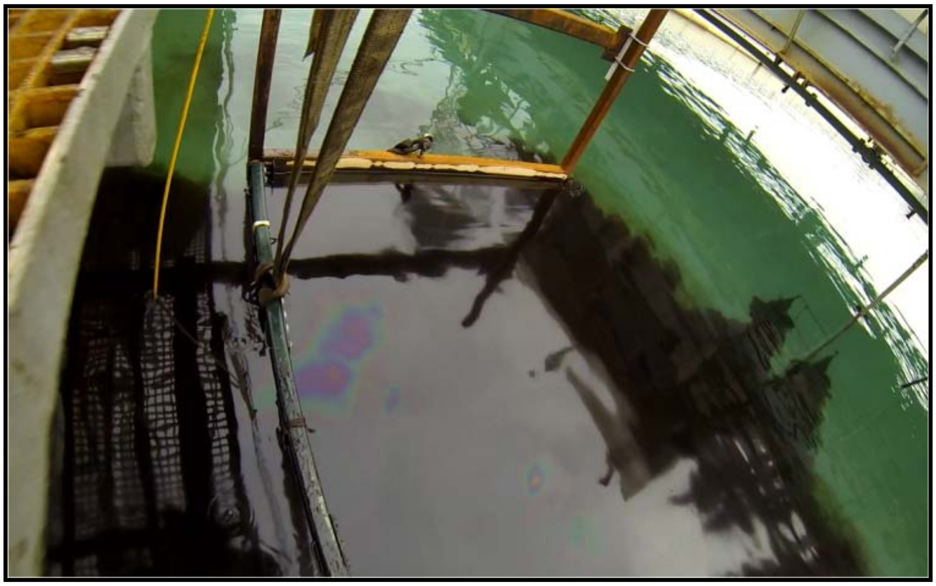

Figure 9. Example of oil plume being "pushed" by frame.

3.1.6 Path Forward

3.1.6.1 Proposed Concept of Operations (CONOPS)

Figure 10 depicts ANL's concept for the eventual deployment of its adsorbent foam in the field. The operational vision for deployment in the field would involve leveraging trawling equipment and well-developed fishing practices to use foam-modified nets to recover oil plumes from the water column. Treated polyurethane foam strips would be encased in nylon mesh bags and then attached to a large net similar to those used for commercial mid-water trawling. One or more fishing trawlers would deploy these nets using winches to lower the net to the appropriate depth and drag it through the oil plume. The net would be designed with an open end to allow aquatic animals to escape. After the treated foam becomes saturated with submerged oil, the net would be lifted back aboard the vessel and passed through perforated rollers to squeeze out the oil and regenerate the foam. This process would be repeated until the plume is mitigated. The collected oil would be stored in a reservoir or pumped into holding tanks.

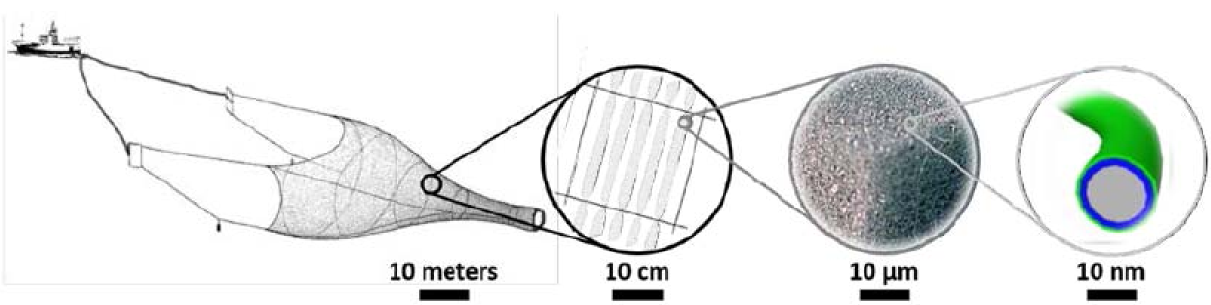

Figure 10. Schematic of ANL proposed CONOPS.

3.1.6.2 Further Developments

During the Ohmsett tests, ANL and the RDC identified some areas for further study and development. Specific equipment and detailed procedures for deployment and recovery, especially efficient sorbent wringing and safe oil handling, still need to be identified and developed.

One key finding during the tests was that the foam would shed water immediately when pulled out of the tank. Indications were that very little or no oil dripped off the saturated foam during this time. Therefore, it will be important to quantify the water-shedding process to guide use of this technology in an operational setting. This can lead to responders following a prescribed drip time over the contaminated water surface before starting the wringing process. This has a large bearing on oil spill recovery operations in the field as time dedicated to shedding and wringing the oil into recovery containers is time spent not actually recovering the oil itself. At this time, it is unknown what the frequency of the wringing operations would be with this approach for a given oil plume, which is dependent on the adsorption capacity of the final mitigation system. Also, the amount of oil responders can pick up with this foam technology is limited to the amount of collection tanks they have. Due to tank capacity limitations, it is crucial to limit the amount of water picked up to maximize the storage of recovered oil.

To deploy this technology in the field, manufacturing of the treated foam would need to be substantially scaled up. This would entail further development work to utilize low-cost and high-throughput manufacturing as well as to ensure reproducible and homogeneous performance of the product. It was noted during testing that the lattice frame needed openings to allow the frame to pass through the water column without causing severe drag resistance. However, this also allows oil to flow through the foam openings when it could have been captured instead. Testing in the field using nets of different designs would help optimize the oil-collection efficiency. Another parameter that may need adjustment is the porosity and pore size of the foam sorbents. Test results indicate that some fraction of very small oil droplets may be able to pass through the pores without encountering the pore walls and being captured. Optimizing the pore structure as well as the net design may be able to overcome this issue.

3.2 Dynaflow Microbubble Flotation System

3.2.1 System Description

Dynaflow developed a microbubble flotation system capable of being towed behind a vessel that is designed to remove neutrally buoyant oil droplets from the water column using microbubble injection with DYNASWIRL® bubble generators. The DYNASWIRL® cavitating jets create microbubble air plumes with bubble diameters ranging from a few μm to 1 millimeter (mm) with the intention of lifting neutrally buoyant oil droplets to the surface where they can be removed using conventional oil recovery equipment. The smaller, finer bubbles attach to neutrally buoyant oil droplets while the larger ones lift the overall microbubble-oil droplet mixture to the water surface.

3.2.2 Summary of Phase II-A Efforts

During Phase II-A, Dynaflow successfully tested a conceptual system consisting of two DYNASWIRL® bubble generators in a laboratory setting with vegetable oil and three petroleum crude oils provided by BSEE (Anadarko, ANS, and HOOPS) in a 1,350 gallon six-cubic-foot tank. A cavitating jet was used to generate an oil emulsion in a separate drum, which was then injected into the tank to ensure production of oil droplets fine enough to be practically neutrally buoyant. Dynaflow measured bubble size distributions, concentrations of air, and rise speed using high speed microphotography techniques. They used a MotionPro IDT Y3 camera and processed images using image analysis software developed by the National Institute of Health (Chahine et al., 2016). The major findings from Phase II-A are discussed below. See Balsley et al. (2016) for more details about the Phase II-A work.

3.2.2.1 Bubble Generator Orientation

Orienting the bubble generators downward so that the bubbles were ejected into a cylindrical enclosure that redirected the flow upward improved performance by reducing the upward ejection speed of the bubbles (Figure 11).

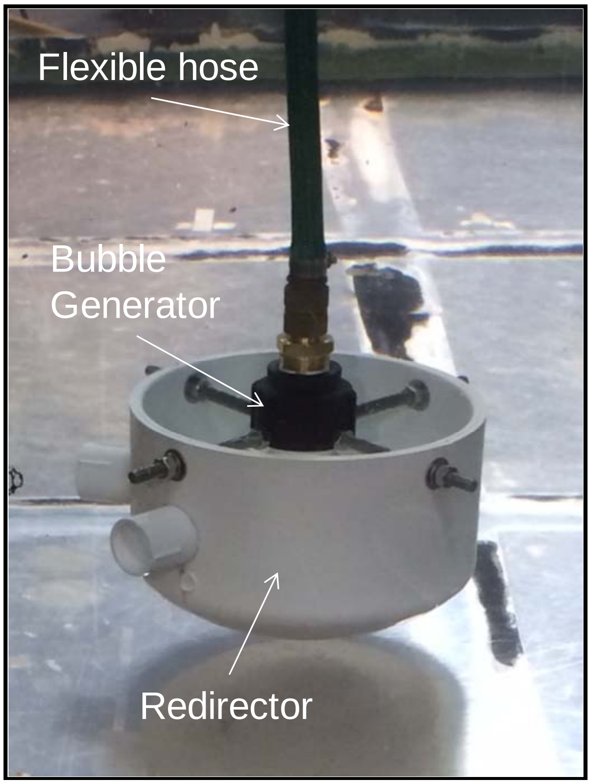

Figure 11. Single bubble generator mounted in redirector.

3.2.2.2 Salinity Effects

Salinity was found to have a significant positive effect on the flotation efficiency for the tests in the lab. The capture efficiency of the bubbles was increased in salt water when compared with fresh water. This was primarily due to the presence of smaller bubble radii, since smaller bubbles are more efficient at attaching to the oil droplets.

3.2.2.3 Oil Droplet Size Distribution

Figure 12 shows droplet size distribution for vegetable oil and Anadarko crude oil in thousands per cubic meter between 20 µm and 350 µm generated by the oil dispersion nozzle. The figure shows that smaller droplets sizes were created with Anadarko crude than with the vegetable oil.

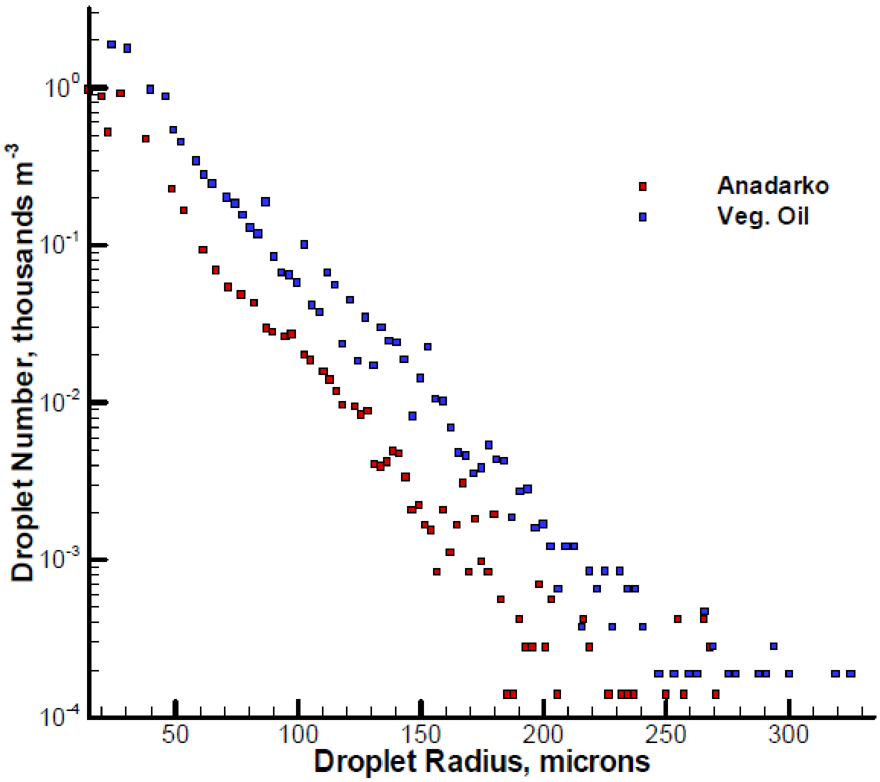

Figure 12. Droplet size distribution for vegetable oil and Anadarko crude oil.

3.2.2.4 Oil Dispersion Process

Dynaflow's oil dispersion process produced small oil droplets with semi-neutral buoyancy, which was estimated from the observation of oil particle rise times (between 0.3 and 5 mm/s). Rise speeds of oil droplets after the air bubbles were generated were approximately 3 to 15 mm/s. Tests were run for four hours and oil collected at 30-minute intervals.

3.2.3 Phase II-B Laboratory Testing

A number of developments and laboratory tests were conducted in Phase II-B prior to the testing at Ohmsett. These included:

- Fabrication of microbubble generators and verification of bubble size production.
- Further testing of oil recovery using the microbubble generators.
- Flow and pressure testing of the prototype system.
- Design and construction of the demonstration prototype.

3.2.3.1 Fabrication of Microbubble Generators and Verification of Bubble Size Production

Dynaflow experimented with the fabrication methods of the generator using different materials and procedures in order to minimize production time without affecting performance. It found that the method of manufacturing did not affect the performance of the bubble generators to a great extent, although the 3D printed nozzles and the composite 3D and machined outer wall composite nozzles produced slightly more bubbles with radii less than 100 µm than did the original machined nozzles. In general, as long as the major design criteria (slot geometry, orifice diameter, amount of swirl, etc.) were observed, the bubble generators performed the same.

3.2.3.2 Further Testing of Oil Recovery using the Microbubble Generators

Dynaflow conducted recovery tests of HOOPS oil using two DYNASWIRL® micro-bubble generators in their 1,350 gallon tank to add to the results obtained in Phase II-A using vegetable oil, Anadarko, and ANS crude oil. Each oil type used was emulsified before injection into the tank, which resulted in finely dispersed and quasi-neutrally buoyant droplets prior to each experiment.

Dynaflow ran the oil recovery experiments for these tests by adding bubbles only for the first 20 minutes of the experiment. The team reasoned that because it takes a long time for the very small bubbles to rise to the surface, the effect of the bubbles inserted after the first 20 minutes would be sufficient for a 240-minute test.

Dynaflow collected oil that floated to the surface of the tank using a 1H Tube Oil Skimmer from Oil Skimmer Inc. equipped with a 16 ft (4.9.m) long polyurethane tube (Figure 13). The tube is forced to slide continuously along the tube axis (as a belt) through rollers controlled by a motor. The principle of operation of this tube skimmer is that oil on the free surface attaches to the polyurethane tube and is dragged out from the tank. The tube is pulled across the free surface of the tank and over a series of scrapers that remove the oil from the tube and drop it into a stainless steel hopper. Dynaflow collected samples from the hopper in flasks for quantification of the oil at 30-minute intervals during testing.

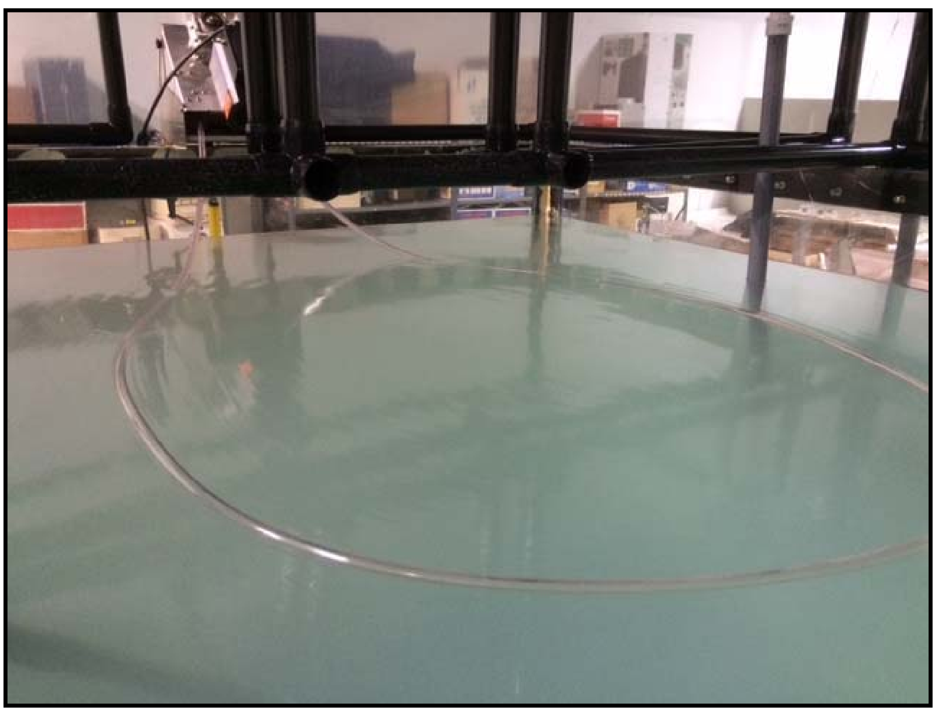

Figure 13. H1 Tube Oil Skimmer installed in Dynaflow’s tank.

Table 4 provides a summary of overall oil removal of the three types of crude oil with and without the addition of bubbles for the 240-minute tests in its laboratory. Figure 14 shows the cumulative recovery of the oil from these tests. The Anadarko and ANS results are from Phase II-A and the HOOPS results are from Phase II-B. The skimmer ran continuously to collect the recovery oil, and as shown in the figure, the oil continued to be collected at a relatively high rate well after the bubble injection stopped. In all three cases, the recovery of crude oil was much higher when microbubbles were injected into the oil plume. HOOPS oil appeared to be the most difficult of the three to recover and ANS the easiest.

Table 4. Summary of overall oil removal in the 1,350 gallon tank.

Oil Type	Vol. Oil Added (mL)	Initial Oil Concentration (mL/liter(L))	Final Oil Concentration (mL/L)	Vol. Oil Recovered (mL)	% Oil Recovered
Anadarko- Gravity only	97.4	0.0191	0.0183	3.9	4 %
Anadarko - Flotation	99.8	0.0196	0.0067	65.7	66 %
ANS – Gravity only	84	0.0165	0.0148	8.4	10 %
ANS - Flotation	118	0.0232	0.0055	81.4	74 %
HOOPS – Gravity only	87.4	0.0171	0.0148	12.9	14%
HOOPS Flotation	107	0.0211	0.0112	50.3	46%

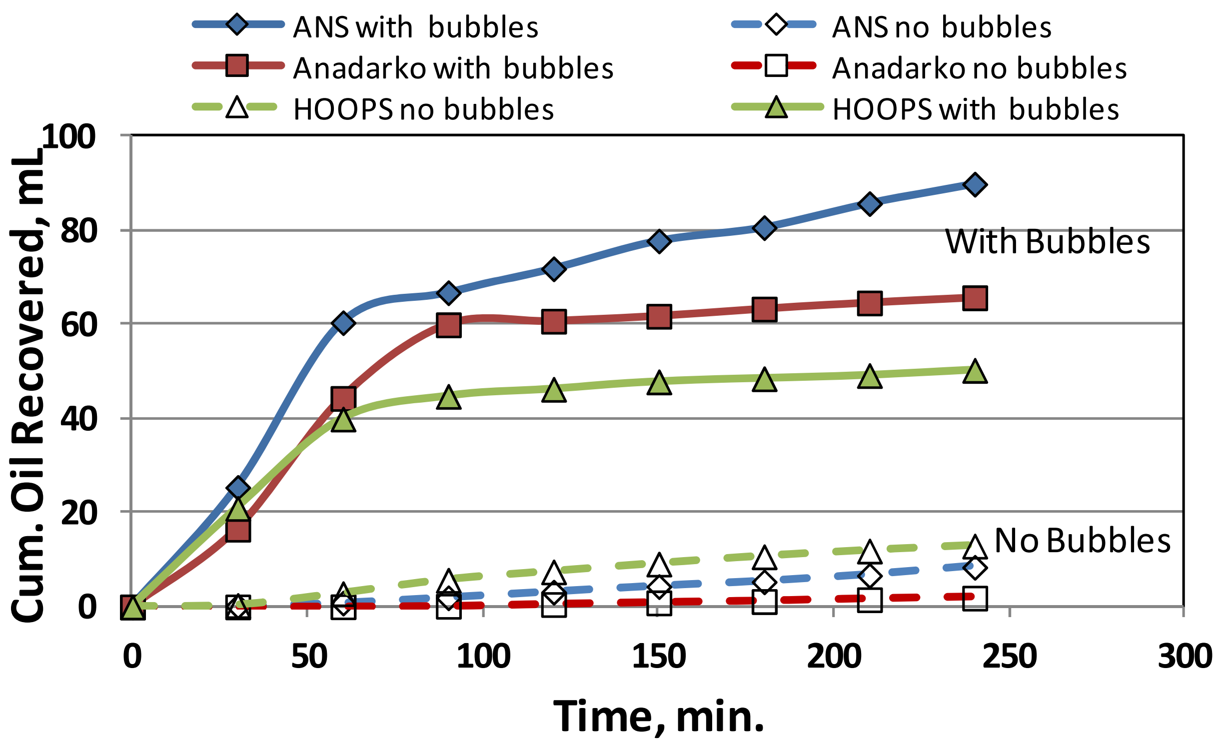

Figure 14. Comparison of cumulative oil recovery during laboratory experiments.

3.2.3.3 Flow and Pressure Testing of the Prototype System

Dynaflow assembled and tested the air injection inlet, which consisted of an inverted U-shape pipe section upstream of the pump inlet with an air port at its highest horizontal portion. This configuration uses the high velocity in the inlet pipe and the drop in the hydrostatic head to generate a low pressure at the air port. The port is equipped with a control valve to enable suction of the desired quantity of ambient air into the pump and then into the bubble generators. During testing, the flow rate through each of the nozzles was checked individually and found to be the same for each nozzle, 7 gallons per minute (gpm) using the 2 horsepower (hp) pump at 20 pounds per square inch (psi). The maximum flow rate with all pumps operating was 70 gpm at 20 psi at the pump exit (7 gpm per nozzle with 10 nozzles).

The position of the manifold with respect to the pump is important because of pressure loss in the line. The further apart the distance between the manifold and the nozzles is, the larger the pressure loss is. For a system deployed in the field, especially in deep water, this requires more power to maintain the necessary pressure. In the laboratory tests, operating the system with the manifold bubble generator nozzles increased the flexibility of the system with only a small loss of pressure. However, Dynaflow was not satisfied with the overall pressure loss in the manifold, and the air flowing from the air port had difficulty becoming equally distributed to each of the ten branches. The team redesigned the manifold to reduce pressure drop and optimize air distribution.

A cylindrical short plenum was used to distribute the flow evenly to all ten bubble generators (see Figure 15). With this design, the two-phase flow (air-water mixture) enters along the axis of the cylinder, impacts the bottom walls with the flow remaining axisymmetric. This is redistributed uniformly to all ten radial outlets in the cylinder sides. This configuration increased the maximum pressure to ~22 psi immediately downstream of the pump. The 0.75-inch diameter 25 ft (7.6 m) long hoses between the valve and the generators result in a pressure loss of the order of 1.8 psi. Valves were then added to the manifold so that flow to each of the bubble generators could be controlled and selected generators could be turned on or off as desired during operation. This design was used in the Ohmsett tests.

Figure 15. Circular manifold for air distribution to the ten bubble generators.

3.2.3.4 *Design and Construction of the Demonstration Prototype*

During prototype development, Dynaflow installed ten bubble generators on a hexagonal shaped support structure made from 1-inch polyvinyl chloride (PVC) piping designed to keep the bubble generators at a fixed distance from each other when the array was moved in the water. Figure 16 shows the top and side sketches of the prototype designed to be attached to the Ohmsett main bridge, which controlled its movement during the test runs. Since the prototype was designed specifically for testing at Ohmsett, Dynaflow attached small wheels to the bottom of the bubble redirectors to allow for the ease of movement over the tank's concrete floor. The team selected the number of generators based on their calculation of each generator's volume of influence (volume occupied by the bubble plume above a generator) and its corresponding cross section of the air bubbles at the water surface. Ohmsett staff provided the test area dimensions to Dynaflow in advance to help them size the prototype for its tests.

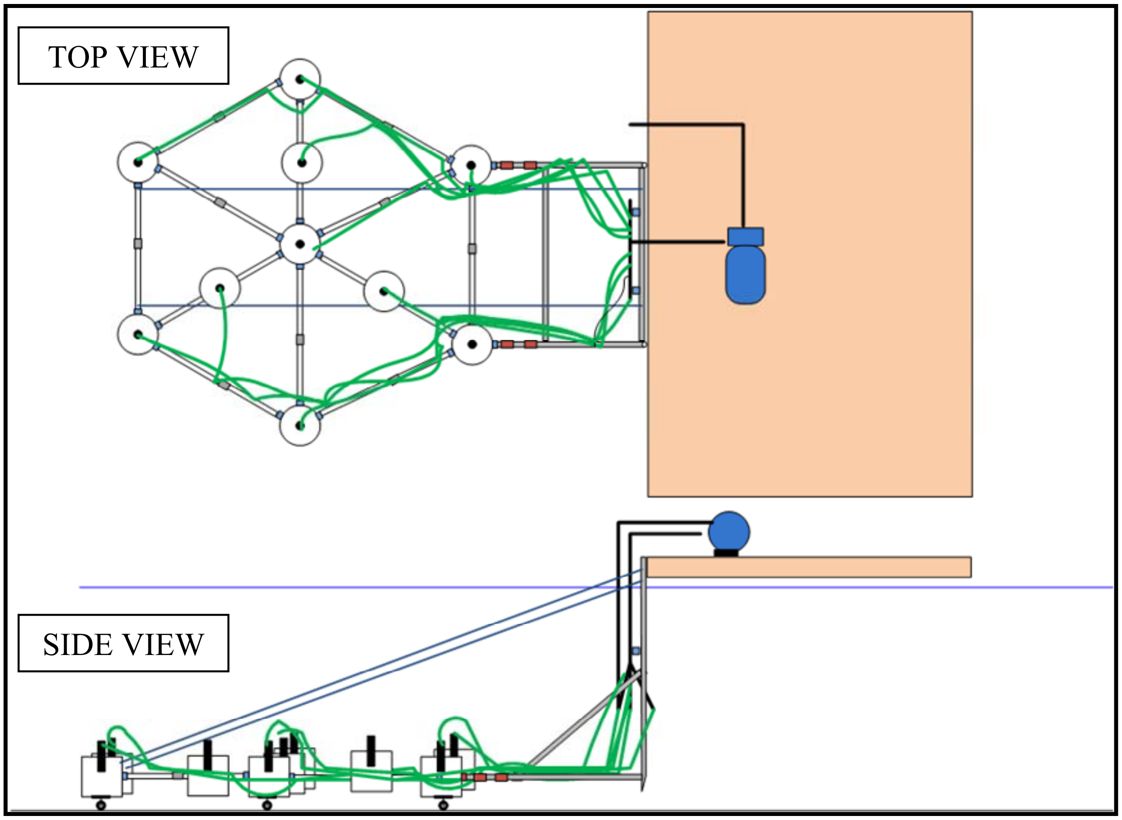

Figure 16. Sketch of Dynaflow prototype attached to the Ohmsett moving bridge.

3.2.4 Test Overview

3.2.4.1 *Phase II-B Test Setup*

For the Dynaflow tests, Ohmsett personnel set up a test area approximately 30 ft (9.1 m) long x 10 ft (3 m) wide within the main tank. Each side of the test area was made up of ballasted plastic sheeting that ran to the tank bottom and the 30-ft (9.1-m) sides ran parallel to the tank wall. The ballasted plastic sheeting was suspended by booms, which formed the perimeter of the test area (see Figure 17). The test area was located approximately four feet from the west wall to allow Dynaflow's system to freely roll along the tank floor.

Figure 17. Isolated test section in the Ohmsett tank.

At the north end side of the test area, a separate section was established for oil collection. The test and collection areas were separated by a plastic sheeting barrier that could be lowered below the water surface to allow movement of surface oil from the test area into the separate section during recovery periods.

Ohmsett staff created the oil plume using a tee-bar distribution manifold approximately six feet wide and equipped with fifteen atomizing nozzles evenly spaced to achieve a total flow rate of approximately 5 gpm. A portable pump skid located on the main bridge fed the manifold. During use, an Ohmsett technician controlled the pumping system from the variable frequency drive (VFD) control panel. The manifold was positioned approximately one foot above the basin floor and adjacent to the main bridge tow point. As the main bridge transited slowly from north to south, the manifold delivered crude oil into the test area with droplet diameters between 10 and 50 µm. As soon as oil flow ceased, the main bridge was moved back to the southernmost end of the tank and then the microbubble generators were turned on for recovery operations. The main bridge was used to move the prototype system along the 30-ft (9.1-m) length of the test section.

3.2.4.2 *Baseline Tests*

Prior to the system testing, Ohmsett staff performed baseline tests to demonstrate the process of collecting surfaced oil at 30- and 60-minute intervals and quantify the volume of oil to surface naturally in the test area. They performed additional baseline tests at the end of the test series to determine surfaced oil volumes without circulation in the area and for quantifying surfaced oil over 90 minutes at 30-minute intervals. The results of these baseline tests could then be compared to tests using the microbubble generator under similar test conditions (see Section 3.2.5).

During preliminary tests, Ohmsett staff injected 27 gallons of ANS crude oil into the test area using a manifold with 0.042 inch diameter orifice nozzles. It was found that less oil was recovered after 30 and 60 minutes when ANS crude was used as opposed to HOOPS when left to rise naturally. In other words, ANS crude oil took longer to surface than did the HOOPS oil thus all of the subsequent tests were performed using ANS.

Ohmsett staff recorded LISST data at the end of the test runs (Test 30) to provide oil droplet size distribution with ANS crude oil (Figure 18). They captured the LISST file approximately 5 minutes into the distribution of oil from the spray nozzles before the concentration became high enough to foul the sensor.

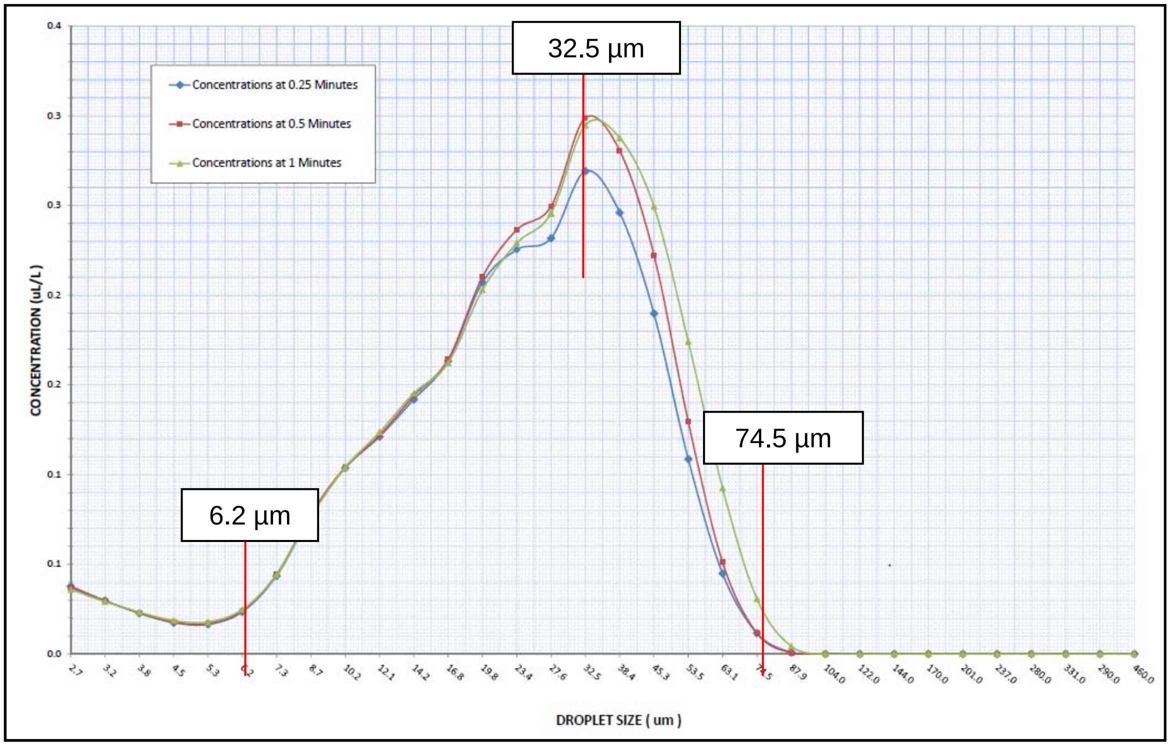

Figure 18. Oil droplet size and concentration using LISST.

3.2.4.3 Test Procedure

Dynaflow operated its bubble flotation system at various combinations of pumping pressures, air inlet rates, and numbers of bubble generators. Figure 19 shows the system underwater during the oil release but not yet operating.

Prior to each test, the background concentration of the clean water in the test area was confirmed using LISST. Each test began with the injection of either 27 gallons (0.15%) or 45 gallons (0.25%) of ANS crude oil into the test area using the injection manifold previously described. The oil release was performed from the moving main bridge, which advanced through the test area at a speed of 0.04 knot (0.068 feet per second). It took approximately five to six minutes to inject 27 gallons of oil, and approximately 10 minutes to inject 45 gallons.

At the conclusion of oil release, bubble generation began with the bridge moving at a predetermined speed from one end of the test area to the other, and then in the reverse direction. The microbubble injection continued for the entire duration of the test period, or 60 minutes. Some tests lasted for 90 minutes to gather additional data points but for those tests, the bubble generators still shut off at the 60-minute mark.

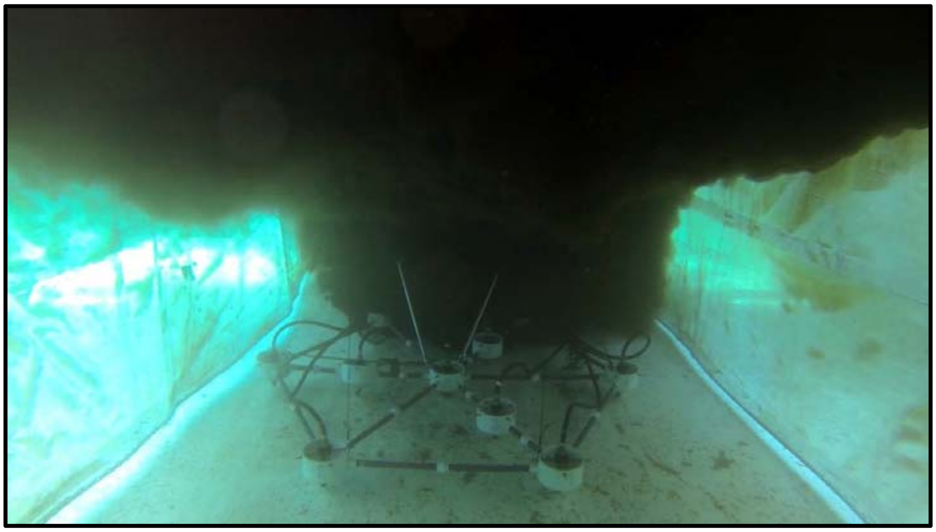

Figure 19. Dynaflow underwater setup during oil release.

The constant bridge movement allowed for an even distribution of air bubbles throughout the test area to maximize opportunities to adhere to the oil droplets and forcing the mixture to the water surface. The following operating parameters of the microbubble prototype were varied during the demonstration week:

- The number of bubble generators used: 6 to 8.
- The pumping pressure: 13, 18, 20, 22 psi.
- The air inlet rate: 2.0 liters per minute (L/min) to 3.5 L/min (the amount of air injected changes the ratio of the air volume to the total volume of air-water mixture. therefore increasing the number of bubbles generated).
- The motion of the array in the tank: continuous motion at 0.04 knot (kt), or semi-stationary (i.e. 10 minutes at the far end, 10 minutes in the center, 10 minutes at the near end, and everything repeated once over).
- The number of oil collection sweeps was varied from two sweeps per test at 30-minute intervals (60 minutes total) to three sweeps at 30-minute intervals (90 minutes total).

Test runs were performed in two variations with respect to treating the test area. In one case the system was operated while continuously traveling back and forth in the 30-foot direction at 0.04 kt. In the second case, the system was continually operated but was stationary for 10-minute intervals at three evenly spaced positions. Since the Dynaflow system footprint was approximately 10 ft (3 m) long, the overall test area length of 30 ft (9.1 m) was treated ten feet at a time for 10 minutes in each location to comprise each 30-minute interval.

Ohmsett staff collected the oil from the surface of the test area 30 and 60 minutes after the end of the oil release. During collection, the moving bridge was moved to the south end of the enclosure. The north end wall between the test and collection areas was lowered. Ohmsett personnel standing on the main bridge used electric leaf blowers that pushed the surface oil towards the collection area as the main bridge advanced north at a slow speed. After the north end wall was raised back above the water level, the contained oil was removed using the J-trap skimmer (Figure 20).

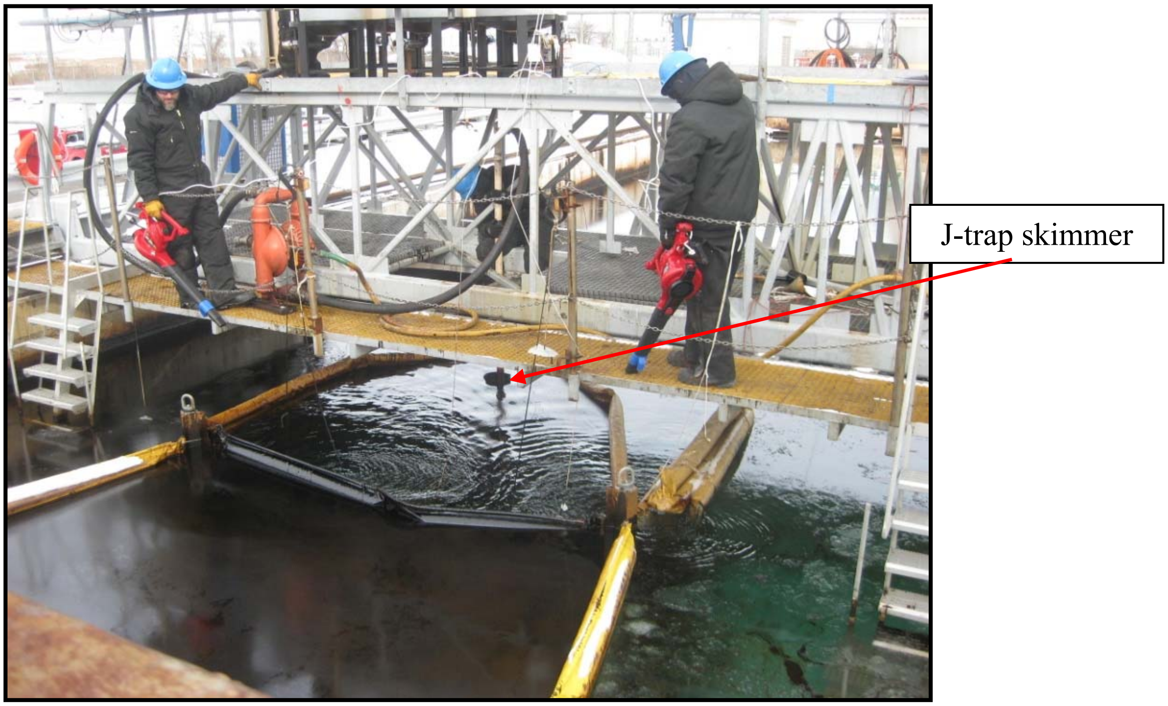

Figure 20. Oil recovery collection area.

The collected oil was then held in drums for at least 60 minutes to allow for separation between water and oil. Ohmsett staff then decanted the drums by draining the water from the bottom until oil in the flow was observed. They determined the volume of the oil by measuring its depth in the drums. Samples were collected and centrifuged to determine the amount of entrained water. Final oil volumes recovered were corrected to this value. To determine the efficiency of the recovery method described above, Ohmsett staff added 25 gallons of oil to the surface of the test area and collected the oil with the leaf blower method. 86.9 % of the oil that was released into the test area was recovered, which indicates that little oil is lost during the recovery process.

After the conclusion of each test, Ohmsett staff began to clear out the remaining oil droplets/surface oil by removing the ballasted plastic sheeting on the north and south sides of the test area. The natural current in the tank due to the filtration system moved the remaining oil droplets from south to north. Oil droplets adhering to the plastic sheeting were minor and were not expected to affect the quality of the water column in the next run. LISST was used to determine if the water column was "clean enough" and ready for testing again. When ready, the ballasted plastic sheeting was replaced at the north and south sides of the test area and the team performed the next test.

3.2.5 Test Results and Discussion

Baseline and actual test results are displayed in Table 5. Baseline tests occurred by releasing and collecting oil without using Dynaflow's mitigation system. They were performed in order to determine how much oil rose naturally to the surface. The cumulative recovery numbers could then be used to compare with cumulative oil recovery numbers with the microbubble generators turned on. Further details of the tests and results can be found in APPENDIX A.2.

Table 5. Results of Dynaflow Ohmsett tests.

Ohmsett Test Number	Test	Oil Added, (gallons)	No. of Bubble Generators	Pump (psi)	Air Injection Rate, (L/min)	Conditions	Amount Oil Recovered, (gallons)	Recovered Oil, 30 minutes	Recovered Oil, 60 minutes	Recovered Oil, 90 minutes
22	**Baseline**	27	0	0	0	Circulation in tank	7.43	18.8%	27.5%	
23	**Baseline**	27	0	0	0	Circulation in tank	11.41	29.1%	42.3%	
24	**Micro-bubble**	27	8	13	2.0	moving, circulation	7.43	19.3%	27.5%	
25	**Micro-bubble**	27	8	13	2.0	moving, circulation	7.38	20.4%	27.3%	
32	**Baseline**	27	0	0	0	No circulation	11.18	24.9%	40.8%	
26	**Micro-bubble**	27	7	18	2.5	moving, no circulation	6.57	17.5%	24.7%	
27	**Micro-bubble**	27	6	22	2.5	Semi-stationary, no circulation	7.27	24.0%	26.9%	
33	**Baseline**	45	0	0	0	No Circulation	21.2	23.5%	40.2%	47.1%
29	**Micro-bubble**	45	6	22	2.5	Semi-stationary, no circulation	17.46	22.9%	32.7%	38.8%
30	**Micro-bubble**	45	6	20	3.5	moving , no circulation	17.17	21.9%	32.4%	38.2%

Results did not show any significant differences between baseline and actual test recovery numbers. In some cases, recovery numbers from using the mitigation system are surprisingly worse than those of baseline tests. These findings differ from the results of the laboratory tests at Dynaflow's facility during Phase II-A and Phase II-B pre-Ohmsett work, which showed better removal of neutrally buoyant oil droplets. Possible reasons include differences in: initial sizes of oil droplets during release, air bubble generation, ability of the air bubbles to encounter the oil, and lengths of the observation and measurement periods.

3.2.5.1 *Oil Droplet Size and Concentration*

Dynaflow and Ohmsett used different techniques to create the oil droplets and measure their size and concentration, so a direct comparison of the two is difficult. Dynaflow used a cavitating jet method to disperse the oil and measured the sizes of the oil droplets using high speed video and image analysis. As shown in Figure 12 in Section 3.2.2, 20 µm droplets had a concentration of about 10,000 per cubic meter. The concentration decreased in size down to the 200 µm droplets having a concentration of about 10 per cubic meter. Ohmsett used nozzles to create their plume and measured the droplet size using LISST. As shown in Figure 18, oil droplet sizes ranged from 6.2 µm to 74.5 µm, with the largest concentration being at about 32.5 µm. Based on these numbers, the differences in oil droplet size and concentration do not appear to be significant.

3.2.5.2 Air Bubble Size and Concentration

According to Dynaflow, the bubble generator pump had difficulty producing the required flow rate for the generators, which raised questions about proper bubble generation, both in size and concentration (Chahine et al., 2017). Ideally, there should be at least some bubbles that are as small as the oil droplets to attach to them, and some larger size bubbles to push the droplets to the surface. As discussed earlier, the LISST data from Test 30 (Figure 18) shows the oil droplet size ranging from 6.2 µm to 74.5 µm, centered around approximately 32.5 µm. It is possible there were not enough bubbles in the smaller size range to attach to the oil droplets.

3.2.5.3 Ability of the Air Bubbles to Encounter the Oil

In the laboratory tests, most of the oil droplets appeared to be neutrally buoyant, remaining in the water column for several hours with less than 10 % of the oil surfacing within four hours although the tube skimmer was used to recover the oil, which may account for the low recovery number. At Ohmsett using electric leaf blowers, as much as 40 % of the injected oil was recovered within one hour. However, the remaining 60 % of the oil in the water column was still exposed to the microbubbles. Despite this exposure, recovery numbers are still approximately the same or worse when compared to those of baseline tests. It is possible that the movement of the array system within the fixed test area may have negatively contributed to the system's performance.

3.2.5.4 Differences in the Lengths of the Observation and Measurement Periods

Another main difference between the Dynaflow laboratory and the Ohmsett tests was the lengths of the observation and measurement periods. Since the observation period at Ohmsett was mostly one hour in duration and up to 40 % rose to the surface naturally during this time, it can be deduced that most of the oil droplets that were recovered were of the larger variety. The smaller size droplets (~ 25 µm) would have needed, as in the laboratory test observations, a period of time longer than 2 hours. However, most of the oil droplets in this size range were mostly recovered in Dynaflow's test tank within 90 minutes after using the air bubbles. From Table 5, it can be seen that two 90-minute tests were performed with 45 gallons of ANS crude. Compared with the baseline test numbers, results continue to show less recovery effectiveness with no indications of improving, even after 90 minutes.

As discussed in Section 3.2.3.2, the laboratory tests used only 20 minutes of bubble generators. During the Ohmsett tests the generators were run for 60 minutes. However, the extra bubbles produced should have resulted in a higher rather than lower recovery rate.

3.2.6 Path Forward

3.2.6.1 Proposed CONOPS

Figure 21 provides an overall vision for how Dynaflow's system is to be used in the field. In this conceived deployment scenario, bubble generators would be deployed from a ship or a floating platform, which would also feed the bubble generator array with both water and air. The position and depth of each bubble generator will be controlled by tethering it to an anchored line. The tether length between the ship and bubble generator would control the depth of bubble generator, and the anchor will maintain the position of the bubble generator. In areas of high current, another ship would be used to deploy floating booms to capture and contain the recovered floated oil. To ensure effective oil capture, the volume of the bubble plume (number of generators) should be large enough to account for uncertainties in the oil plume trajectory due to the current and other environmental condition variations such that the oil plume is always covered by the bubble plume to induce oil flotation.

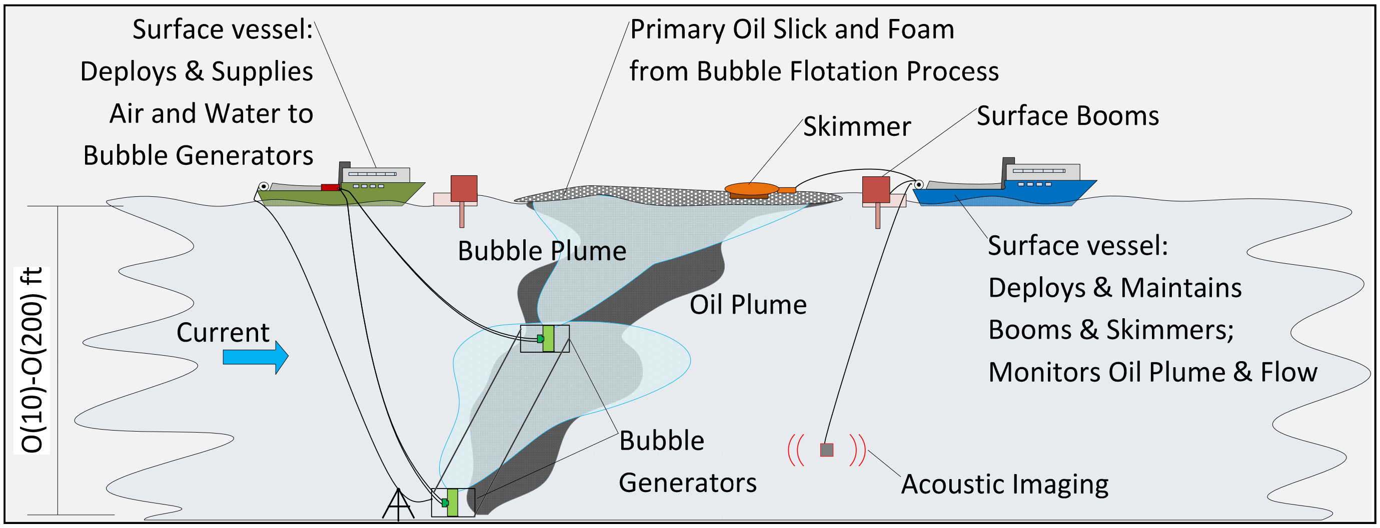

Figure 21. Overall vision for Dynaflow's system deployed in the field.

3.2.6.2 Further Developments

Dynaflow's system requires the following steps for full-scale system development.

- Utilize a more powerful and robust pumping system to create a larger volume of air bubbles that would have more of an impact on the oil recovery numbers.
- Strengthen the support structure of the array to maintain the generators at the desired depth.
- Design the air entrainment line with a smaller pipe diameter to increase the velocity in the air suction areas and enable entrainment of larger amounts of air into the bubble generators.
- Test the bubble generators, array, and supporting equipment, such as from work boats, under maritime conditions.

4 SUMMARY AND RECOMMENDATION

Table 6 summarizes how each system meets the BAA attributes, listed in order of importance.

Table 6. Attributes matrix.

Attribute	ANL Adsorbent Foam	Dynaflow Microbubble Flotation System
1. Extent of oil mitigation or removal rates and quantities	In Phase II-B testing, sorption of oil from within the water column was successfully demonstrated, but with low removal percentages.	The DYNAJETS® bubble generators technology (bubble flotation) was shown to be effective in removing small neutrally buoyant oil droplets from water in the laboratory tests. Tests at Ohmsett did not show the same removal rates.
2. Types of oil mitigated (e.g., droplets, tarballs, dissolved oil)	Adsorption of droplets was demonstrated using several types of crude oil. However, a fraction of small oil droplets appeared to have passed through the foam pores without making contact. Tarballs will not be taken up by the foam since the pores within the foam are much smaller than most tarballs.	Three types of crude oils provided by BSEE were tested and mitigated in the laboratory tests: ANS, Anadarko, and HOOPS. In the tests at Ohmsett, ANS crude oil was used but the bubble generator technology did not prove to be effective at removing the dispensed oil.
3. Minimization of environmental impacts with a focus on wildlife and plant life	Submersion of the foam into bodies of water should have no adverse impact on the local wildlife or plants.	The technology introduces air/oxygen to the water and should only help the regions of hypoxia caused by microbial degradation of the oil. However, the proposed field set up with multiple pieces of equipment for the mitigation effort would require anchoring into the bottom riverbed/seafloor, which may cause environmental disturbances.
4. Effective limits in terms of depth of oil and deployment	The foam technology itself is not directly affected by depth of submersion. Fluid viscosities will be higher at large depths, which may affect the speed of adsorption.	The operation of the DYNASWIRL® generators depends only on the operation limits of the pump used for the generator. Pumps are available to enable operation at the specified maximum depth of 200 feet. The DYNASWIRL® nozzles do not require modification.
5. Effective limits in terms of environmental conditions such as current, wave height, winds, day/night, inclement weather, etc.	Recovery numbers were lower when the foam was dragged through a body of clean water 30 seconds after exposure to oil, which may indicate leaching issues.	Close to the water surface, both bubbles and oil trajectories droplets will be affected by any turbulent water motion but bubbles will still adsorb oil droplets on their surfaces. The water surface conditions will have an effect on the equipment used to collect the oil.
6. Ease of use to include deployability and recovery of equipment	ANL proposes to integrate foam with a trawl net for recovery operations. Final system for the wringing of foam has not yet been explored; ease of use cannot be fully described at this time.	In the Ohmsett tests, the bubble generator array was easy to deploy and recover but in the real world, there would be many moving parts for the responders to handle, including tethers, anchors, and possibly buoys. Water, air, and power for the bubble generators would need to be supplied from the support ship or the platform. The number of bubble generators would be dependent on the size of the submerged oil plume.
7. Transportability	The entire system would be housed on a trawler, which can readily navigate to the site of the spill.	The physical size of the bubble generator array used in the tests was small and was easily transported in a pick-up truck. The number of equipment will be dependent on the size of the submerged oil plume, which can be significant for a large spill.

Table 6. Attributes matrix (Cont'd).

Attribute	ANL Adsorbent Foam	Dynaflow Microbubble Flotation System
8. Operability in fresh/seawater	The underlying mechanisms for the somewhat decreased oil selectivity in salt water relative to fresh water remain as a topic for further study.	The micro-bubble generators were demonstrated to operate well in a range of salinities from 0 to 35 parts per thousand (ppt) with improved performance in salt water.
9. Ability to observe and monitor subsurface oil collection	The oil collected from the treated foam would be stored in a container after recovery operations, from which its quantity could readily be monitored.	In the Phase II-A study this was observed by the high speed photography of bubbles/oil particles. The rise speed was reduced relative to bubbles only indicating oil collection. However, this will not be possible in the field.
10. Reusability	In Phase II-B, the treated polyurethane foam pads were used for all of the tests, and performance was consistent despite repeated use.	The bubble generators are constructed of materials able to withstand marine environments. It is expected that there will be limited wear or degradation of the bubble generators with use.
11. Safety to personnel deploying and recovering	The materials are non-toxic and reusable, and present no known threats to responders. However, the proposed integration of foam with trawl nets can make it a dangerous and messy operation for responders, especially when large volumes of foam pads need to be wrung each time they are saturated with oil.	There will not be any unusual safety concerns, other than those associated with standard electric and maritime operations.

Both systems show some promise for mitigation of oil in the water column but need further development before they can be recommended for field testing. The ANL treated foam picked up a much smaller percentage of oil compared to water in the Ohmsett tests than it did in the laboratory. Several factors that may have caused this issue have been identified but overall, ANL would need to develop a more realistic field setup that allows for a better oil encounter rate, efficient sorbent wringing, and safe oil handling. Dynaflow's microbubble flotation system also did not perform as well at Ohmsett as it did in the laboratory. Results did not show any significant differences between baseline and actual test recovery numbers. Dynaflow has suggested steps for full-scale system development to address the potential reasons for this performance.

5 ACKNOWLEDGEMENT

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APPENDIX A. TEST PROCEDURE AND RESULTS

A.1 Argonne National Laboratory

A.1.1 Test Setup

Figure A–1 gives an overview of the ANL test configuration.

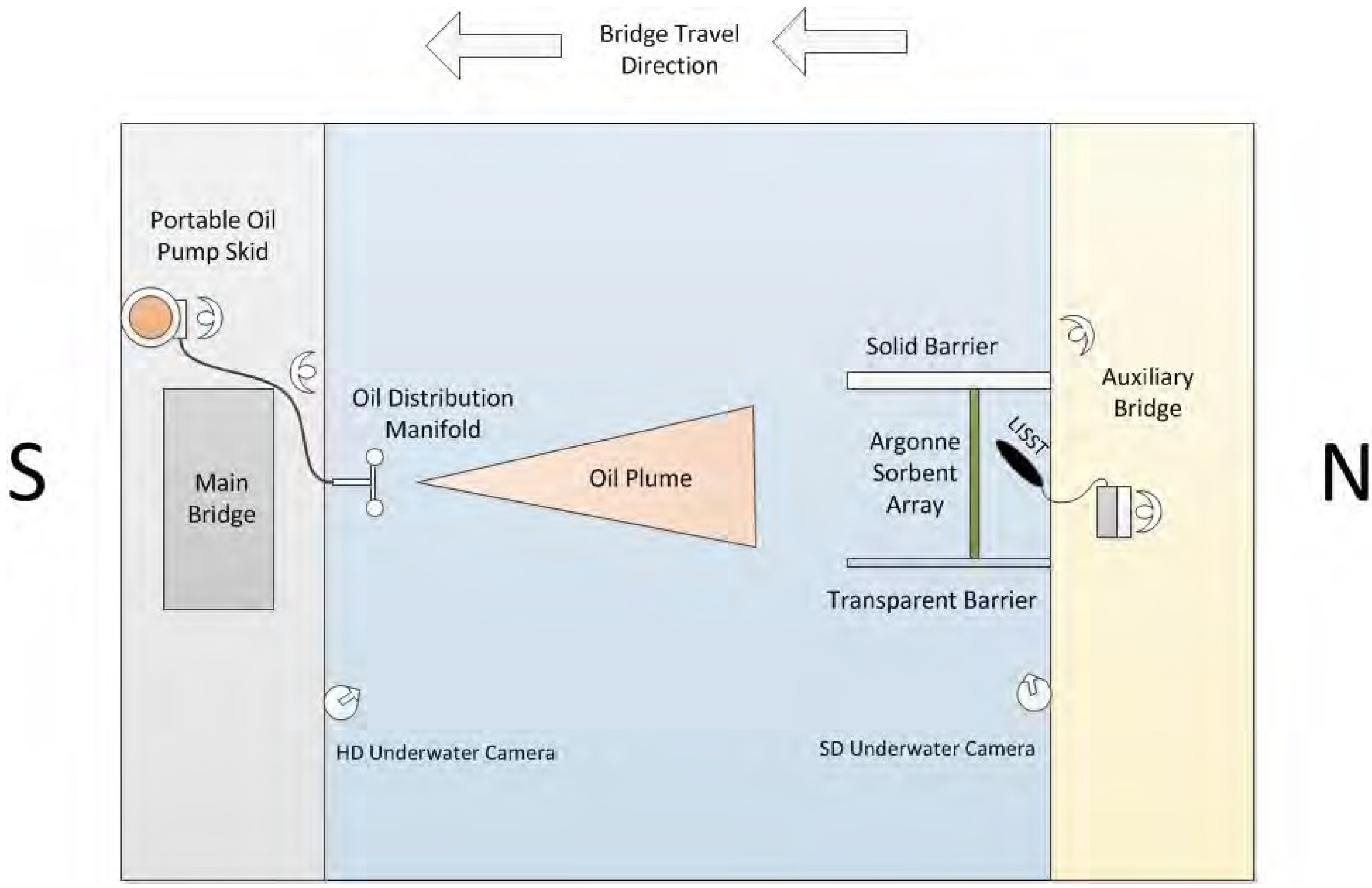

Figure A–1. ANL test configuration.

A.1.2 Test Method

Ohmsett staff performed twelve tests with the Argonne system. Prior to each test run, they adjusted bridge spacing distance and nozzle layout to best suit the test parameters. Bridge spacing ranged from 10 to 23 feet depending on horizontal oil plume width while nozzle angles were adjusted for a uniform vertical oil plume pattern. Ohmsett staff filled the oil distribution hopper with the desired test oil (HOOPS, diesel, or ANS) and recorded initial oil tank level data using an ultrasonic probe and measuring stick to calculate starting oil tank volume prior to release. They bottom-weighted new and freshly wrung sorbent pads and attached them to the lattice frame in the desired configuration using spring clips. ANL recorded notes on each sorbent panel configuration as several changes were made throughout testing.

To begin each test, Ohmsett staff accelerated the main bridge to the desired test speed while a technician recorded background water column oil droplet data. The LISST-100x instrument was located just behind the sorbent array. After obtaining a background reading, a technician started the oil distribution pump system and allowed it to reach operating pressure prior to beginning each release of oil. Cameras located above and below water captured footage of each test as well as still photos for documentation. While traveling at a speed of 0.1 to 0.2 knots, the oil release was initiated from the VFD control panel of the distribution pump. A technician recorded the elapsed time of discharge while another technician monitored oil tank volume. The LISST-100x continued to record data throughout testing to monitor particle size distribution aft of the sorbent panel array, although the amount of oil in this area eventually exceeded the LISST operational range. Ohmsett results also include a Test Parameter Summary containing bridge spacing, bridge speed, oil type, nozzle configuration, and distribution data for each test.

A.1.3 Results

Tables A-1 through A-4 contained the results from the tests separated by row and sorbent (sample) type, ANL numbered the tests as 1-12. Ohmsett staff started the test numbers at 8. The Ohmsett numbers are used in the discussions in the body of the report. These tables also contain a summary of the parameters for each test.

Table A-1. ANL results Tests 8, 9, and 10.

Test Number and Type	Row/Sample	Number of Foam Pads in each Row	Total Volume Collected (Oil+Water) (mL)	Volume of Oil Collected (mL)	Selectivity Ratio of Oil to Total Volume (%)	Testing Parameters
Test 1 **HOOPS** Polyurethane	1	4	3465	223.2	6.4	Oil Type: **HOOPS** Ohmsett Test Number / Date: 12.06 - Test 8
	2	3	2425	315.3	13.0	Speed (knots): 0.1 Bridge Spacing (feet): 13
	3	4	3140	582	18.5	Post Oil Drag: 0' Nozzle Configuration: 8 × .042"
	4	2	1350	175.8	13.0	Duration (min): 3.92 Flow Rate (gpm): 1.38
	Untreated -PU	1	820	10	1.2	Pump Pressure (psi): 80 Tank Initial / Final (inches): 2.282 / 2.131
Total	Treated - PU	13	10380	1296.3	12.8	
Test 2 **HOOPS** Polyurethane	1	4	3125	244.4	7.8	Oil Type: **HOOPS** Ohmsett Test Number / Date: 12.06 - Test 9
	2	3	2230	215	9.6	Speed (knots): .1 to .12 Bridge Spacing (feet): 10
	3	4	2150	210	9.8	Post Oil Drag: 100' Nozzle Configuration: 6 × .042"
	4	2	900	62.3	6.9	Duration (min): 10.58 Flow Rate (gpm): 1.13
	Untreated -PU	1	750	5	0.7	Pump Pressure (psi): 80 Tank Initial / Final (inches): 2.111 / 1.776
Total	Treated - PU	13	8405	731.7	8.5	
Test 3 **HOOPS** Polyurethane	1	4	2375	437.4	18.4	Oil Type: **HOOPS** Ohmsett Test Number / Date: 12.06 - Test 10
	2	3	1650	369	22.4	Speed (knots): 0.12 Bridge Spacing (feet): 11
	3	4	2140	280.8	13.1	Post Oil Drag: 0' Nozzle Configuration: 6 × .042"
	4	2	1000	81.4	8.1	Duration (min): 11.88 Flow Rate (gpm): 1.02
	Untreated -PU	1	760	0	0.0	Pump Pressure (psi): 80 Tank Initial / Final (inches): 1.784 / 1.446
Total	Treated - PU	13	7165	1168.6	15.5	

Table A-2. ANL results Tests 11, 12, and 13.

Test Number and Type	Row/Sample	Number of Foam Pads in each Row	Total Volume Collected (Oil+Water) (mL)	Volume of Oil Collected (mL)	Selectivity Ratio of Oil to Total Volume (%)	Testing Parameters
Test 4 **HOOPS** Polyurethane	1	4	6850	779	11.4	Oil Type: **HOOPS** Ohmsett Test Number / Date: 12.06 - Test 11 Speed (knots): 0.2 Bridge Spacing (feet): 15/11 Post Oil Drag: 0' Nozzle Configuration: 6 x .042" Duration (min): 9.9 Flow Rate (gpm): 1.19 Pump Pressure (psi): 80 Tank Initial / Final (inches): 1.452 / 1.123
	2	3				
	3	4				
	4	2				
	Untreated -PU	1	850	0	0.0	
Total	Treated - PU	13	6850	779	11.4	
Test 5 **HOOPS** Polyurethane	1	4	1490	218.4	14.7	Oil Type: **HOOPS** Ohmsett Test Number / Date: 12.07 - Test 12 Speed (knots): 0.2 Bridge Spacing (feet): 11 Post Oil Drag: 30 sec Nozzle Configuration: 8 x .042" Duration (min): 7.63 Flow Rate (gpm): 1.65 Pump Pressure (psi): 80 Tank Initial / Final (inches): 2.513 / 2.16
	2	3	2600	160	6.2	
	3	4	1725	168	9.7	
	4	2	840	121.5	14.5	
	Untreated -PU	1	795	15	1.9	
Total	Treated - PU	13	6655	667.9	11.3	
Test 6 **HOOPS** Polyurethane	1	4	1650	296.5	18.0	Oil Type: **HOOPS** Ohmsett Test Number / Date: 12.07 - Test 13 Speed (knots): 0.2 Bridge Spacing (feet): 11 Post Oil Drag: Nozzle Configuration: 8 x .042" Duration (min): 8.82 Flow Rate (gpm): 1.36 Pump Pressure (psi): 80 Tank Initial / Final (inches): 2.16 / 1.824
	2	3	1275	240	18.8	
	3	4	1800	304	16.9	
	4	2	840	100	11.9	
	Untreated -PU	1	880	5	0.6	
Total	Treated - PU	13	5565	940.5	16.4	

Table A-3. ANL results Tests 14, 15, and 16.

Test Number and Type	Row/Sample	Number of Foam Pads in each Row	Total Volume Collected (Oil+Water) (mL)	Volume of Oil Collected (mL)	Selectivity Ratio of Oil to Total Volume (%)	Testing Parameters
Test 7 **HOOPS** Polyurethane Polyimide PIG	1 - PU	4	1575	336	21.3	Oil Type: HOOPS Ohmsett Test Number / Date: 12.07 - Test 14 Speed (knots): 0.2 Bridge Spacing (feet): 11 Post Oil Drag Nozzle Configuration: 8 x .042" Duration (min): 8.92 Flow Rate (gpm): 1.43 Pump Pressure (psi): 80 Tank Initial (inches): 1.826 Tank Final (inches): 1.47
	2 - PU	3	1275	262.2	20.6	
	4 - PU	2	815	10	1.2	
	3 - PIG	1	420	136.5	32.5	
	3 - Polyimide	3	3425	1084.6	31.7	
	Untreated - PU	1	610	10	1.6	
Total	All Treated	13	7510	1829.3	21.5	
	Polyurethane	9	3665	608.2	14.4	
	Polyimide	3	420	136.5	32.5	
	PIG	1	270	136.5	32.5	
Test 8 **Diesel Fuel** Polyurethane Polyimide PIG	1 - PU	4	1400	317.5	22.7	Oil Type: DIESEL Ohmsett Test Number / Date: 12.08 - Test 15 Speed (knots): 0.2 Bridge Spacing (feet): 11 Post Oil Drag Nozzle Configuration: 8 x .042" Duration (min): 9.32 Flow Rate (gpm): 1.3 Pump Pressure (psi): 80 Tank Initial (inches): 3.34 Tank Final (inches): 3
	2 - PU	3	1050	121.8	11.6	
	4 - PU	2	710	50	7.0	
	3 - PIG	1	220	20	9.1	
	3 - PI	3	2325	69.4	3.0	
	Untreated - PU	1	440	5	1.1	
Total	Treated - PU	9	3160	489.3	13.8	
Test 9 **ANS** Polyurethane Polyimide PIG	1 - PU	4	1915	375	19.6	Oil Type: ANS Ohmsett Test Number / Date: 12.08 - Test 16 Speed (knots): 0.2 Bridge Spacing (feet): 11 Post Oil Drag Nozzle Configuration: 8 x .042" Duration (min): 9.02 Flow Rate (gpm): 0.96 Pump Pressure (psi): 80 Tank Initial (inches): 3.43 Tank Final (inches): 3.188
	2 - PU	3	1450	324	22.3	
	3 - PU	2	840	214.6	25.5	
	4 - PU	2	900	270	30.0	
	3 - PIG	1	250	50	20.0	
	3 - PI	1	900	55	6.1	
	Untreated - PU	1	600	5	0.8	
Total	Treated - PU	11	5105	1183.6	24.4	

Table A-4. ANL results Tests 17, 18, and 19.

Test Number and Type	Row/Sample	Number of Foam Pads in each Row	Total Volume Collected (Oil+Water) (mL)	Volume of Oil Collected (mL)	Selectivity Ratio of Oil to Total Volume (%)
Test 10 ANS Polyurethane Polyimide PIG	1 - PU	4	1250	390.5	31.2
	2 - PU	3	1550	365	23.5
	3 - PU	2	940	181.7	19.3
	4 - PU	2	780	171.6	22.0
	3 - PIG	1	130	10	7.7
	3 - PI	1	820	68	8.3
	Untreated - PU	1	520	10	1.9
Total	Treated - PU	11	4520	1108.8	24.0

Testing Parameters	
Oil Type	ANS
Ohmsett Test Number / Date	12.08 - Test 17
Speed (knots)	0.2
Bridge Spacing (feet)	11
Post Oil Drag	
Nozzle Configuration	8 x .042"
Duration (min)	10.98
Flow Rate (gpm)	1.27
Pump Pressure (psi)	80
Tank Initial (inches)	3.178
Tank Final (inches)	2.787

Test Number and Type	Row/Sample	Number of Foam Pads in each Row	Total Volume Collected (Oil+Water) (mL)	Volume of Oil Collected (mL)	Selectivity Ratio of Oil to Total Volume (%)
Test 11 ANS Polyurethane Polyimide PIG	1 - PU	4	1550	148.5	9.6
	2 - PU	3	1225	105	8.6
	3 - PU	2	760	75	9.9
	4 - PU	2	625	75	12.0
	3 - PIG	1	125	10	8.0
	3 - PI	1	830	100	12.0
	Untreated - PU	1	625	10	1.6
Total	Treated - PU	11	4160	403.5	10.0

Testing Parameters	
Oil Type	ANS
Ohmsett Test Number / Date	12.08 - Test 18
Speed (knots)	0.1
Bridge Spacing (feet)	11
Post Oil Drag	
Nozzle Configuration	8 x .042"
Duration (min)	7.73
Flow Rate (gpm)	1.51
Pump Pressure (psi)	80
Tank Initial (inches)	2.787
Tank Final (inches)	2.46

Test Number and Type	Row/Sample	Number of Foam Pads in each Row	Total Volume Collected (Oil+Water) (mL)	Volume of Oil Collected (mL)	Selectivity Ratio of Oil to Total Volume (%)
Test 12 ANS Polyurethane Polyimide PIG	1 - PU	4	1725	80	4.6
	2 - PU	3	1290	62.5	4.8
	3 - PU	2	825	90	10.9
	4 - PU	2	740	55	7.4
	3 - PIG	1	160	10	6.3
	3 - PI	1	810	40	4.9
	Untreated - PU	1	820	10	1.2
Total	Treated - PU	11	4580	287.5	7.0

Testing Parameters	
Oil Type	ANS
Ohmsett Test Number / Date	12.09 - Test 19
Speed (knots)	0.1
Bridge Spacing (feet)	11
Post Oil Drag	30 sec
Nozzle Configuration	8 x .042"
Duration (min)	8.55
Flow Rate (gpm)	1.49
Pump Pressure (psi)	80
Tank Initial (inches)	2.451
Tank Final (inches)	2.095

A.2 Dynaflow

A.2.1 Test Setup

Figure A–2 gives a schematic of Dynaflow setup, not including the oil collection area.

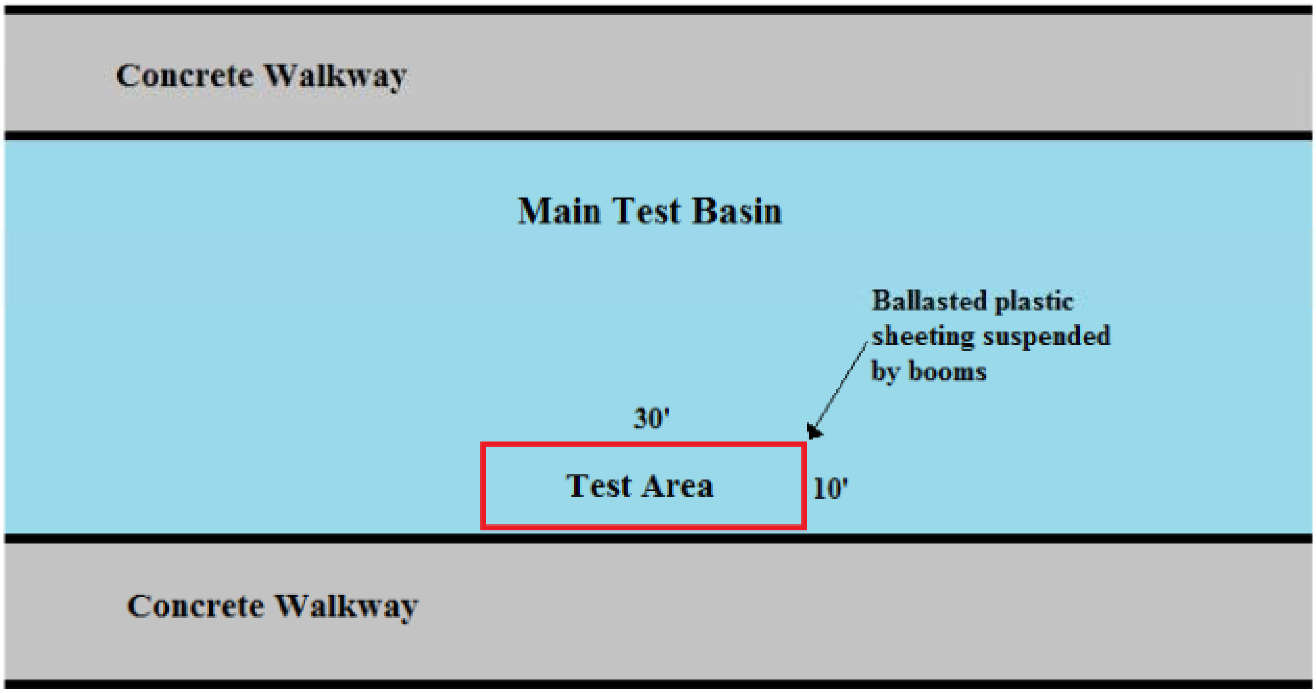

Figure A–2. Schematic of Dynaflow setup.

A.2.2 Test Method

Prior to each test day Ohmsett personnel added the anticipated amount of fresh oil to the supply tank of the distribution pump from totes kept in Ohmsett storage. They obtained an initial sounding from the top edge of the tank using a measuring stick. They used HOOPS and ANS oils for initial baseline testing in the test basin, and ANS for all baseline and Dynaflow tests. Nominal dispensed oil volumes for testing were 27 or 45 gallons (0.15% or 0.25% concentration) depending on testing parameters.

Beginning with a clean test area, Ohmsett personnel placed the LISST instrument into the test area to record background oil concentrations. They started data collection and photo video files prior to generation of the test plume and Dynaflow system operation. Technicians started the oil distribution pump and allowed it to reach operating pressure before switching the valves to begin flow to the Tee-Bar manifold. Once plume generation was confirmed, bridge movement began at 0.04 knots through the test area, which allowed for the plume to be dispensed evenly from one end of the test area to the other. The oil flow dispensing rate throughout the test series averaged approximately 4.5 gpm. Bridge travel continued until the predetermined volume of oil had been released. After the plume creation was complete, the Dynaflow system was turned on and the beginning of the test period marked.

Test runs were performed in two variations with respect to treating the test area. In one case the system was operated while continuously traveling back and forth in the 30 foot direction at 0.04 knots. In the second case, the system was continually operated but was stationary for 10 minute intervals at three evenly spaced positions. Since the Dynaflow system footprint was approximately 10 feet long, the overall test area length of 30 feet was treated ten feet at a time for 10 minutes in each location to comprise each 30 minute interval.

At 30 and 60 minute intervals, a surface sweep was performed using leaf blowers to push all surfaced oil into the northern containment area. Movement of the bridge and system was timed such that sweeping of surfaced oil started from the south end at 30 and 60 minutes. The sweeping operation was performed at 0.07 knots and was completed in approximately 4 to 5 minutes. Immediately after the sweep, oil was recovered into collection tanks using a J-Trap and double diaphragm pump. Continuous passes of the bubble generator were made until the 60 minute mark, where another surface sweep was performed and surface oil recovered. For several tests (as noted), an additional sweep was performed at the 90 minute mark without the Dynaflow system operating during the 60 to 90 minute interval.

After a sufficient waiting period, Ohmsett personnel decanted the collection tanks to remove free water. They then took a representative sample and analyzed it for bottom solids and water (BS&W) in Ohmsett's on-site laboratory. The BS&W results, in concert with final collection tank soundings, were used for computation of total oil volume surfaced.

A.2.3 Description of Data Provided by Ohmsett

Prior to the system testing, Ohmsett personnel performed preliminary baseline tests (20-23) to quantify the volume of oil that naturally surfaced at the 30 and 60 minute marks. The Test Parameter Summary (MAR, LLC (2017b)) provided in the "Spreadsheet Data/Results" section provides by test number the parameters, notes and test description. Additional spreadsheets provided are; Detailed Measurements of Surfaced Oil for Baseline Tests and Detailed Measurements of Surfaced Oil for Dynaflow Tests. A total of seven tests were performed deploying the Dynaflow system (Tests 24 to 27, and 29 to 31); the raw data with surfaced oil volume calculations are presented. Raw data is compiled from various logs generated during tests and are also provided in supporting sections. Additional baseline tests (32 and 33) were performed at the end of the test series to determine surfaced oil volumes without circulation in the area and for quantifying surfaced oil over 90 minutes at 30 minute intervals.

During the series, one test (28) was performed to validate the collection method. During this test 25 gallons was dispensed to the surface and allowed to spread. The sweeping technique was then employed to recover the oil as performed in all tests. Approximately 87% of the dispensed oil was recovered.

Ohmsett personnel typically acquired files containing LISST particle size data prior to a test to obtain background information on the presence of oil in the water column. Since the instrument does not discern between oil droplets, air bubbles, or other particles it was not used during tests with two exceptions. Personnel acquired a LISST file during Test 30 to determine the droplet size distribution for the selected nozzle with the ANS oil. They also recorded a LISST file during Test 31 with the LISST positioned in the water column above the bubbler array while operating without oil to obtain air bubble droplet size data (Figure A–3).

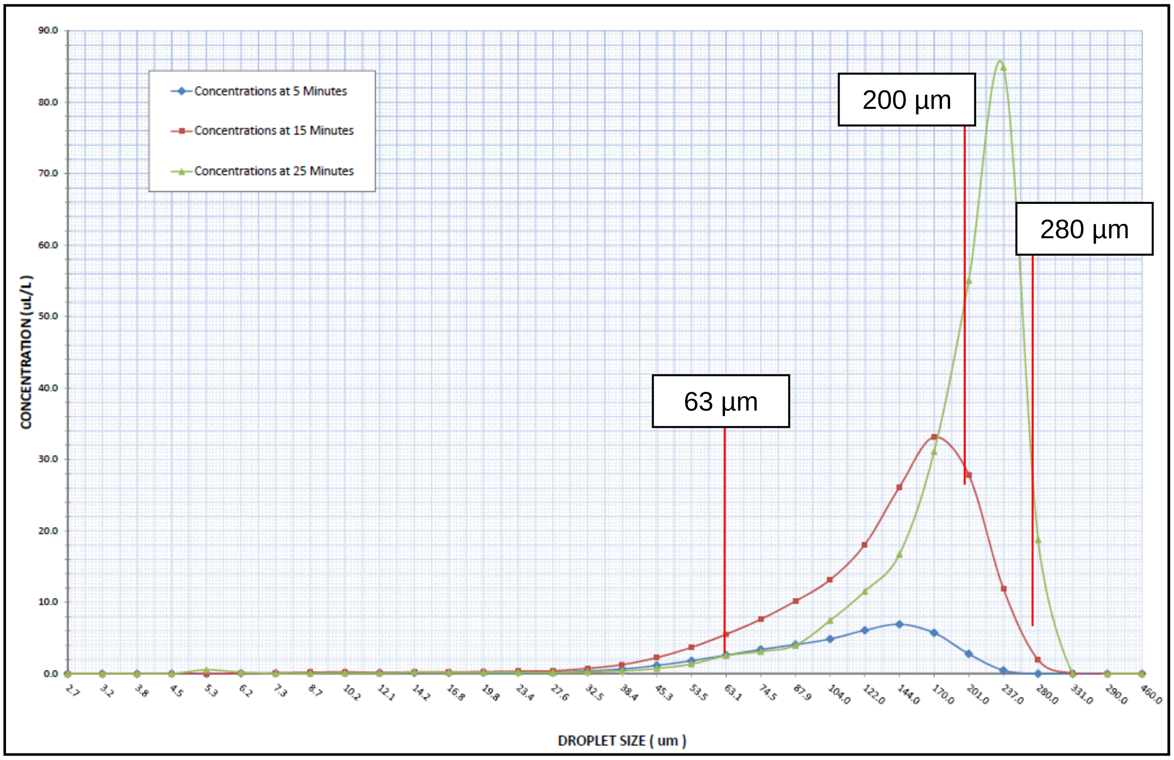

Figure A–3. Dynaflow air bubble size and concentration using LISST.

A.2.4 Ohmsett Test Results

After initially setting up, making adjustments to the manifold, and attaching it to the moving bridge, Ohmsett personnel performed six tests, two each day from 10-12 January 2017. Each test began with the injection of either 27 gallons (0.15%) or 45 gallons (0.25%) of ANS crude oil into the test section using the injection manifold constructed by Ohmsett. The injection was done from the moving bridge, which was advanced through the test area at a speed of 0.04 nautical miles per hour (0.068 feet per second). It took approximately 6 minutes to inject 27 gallons of oil. The oil injection and recovery methods were the same as in the baseline tests. Immediately after the end of oil injection, bubble generation was begun, the bridge was moved at the selected speed, and microbubble injection continued for 60 minutes. The following operating parameters of the microbubble prototype were varied in these tests:

- The number of bubble generators used: 6 to 8,
- The pumping pressure: 13, 18, 20, 22 psi,
- The air inlet rate: 2.0 L/min to 3.5 L/min,
- The motion of the array in the tank: continuous motion at 0.04 knot, or semi-stationary (i.e., 10 minutes at the near end, 10 minutes in the center, 10 minutes at the far end).

Technicians controlled the number of bubble generators used by closing or opening the valves at the manifold. Decreasing the number of bubble generators increased the pumping pressure and the flow rate through each bubble generator. They controlled the air inlet rate with the valve at the air flow meter on the low pressure side of the pump. Table A-5 summarizes the conditions and results of the tests.

Table A-5. Results of Dynaflow Ohmsett tests.

Line No.	Ohmsett Test Number	Test	Oil Added, (gallons)	No. of Bubble Gen.	Pump (psi)	Air Injection Rate, (L/min)	Conditions	Oil Recovered, (gallons)	% Oil 30 minutes	% Oil 60 minites	% Oil 90 minutes
1	**22**	**Baseline**	27	0	0	0	Circulation in tank	7.43	18.8	27.5	
2	**23**	**Baseline**	27	0	0	0	Circulation in tank	11.41	29.1	42.3	
4	**24**	**Micro-bubble Injection**	27	8	13	2.0	Moving, circulation	7.43	19.3	27.5	
5	**25**	**Micro-bubble Injection**	27	8	13	2.0	Moving, circulation	7.38	20.4	27.3	
3	**32**	**Baseline**	27	0	0	0	No circulation	11.18	24.9	40.8	
6	**26**	**Micro-bubble Injection**	27	7	18	2.5	Moving, no circulation	6.57	17.5	24.7	
7	**27**	**Micro-bubble Injection**	27	6	22	2.5	Semi-stationary, no circulation	7.27	24.0	26.9	
8	**33**	**Baseline**	45	0	0	0	No Circulation	21.2	23.5	40.2	47.1
9	**29**	**Micro-bubble Injection**	45	6	22	2.5	Semi-stationary, no circulation	17.46	22.9	32.7	38.8
10	**30**	**Micro-bubble Injection**	45	6	20	3.5	moving , no circulation	17.17	21.9	32.4	38.2

Test numbers 24 and 25 were done using 8 bubble generators at a pumping pressure of 13 psi, and an air injection rate of 2 L/min. The array was continuously moved through the test section for the entire length of the test. In these two tests Ohmsett staff ran the circulation pump in the tank isolated test section. Test personnel originally thought the pump would help keep the droplets in the tank longer. They turned if off for subsequent tests and discovered it appeared to make no difference.

Tests 26 and 27 were also run at the lower initial oil concentration, 0.15%. In these tests, the number of bubble generators used was decreased to 7 and then to 6. The air inlet rate was also increase to 2.5 L/min. The motion of the array was also changed from continuous motion to semi-stationary. The last two tests, 29 and 30, were performed at the higher oil concentration, 0.25%. The number of bubble generators used was 6 and the pressure at the manifold could be raised to 22 psi and 20 psi respectively. The air inlet rates were 2.5 L/min and 3.5 L/min respectively. The fifth test was performed with continuous motion while the sixth was done semi-stationary. During these tests an additional oil collection sweep was made after 90 minutes from the start of the test.