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Detection of Oil in Water Column, Final Report: Detection Prototype Tests

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Homeland Security

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16. Abstract (MAXIMUM 200 WORDS)
This report summarizes the results of Phase II (Detection Prototype Tests) of an RDC effort to develop a readily deployable system for the in-situ detection, identification, and characterization of submerged oil in the water column. The first phase of the project involved initial development and testing of three technologies to address the detection problem. This second phase involved testing two of the prototypes at the Ohmsett facility in Leonardo, New Jersey. A system developed by NORBIT US Ltd. addresses the detection of hydrocarbons using the backscatter from acoustic signals from a Wide Band Multibeam Sonar (WBMS). A system developed by WET Labs, named Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW), uses the scattering and refraction of light to determine the mass and volume concentration, droplet size and density of the entrained oil.

Both systems demonstrated the qualitative ability to detect and/or map oil suspended in the water column with high levels of confidence as well as provide the data quickly and efficiently. Testing of the systems' quantitative ability to characterize the oil plume, however, was not possible due to difficulties with correlating and validating the submerged plumes' specific droplet size and concentration characteristics with the equipment currently available at the Ohmsett facility.

It is recommended that both prototypes be further developed and tested in field tests that eliminate the limitations seen in tank testing. It is also recommended that Ohmsett continue to develop its capability to create suspended oil plumes as well as investigate additional procedures for confirming particle size distribution and concentration during testing.

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EXECUTIVE SUMMARY

The U.S. Coast Guard Research and Development Center (RDC) undertook a Research and Development (R&D) effort to identify and further develop and test systems that can detect and characterize oil plumes in the water column. An earlier report summarized the results of Phase I (Concept Design) of the effort, in which remote sensing technology developers were solicited to configure and describe systems that were at least at the proof-of-concept stage of development that could potentially address this need (Fitzpatrick and Tebeau, 2013). This report summarizes Phase II, in which two technologies from Phase I were chosen for prototype development and testing at the Ohmsett facility in New Jersey. This effort is part of the overall R&D effort to advance response technology for various types of submerged oil spills. This subtask addressing entrained oil is similar in scope and objective to an earlier effort to detect, identify, and characterize oil resting on the bottom (Hansen et al., 2009).

Conducting the prototype tests required simulating submerged oil plume conditions in the Ohmsett facility test tank. Prior to conducting these tests, Ohmsett personnel developed the capability to create oil plumes of particle size and distribution range that closely replicate that of an actual release scenario, including chemically and physically dispersed oil. They developed an oil delivery system that could create plumes with two types of oil (Anadarko Crude and diesel fuel) with, and without, dispersant. In the small tank where the oil delivery system was developed, the oil particles remained suspended in the water column for up to twenty minutes. Unfortunately, this ability to maintain a suspended plume of oil was not repeatable to the same degree in the large tank.

Replicating an actual release scenario in the large Ohmsett tank presented a significant challenge for additional reasons. Unlike the ocean, a tank is a restricted environment where acoustic and optical signals can be reflected and distorted by the walls and bottom of the tank, as well as the equipment placed in the tank to conduct the tests. The relatively shallow depth of the Ohmsett tank makes it difficult to simulate submerged spills. Strong winds in the north and south directions can affect the shape of the submerged plume, making it difficult to assess with the sensors. Also, important oceanic phenomena such as density stratification and naturally occurring particulate matter, which will affect the performance of sensors in the ocean, are not present in a tank environment. The test procedures, however, included measures to account for and minimize the effects of these differences.

One system tested, developed by NORBIT US Ltd., addressed the detection of hydrocarbons using the backscatter from acoustic signals from a Wide Band Multibeam Sonar (WBMS). NORBIT demonstrated the ability to detect both types of oil, with, and without, dispersant at short distances. Long range tests were also conducted; however, the high reverberation from tank boundaries, as mentioned above, rendered those tests inconclusive. Regardless, this system shows promise for detecting plumes from a distance and should be tested in the field. A field test would yield more beneficial results since the sensor would not be affected by the reflectivity of the tank walls.

The second system, developed by WET Labs and named Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW), uses the reflection and refraction of light by suspended oil droplets to determine the volume concentration of the entrained oil. Phase II work has demonstrated the feasibility of developing a compact, inexpensive, multi-angle scattering instrument with an automated inversion algorithm and intuitive smart phone display that detects oil droplets in water. This system shows promise for mapping plumes and should be tested in the field with a towed vehicle that is able to cover large areas.

The stated objective of the RDC project is to identify and further develop and test a system that can detect and characterize oil that is entrained and dispersed in the water column. Both systems have demonstrated the qualitative ability to detect and/or map oil suspended in the water column with high levels of confidence and provide the data quickly and efficiently. However, the quantitative evaluation of the systems' abilities to characterize the oil plume was not possible at the Ohmsett facility for the reasons given above. Therefore, the RDC recognizes that both systems need further testing to determine their ultimate utility for oil spill response, and has recommended to both venders that they conduct further testing of their systems in the field.

Recommendations to further develop and improve Ohmsett's ability to conduct submerged oil tests include:

- Determination of oil properties and particle size necessary for neutral buoyancy in calm water.
- Further investigation on oil/nozzle combinations to generate neutrally buoyant particles.
- Investigation into additional procedures to confirm particle size distribution and concentration during testing.

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AUV	Autonomous Underwater Vehicle
BAA	Broad Agency Announcement
BSEE	Bureau of Safety and Environmental Enforcement
cP	Centipoise (10^{-2} poise, a measure of viscosity)
CRRC	Coastal Research and Response Center
CTD	Conductivity, temperature, and depth
DHM	Digital holographic microscope
DO	Dissolved oxygen
DOR	Dispersant to oil ratio
DSP	Digital Signal Processor
ECO-VSF	Volume scattering function sensor
FINDS OIL	Fluorescent IN-situ Detection System for OIL
FLS	Forward-looking sonar
FPGA	Field-programmable Gate Array
ft	Foot or feet
gph	Gallons per hour
gpm	Gallons per minute
GPS	Global Positioning System
Hz	Hertz (cycle(s)/second)
kHz	Kilohertz (1000 Hz)
kPa	Kilopascal
kts	Knots (nautical miles per hour)
LED	Light-emitting diode
LISST	Laser In Situ Scattering and Transmissometry
LUT	Look-up table
µm	Micron or micrometer (10^{-6} meters)
m	Meter(s)
mm	Millimeter (10^{-3} meters)
N-S	North-south
NRC	National Research Council
OPA 90	Oil Pollution Act of 1990
ppb	Parts per billion
ppm	Parts per million

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

PSD	Particle size distribution
psi	Pounds per square inch
R&D	Research and Development
RDC	USCG Research and Development Center
ROV	Remotely Operated Vehicle
SMART	Special Monitoring of Applied Response Technologies
USCG	U.S. Coast Guard
VAC	Volts alternating current
VDC	Volts direct current
VSF	Volume scattering function
W	Watt(s)
WBMS	Wide Band Multibeam Sonar
WET Labs	Western Environmental Technology Laboratories Inc.
WINDOW	Wide-angle-scattering Inversion to Detect Oil in Water

1 INTRODUCTION

The Deepwater Horizon oil spill in the Gulf of Mexico revealed several glaring technological gaps in responding to oil spill disasters. One of the challenging issues was determining the size and location of subsurface plumes and making timely decisions to prevent significant ecological damages. While some advances were made during the Deepwater Horizon incident for tracking underwater plumes, a robust, quick, and efficient technology for scanning and sampling the water column to determine the extent of an oil plume and characterize the oil in the plume (oil type, concentration, droplet size, and physical properties) is needed. The technology would need to provide data in real-time and be presented in an easily comprehensible format to enable a more efficient monitoring of the submerged plume and possible initiation of countermeasures and recovery.

Most oil spills occur over a shorter period of time and closer to shore than the Deepwater Horizon oil spill. Often there is a very short timeframe for decision-making to protect the environment and critical infrastructure by closing water-intakes and fisheries, and booming sensitive wildlife areas and important commercial facilities located along the shore and on rivers. In addition, initiating dispersant application or oil recovery operations is time sensitive. Challenges in detecting oil within the water column include poor visibility, difficulty in tracking oil movements in fast-moving currents, and not being able to discover very low levels of oil or dispersed oil at all depths. Current subsurface oil sensing technologies are tailored for detecting oil at a single location and must be moved along numerous transects over a period of time to accurately map contamination both horizontally and vertically. Often the configuration and location of an oil plume will have changed by the time the data from the surveys are processed and disseminated.

1.1 Objective

To address this technology gap, the USCG Research and Development Center (RDC) undertook a Research and Development (R&D) effort to identify and further develop and test a system that can detect and characterize oil that is entrained and dispersed in the water column. During Phase I (Concept Design) of the effort, remote sensing technology developers were solicited through a Broad Agency Announcement (BAA) to configure and describe systems that were at least at the proof-of-concept stage of development that could potentially address the remote sensing of oil in the water column. Two vendors responded describing and proposing a total of three systems for further development in three separate reports (summarized in Fitzpatrick and Tebeau, 2013).

This report summarizes the results of Phase II (Development and Testing of Detection Prototypes), which involves further development, refinement, and integration of the technology components in a field-deployable configuration, and testing two prototypes in a simulated oil spill environment at Ohmsett, the National Oil Spill Response Research and Renewable Energy Test Facility. This effort is a part of a larger effort in the R&D program to develop countermeasures against submerged oil spills.

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 surface of the water is often a difficult task with mechanical 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 spreading and dispersing in three dimensions, visibility is limited, deploying divers is dangerous, and 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 sink 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.

Oil in the Water Column

The term submerged oil generally refers to any oil that is not floating on the surface. In an oil spill involving submerged oil, three location scenarios are possible:

- Overwashed: thicker oil that is floating near the water surface but is covered by a layer of water due to wave action. This can obscure the oil slick from visual monitoring and remote sensing at the surface.
- Suspended: oil globules or droplets that are neutrally buoyant at depth and move in the water column under the influence of currents.
- Sunken: oil that is negatively buoyant and rests on the bottom of the water body. (Detection technologies for sunken oil were addressed in a previous USCG RDC study and reported in Hansen et. al, 2009).

Spilled oil can be suspended in the water column in a number of ways, which can be considered in roughly three distinct scenarios. The physical and chemical properties of oil resulting from these three scenarios can be very different and change with time. Submerged oil can come from a number of sources:

- Heavy oils from a surface spill that tend to sink under certain conditions, and is generally called submerged oil while it is in the water column and sunken oil when it reached the sea bottom.
- Oil rising to the surface from a subsea release.
- Fine droplets of oil resulting from chemical dispersants being applied to either a surface spill or subsea release or due to natural dispersion.

As described by the National Academy of Sciences (1999), Michel (2006), and Fingas (2011), each of the above scenarios presents its own challenges depending on the location and condition of the oil. This is particularly true when attempting to detect, identify, and characterize oil that is suspended in the water column. Physically capturing oil samples using rope and net snares towed through the water column has been employed in several spills, but is labor intensive and provides only a general indication of the amount of oil, geographical location, and depth. Some advances with sensors were made during the Deepwater Horizon incident response. However, a system for quickly and efficiently detecting and mapping a submerged oil plume is still needed.

1.3 Approach

1.3.1 Contracting Approach

The RDC developed specifications and released a BAA in November 2011 calling for a two-phased approach to developing and testing a technology to detect oil within the water column. The scope of the BAA included Phase I (Concept Design) and an option for Phase II (Prototype Development and Testing).

The RDC received eight responses (from seven vendors) to the BAA. It chose three ideas for Phase I proof-of-concept description and preliminary testing. These included:

- NORBIT Wide Band Multibeam Sonar (WBMS)
- Western Environmental Technology Laboratories Inc. (WET Labs) Fluorescent IN-situ Detection System for OIL (FINDS OIL)
- WET Labs Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW)

Based on the Phase I reports, the RDC chose two of these technologies for Phase II prototype testing at the Ohmsett facility: WBMS and WINDOW.

1.3.2 Performance/Capability Requirements

The BAA specifications required the contractor to develop a design concept for a prototype oil detection system. The BAA specified that this system be able to detect, identify, and characterize commonly spilled light oils (diesel), crude oils, and heavy oils, such as Bunker C oil, that may be temporarily suspended in the water column. The system must also have the ability to quickly process and plot the data and relay the information in an easily interpretable format to allow spill responders to make timely key decisions regarding mitigation and countermeasures.

The BAA further specified that the design concept demonstrate as many of the following capabilities as possible (listed in approximate order of importance):

1. Provides results in near real time (less than 1 hour);
2. Calibrates easily for different oils;
3. *Detects oil at depths up to 200 feet (ft) (~ 61 meters (m));*
4. Works in currents or tow speeds up to 5 knots *(partial test)*;
5. Reports minimal false alarms *(partial test)*;
6. *Allows smooth data flow from field to command center;*
7. Detects dispersed crude oil at levels of 0.5 parts per billion (ppb) or lower;
8. Sweeps an area of water column 3 ft by 3 ft (0.9 m by 0.9 m);
9. Provides digital readout or measured values and digitally logs field data;
10. Is field rugged *(partial test)*;
11. Is portable;
12. *Is compatible with fresh and salt water;*
13. Determines droplet size, density (specific gravity) and/or kinematic viscosity;
14. *Adapts to various depths (deep vs. shallow);*
15. *Operates from vessel in variety of conditions;*
16. Deploys quickly and easily;
17. *Measures dissolved oxygen (DO);* and
18. Grabs water samples for further laboratory testing.

Note: Items in *italics* (3, 6, 12, 14, 15, and 17) cannot be tested at Ohmsett.

1.4 Phase I Summary

The systems proposed and evaluated in Phase I included one acoustic system and two optical systems. The acoustic system, developed by NORBIT US Ltd., addresses the detection of hydrocarbons using the backscatter from acoustic signals from a Wide Band Multibeam Sonar (WBMS) at a nominal operating frequency of 400 kilohertz (kHz). The ultra wide band-width (160 hertz (Hz)) allows for detection of a wide range of particles (e.g., air bubbles or oil droplets) in the water column. It is relatively lightweight and compact and has moderate power consumption (uses 25W but can be operated in a power save mode down to 10W). Its ability to detect plumes of both fresh water in a seawater environment and dispersed oil was tested during the proof-of-concept phase. In both cases the system identified an acoustic anomaly associated with the entrained substance. Further development was suggested to resolve false positives in detection by improving software to conclusively identify oil in real-time without subjective analysis of imagery by the operator. The system was deemed ready for follow-on testing at the Ohmsett facility despite concerns regarding interference caused by acoustic reflections from the bottom and walls of the tank.

The first optical system, developed by WET Labs and named the Fluorescent IN-situ Detection System for OIL (FINDS OIL), uses flow-through fluorometric measurements as a primary means of detection and fluorescent backscatter to identify and characterize petroleum hydrocarbons encountered by the instrument. The detection occurs when seawater is passed through a fluorometer and its fluorescence intensity is measured at various wavelengths to identify the type and concentration of petroleum hydrocarbon encountered. The drawback with this approach is the limited volume sampled and the uncertainty as to how extensive the hydrocarbon contamination may be in the section of water column the instrument is sampling. With respect to testing at the Ohmsett facility, the developers expressed concern about maintaining consistency of oil concentration and distribution in a test plume in the Ohmsett tank, and suggested that a smaller test tank where replication of conditions was more achievable might be better suited for testing hydrocarbon detection and characterization capabilities. They also suggested that tests of deployability and maneuverability were better addressed in open water testing. As a result, this system was not chosen for testing at Ohmsett.

A second optical system, also by WET Labs and named Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW), uses the reflection and refraction of light by suspended oil droplets to determine the mass and volume concentration, droplet size, and density of the entrained oil. The wide-angle light scattering technique is best suited to detecting and characterizing spherical particles such as air bubbles or oil droplets. As the scattering signatures of oil droplets are collected, they are run through an inversion algorithm to determine their oil droplet size distribution, density, and viscosity. The information on the extent and properties of the mapped oil plume is disseminated in the form of jpeg images through a wireless network. Preliminary proof-of-concept testing in the lab showed the system is capable of detecting suspended oil droplets and quantifying their concentration, size distribution, and density. There was some concern with respect to the system's ability to detect and characterize oil that may be aggregated with other marine materials (hence becoming non-spherical in shape and exhibiting unexpected scattering signatures). Suggested development activities in preparation for Phase II included inversion algorithm enhancement.

2 PHASE II PLANNING

The primary objective of the Phase II testing was to determine if the WBMS and WINDOW instruments could detect oil suspended in the water column. In order to do this, Ohmsett personnel needed to develop the capability to create oil plumes within the water column that remain neutrally buoyant for an extended period of time. Section 2.1 describes this effort. Ohmsett personnel then created test plans specifically designed for each of the two instruments. This effort is discussed in Section 2.2.

2.1 Ohmsett Oil Delivery System Development

Research and development of new technologies requires not only the development of the technology itself, but also development of appropriate test apparatus and methods. Since oil in the water column research is in its infancy, the initial phase of the Ohmsett testing was dedicated to performing experiments for choosing appropriate oils, developing methods to create neutrally buoyant oil plumes, and quantifying their droplet sizes and distributions. The oil delivery system design process and results are summarized here. More details can be found in APPENDIX A, including the oil droplet sizes and distributions corresponding to a range of nozzle orifices, pressures, oil types, and times of release.

The requirement for the oil delivery system was to create oil plumes of particle size and distribution range that closely replicate that of an actual release scenario, including chemically and physically dispersed oil. Ohmsett personnel worked with the RDC and the Bureau of Safety and Environmental Enforcement (BSEE) to define the test parameters and fully develop the oil delivery system.

Initial design of the oil delivery system incorporated baseline parameters used during earlier subsea dispersant research at Ohmsett. It also included engineering estimates to identify the ranges of operational pressures and nozzle orifice diameters to create minute oil droplets underwater. According to the literature (Lewis, 2004), the nominal diameter necessary for oil droplets to remain neutrally buoyant under moderate sea conditions is approximately 70 microns (μm), depending on physical parameters such as oil and water densities, water salinity, and temperature.

Ohmsett personnel quantified oil droplet size distributions for various pressures, nozzle sizes, and oils. Oil droplet size, distribution and concentration measurements were obtained using a Sequoia LISST-100X particle size analyzer. Figure 1 shows the small scale test tank used for these experiments. The tank measured 4'x 4'x 8' with a 1000 gallon capacity and was filled with fresh salt water from the Ohmsett main test basin for each experiment. Based on these experiments, researchers concluded that using the smallest available orifice nozzle (0.016 inch) and highest available pressure (140-150 pounds per square inch (psi) range) provided the most desirable droplet size distribution. An example plume is shown in Figure 2.

Preliminary testing also investigated:

- Resulting plume characteristics with two consistent and available oil types for subsequent testing in their natural and dispersant treated forms: diesel and Anadarko Crude.
- The feasibility of successfully releasing usable oil plumes with the chosen oil types.
- The level of difficulty in creating, tracking, and monitoring reproducible oil plumes.
- Resulting oil droplet size distributions and concentrations for a matrix of controlled variables including nozzle type/size, nozzle orientation, oil discharge pressures, time of discharge, and dispersant dosing as appropriate.
- Development of the final oil spill/plume delivery system and use of multiple nozzles (see Figure 3).

Figure 1. Oil delivery system test tank.

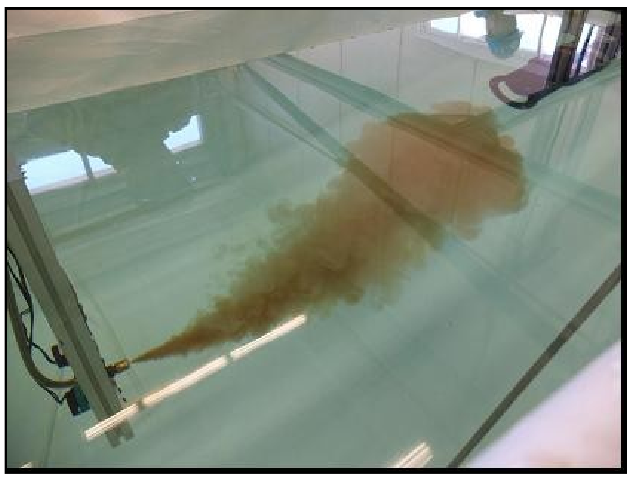

Figure 2. Example plume in small test tank.

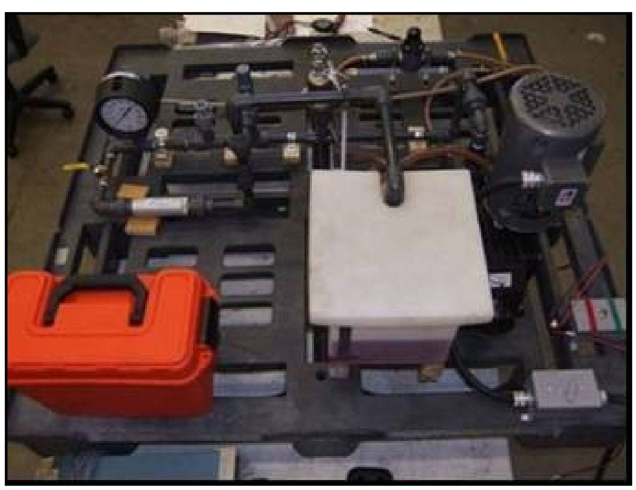

Figure 3. Oil dispensing system.

2.2 Test Planning

Ohmsett/Government personnel developed a draft test plan and provided it to the vendors to review. The plan described the system and methodology for the release of oil plumes into the test basin, incorporating the results of the development phase described above. In addition to expected oil plume droplet size distribution, the proposed test matrices included test parameters such as sensor distance from plume, advancing speeds, surface conditions, equipment locations, and oil types.

Ohmsett personnel contacted each equipment vendor to discuss the functionality, mounting, and support needed for system testing. Plans were developed based on specific vendor requirements related to plume parameters and locations. Each vendor's test set-up was different due to the difference in detection approach: acoustic vs. optical. The WBMS (acoustic) system collects data remotely from outside the plume while the WINDOW (optical) system collects data from within an oil plume. See APPENDIX B for more details about the test plans and procedures.

2.2.1 Test Setup

Figure 3 above showed the oil dispensing system developed for these tests. Test oil is pressurized using an OMNI PULSAFEEDER DC4D metering pump, with a Blacoh CTS 1020B-5 pulsation damping device used to smooth the pressure pulses. The pressurized oil flows through 0.25 inch (6.4 millimeter (mm)) reinforced rubber hose. A Grifco BPM 050 P back pressure valve is used to regulate line pressure upstream of the spray nozzles, forcing oil through Spraying Systems Co. nozzles. The spray nozzles are attached to an electrically actuated solenoid valve. When a remotely operated switch energizes the valve, oil flows through the nozzles creating a submerged oil plume in the test tank (Figure 4). Based on preliminary testing at Ohmsett using diesel and Anadarko Crude, three (3) Spraying Systems Co. 1/4 NN-0.6 (0.016 inch orifice) nozzles were recommended for this test series, with the metering pump adjusted to provide an oil pressure of 140-150 psi (965-1034 kilopascal (kPa)). During actual tests, varying configurations of nozzle quantities and sizes were explored to create plumes with varying droplet size distributions and concentrations.

Figure 4. Creating an oil plume in the large tank.

During the tests, the pumping system was staged on the main bridge. A quick-release vertical shaft was used to support the nozzles, allowing the nozzles to be set at virtually any depth in the tank. During preliminary testing, the submerged oil plume slowly rose despite the small (< 70 µm) droplet size. Further testing in Ohmsett's main test tank confirmed the deeper the nozzles were set, the longer it took for the plume to rise to the surface. Thus the Ohmsett staff recommended that the nozzles be set near the bottom of the tank, approximately 7.3 ft (2.24 m) below the water surface, to maximize the amount of time the plume would be suspended in the water column.

The nozzle support shaft was mounted to a trolley that rides on a rail on the north side of the main bridge (see Figure 5). As the main bridge is able to move north or south, and the trolley can move east or west, the nozzles could be readily positioned at any position in the tank.

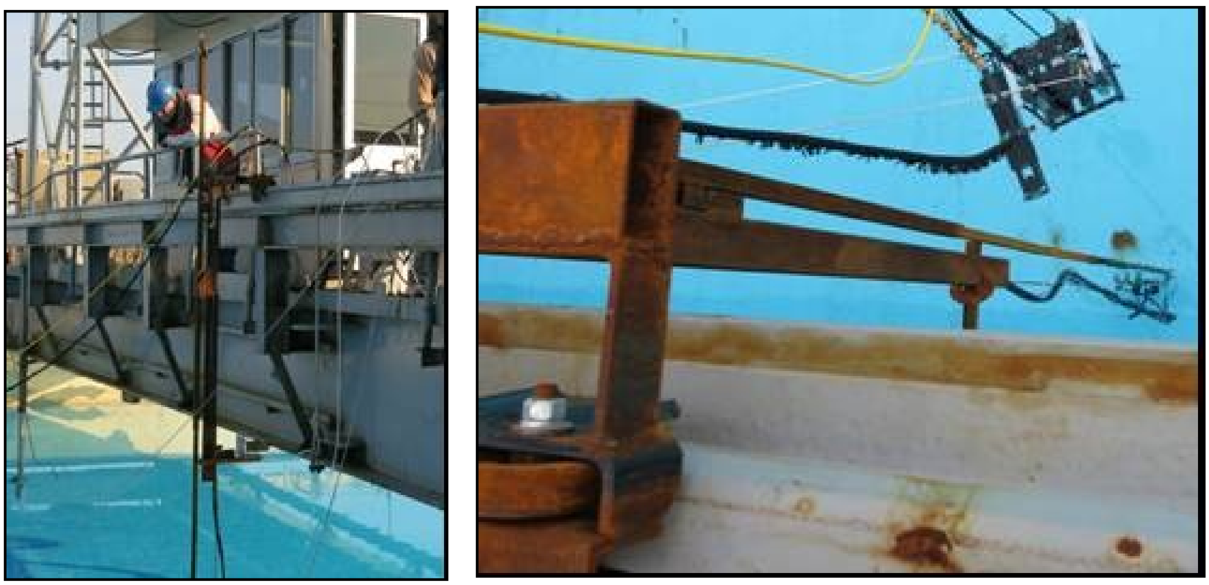

Figure 5. Trolley on Ohmsett main bridge.

2.2.2 Test Procedure

As mentioned earlier, the two prototype detection systems selected for testing represent two distinct detection technologies:

- Acoustics (sonar) (i.e., NORBIT WBMS), which collects data at various distances from the plume.
- Scattering of light (i.e., WET Labs WINDOW), which collects data while transiting through the plume.

The basic test plan called for each contractor to collect data in relatively clean tank water (background data), followed by Ohmsett's staff creating a suspended oil plume, and the contractor acquiring additional data to determine if their equipment can detect the plume. As the water in the test basin is relatively quiescent compared to the ocean, small oil droplets created in the test basin tend to rise faster than they would in a more turbulent environment. Initially, the test procedure was similar for both contractors, but the time the oil remained suspended in the water column, on the order of minutes, required adjusting the test method so that each contractor would have sufficient time to acquire data. Details of the planned and actual test procedures can be found in APPENDIX B.

The tests conducted in Ohmsett's main test basin used two different oils, diesel and Anadarko Crude, to create oil plumes suspended in the water column. Tests were also conducted to determine if the instruments could detect diesel and Anadarko Crude plumes that were pretreated with COREXIT 9500 dispersant. The treated oil plumes provided a higher concentration of smaller droplet sizes below 70 µm. Ohmsett personnel used a Sequoia Laser In Situ Scattering and Transmissometry (LISST) 100X off-the-shelf particle size analyzer to measure the experimental plume characteristics. The LISST measures the particle concentration within the water that passes through its optical chamber; thereby providing results from a relatively small point location (see Figure 6– from the LISST User's Manual). This instrument was also used during the preliminary droplet size analysis and the development of the oil delivery system. However, some studies show the LISST may be unreliable for measuring concentrations under 20 parts per million (ppm) or over 500 ppm (Panetta et al., 2013). Some of the plumes apparently had concentrations well outside these levels.

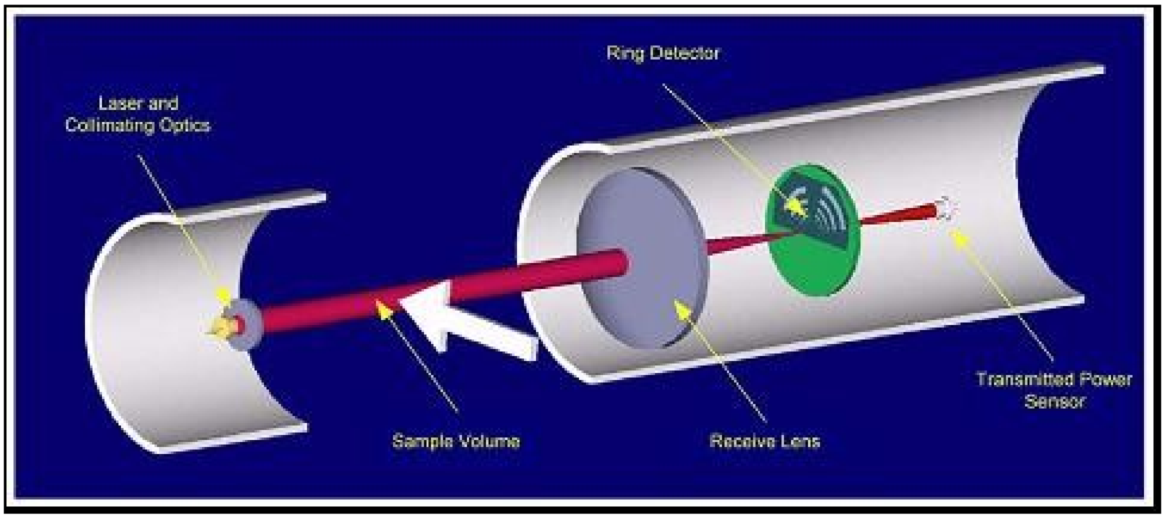

Figure 6. Diagram of LISST sensor.

3 PHASE II TESTING

3.1 NORBIT Wide Band Multibeam Acoustic Sensor

Acoustic detection methods rely on the different acoustic properties of oil compared to those of water because of the different densities and hence, sound speeds of the materials. NORBIT utilizes the Wide Band Multibeam Sonar (WBMS) as an acoustic sensor to provide three-dimensional (3D) topology of the oil plume.

3.1.1 System Description/Overview

The WBMS platform incorporates modern components and extensively uses Field-Programmable Gate Array (FPGA) as well as Digital Signal Processor (DSP) technology to maximize the flexibility of the system. The WBMS is specifically designed as an ultra wide band (160 kHz band width) system operating at a nominal frequency of 400 kHz. It has a circular array topography, ensuring more uniform beam opening angles across the coverage area. The fundamental acoustic resolution is less than 1 degree. It is a very compact unit, with moderate power consumption. The sonar has integrated processing capabilities so that water column scattering profiles can be generated in the sonar head itself. The system is designed to be readily deployable on a towed vehicle, remotely operated vehicle (ROV), or Autonomous Underwater Vehicle (AUV).

3.1.2 Components

The WBMS platform has a very simple design, with the sonar transducers and processors integrated in a single unit (see Figure 7). This makes it easy to adapt the sonar to various platforms, as some signal processing can be done in the sonar itself, although access to time series data storage is required. Access to time series data can be accomplished either by storage of the data locally in the system or in the platform carrying the sonar or, if possible, topside on a computer.

Figure 7. WBMS sonar.

3.1.3 Summary of Phase I Efforts

During Phase I, NORBIT performed two main tests, one in Norway and one in New Jersey (Ohmsett facility). At the test in Norway, fresh water was fed into seawater through a hose and the sonar monitored the fresh water as it mixed into the sea water. The test demonstrated the sonar's capabilities to differentiate between two fluids with relatively small impedance differences associated with the different densities.

The test at the Ohmsett facility was conducted with an oil company testing the effects of dispersant on oil. The WBMS sonar was mounted in the middle of the water column and was able to detect the oil plumes as they were broken into smaller particles as a result of the dispersants being applied to the oil on the surface.

The main problem with testing any type of sonar system is to find a tank that reduces or eliminates the reverberation of sound off of the sides and bottom that impact the tests. Since only relatively small tanks are capable of being used with oil, the ranges between the sonar and targets is usually relatively small, on the order of 3-6 feet (1-2 m). The results of any laboratory measurements may not be directly applied to further distances using theory alone and additional testing would be useful during an actual spill.

3.1.4 Phase II Test Planning

The purpose of the Phase II test was to determine the ability of the WBMS to detect oil suspended in the water column, including boundaries of the detection capabilities from a concentration as well as range perspective. An optimum setup for the WBMS would be open calm sea, or in a very big test tank, where the test would not be limited by walls/bottom. A depth of about 70 ft (21 m) would be required to be able to perform the test without surface reflections. That would allow other interferences to be eliminated and pure data on oil obtained. This set-up was obviously not possible at Ohmsett but was approximated as closely as possible. Figure 8 provides a sketch of the ideal suggested test-setup for Phase II testing at the Ohmsett facility as proposed by NORBIT (Eriksen, et al., 2014).

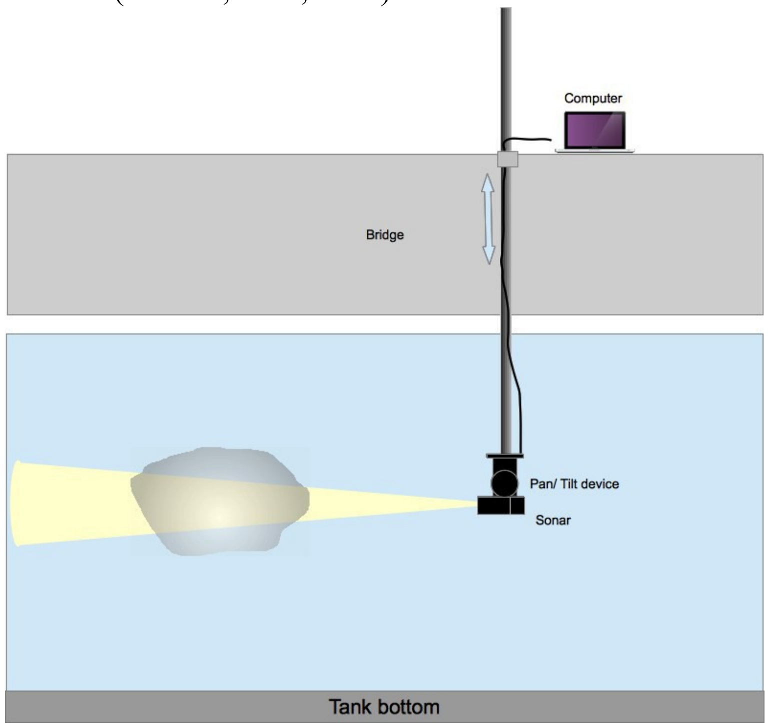

Figure 8. Proposed test set-up for WBMS Phase II.

NORBIT recommended the tests include the following steps (Eriksen, 2013):

- Plume is released mid-water column. NORBIT personnel will use the nozzle to align sonar during the plume creation phase.
- Nozzle and equipment used for the release should be removed from the tank immediately after oil release in order to avoid any acoustic reflections from the equipment.
- Sonar will then record data as the plume is suspended and rises to the surface, utilizing a rotator to keep the sonar pointing in the right direction as well as creating the 3D raw dataset. The rotator can be controlled from the sonar survey computer or directed by the user. The raw data files will contain the angular information (rotator position).
- The bridge can be moved during testing in order to measure different distances to the plume for the same release. Suggested distances are approximately 6.5 ft, 16.5 ft, 33 ft, 66 ft, and 98 ft (2 m, 5 m, 10 m, 20 m, and 30 m).

3.1.5 Test Overview

NORBIT utilized the WBMS as an acoustic sensor to provide both two-dimensional (2D) and 3D topology of the oil plume (see Figure 9). The sonars were mounted on a rotator to enable sweeping across the oil plume. The rotator was fixed to a pole mounted on the bridge. The pole was long enough to move vertically from water surface to just above tank bottom, making it possible to scan the full water column. The sonar was connected to a survey computer and powered from the bridge.

Figure 9. WBMS system with two sonars (left) and anechoic mat (right).

The sonars and nozzles for oil injection were mounted on the same side of the main bridge. Figure 10 shows the typical WBMS set-up with the underwater camera stalk on the left, the spray manifold stalk on the trolley in the center, and the WBMS sensor mounted to the main bridge tow point on the right.

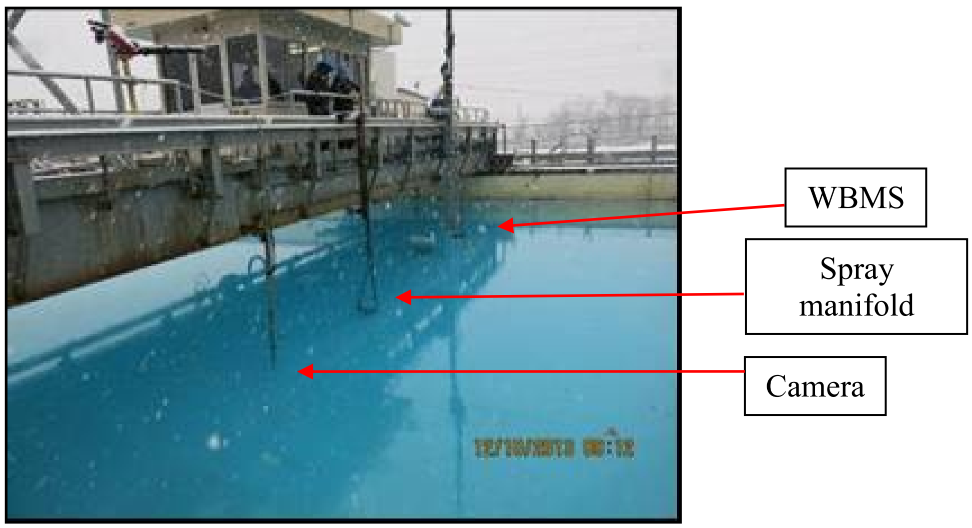

Figure 10. Typical WBMS set-up.

The tests were conducted between 9 and 13 December 2013. Test variables included:

- Type of oil – two types of oil were tested: diesel and Anadarko Crude, both with and without the dispersant COREXIT 9500 with a dispersant to oil ratio (DOR) of 1:20.
- Nozzle – two types of nozzles were used (0.016 and 0.020 inch), known to produce the same size of oil droplets with slightly different concentration. They were used mostly in triplet configuration.
- Distance between sonar and nozzles (range: 3 to ~ 38 ft (1 to ~ 11.5 m)).
- Depth of sonar – the nominal depths used were 1 ft, 2 ft, and 7 ft (~ 0.3 m, 0.6 m, and 2.1 m) below the waterline.
- Orientation of sonar – the horizontal WMBS was used most of the time. For shorter distances, e.g. Test #60, the vertical forward-looking sonar (FLS) was used for visualization purposes.
- Height/depth of nozzles (1 or 2 ft (0.3 or 0.6 m)) from the bottom.
- Orientation of nozzles – facing towards the sonar or at right angles to it.
- Duration of oil release – originally 3 minutes, later changed to 30 seconds.

Figure 11 shows an example of a 30-second test plume. Notice the top of the plume has already reached the surface at this point in time where the oil injection is about to be stopped and the injection hardware removed. The positions of the sonar and nozzles were changed several times so the location of the plume was in a quieter spot in the tank. For example, Figure 12 shows a quiet area between the sonar (at bottom) and the return of the sonar reflections from the tank bottom, tank sides or water surface.

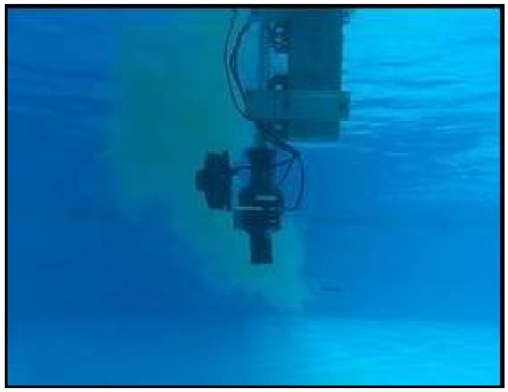

Figure 11. Example 30-sec test plume.

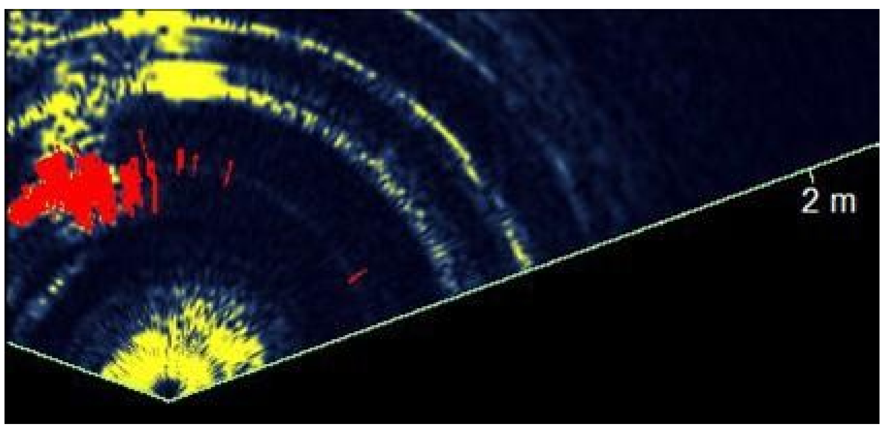

Figure 12. Example of automatic detection results.

3.1.6 Test Results

The WBMS test results are summarized in Table 1. There are two types of detection reported from WBMS testing: automatic detection and supervised (or manual) detection. NORBIT put significant effort into developing algorithms for automatic detection.

Table 1. Summary of WBMS results.

Oil type, nozzle configuration (#xsize (inch)) and spill duration	Test no.	Spill range (m)	Automatic detection duration [sec] N/A – not performed N/D – no Detection	Supervised detection duration after spill stops [sec] N/A – not performed N/D – no Detection
Diesel, 3x0.016, 3 min	3	2	60	120
	4, 5, 6	4	N/A	300
	3b	5	N/A	N/D
Diesel, 3x0.020, 3 min	14	1	60	360
	13	2.5	20	60
	9	5	N/D	5
	8	7	N/D	1
Diesel, 3x0.020, 30 sec	51	1	N/A	70
	49	5	N/A	60
	50	11	N/A	30
Anadarko, 3x0.016, 3 min	20	3	30	30
	21	6	N/D	N/D
Diesel + dispersant, 3x0.016, 3 min	23, 24, 32	2	N/A	120
	26, 27	6	N/A	60
	30	7.5	N/A	60
	28	8	N/D	N/D
Diesel + dispersant, 3x0.020, 30 sec	57	1	N/A	65
	58	6	N/A	300
	61	11	N/A	180
Anadarko + dispersant, x0.020, 3 min	37, 38	2	N/A	20
Anadarko + dispersant, x0.020, 30 sec, nozzle change	41	2	N/A	180
	42	5	N/A	40
	43	7	N/A	10
	44	9	N/A	20
	47	12	N/A	60

N/A – automatic detection not performed in the real time. The data is recorded so further analysis is possible if needed.

N/D – no automatic detection due to high reverberation levels during the tests

A modified approach was used in order to make the detections less prone to “random” movements. The general system utilizes an adaptive background mixture model for real-time tracking to detect subtle movements in images, which can further be used in high level analysis on anomalies in sub-sea scans. The output of such a system is a measure on whether oil is present in the scans and issues an alarm if that is the case. Figure 12 above shows an example of automatic detection results from Test #17 (Ohmsett test #229) with pure diesel. The red marks indicate oil.

NORBIT attempted to define a minimum concentration level for the detections listed in Table 1 but it was based on data collected for a couple of runs of the LISST after the sonar equipment had been removed from the tank. The inconsistency of the shape of the plumes due to the specific environmental conditions does not permit the comparison of these data. Analysis of these data combined with Panetta et al. (2013) may provide some correlation in the future.

The result for a single scan does not give enough information about whether an oil plume is present within it or not. However, results from consecutive scans can give information on whether a spill has occurred. The second stage of detections is the off-line automatic detection, where data acquired in the real-time automatic detection mode is reanalyzed to better define the extent of the plume and focus in on the area of interest. This stage of detection is used to feed successive information to a classification algorithm, which uses other information like scattering strength, morphology, and statistical distribution to produce a 3D morphology of the plume. Manual detection involves the operator viewing the sonar image on a computer screen (see Figure 13). It is possible the sonar may be detecting part of the plume that cannot be seen by a naked eye. So when the sonar operators were looking back and forth between the video camera output and the sonar data, the results may not always match.

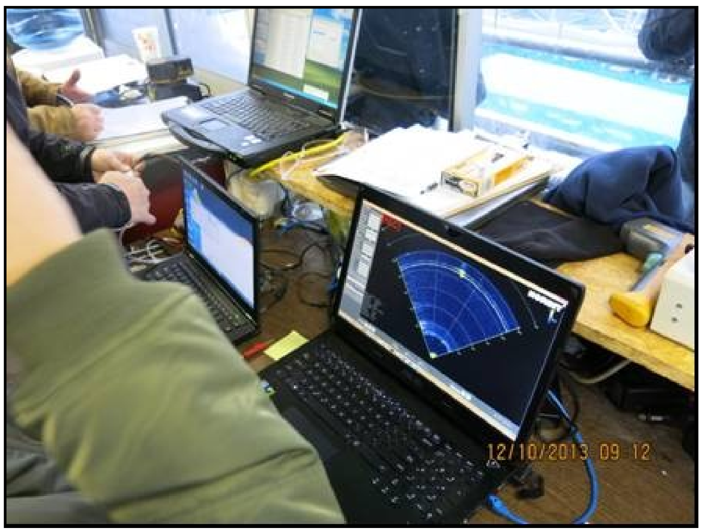

Figure 13. WBMS computer user interface.

Figure 14 shows underwater snapshots from test #32 (Ohmsett test #233) – diesel with dispersant. The sonar was set at a range of 2 m from the plume, scanning vertically. The sonar has an anechoic mat attached to reduce acoustic reverberation and reduce the level of the bottom-bounced acoustic returns. Figure 15 shows the manual detection results before (left) and after (right) the plume was released. Figure 16 shows the 3D visualization of the plume.

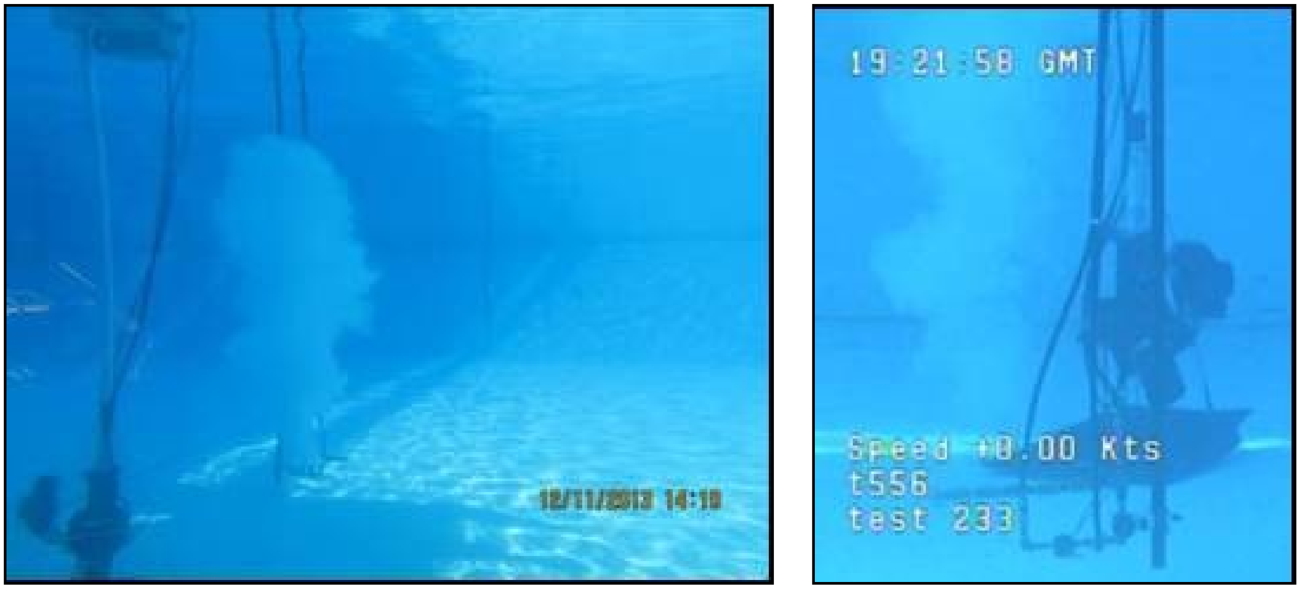

Figure 14. Release of diesel with dispersant, sonar and nozzles 2 ft from bottom.

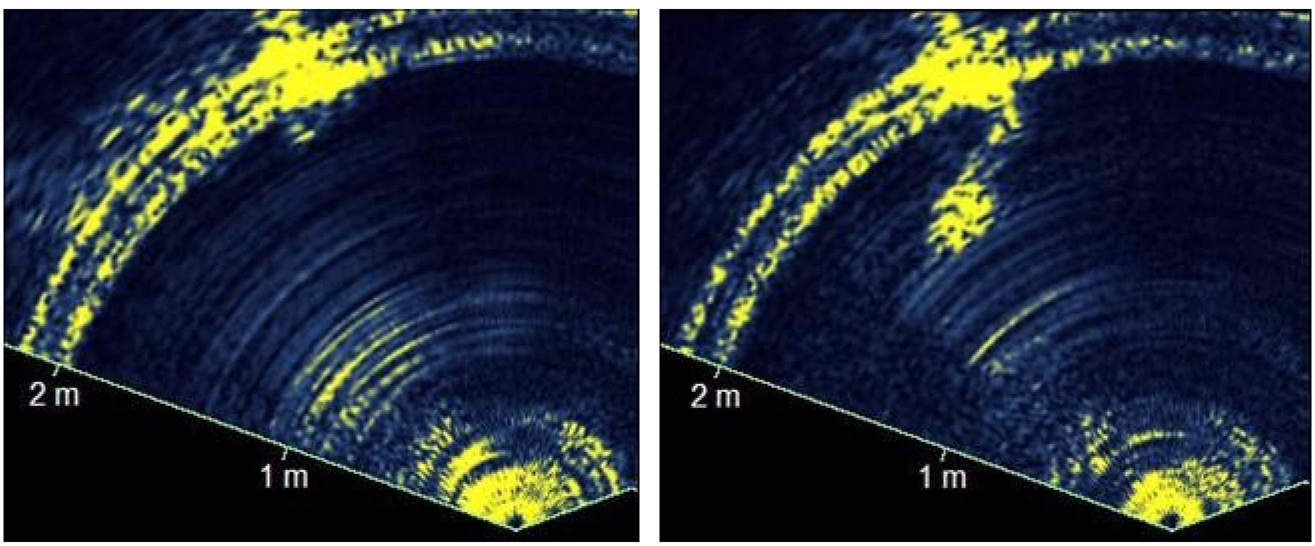

Figure 15. WBMS test #32/233 before (left) and after (right) plume was discharged.

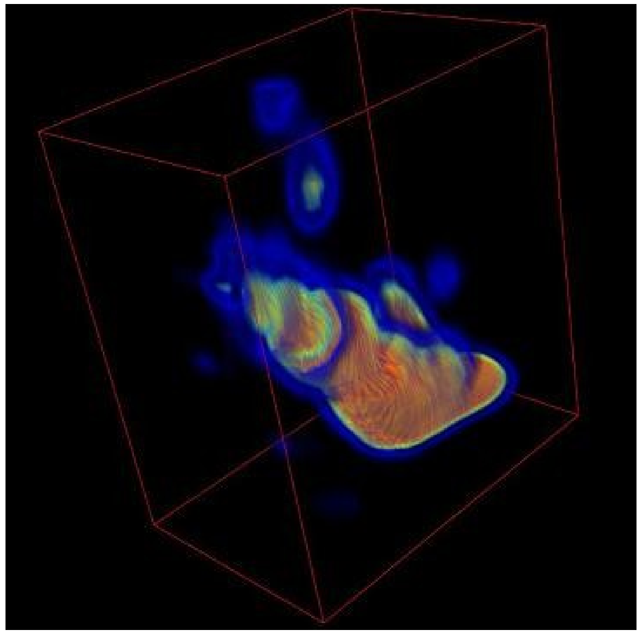

Figure 16. WBMS test #32/233 3D visualization.

NORBIT dedicated one test (#55/255) to calibrate the system to output absolute sound level in order to estimate detection range. They concluded the system can detect everything above the volume scattering strength of the water, and the margin above which the plume can be detected will depend on the additional parameters for the detection algorithm, like the morphology of the plume. As with any detection algorithm, the more information that is available for it, the better job it can do.

As mentioned at the end of Phase I, testing acoustical devices in tanks not setup for this greatly complicates data collection. Most of the time for this test was spent trying to place the nozzles in a good position with respect to the sonar so that the plume's location was in a quieter area. NORBIT stated that extrapolation of results on the short range data shows that relatively large plumes (10-13 ft (3-4 m) diameter) can be detected up to 300 ft (~ 90 m) range from the sonar. This range is however limited when the plume is smaller or strong acoustic scatterers are in close proximity to the plume.

3.1.7 Further Development

NORBIT reports conducting several meetings with industry representatives to discuss implementation of this technology on various platforms. It has been determined that the best platform for implementation would be an AUV or ROV, or alternatively an active movable towed platform, providing the ability to move the sonar in the water column, and thereby getting closer to the plumes.

3.1.7.1 Needs for Full-scale Development

Based on the tests performed some future work is recommended. The most important improvement seems to be a steerable projector which will avoid the use of a mechanical rotator. There are several advantages of using the electronic steerable projector rather than the mechanical steering. The obvious advantage is the ability to sweep the space in front of the sonar in just seconds. Also the installation will be lighter and more robust. Further work on automated detection of plumes utilizing 3D information is recommended as well.

3.1.7.2 Activities Needed to Complete Design

NORBIT reports the steerable projector development is nearly finished. From the Phase II tests it seems the steerable projector will provide significant enhancement for the detection process and the robustness of the detection system. It will allow the system to build the 3D morphology of the plume and improve the probability of detection. It will also lower the probability of false alarm by examining the morphology.

NORBIT also reports the detection algorithm is under advance development. The improvements are made continuously as more and more data are available to the NORBIT team. The detection algorithm is developed incorporating several layers of intelligence. When finished, it may be possible to integrate the algorithm into the sonar head similarly to the bottom detection algorithm used in the bathymetry version of this system.

3.2 WET Labs WINDOW

3.2.1 System Description/Overview

The WET Labs WINDOW design is a compact, multi-angle scattering instrument that measures refracted and reflected light off suspended particles to determine the droplet size distribution based on the distinct scattering angles. The system is designed to use an automated inversion algorithm to quantify the size distribution and abundance of oil droplets in water and determine the refractive index of the oil to derive density and viscosity.

Particles that are most readily detected and quantified with this technique are those that are nearly spherical, namely bubbles and oil droplets, because such particles produce spherical lensing effects characterized by distinct and unique constructive and deconstructive interference patterns in angular scattering. When superimposed on smooth, regularly shaped scattering functions from naturally occurring background particle populations, these unique scattering functions can be readily discriminated and then used to derive particle size, plume dimensions, and density of the suspended oil droplets.

3.2.2 Components

The sensing system consists of an in-water sensing package and a surface deck unit with laptop PC and integrated Global Positioning System (GPS). The system can be powered by 110 volts alternating current (VAC) power, or a deep cycle 12 volts direct current (VDC) battery can be used if VAC power is not available.

Data in the form of mapped oil properties are transmitted wirelessly through a cellular network PC and are thus made available to all interested parties with cellular access. The sensor system is deployable by hand or from a compact, portable hoist system, or on a towed platform, allowing profiling from small boats.

The sensor suite for the oil detection system (Figure 17) consists of:

- Three ECO-VSF (volume scattering function) sensors, each measuring optical scattering at three angles (nine total scattering measurements with angular resolution of 60 to 160 degrees in 10 degree increments); each sensor head has an automated rotating wiper to keep the optical windows clean.
- SeaBird Electronics SBE 49 conductivity, depth, and temperature (CTD) sensor.
- SeaBird Electronics SBE 43 membrane dissolved oxygen (DO) sensor.

The ECO-VSF sensors are soda can sized and employ inexpensive light-emitting diode (LED) sources and silicon diode detectors. The sensing heads, including optics and electronics, are completely potted with epoxy, so that the sensors are extremely robust to demanding field use.

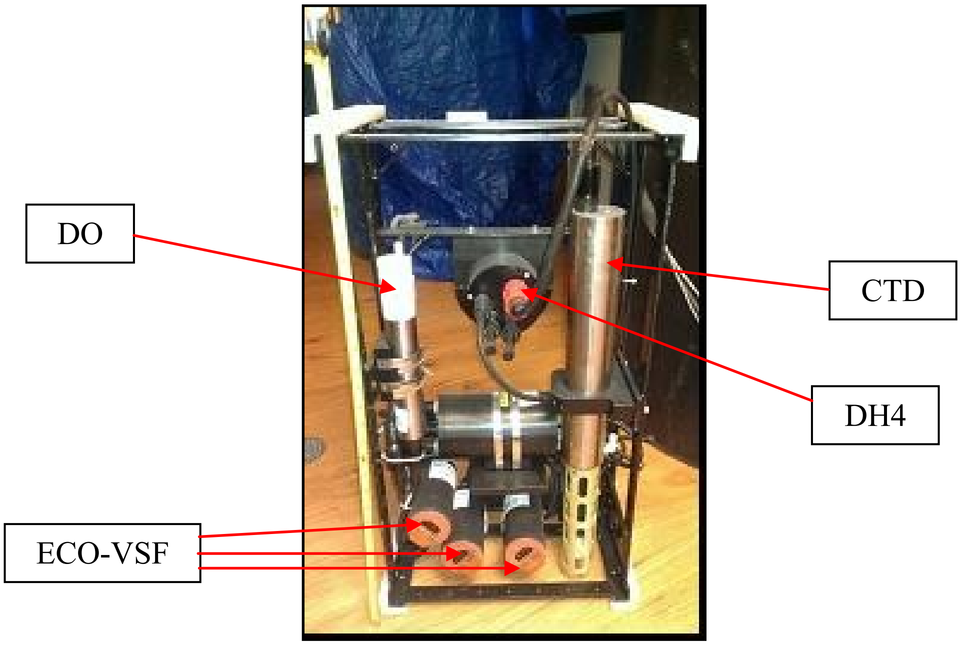

Figure 17. WINDOW sensor suite.

The data handler (WET Labs DH4) is in the middle of the sensors and the power conversion module is located in the center above the sensors and data processor, with cable attached. The cage is 27 in X 12 in X 8 in (0.68 m X 0.3 m X 0.2 m).

The sampling rate for all sensors is 1 Hz. Accessory ports are available for additional sensors such as oil-in-water fluorometers. A robust deck controller unit in a waterproof case connects to the sensor package via a sea cable providing data and power conductors. Isolated battery power and data acquisition with no sea cable are also an option where the data are downloaded after acquisition.

The deck unit has an integrated GPS unit or can receive ship GPS input. The deck unit laptop PC (see Figure 18) provides the operator software interface, providing a digital, real-time readout.

3.2.3 Summary of Phase I Efforts

The primary objective of Phase I lab testing was to quantify the accuracy and sensitivity of the system for detecting droplets of different oils in natural seawater. Three sets of experiments were carried out with droplets suspended in purified salt water, so that the droplets themselves were the primary scattering component. Oils of low, medium, and high refractive index were separately, vigorously mixed in solution for each experiment. Following these experiments, another set of experiments was carried out using the same dispersed oils, but with a background of purified salt water containing a broad size distribution of suspended sediments collected from Narragansett Bay.

Figure 18. WINDOW deck unit.

Through Phase I testing, the method and inversion algorithm proved capable of quantifying droplet size distributions and density with reasonable accuracy (within several percent), verified with ancillary measurements from holographic imaging. Phase I testing included the natural condition of the droplets suspended within a complex mixture of naturally occurring aquatic particles with broad size range.

Further development activities in preparation for Phase II would focus on inversion algorithm enhancement. There was also some concern with respect to the system's ability to detect and characterize oil that may be aggregated with other marine materials (hence becoming non-spherical in shape and exhibiting unexpected scattering signatures).

3.2.4 Phase II Test Planning

Before the Phase II test, there were several discussions between WET Labs and Government personnel to design the test experiments. Several simulations of oil dispersal were carried out by WET Labs to aid these discussions, results of which are presented in their Prototype Testing Recommendations (Twardoswki, 2013). Recommended validation methods are also discussed in that document.

Based on the simulations, the ECO-VSF sensors were re-tuned to decrease the sensitivity for detecting very low concentrations of oil. This is expected to avoid saturation (i.e., allow detection) for very high concentrations, and help to avoid background interference from residual suspended oil from previous tests.

3.2.5 Test Overview

The WINDOW system was tested at Ohmsett between 2 and 5 December, 2013. In general, there were four different test scenarios:

- **Stationary** – the instrument package was above the oil spray manifold and positioned to sample the plumes as they rose, expanded, and dissipated.

- **Transect** – the defined plume was created then the main bridge and instrumentation package traveled north and south repeatedly through the plume. The instruments started in clean water (out of the plume), traveled through the plume until they reached clean water again then changed direction. The process was repeated until the plume concentration diminished (the instruments reached their lower detection limits).
- **Mapping** – a 30 ft (~ 9.2 m) long plume was created across the test basin in the east-to-west direction. While continually dispensing oil, the trolley nozzle manifold was guided at a constant rate along the trolley rail. Once the plume was created, the WINDOW system intersected the plume near the east end of the plume traveling north. Once in clean water, the instruments were jogged toward the west 5 ft (~ 1.5 m) then traveled south intersecting the plume. The instruments were guided back and forth along the bridge so that they repeatedly encountered the plume. A minimum of five transects were performed (then repeated).
- **High Speed Tow** – the instruments were towed at speeds up to 3.5 knots (kts) while passing through a plume.

For most of the tests, the top of the WINDOW sensor package was suspended about 1.5 ft (0.46 m) below the air-water interface using the bridge platform crane, stabilized with guy wires. The Ohmsett LISST device was attached horizontally to the side of the WET Labs package (Figure 19).

Figure 19. LISST attached to WINDOW sensor cage.

Oil was injected under pressure using the custom Ohmsett oil delivery system with nozzles positioned about 8 inches (~ 0.2 m) from the bottom of the tank. After a plume of oil was injected, the bridge platform was held stationary or moved back and forth through the plume depending on the requirements of the experiment. Figure 20 shows the typical experimental set-up.

Figure 20. Example experimental set-up for WINDOW.

Prior to each oil release, a background measurement was taken at the starting point to later be subtracted from the sensor measurement to calculate the detected concentration of oil. To begin each experiment, oil was injected by Ohmsett's oil delivery system. For most experiments, the oil release was at a single stationary point, approximately 25 ft (7.6 m) from the west tank wall. For two experiments (#113 and #116), the oil was released as a horizontal plume approximately 30 ft (9.1 m) long, beginning approximately 25 ft from the west tank wall, then moving along the bridge towards the east tank wall. At the conclusion of the release, the bridge moved in a north-south direction at 0.20 kts intersecting the plume until the WINDOW system and LISST device reached their lower detection limits. The bridge was then reversed, re-transitting the entire plume through the original starting point until the sensors once again reached their lower detection limit. These transects were continued until the plume had dispersed beyond detection limits (no oil detected).

During some of the experiments (#108, #109, #110, #111, and #114), the sensor package was raised approximately 6 inches (0.15 m) to remain within the oil plume as observed visually from the surface. For the last three of these experiments, the sensor package was moved laterally about 3.3 ft (1 m) after the first pass, so that the "hole" in the oil plume created by drawing in clean water behind the system with the first pass was not resampled. Additionally, one experiment (#117) began with a stationary vertical profile of the entire tank water column, followed by north- south (N-S) transects at an approximate depth of 2 ft (0.6 m). Table 2 shows the WINDOW test matrix.

Table 2. WINDOW test matrix.

OIL TYPE (DATE)	TIME	TEST #	NOZZLE CONFIG QTY/SIZE (inch)	VOLUME OF OIL DISPENSED (gallon(s))	DISPENSE RATE (gallons per hour (gph))	OIL SPRAY DURATION (min)	SCENARIO
Diesel (12/2/2013)	11:22 am	101	3/0.016	0.168	3.35	3.0	Stationary
	1:22 pm	102	3/0.016	0.117	2.33	3.0	Stationary: (1 of 3 nozzles clogged)
	1:56 pm	103	3/0.016	0.185	3.7	3.0	Transect
	2:23 pm	104	3/0.016	0.201	4.02	3.0	Transect
	2:50 pm	105	3/0.016	0.168	3.35	3.0	Transect
Anadarko (12/3/2013)	9:59 am	106	3/0.016	0.168	3.35	3.0	Transect
	10:33 am	107	3/0.016	N/A	N/A	N/A	Aborted – clogged nozzles
	11:05 am	108	3/0.016	0.201	4.02	3.0	Transect
	11:25 am	109	3/0.016	0.201	4.02	3.0	Transect
Anadarko w/dispersant (12/3 & 12/4)	1:35 pm	110	3/0.016	0.201	4.02	3.0	Transect
	2:20 pm	111	3/0.016	0.168	3.35	3.0	Transect
	10:17 am	113	5/0.16	0.436	4.36	6.0	Mapping
Diesel w/dispersant (12/4 & 12/5)	12:46 pm	114	5/0.16	0.201	4.02	3.0	Transect
	1:23 pm	115	5/0.16	0.134	2.68	3.0	Transect
	2:11 pm	116	5/0.16	0.369	3.4	6.5	Transect
	9:31 am	117	2/0.016, 2/0.020, 1/0.028, 1/0.042	0.771	24.99	1.9	Transects
	11:25 am	118	N/A	N/A	N/A	N/A	High speed tow
	11:35 am	119	N/A	N/A	N/A	N/A	High speed tow
	11:50 am	120	2/0.016, 2/0.020, 1/0.028, 1/0.042	1.005	24.12	2.5	High speed tow

3.2.6 Test Results

As described earlier, two types of oils were tested, with and without dispersant: diesel and Anadarko Crude. Different nozzle orifices were used to generate oil droplets with varying size distributions. Concurrent measurements of oil droplet size distributions with the Sequoia LISST were made by Ohmsett personnel, and WET Labs personnel collected discrete grab samples for particle size analysis with a bench top digital holographic microscope set up in the cabin on the moving bridge over the tank. However, comparisons of the oil droplet sizes as measured by the different instruments were inconclusive.

The following plots show example WINDOW results. These plots show the measured oil concentration as a function of time as the experiment progressed. For stationary experiments (e.g., Figure 21), these graphs show the concentration of the initial oil plume and rapid dispersion as the plume drifted by the sensor and away from the release point. For transect experiments (e.g., Figure 22), the first peak is the initial release point, followed by repeated transects through the dispersing plume. Direction reversals occurred during the low concentration periods between larger peaks.

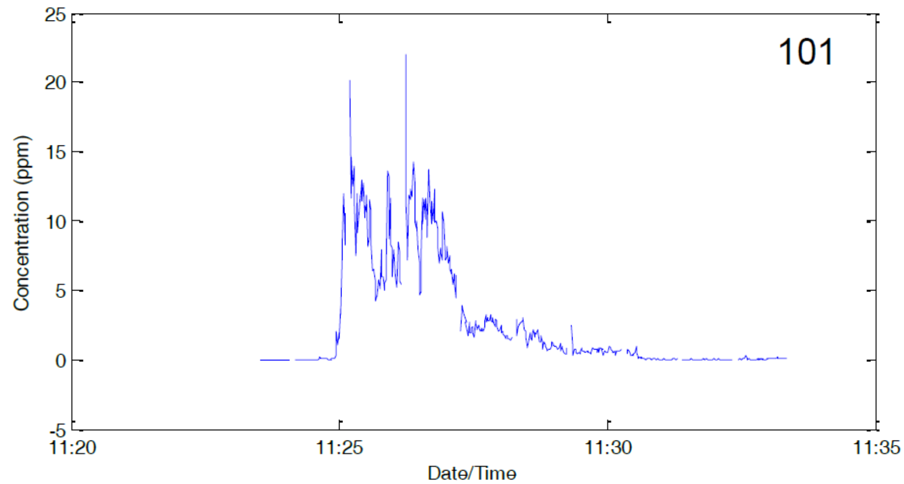

Figure 21. Example oil concentration plot for stationary experiments.

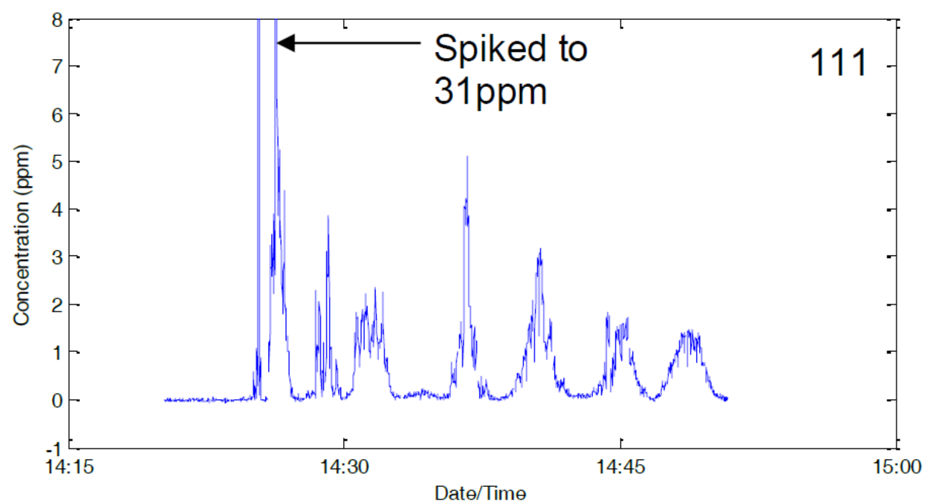

Figure 22. Example oil concentration plot for transect experiments.

One experiment (#117) consisted of a vertical profile of the water column, followed by N-S transects. The sensor package was located at the bottom of the tank during the initial oil release (Figure 23), then raised to the surface, lowered to the bottom, and raised to the surface again. Standard N-S transects were then repeated until a low oil concentration was detected. This was done to determine the vertical plume resolution capabilities. Some evidence of decreasing oil concentration with decreasing depth was seen (Figure 24), but the value of these results is limited by the small spatial and temporal range of the sample. This test could have yielded more significant results if there was a greater opportunity for the oil plume to achieve relative stability after the initial release; and if vertical profiles were taken at multiple locations within the plume, showing the oil concentration over a larger section of the plume.

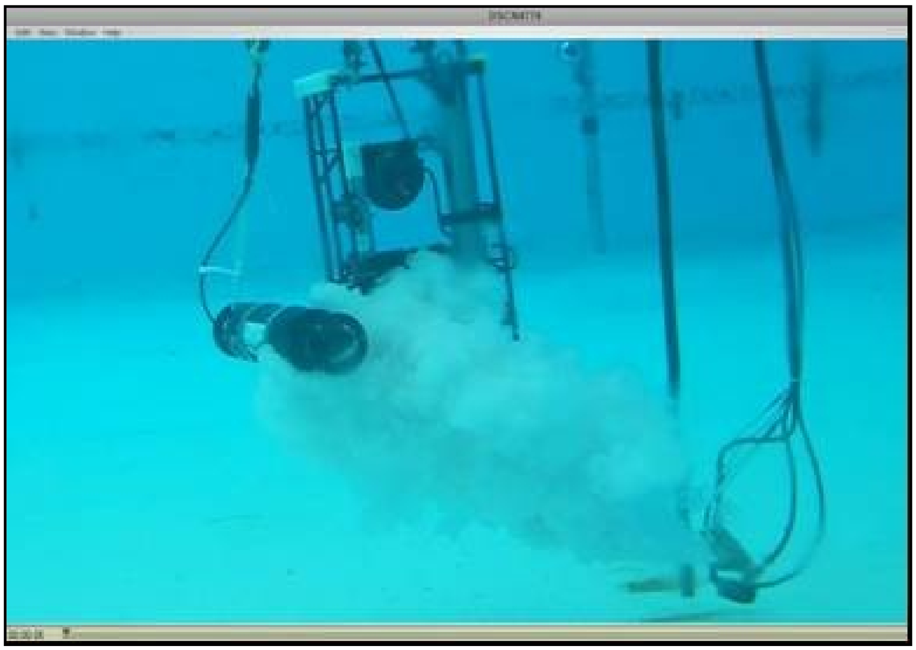

Figure 23. Photo showing instrument at bottom of tank during oil release.

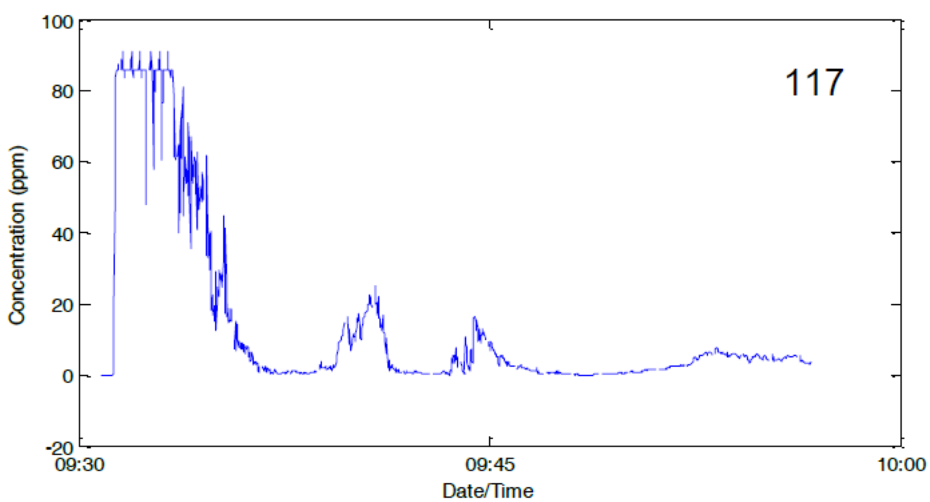

Figure 24. Oil concentration plot for Test #117 – vertical profile.

Comparing results for releases of oil with and without dispersant showed that, as expected, releases with dispersant remained suspended in the water column in higher concentrations for longer time periods than releases with pure oil. For a release of Anadarko Crude without dispersant, the initial peak was very high (Figure 25). Subsequent transects showed sequentially lower concentrations with a broadening peak, indicating rapid dispersion away from the initial release point, including rapid vertical migration towards the surface due to buoyancy. Comparing to a similar release of Anadarko mixed with chemical dispersant, after the initial peak subsided, further transects showed slower rates of concentration declines as the oil droplets stabilized with dispersant remaining in the water column (Figure 26). Persistence in the water column is associated with decreased buoyancy from the dispersant coating, but also results from a smaller average size of the coated oil droplets.

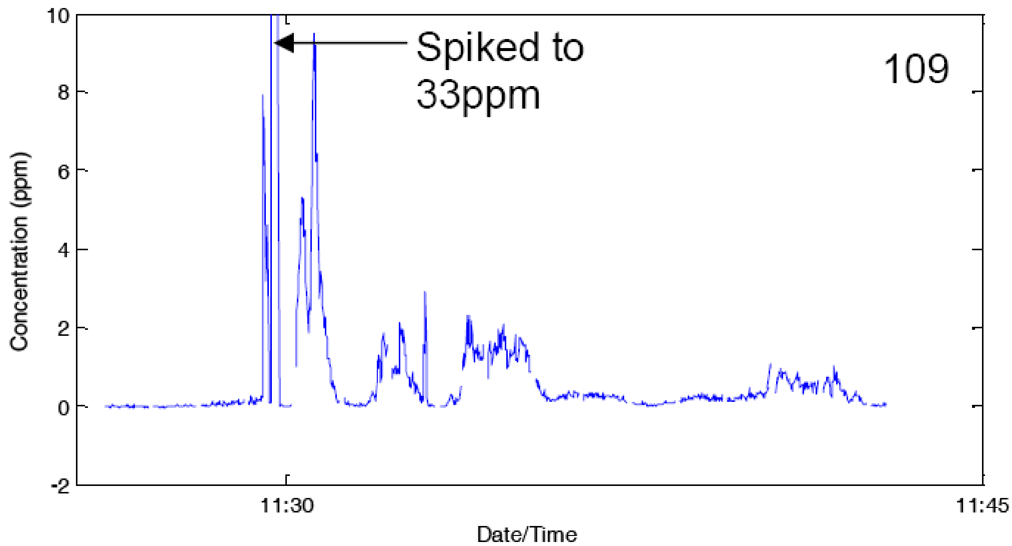

Figure 25. Pure Anadarko Crude.

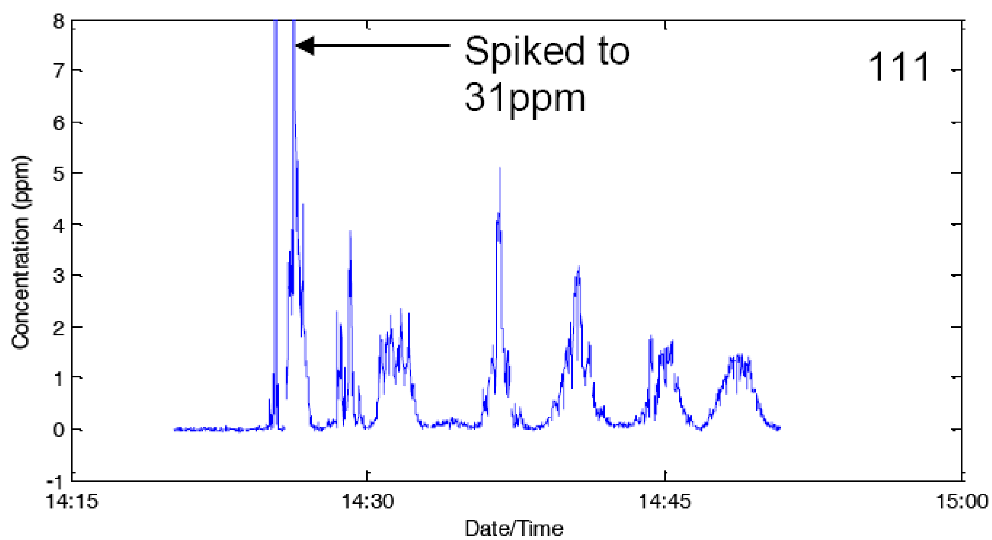

Figure 26. Anadarko Crude with dispersant.

3.2.6.1 Mapping

Test #113 involved mapping the plume. As described earlier, a 30-ft long plume was created across the test basin in the east-to-west direction. While continually dispensing, the trolley nozzle manifold was guided at a constant rate along the trolley rail. Once the plume was created, the WINDOW instruments intersected the plume near the east end of the plume traveling north. Once in clean water, the instruments were jogged toward the west 5 ft. then traveled south intersecting the plume. A total of five N-S transects were performed (then repeated). Figure 27 shows a conceptual representation of what the transects looked like in relation to the plume. Figure 28 shows the resulting oil concentration plot. And attempt was made to test a mapping function at Ohmsett but proved difficult due to "GPS wander." This process should be tested using a larger area in the field. It could conceivably be used in the field to map the areal extent of an oil plume.

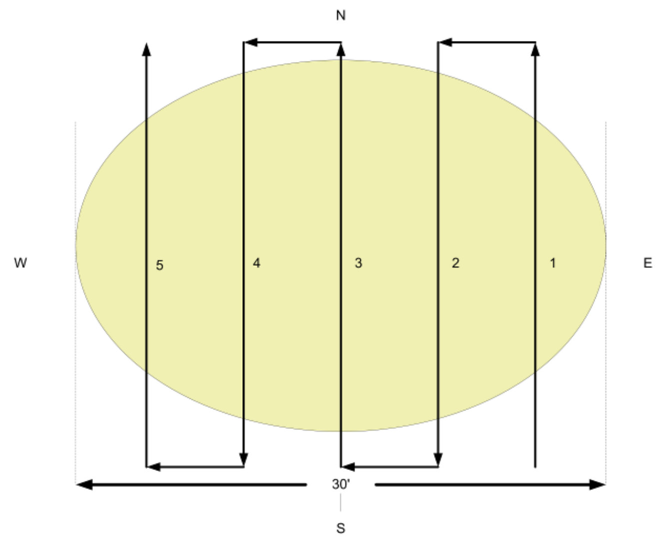

Figure 27. Test #113 conceptual mapping transects.

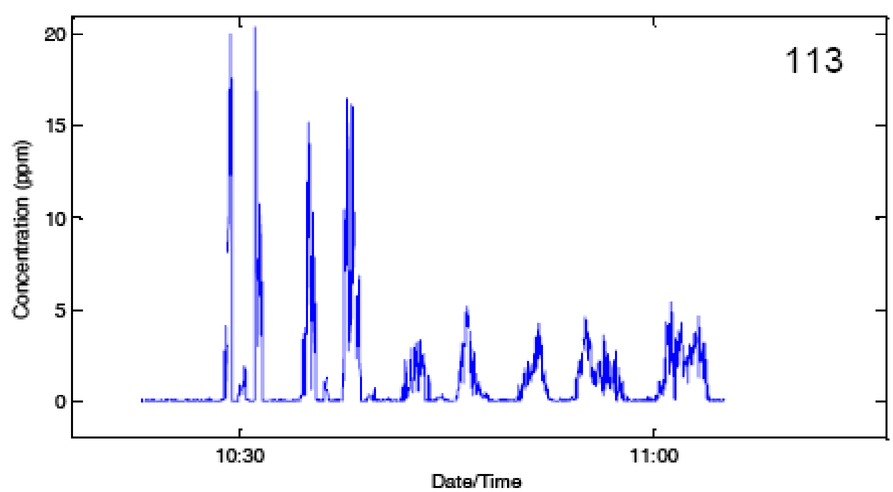

Figure 28. Test #113 oil concentration as a function of time.

3.2.7 Further Development

The next step is to conduct a field test in a towed configuration. The design of the case housing the sensors can be improved to allow for faster tow speeds. WET Labs envisions a commercially-transitioned sensor system with a single integrated unit making the measurements at all the required angles, instead of three individual sensors interfaced via cables to a data handling device.

4 SUMMARY OF PHASE II TEST RESULTS

4.1 General

Ohmsett developed the capability to release submerged oil plumes within the water column using an oil delivery system. The intention was for the plumes to remain neutrally buoyant for an extended period of time. Preliminary test runs with different types of oil led to the conclusions that straight Anadarko Crude and diesel (no dispersant added to each) atomized the best due to their low viscosity nature. During the preliminary test runs in the small tank, the duration of spraying was three minutes after which the water/oil was mixed for three minutes to equally distribute the dispersed oil within the water column. Under these conditions, the droplet concentration from the release of Anadarko Crude was fairly stable for up to twenty minutes (Figure 29). The expectation was that this would translate to the large tank as well.

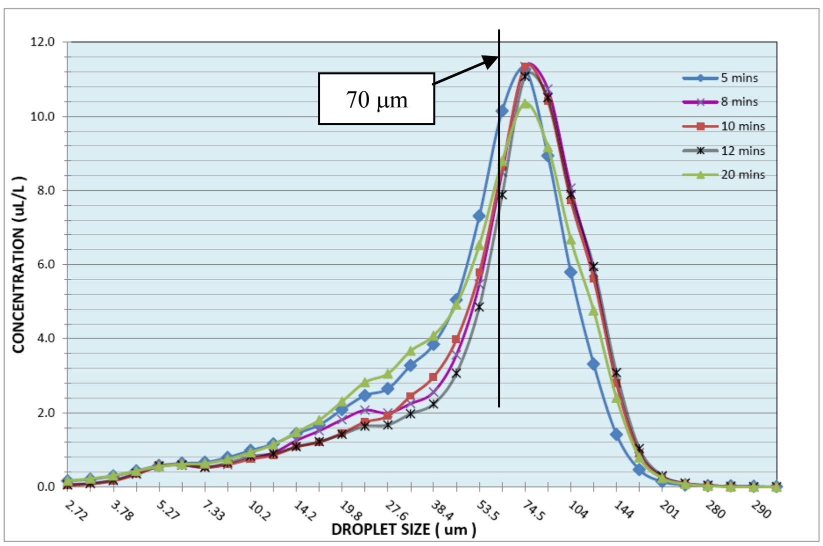

Figure 29. Anadarko Crude particle size distribution vs. concentration in small tank using the LISST instrument.

Unfortunately, this was not the case. The reality was that for a 3-minute release, the majority of the straight Anadarko Crude and diesel plumes began reaching the water surface before the test could commence. Unlike the preliminary test runs that took place in the small tank, it was not possible to stir the plume in the large tank to keep the oil droplets suspended in the water column. Figure 30 is an example of how quickly the plume changed in the large tank over time. The plot shows the LISST measurements of particle concentration as a function of droplet size and time for test #106 in which straight Anadarko Crude was used – a very different result from the small test tank. This rate of attenuation made it very difficult for the sensors to detect and map the plumes in the water column. See APPENDIX D for results of other plume releases in the large tank with LISST. It is noted that although plumes of oil mixed with COREXIT 9500 remain in the water column for a longer period of time, the concentration continues to attenuate over time.

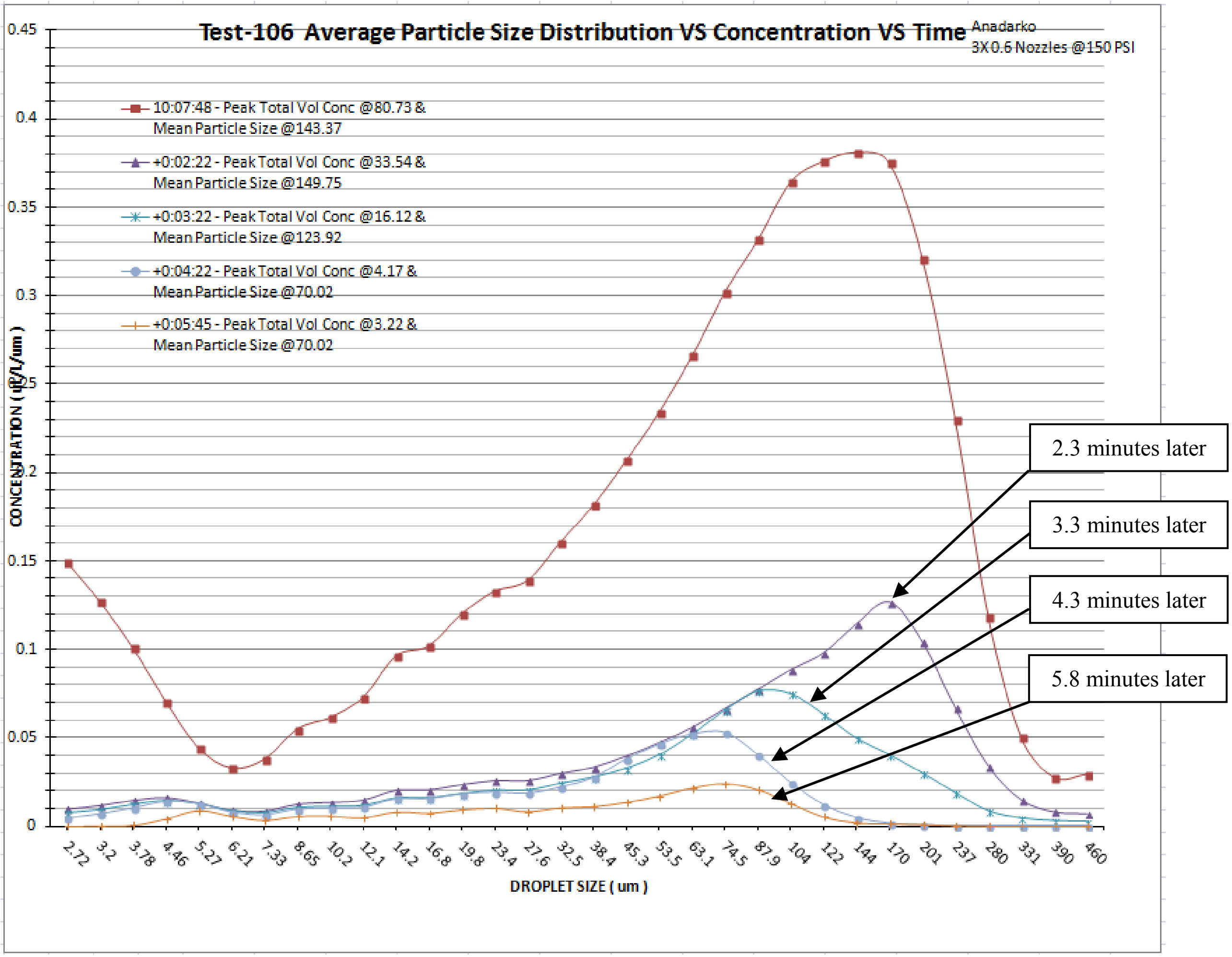

Figure 30. LISST droplet size concentration measurement from WINDOW Test #106.

Attempts were made to use the LISST to confirm what the other instruments were sensing and reporting. However, this proved to be almost impossible to achieve. In the case of the WBMS tests, the LISST runs were made after the WBMS runs were finished. From the plots in APPENDIX D, it can be shown that each plume release was not exactly the same as the previous release due to a number of possible factors. Possibilities include variations in the degree of clogging during each release or changes in the wind speed on the water surface from one test to the next, affecting the direction and range of the plume. Since it is impractical to drain the large tank, clean the walls, and refill it for each experiment, it was assumed that the submerged oil plume from a test experiment would make its way to the north end of the tank. In theory, this occurs because the filter pump in the north end of the tank allows the water to slowly move from south to north. However it may be possible that some oil droplets continued to linger in the water column from the last test to contaminate the next. Even though the LISST showed a reading of almost zero presence of oil, the fact remains that it captures only a small area of the water column and thus may have not detected the presence of oil droplets in other areas of the test region.

For the WINDOW tests, the LISST was attached to the WINDOW sensor cage and took measurements at the same time. Despite this placement, the instruments produced very different results. For example, Figure 31 shows the LISST droplet size concentration measurement from WINDOW Test #109. Figure 32 shows the WINDOW droplet size concentration calculation from the same test.

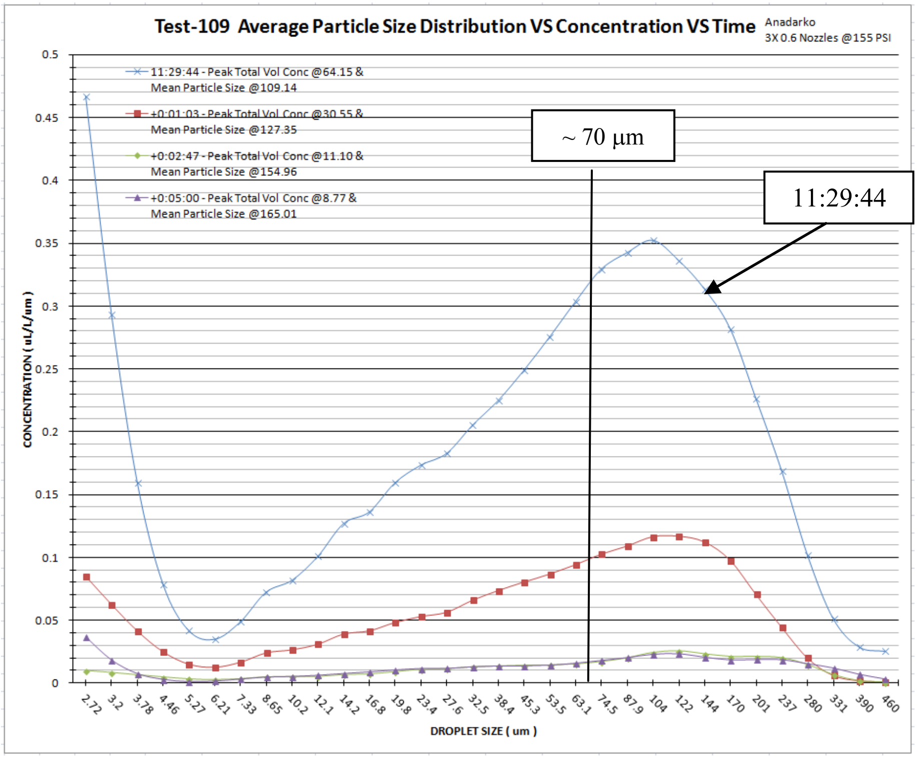

Figure 31. LISST droplet size concentration measurement from WINDOW Test #109.

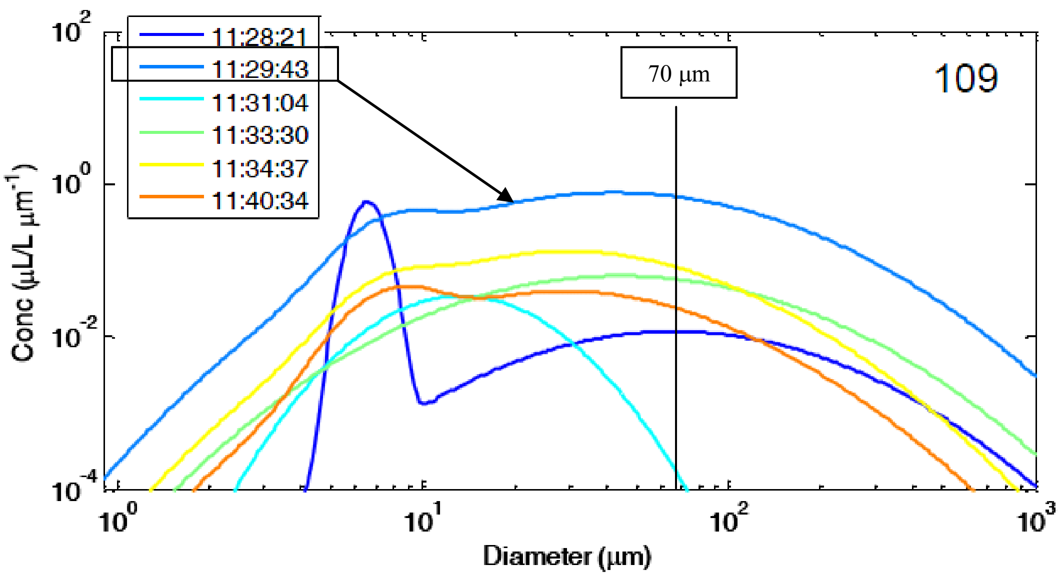

Figure 32. WINDOW droplet size concentration from Test #109.

To compare the data, the time of 11:29:44 from the LISST plot is used against the WINDOW concentration data during the time of 11:29:43 (light blue line – highest on graph). Considering both peaks, it appears that the LISST instrument shows a concentration peak at approximately 104 microns whereas the ECO sensors show that the concentration peaks occur over the range of 7 to 10 microns and 30 to 60 microns. The large differences in the peak concentrations indicate that the two instruments measured the plume differently.

It is unclear to the RDC what the primary factors are for the differences in results between the two sensors. Most results produced from the Ohmsett trials are similar to that of Test #109 where the concentration peaks identified by LISST and ECO sensors are different. Video evidence for some oil releases suggests that the LISST may have been fouled prior to commencing a transect test. Since the transecting did not start until the end of the 3-minute oil release, the plume sometimes would reach the LISST prior to the start of a test experiment. The ECO sensors should be unaffected by this pre-test plume contact since they had automated rotating wipers that kept the optical windows clean. Additionally, the faces of the ECO sensors are set approximately 6 inches behind the LISST's detection area so the sensors were not exactly measuring the same plane of the cross section of the plume. Some videos show the ECO sensors remained outside of the plume while the LISST was in contact with it before the test would commence. This means the LISST may have been fouled and thus the results do not lend confidence in that the characteristics of the plumes were validated. Although the exact nature of the plume could not be validated, the LISST did indeed show a large difference in the measurements between the background and in the center of the plume, indicating that oil was indeed present in the water column.

WINDOW Test #115 showed the most similar results between the two sensors (Figure 33 and Figure 34). The time of 13:29:38 from the LISST plot is used to compare against the WINDOW concentration data during the time of 13:29:46 (dark blue line, overshadowed by the light green line). From the LISST plot, the concentration peak appears to cover droplet sizes of 16 to 20 microns. The ECO sensors show that the concentration peak occurs over the range of 10 to 20 microns.

A video clip of Test #115 shows the plume rising slowly to the surface in a relatively vertical direction, keeping the bulk of the plume well away from the sensors. The first transect shows very similar results between the LISST and ECO sensors, which leads to the possibility that if both sensors are cleaned thoroughly before an experiment and placed in clean water without exposure to oil prior to a test run, then the submerged oil plume could be validated using the LISST. The submerged oil releases in the water column provide a new dimension of testing for Ohmsett. Consequently there are lessons to be learned to properly validate the characteristics of a subsurface oil plume. However, other aspects of the sensor equipment were able to be tested in the large tank with success.

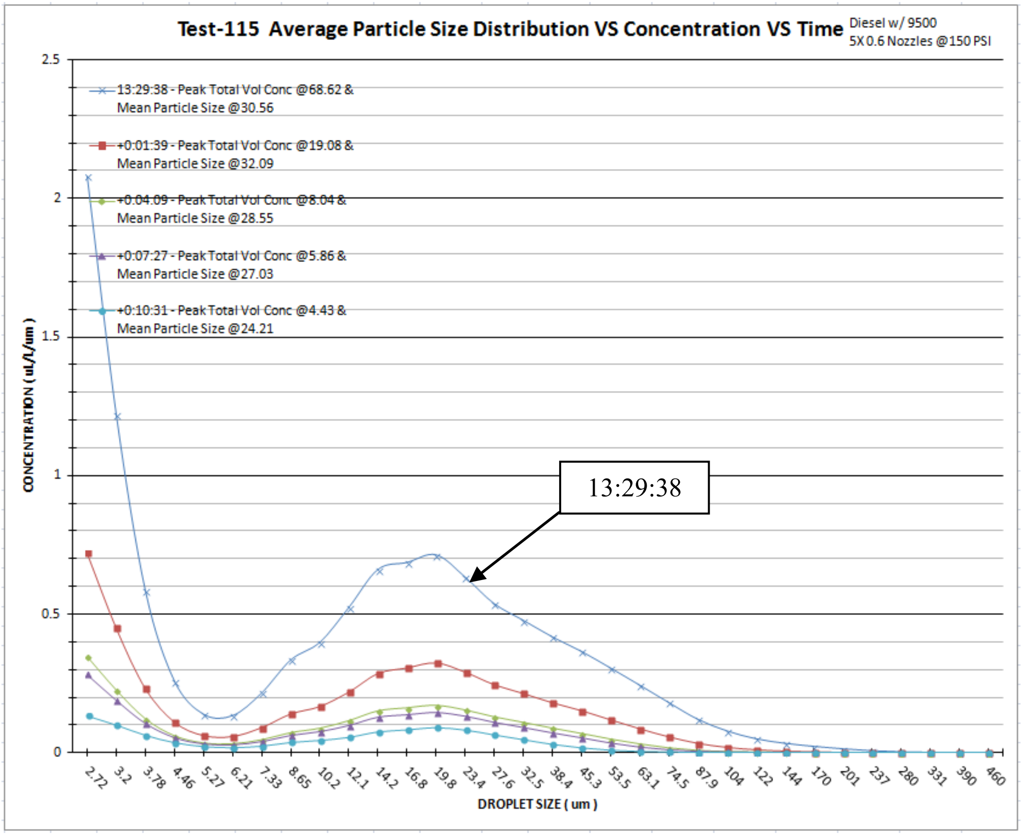

Figure 33. LISST droplet size concentration measurement from WINDOW Test #115.

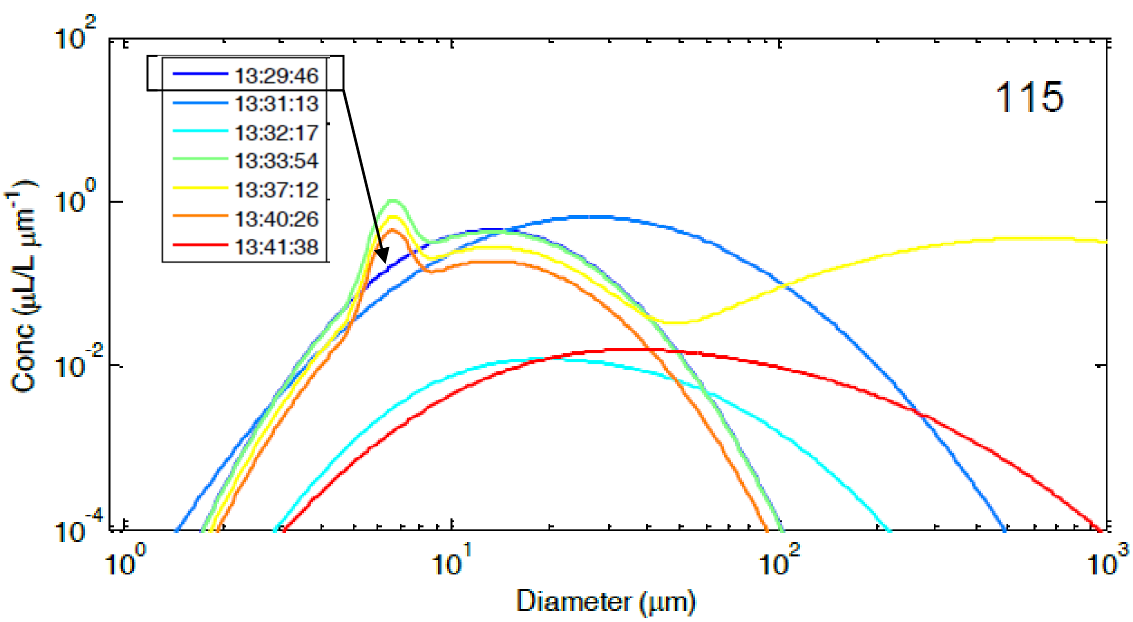

Figure 34. WINDOW droplet size concentration from Test #115.

4.2 NORBIT WBMS

Results from the trials showed that oil plumes could be detected reliably up to about a 40-ft (12-m) range with low but unknown concentrations. All test cases showed that the oil droplets rose relatively quickly to the surface so the plumes were dispersed within minutes. The detection range was limited by the very strong reflections from the tank boundaries; however, the estimated range for detection shows the system should be capable of detecting large leaks (270 ft^2 (25 m^2) cross-section) up to 295 ft (90 m) of range for these type of plumes. It also appears that the sonar can differentiate the general shape of the plume and obtain some information inside the plume but the actual concentration limits and particle sizes are not clear due to the lack of correlated information.

The 2D and 3D visualizations have shown a good potential for automation. Currently the mechanical movements of the sonar transducer have been used for proof-of-concept but electronic beam sweeping is highly recommended.

4.3 WET Labs WINDOW

Phase II work has demonstrated the feasibility of developing a compact, inexpensive, multi-angle scattering instrument with an automated inversion algorithm and intuitive smart phone display that quantifies the size distribution and determines the refractive index of the oil to readily derive density and viscosity.

All measurements with a static sensor package suspended above an injected plume of diesel or Anadarko showed a substantial hydrocarbon signal (typically 5-15 ppm concentration) during the duration of the oil release. After the period of oil release, a precipitous drop off in concentration was observed, although oil could still be detected for several minutes. Measured concentration levels were consistent with levels expected from the simulations.

Transecting through released plumes showed oil at the general location of the initial release, as expected. Distributions of plumes generally showed spiking variability instead of smooth Gaussian profiles because the package itself induced substantial mixing and patchiness of the oil plume with every pass, although when care was taken to not pass through the same location, plume distributions in many cases showed such smooth Gaussian features. Gaussian plume distributions are an expectation of diffusion dominated dispersion, as shown in the simulations.

4.4 Requirements Matrix

Table 3 summarizes how each system meets the BAA requirements as tested at Ohmsett, listed in order of importance.

1. Provides results in near real time (less than 1 hour);
2. Calibrates easily for different oils;
4. Works in currents or tow speeds up to 5 knots *(partial test)*;
5. Reports minimal false alarms;
7. Detects dispersed crude oil at levels of 0.5 ppb or lower;
8. Sweeps an area of water column 3 ft by 3 ft (0.9 m by 0.9 m);
9. Provides digital readout or measured values and digitally logs field data;
10. Is field rugged *(partial test)*;

11. Is portable;
13. Determines droplet size, density (specific gravity) and/or kinematic viscosity;
16. Deploys quickly and easily; and
18. Grabs water samples for further laboratory testing.

Table 3. Requirements matrix for Ohmsett.

Capability	WBMS	WINDOW
1. Provides results in near real time (less than 1 hour)	In setups with full bandwidth to the surface it will be real time data, in situations with sensor storage, data must be retrieved and processed.	Results were provided in < 1 min.
2. Calibrates easily for different oils	No calibration is needed other than a secondary verification of the oil.	Standard factory calibration to absolute VSF units once per year.
4. Works in currents or tow speeds up to 5 knots	Acoustic processing will not be affected by currents up to 5 kt.	Yes (3.5 kt at Ohmsett; >5 kt previously).
5. Reports minimal false alarms	A verification of the plume is needed and the false alarm should be zero. If the acoustic tool is used without verification there will naturally be a risk of detecting other substances with different impedances.	No evidence of reports of false positives or false negatives during Ohmsett testing
7. Detects dispersed oil at levels of 0.5 ppb or lower	The sensor will be able to detect dispersed crude oil, during tests the sensor appeared to detect below 20 ppm, and probably 0.5 ppb is not realistic.	Detection range was about 80 ppb to 80 ppm
8. Sweeps an area of water column 3 ft by 3 ft	Multibeam technology can sweep a significantly bigger area; tens of meters are realistic if there are dispersed oil plumes.	Sample volume is on the order of mL, but towing the sensors provided 3D resolution of oil concentrations throughout the water column
9. Provides digital readout or measured values and digitally logs field data	Yes	Yes
10. Is field rugged	Yes	Yes
11. Is portable	Yes	Yes
13. Determine droplet size, density (specific gravity) and/or kinematic viscosity	Inconclusive due to facility limitations.	Inconclusive due to facility limitations.
16. Deploys quickly and easily	NORBIT sonar is very compact and designed for easy and quick deployment; actual deployment time will vary depending on the platform.	Yes
18. Grabs water samples for further laboratory testing	No	Collected samples using hydrophilic tubing; the sensor system itself does not collect discrete samples.

Tablee 4 summarizes the requirements that need additional testing beyond Ohmsett, some of which were addressed in Phase I:

3. *Detects oil at depths up to 200 ft (~ 61 m);*
6. *Allows smooth data flow from field to command center;*
12. *Compatible with fresh and salt water;*
14. *Adapts to various depths (deep vs. shallow);*
15. *Operates from vessel in variety of conditions; and*
17. *Measures dissolved oxygen (DO).*

Table 4. Field requirements.

Capability	WBMS	WINDOW
3. Detects oil at depths up to 200 ft	No limitations; performance depends on the reflectivity from the plume.	Yes but not addressed at Ohmsett.
6. Allows smooth data flow from field to command center	Not addressed at Ohmsett.	Yes but not addressed at Ohmsett.
12. Compatible with fresh and salt water	Yes, small calibration if specific acoustic levels are required. This was not addressed at Ohmsett.	Yes but not addressed at Ohmsett.
14. Adapts to various depths (deep vs. shallow)	No difference from an acoustic standpoint.	Yes but not addressed at Ohmsett.
15. Operates from vessel in variety of conditions	Sonar operates in a variety of weather conditions. It is clearly an advantage to have the sonar mounted on a platform which is as stable as possible.	Not addressed. There are no foreseen limitations in terms of environmental conditions from a vessel.
17. Measures dissolved oxygen	No	Yes, sensor mounted at Ohmsett but data not reviewed.

5 RECOMMENDATIONS

5.1 NORBIT WBMS

The NORBIT WBMS system uses a well-developed, commercially available technology that has been used in various marine applications. Because the system scans the water column with multiple beams of different frequencies, the detection of a range of acoustic anomalies is possible. The system can survey a wide area of the water column although the exact concentrations are not known. Some of these plumes may have concentrations below 10 ppm.

The primary disadvantage of the system is the inability to conclusively discriminate petroleum hydrocarbons from other materials which may have a similar acoustic signature. The system may be able to detect oil in the water column, but positive identification and characterization may be difficult, especially if the oil disperses as individual droplets or is interspersed with silt or sand. More work is needed to be able to determine oil concentration and physical properties. In addition, acoustic profiling at multiple frequencies generates a large amount of data which must be stored and processed. This may limit real-time availability of data and imagery to support rapid decision-making. Finally, computer-automated interpretation and mapping of acoustic imagery is challenging, and real-time interpretation currently requires subjective analysis by a trained operator.

This system shows promise for detecting plumes from a distance and should be tested in the field. A field test would yield more beneficial results since the sensor would not be hampered by the reflectivity of the tank walls.

5.2 WET Labs WINDOW

As described in Table 3, the WINDOW prototype was able to meet most test requirements and effectively proved that the sensor was able to detect the presence of oil with minimal false alarms. It was noted that the prototype did not pick up the presence of oil when positioned in the tank without the oil plume ("clean" water) before and after a transect through the oil plume. Although the volumetric concentration data is shown instantaneously, processing raw data with the algorithm to characterize the plume takes time but can feasibly be performed in less than one hour.

Even though the instrument takes point source measurements, it still has rapid profiling capability that can take enough data points to create a detailed map, which was partially shown at Ohmsett. However, the GPS wander combined with the small size of the facility makes it unfeasible to create an accurate map of the submerged oil plume. The prototype still shows promise for mapping plumes over large areas and should be tested in the field with a fully furnished towed vehicle.

The prototype developed by WET Labs WINDOW team is portable, robust, and can operate in a variety of environmental conditions. It is able to determine the presence of oil and characterize the submerged oil plume although its accuracy could not be proven at Ohmsett. Its ability to capture screenshots of the developed map and send to smartphone users in JPEG format would be valuable to oil spill responders in being able to act quickly and efficiently. The RDC recommends that this prototype be further tested in the field with naturally occurring organic matter. The algorithm would need to be challenged with aggregated oils or particles mixed with oil in a fully towed package. The surveying would need to be timed to determine its quickness in determining the presence of oil and characterizing it as well. Its ability to disseminate information to the command center smoothly from the field should be explored as well.

5.3 Ohmsett

It is recommended that Ohmsett's ability to create oil plumes within the water column that remain neutrally buoyant for an extended period is enhanced. There are a number of improvements that could be explored including:

- Determining what particle size is necessary for neutral buoyancy in calm water. The research suggesting particles < 70 μm would be neutrally buoyant assumed moderate seas (Lewis, 2004). However, Fingas (2013) suggests that particles greater than 50 μm would rise quickly to the surface whereas smaller droplets of 20 μm or less remain stable in the water column for short periods of time.
- Introducing a wave condition to the testing because it is possible that the 70 μm droplet size may be neutrally buoyant when energy is present.
- Investigating the benefits of testing while a plume is continually being dispensed from the oil delivery system.

- Investigating the effects of using higher nozzle pressures with higher viscosity oils to potentially replicate plumes released from offshore wells.
- Finding an oil/nozzle combination that creates particles that remain suspended longer.
- Passing the LISST through the plume and determine the general disturbance using a sonar.
- Investigating additional procedures for confirming particle size distribution and plume shape during tests. If LISST is used for this, it would mean ensuring that both devices are registering information from the same part of the plume. A method to analyze still photographs of the visual part of the plume and document the size in all three dimensions could be helpful. Other methods may include a submersible holographic microscope and turbidity measurements.

5.4 Summary

The nominal objective of this RDC project was to identify, further develop, and test systems that can detect and characterize oil that is entrained and dispersed in the water column. Both prototypes have demonstrated the qualitative ability to detect and/or map oil suspended in the water column. Refer to Table 3 and Table 4 for details about the prototypes meeting most of the test requirements. The WBMS and WINDOW prototypes show promises in their abilities to quickly determine the presence of oil and relay the information to responders. In turn, they can make timely decisions to mitigate the impact of the submerged oil on the surrounding environment and infrastructure. There is further work to be done on both prototypes to test their abilities in field conditions as described above.

The Ohmsett staff developed an oil delivery system that was used for the first time at the facility with this oil in the water column project. It allowed the prototypes to demonstrate their abilities and enabled RDC to determine whether or not the diverse test requirements were met and thus suitable for field use. As well as the oil delivery system worked, there were many lessons learned. The biggest lesson was that the procedure in order to validate the oil plumes' characteristics to the best of Ohmsett's ability should be improved. It was difficult to ascertain with confidence that every oil plume created was repeatable. This prevented a quantitative evaluation of the prototypes' abilities to characterize the oil plume. Thus the BAA requirement number 13, which is determine the droplet size, density (specific gravity) and/or kinematic viscosity, could not be proven.

Some preliminary recommendations include taking samples of different areas of an oil plume and using a holographic microscope (not used in this project) to determine its characteristics. Every measure should be made to prevent the clogging of nozzles to ensure that every oil plume release is repeatable. Prior to a transect, the instruments should be kept well away from the oil plume, which does not always travel vertically after a release due to water movements in the tank. Another recommendation is to explore other oil types since straight Anadarko Crude and diesel (without the addition of COREXIT 9500) rose to the surface too quickly after a 3-minute release to allow for a proper evaluation of the oil plume's characteristics. Additionally, higher pump pressure should be explored to create smaller droplet sizes. Should a rigorous, proven test procedure be followed where it is ensured that every oil release is repeatable, the Ohmsett staff and other researchers may be confident that the data from the LISST or results from the holographic microscope can be used as a reference when comparing data from other new oil detection systems.

The oil delivery system itself was a newly developed capability for Ohmsett and it had its own challenges, and further work should be done to improve its capabilities. Despite some difficulties, there are many opportunities to improve on experimenting with oil in the water column at the Ohmsett facility. Even so, it is concluded that all instruments, including the LISST, were able to detect the presence of oil (straight Anadarko Crude, straight diesel, Anadarko Crude with COREXIT 9500, and diesel with COREXIT 9500) in the water column. For all test runs, the sensors collected background data prior to entering an oil plume to show the differences between the readings in "clean" water and oil plumes. Overall, the tests were a success in terms of verifying the detection systems' abilities to determine the presence of oil with high levels of confidence and provide the data quickly and efficiently. The prototypes were lightweight, robust, and deployed quickly and easily. It is recommended that both prototypes be further developed and tested in the field.

6 REFERENCES

6.1 USCG Internal References: Ohmsett and Vendor-Specific Design and Test Reports

Eriksen, M. T. (2013). USCG Contract HSCG32-12-R00005, *Prototype Test Recommendation*. Norbit US Ltd, 2013.

Eriksen, M. T., Eriksen, P. K., Søraunet, A., and Pocwiardowski,P. (2014). USCG Contract HSCG32-12-C-R00005, *Detection of Oil in the Water Column: Utilizing Ultra Wide Band Multibeam Acoustic Camera*. Norbit US Ltd, 2014.

MAR, Inc. (2013a), *Suspended Oil Delivery System Developmental Testing*. Prepared for Bureau of Safety and Environmental Enforcement, October 2013.

MAR, Inc. (2013b), *Evaluation of Oil in the Water Column Detection Systems at Ohmsett Test Plan*. Prepared for Bureau of Safety and Environmental Enforcement, Task Order 556, November 2013.

MAR, Inc. (2013c), Oil in Water Column Sub-sea Detection Systems (Test Binder). Prepared for Bureau of Safety and Environmental Enforcement, Task Order 556, December 2013.

Twardoswki, M. (2013). USCG Contract Number: HSCG32-12-C-R00012, *Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW) Prototype Testing Recommendations*. Western Environmental Technology Laboratories Inc., 2013.

Twardoswki, M. and Zhang, X. (2014). USCG Contract Number: HSCG32-12-C-R00012, *Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW) Phase-II Draft Final Report*. Western Environmental Technology Laboratories Inc., 2014.

6.2 Additional References

ASMA (2006). *Analyses of Survey, Modeling and Remote Sensing Techniques for Monitoring and Assessment of Environmental Impacts of Submerged Oil During Oil Spill Accidents*. Final report, June 2006.

Barbini, R., Colao, F., Fantoni, R., Ferrante, D., Palucci, A., and Ribezzo, S. (2000). Development of a LIDAR Fluorosensor Payload for Submarine Operation, *Proceedings of EARSeL-SIG-Workshop LIDAR*, Dresden/FRG, June 16 – 17, 2000.

Brown, C. E., Fingas, M. F, Gamble R. L., and Mysliski, G. E. (2002). The Remote Detection of Submerged Oil, 3*rd R&D Forum on High Density Oil Spill Response*, International Maritime Organization, Brest, France, March 11-13.

Cabioc'h, F. (2002). Sunken Hydrocarbons and Chemical Products: Possible Responses and Available Methods, *3rd R&D Forum on High-density Oil Spill Response*, International Maritime Organization, 11-13 March 2002, Brest, France.

Chapman, N. (2011). *Operational Guidelines on Sunken and Submerged Oil Assessment and Removal Techniques*, International Maritime Organization (in press).

Coastal Research and Response Center (CRRC). (2006). *Submerged Oil – State of the Practice and Research Needs*, Durham, NH, December 12-13, 2006 (http://www.crrc.unh.edu/workshops/submerged_oil/index.htm).

Conmy, R.N., Coble, P.G., Farr, J., Wood, A.M., Lee, K., Pegau, W.S., Walsh, I.D., Koch, C.R., Abercrombie, M.I., Miles, M.S., Lewis, M.R., Ryan, S.A., Robinson, B.J., King, T.L., Kelble, C.R., and Lacoste, J. (2013). Submersible Optical Sensors Exposed to Chemically Dispersed Crude Oil: Wave Tank Simulations for Improved Oil Spill Monitoring, *Environ. Sci. Technol.*, 2014, *48* (3), pp 1803–1810 Publication Date (Web): December 30, 2013 (Article) DOI: 10.1021/es404206y.

Daling, P.S., Moldestad, M.Ø., Johansen, Ø., Lewis, A., and Rødal, J. (2003). Norwegian Testing of Emulsion Properties at Sea – the Importance of Oil Type and Release Conditions, *Spill Science & Technology Bulletin,* Vol. 8, Nos. 2, pp. 123-126, 2003.

Elliott, J. (2005). An Analysis of Underwater Oil Recovery Techniques 2005. Proceedings 2005 *International Oil Spill Conference*, American Petroleum Institute, 11 pages.

Fant, J.W. & Hansen, K.A. (2005). U.S. Coast Guard Oil Spill Remote Sensing: Preliminary Laser Fluorosensor Studies, *Proceedings of the Twenty-eighth Arctic Marine Oilspill Program Technical Seminar*, pp. 861-872. Environment Canada, Ottawa, ON.

Fant, J.W. and Hansen, K.A. (2006). U.S. Coast Guard Laser Fluorosensor Testing, *Proceedings of the Twenty-ninth Arctic Marine Oilspill Program Technical Seminar*, pp. 951-964. Environment Canada, Ottawa, ON.

Fingas, M. (2013). A Review of Natural Dispersion Models, *Proceedings of the Thirty-sxith Arctic Marine Oilspill Program Technical Seminar*, pp. 207-233. Environmental Canada, Ottawa, ON.

Fingas, M. (editor) (2011). Oil Spill Science and Technology - Prevention, Response and Cleanup, Elsevier Inc., Oxford, UK.

Fitzpatrick, M. and Ashburn, O.D. (2011). *Deepwater Horizon Response Submerged and Sunken Oil Symposium*, USCG Research and Development Center, January 2011.

Fitzpatrick, M. and Tebeau, P.A. (2013). *Detection of Oil in Water Column: Sensor Design*, US Department of Homeland Security, February 2013.

Hansen, K.A. (2009). Research Efforts for Detection and Recovery of Submerged Oils, *Proceeding of the 2009 Interspill Conference*, Marseille, France, May 12-14.

Hansen, K.A., Bello, J., Clauson, S., Camilli, R., Bingham, B., Eriksen, M.T., Maillard, E. and Luey, P.J. (2008). Preliminary Results for Oil on the Bottom Detection Technologies, *Proceedings of the Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, 2008.

Hansen, K.A. , Fitzpatrick, M., Herring, P.R., and VanHaverbeke, M. (2009). *Heavy Oil Detection (Prototypes) – Report CG-D-08-09*, US Department of Homeland Security, June 2009.

Hutley, T., Munoz, L., Pascal, B., and Altendorf, J. (2011). National Strike Force Development of a SMART Monitoring System using the Turner Designs C-3 Submersible Fluorometer, *2011 International Oil Spill Conference,* American Petroleum Institute, poster.

Johansen, Ø., Rye, H., and Cooper, C. (2003). DeepSpill – Field Study of a Simulated Oil and Gas Blowout in Deep Water, *Spill Science & Technology Bulletin,* Vol. 8, Nos. 5–6, pp. 433–443, 2003.

Johns, M.W. and Beckmann, D. (2011). Subsea Monitoring and Analytical Results: Subsea Dispersed Oil, MC252 Deepwater Horizon Release, *2011 International Oil Spill Conference,* American Petroleum Institute, poster.

Kepkay, P., Bugden, J., Li, Z., Lee, K., Coble, P., Conmy, R., and Wood, M. (2011). Tracking Oil Dispersion in the Gulf of Mexico by Fluorescence Intensity (FI) and the Fluorescence Intensity Ratio (FIR), *2011 International Oil Spill Conference,* American Petroleum Institute, poster.

Lambert, P., Goldthorp, M., Fieldhouse, B., Wang, Z., and Fingas, M.F. (2001). A Review of Oil-in-water Monitoring Techniques, *2001 International Oil Spill Conference,* American Petroleum Institute, 6 pages.

Lee, K., Nedwed, T., and Prince, R.C. (2011). Lab Tests on the Biodegradation Rates of Chemically Dispersed Oil Must Consider Natural Dilution, *2011 International Oil Spill Conference,* American Petroleum Institute, 12 pages.

Lewis, A. (2004). Determination of the Limiting Oil Viscosity for Chemical Dispersion at Sea, final report for the Defra, ITOPF, MCA, and OSRL. MCA Project MSA 10/9/180. http://ukerc.rl.ac.uk/pdf/AE0817_report.pdf

Li, Z., Lee, K., Kepkey, P.E., Mikkelsen, O., and Pottsmith, C. (2011). Monitoring Dispersed Oil Droplet Size Distribution at the Gulf of Mexico Deepwater Horizon Spill Site, *2011 International Oil Spill Conference,* American Petroleum Institute, 15 pages.

Marcos, Seymour, J. R., Luhar, M., Durham, W. M., Mitchell, J. G., Macke, A., and Stocker, R. (2011). Microbial alignment in flow changes ocean light climate, *Proceedings of the National Academy of Sciences 108*, 3860-3864.

Michel, J. (2006). *Assessment and Recovery of Submerged Oil: current State Analysis*, prepared for US Coast Guard Research and Development Center, June, 2006.

Michel, J. (2008). Spills of Non-Floating Oils – Evaluation of Response Technologies: *Proceedings 2008 International Oil Spill Conference*, American Petroleum Institute.

National Research Council (NRC). (1999). *Spills of Non-Floating Oils: Risk and Response*. National Academy Press, Washington, D.C.

Norwegian Testing of Emulsion Properties at Sea (2003). The Importance of Oil Type and Release Conditions. Spill Science & Technology Bulletin, Vol. 8, No. 2, pp. 123–136.

Panetta, P.D., Bland, L.G., Winfield, K., McElhone, D., Cartwright, G.G., and Friedrichs, C.T. (2013). *Assessment of Dispersant Effectiveness Using Ultrasound to Measure Oil Droplet Particle Size Distributions*. Prepared for Bureau of Safety and Environmental Enforcement, February 2013.

Rymell, M. (2009). RP595, Sunken and submerged oils – behavior and response, *A Report for the Maritime and Coastguard Agency*, BMT Cordah Limited, February, 2009.

Schnitz, P.R. and Wolf, M.A. (2001). Nonfloating Oil Spill Response Planning, *2001 International Oil Spill Conference,* American Petroleum Institute, 5 pages.

Sequoia. LISST-100X Particle Size Analyzer User's Manual, Version 4.62.

U.S. Coast Guard, National Oceanic and Atmospheric Administration, U.S. Environmental Protection Agency, Centers for Disease Control and Prevention, and Minerals Management Service (2006). *Special Monitoring of Applied Response Technologies*.

Usher, D. (2006). Responding to Submerged Oils in Freshwater Environments, *Freshwater Spills Symposium*, 2006.

Vargas, F.M. and Chapman, W.G. (2010). Application of the One-Third rule in hydrocarbon and crude oil systems, *Fluid Phase Equilibria*, 290, 103-108.

WET Labs, Inc. (2012). *WETStar Fluorometer User's Guide, Revision T*. March 2012.

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APPENDIX A. SUSPENDED OIL DELIVERY SYSTEM DEVELOPMENT

A.1 Objective

The primary goal of this effort was to develop the capability to create oil plumes within the water column that remain neutrally buoyant for an extended period of time. Plumes were to be created using two types of oils in their raw state and with the addition of dispersant. Essential components necessary to achieve this goal were an oil delivery system and a means of accurately measuring plume characteristics. The first step was to design and fabricate an oil delivery system capable of providing varying pressures and flows to orifice nozzles underwater. The LISST 100X sensor was chosen to measure experimental plume characteristics. This Appendix summarizes the testing process used to develop the oil delivery system at Ohmsett. For complete details see MAR, Inc. (2013a).

A.2 Background

Research into designing the oil delivery system revealed that there is limited information available related to equipment and methods to create controlled oil plume releases underwater. Initial design of the oil delivery system considered a combination of baseline parameters used during a previous subsea dispersant research project at Ohmsett and engineering estimates to identify the ranges of operational pressures and nozzle orifice sizes to create minute oil droplets underwater.

A.3 Description of Oil Delivery System

A primary component of the oil delivery system is the nozzle. Controllable parameters include nozzle type and orifice diameter. For this design, an "atomizing" type nozzle was chosen with orifice sizes ranging from 0.016 inches to 0.086 inches. Delivering oils to the nozzle required a pump capable of achieving high pressures at low flow rates. These operating parameters are best met by industrial metering pumps. These pumps are typically used in process applications to inject low doses of an agent into a pressurized fluid stream. The pump selected for this application was capable of providing a constant pressure of 150 psi at any flow rate up to 1.4 gallons per minute (gpm). Figure A-1 shows the schematic drawing for the oil delivery system design. Other components included:

- Pulsation damper: Double diaphragm pumps create a pulsating action. The pulsation damper absorbs the surges of energy and provides the desired constant pressure in the lines.
- Inline filter: This component is used prior to testing to pre-filter the test oil to remove particulate 5 µm and above to prevent clogging of the nozzle.
- Back pressure regulator: This component regulates the pressure on a manifold line at the end of the run to provide constant controllable/adjustable pressure within the oil distribution line feeding the nozzle.
- Solenoid valves: These valves are normally closed valves which require power to activate to the open position. The plumbing arrangement with two solenoid valves simulated the configuration of a three-way valve. With the pump running, this configuration provided a means of establishing an initial flow and backpressure through a recirculation loop and instantaneous switching to discharge and off again.

- Check valves: The check valves located close to the discharge nozzle ensure oil present in the unused line does not leak back through the nozzle and into the test area.
- Pressure relief valve: The pressure relief valve was added as a safety device and set for 150 psi. In the event of a deadheaded line, this device provided a route for the pumped fluid to return to the reservoir.
- Liquid filled pressure gauge: Provided system pressure readings within the supply line during bypass and discharge through the nozzle.

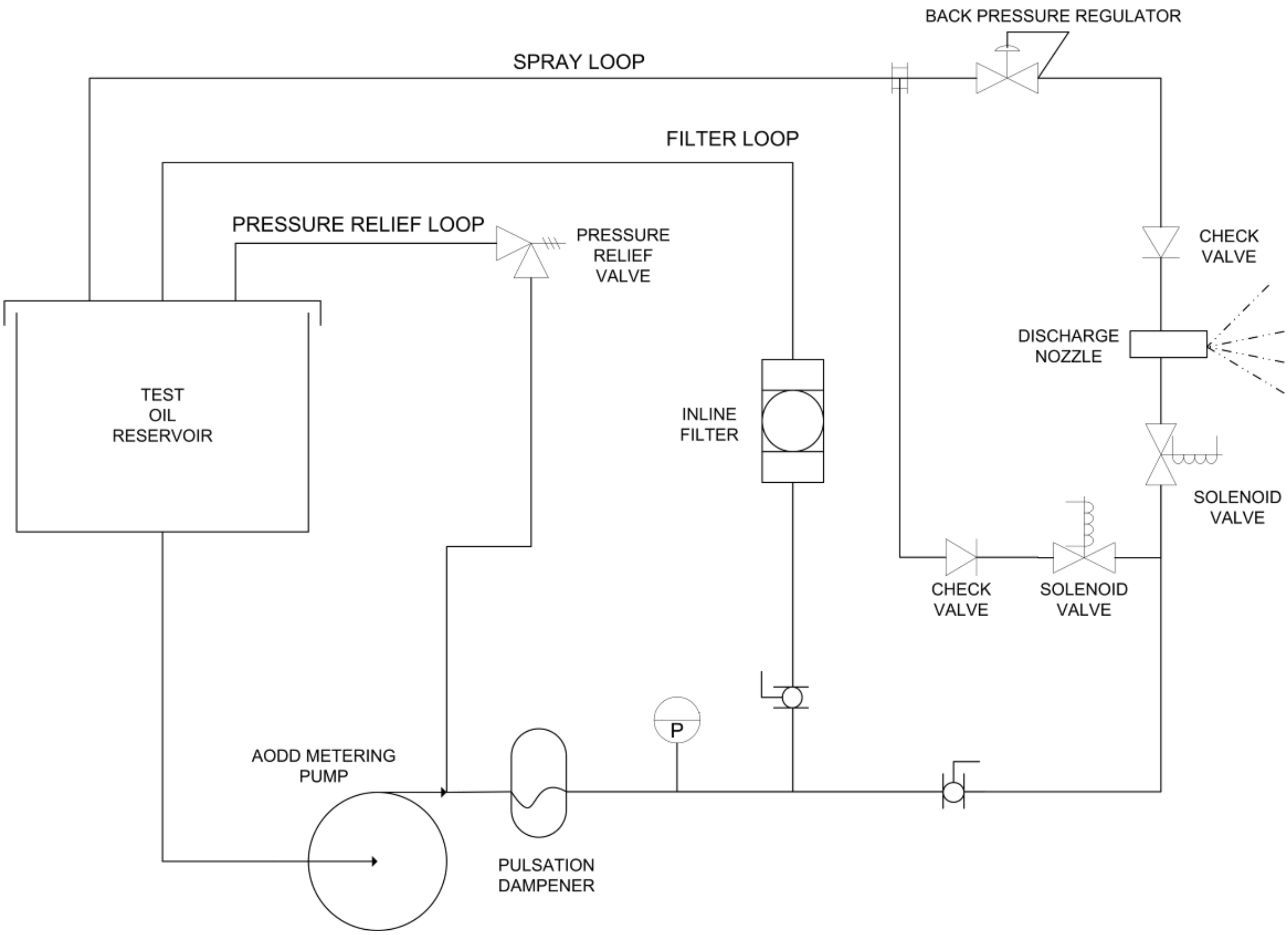

Figure A-1. Oil delivery system schematic.
(Based on MAR, Inc., 2013a)

The components of the oil delivery system were assembled on a fiberglass pallet which served as a rugged level platform and a convenient means of relocating the system by forklift, shown in Figure A-2. Electrically, the pump was wired as 110 volts and controlled by an on/off switch at the pump. Additionally the electric solenoid valves (2) were powered by a 24-volt power supply and wired through a single pole double throw switch simulating the function of a three-way valve. This feature was incorporated into the design allowing the pump to circulate the oil in a bypass mode and then provide instantaneous dispensing of oil at high pressure through the nozzle.

Figure A-2. Oil delivery pump system.

A.4 Test Setup

The test area for the oil delivery system was comprised of three major components: the oil delivery system, a small-scale test tank, and the particle size analyzer. The tank was a modular structurally supported steel tank with a fiber reinforced polypropylene liner measuring 4 ft (1.2 m) high x 4 ft (1.2 m) wide x 8 ft (2.4 m) long (capacity of one thousand gallons) (see Figure A-3).

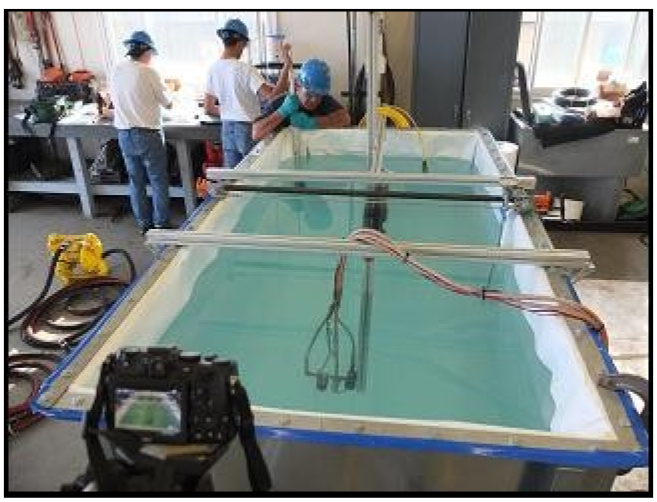

Figure A-3. Modular tank with nozzle apparatus in place.

Water used for testing was pumped directly from the Ohmsett main tank, with a water depth of 3.5 ft (1.1 m) throughout testing. Each test began with clean water. Between tests the tank walls were cleaned to remove residual oils. Some continuation tests were performed in which the initial water and oil droplets remained and spraying times were added to increase the overall concentrations being measured.

Also shown in Figure A-3 are the brackets used for the mounting and placement of the oil spraying nozzle. Brackets were constructed of 80/20 Inc. aluminum beams and allowed for easy adjustment. The position of the nozzle was documented relative to the waterline and distance from the face of the particle size analyzer.

The initial location of the LISST was 1.3 ft (0.4 m) below waterline and 2.5 ft (0.76 m) from the spray nozzle. The depth of the spray nozzle was 2.1 ft (0.64 m) from the waterline and remained there for the entire experiment.

Figure A-4 shows the bracket assembly constructed and used to mount and handle the particle size analyzer. The two vertical members provided a means of easy adjustment to varying depths below the waterline. Not shown in the figure, the vertical members were attached to a cross member which was connected to an overhead hoist. The hoist provided a means of placing and removing the particle size analyzer into the test area. Removal was required to perform a thorough cleaning of the analyzer lenses and to obtain a "clean" background prior to each test.

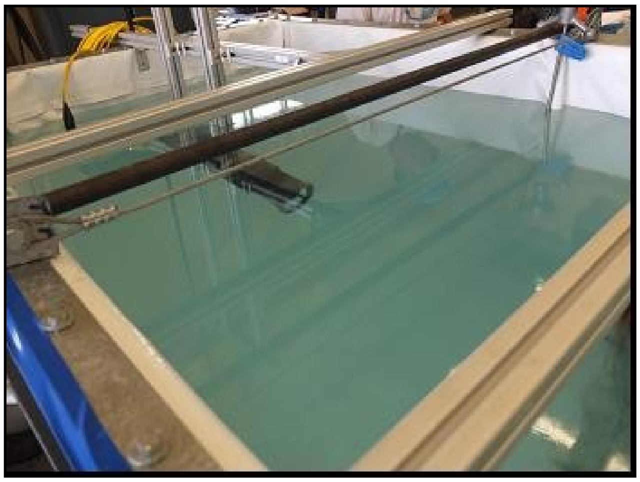

Figure A-4. LISST particle size analyzer in its support frame.

A.5 Test Methodology

A.5.1 Approach

The process of injecting fluids (oil) at high pressures underwater to obtain a specific range of droplet size distributions is a unique area of study. From historic dispersant testing, it is known that oil droplets approximately 70 µm and less tend to remain neutrally buoyant in moderate seas, depending on physical parameters such as oil and water densities and temperature. In general, adding dispersant to the oil creates droplets of much smaller diameters given the same jetting parameters. Selection of nozzles with corresponding pressures, varying viscosities, and resulting droplet sizes with oil are not available within manufacturers' performance specifications. Typical specifications available provide results for the spraying of water into air. To achieve the objective of creating an oil plume, a trial and error approach was taken. A range of possible nozzles were selected allowing for numerous combinations of pressures and orifice sizes. A total of seven nozzles were obtained to explore their ability to atomize the oil into sub-70 µm droplets. The sizes from largest to smallest were:

- -26 (0.086 inch orifice),
- -18 (0.076 inch),
- -10 (0.064 inch),
- -6 (0.042 inch),

- -2 (0.028 inch),
- -1 (0.020 inch) and
- -0.60 (0.016 inch).

Within the modular test tank, oil was dispensed through the selected nozzle at predetermined pressures to create the test plume. Oil droplet size distribution and concentration measurements were obtained using the LISST particle size analyzer. Figure A-5 shows the LISST attached to a mounting frame and suspended from an overhead hoist used to install and remove the instrument from the tank.

Figure A-5. LISST suspended from hoist.

Prior to placing the nozzle apparatus into the test tank, the pump and back pressure regulator were adjusted to operate at the desired pressure. Once adjusted, the flow from the nozzle was captured into a graduated cylinder and timed to quantify flow rates. Figure A-6 shows the relative positioning of the LISST and spray nozzle at the beginning of a test.

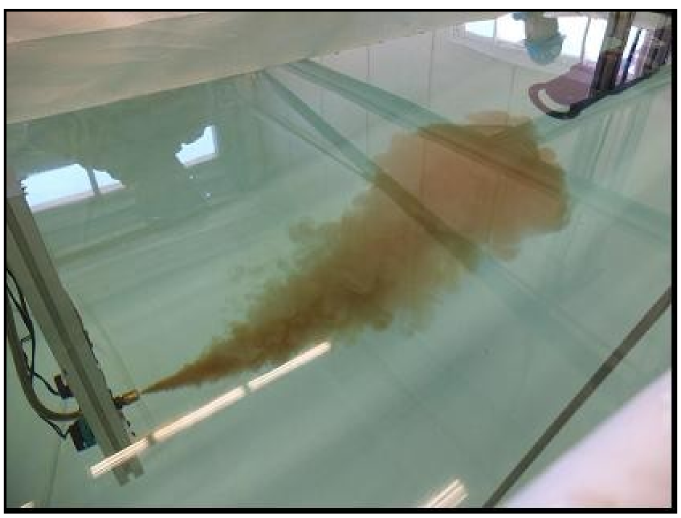

Figure A-6. Test plume being created.

A.5.2 Test Procedure

The procedure employed during experiments evolved slightly based on observations and measurements obtained. The test sequence is described below.

- Pre-set pump and back pressure regulator to "test" pressure.
- Operate oil delivery system in bypass mode.
- Start LISST data collection file. Allow approximately 10 seconds collecting initial background of water.
- Switch oil delivery system on for predetermined duration (durations varied).
- Stop oil delivery system.
- Stir/homogenize droplets within tank (time of mixing varied based on observations).
- Collect LISST data for 20 minutes (times varied).
- End files. Remove LISST for cleaning. Evacuate tank water, clean tank, and replenish.

A.5.3 Test Fluids Properties

Table A-1 contains the property analysis of the test oils and water used during the experiment.

Table A-1. Test oils properties.

Sample Description	Sample #	Viscosity @ Temp (g/cm @ °C)	ρ @ Temp (g/ml @ °C)	Surface Tension (dynes/cm)	Interfacial Tension (dynes/cm)
HYDROCAL	556-01	194.4-16.2 40-10 °C	0.9054 22.7 °C	35.5	21.6
DIESEL	556-02	6.8-17.3 40-10 °C	0.84 22.7 °C	32.6	22.7
DIESEL/ COREXIT9500 (DOR 1:5)	556-03	12.6-16.9 40-10 °C	0.85 22.7 °C	30	22.3
NORTHSTAR	556-04	10.8-17.4 40-10 °C	0.85 22.9 °C	29.7	21.4
NORTHSTAR/ COREXIT9500 (DOR 1:20)	556-05	12.9-16.3 40-10 °C	0.8647 22.7 °C	29.7	21
NORTHSTAR/ COREXIT9500 (DOR 1:5)	556-06	12.5-17.8 40-10 °C	0.87 22.8 °C	29.3	20.7
ANADARKO	556-07	27.7-33.0 40-10 °C	0.91 23.0 °C	33	4.7
ANADARKO/ COREXIT9500 (DOR 1:20)	556-08	11.3-20.3 40-10 °C	0.91 22.9 °C	32.7	4.5
TEST BASIN WATER	556W-01	61.1	1.0205 @ 20.9 °C	30.8	38.8

A.6 Experimental Results

A.6.1 Test Matrix

Main Table 6 defines the matrix of tests performed and the key parameters used during each test. Tank water was replenished between tests with Ohmsett basin water unless noted otherwise.

A.6.2 Description of Results

The objectives of this experiment were two-fold: (1) develop an oil delivery system capable of creating oil plumes within the water column and (2) identify two different oils in which droplet sizes can be created sufficiently small to remain neutrally buoyant for an extended period of time.

Table A-2. Delivery system test matrix.

Test #	Nozzle Size (inch)	Line Pressure (psi)	Oil Type	Visc. (centi-poise)	Discharge Flow Rate (gpm)	Notes
1	0.042	95	Diesel	---	----	Dry run – operate oil delivery system to adjust/ confirm functionality (fresh water)
2	0.042	120	Diesel	~7.5	0.18	Discharged nozzle into graduated cylinder to determine flow rate. Determined other flow rates prior to individual tests
3	0.042	120	Diesel	~7.5	0.18	First test — spray duration = 24.2 sec
4	0.042	140	Diesel	8.6	0.19	Spray duration = 26.2 sec
5	0.042	140	Diesel	8.6	0.19	Continued test 4 to increase oil droplet concentration. Spray duration = 2.0 min
6	N/A	N/A	Diesel	8.6	N/A	Measured oil droplet sizes and concentration from test 5, 18 hrs after test
7	0.042	100	Diesel	~15.0	0.17	Spray duration = 30.3 sec
8	0.028	100	Diesel	~15.0	0.06	Spray duration = 60 sec
9	0.028	140	Diesel	~15.0	0.07	Spray duration = 29.9 sec
10	0.020	140	Diesel	~18	0.040	Spray duration = 60 sec
11	0.016	140	Diesel	~19	0.023	Spray duration = 120 sec
12	0.016	140	Diesel	~19	0.023	Continued test 11(same water) to increase oil droplet concentration. Spray duration = 2.0 min
13	0.016	140	Diesel/ COREXIT 9500 (1:5)	~17	0.023	LISST lenses became fouled, inaccurate data. Spray duration = 2.0 min
14	0.016	140	Diesel/ COREXIT 9500 (1:5)	~20	0.023	Continued test 13 (same water). Spray duration = 2.0 min (4 total)

Table A-2. Test matrix (cont.).

Test #	Nozzle Size	Line Pressure (psi)	Oil Type	Visc. (centi-poise)	Discharge Flow Rate (gpm)	Notes
15	0.016	140	Diesel/ COREXIT 9500 (1:5)	~20	0.023	Continued test 14 (same water), experimented with removing LISST attenuator, lens saturated.
16	0.016	140	Northstar Crude	~21.5	0.043	Spray duration = 60 sec
17	0.016	150	Northstar/ COREXIT 9500 (1:5)	~23	0.048	Spray duration = 60 sec
18	0.016	150	Northstar/ COREXIT 9500 (1:5)	~22	0.047	Spray duration = 60 sec
19	0.016	140	Northstar/ COREXIT 9500 (1:5)	~22	0.047	Continued test 18 (same water). Spray duration = 60 sec T18; 60 sec T19 (2.0 min total)
20	0.016	150	Anadarko	~33	0.045	Spray duration = 60 sec
21	0.016	150	Anadarko	~33	0.045	Continued test 20 (same water) Spray duration = 60 sec T20; 60 sec T21 (2.0 min total)
22	0.016	150	Anadarko/ COREXIT 9500 (1:20)	~22	0.045	Spray duration = 60 sec
23	0.016	145	Anadarko/ COREXIT 9500 (1:20)	~22	0.045	Continued test 22 (same water) Spray duration = 60 sec T22; 60 sec T23 (2.0 min total)
24	0.016	140	Anadarko/ COREXIT 9500 (1:20)	~15	0.045	Performed in basin, video and photo documentation only. Spray duration = 30 sec
25	0.016	140	Anadarko/ COREXIT 9500 (1:20)	~16	0.045	Performed in basin, video and photo documentation only. Spray duration = 30 sec
26	0.016	140	Diesel	~19	0.023	Performed in basin, video and photo documentation only. Spray duration = 30 sec
27	0.016	140	Diesel	~19	0.023	Repeat of test 12, longer spray duration of 180 sec, fresh water
27a	0.016	N/A	Diesel	~19	N/A	Measured concentration and droplet sizes after 30 minutes at different depths to determine stratification
28	0.016	145	Diesel	~19	0.023	Repeat of test 12, longer spray of 180 sec, well mixed immediately after spraying
28a	N/A	N/A	Diesel	~19	N/A	Measured concentration and droplet sizes after 25 minutes at different depths to determine stratification

A.6.2.1 Oil Delivery System

When constructing the oil delivery system there were a few necessary features incorporated into the design to provide the capabilities to accomplish the task. Below is a description of features that were significant, as well as their purpose and how they functioned.

- Three–way simulated valve: This electrical switch operated feature allowed for the pump to be operating in a bypass mode with flow under backpressure at the immediate area of the nozzle. When activated it provided immediate discharge at the nozzle with required line pressure. This operated flawlessly and eliminated pressure ramp up and thereby dispensed oil at test pressures.
- Backpressure regulator: This feature provided backpressure in the return line and was found to provide the range of pressures as desired, as well as sensitivity and ease of adjustment.
- Inline filter loop: Although no problems were encountered with particles clogging the nozzles, upon a redesign it would be recommended to install a supply tank to pre-filter the oils prior to testing and then transfer the fluid to the pump source tank.
- Double diaphragm pump: As specified and claimed by the manufacturer, the pump provided 150 psi at varying flow rates.
- Pulsation damper: The pulsation damper proved effective in stabilizing the line pressure and minimizing pulsation.

The overall performance of the oil delivery system was as expected and no problems were encountered during the test series. The system was operated in a range of 95 to 150 psi, the maximum pressure capability of the pump.

A.6.2.2 Oil Droplet Size Distributions

The following is a chronology of the testing performed and descriptions of the method employed for measurements using the LISST. Typically, oil droplet characteristic measurements were obtained over an extended time frame to quantify changes of droplet size distribution with respect to time. A discussion of observations and subsequent changes to either the test method or setup is included. Graphs are included for the two oils selected. Graphs from all tests are included in MAR, Inc. (2013a).

The initial testing began with a 0.042 inch nozzle. The first oil used was pure diesel sprayed through the nozzle at pressures of 100, 120, and 140 psi. It should be noted that at this point in time, the optimum spraying duration time had not been determined. For the three tests shown, 3, 5 and 7, the spray durations were 24 sec, 120 sec and 30 sec. This variation affects the total concentration values but not the droplet size distribution. Figure A-7 presents the comparison of each pressure in terms of concentration versus droplet size distribution. Figure A-8 shows the percentage of droplets by size for each pressure after twenty minutes. Although the data do not indicate significant differences, based on the cumulative concentration graph, the 140 psi spray did produce a higher percentage of smaller droplets of 53.5 μm and less.

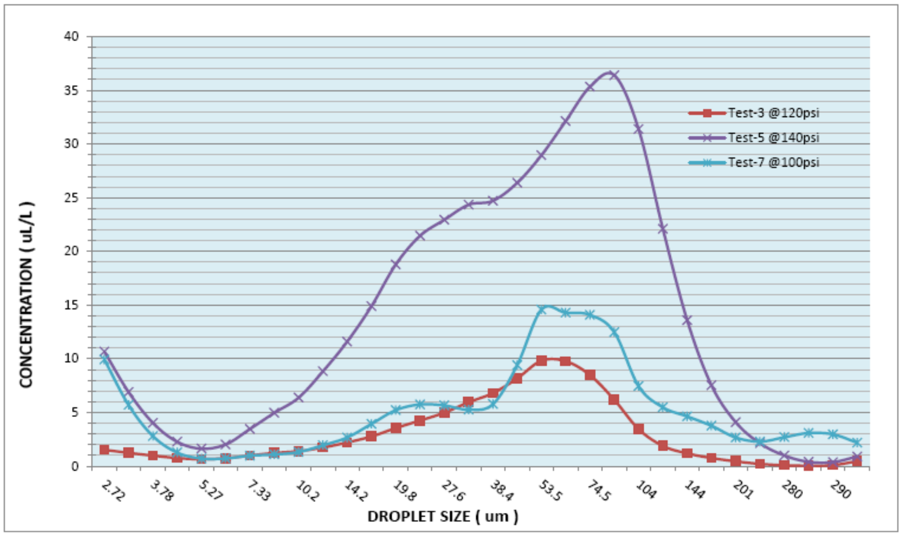

Figure A-7. Diesel droplet size distribution comparison (0.042 inch nozzle). (100, 120, and 140 psi)

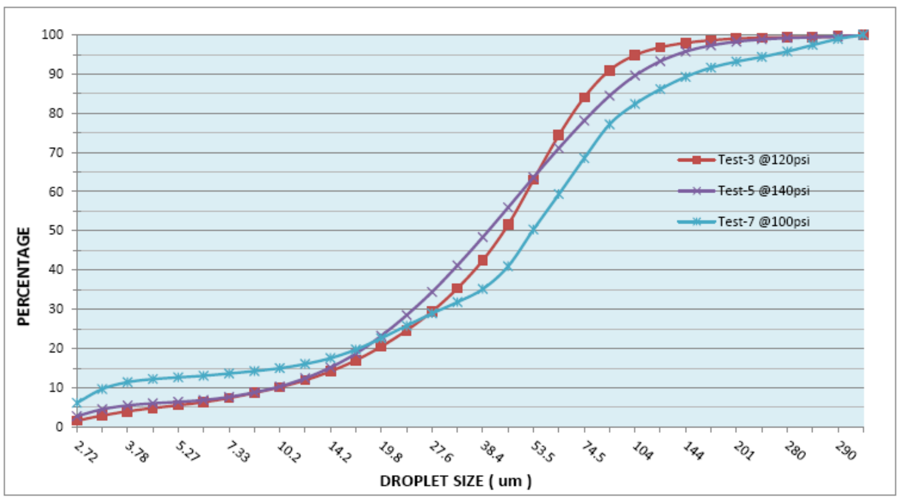

Figure A-8. Diesel percentage vs. droplet size comparison (0.042 inch nozzle). (after 20 minutes @ 100, 120, and 140 psi)

Two experiments were performed using a 0.028 inch nozzle with diesel oil. Spraying at 100 psi appeared to create a larger concentration in the 2.72 µm (and most likely lower) to the 5.27 µm range, but also created a larger concentration of droplets above 70 µm. The distribution results between 100 and 140 psi provided support to move forward using the higher pressure.

The next two smaller nozzles, a 0.020 inch and a 0.016 inch, were used to spray diesel oil at 140 psi. Figure A-9 illustrates the concentration versus droplet size distribution. The curves indicate that the 0.016 inch nozzle created a minimal amount of droplets in the range of 74.5 µm and larger. Also shown, the 0.020 inch nozzle did create a relatively larger volume of droplets in the 74.5 to 200 µm range where the 0.016 inch droplet distribution was 104 µm and smaller.

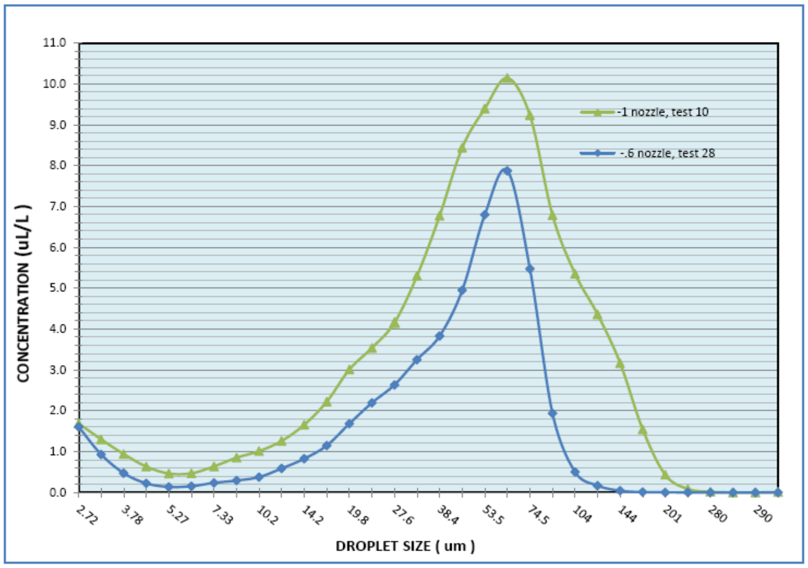

Figure A-9. Comparison of 0.020 vs. 0.016 inch nozzles with diesel.
(140 psi after 20 minutes)

Based on these preliminary experiments, where pressures were varied and nozzle sizes were explored, researchers concluded that using the smallest orifice nozzle and highest pressure provided the most desirable droplet size distribution. Although larger nozzles and lower pressures did create small droplets, these parameters tended to yield a wider band of droplets into the larger than 70µm range.

For subsequent tests in which oil type comparisons were performed, the 0.016 inch nozzle and spraying pressures in the 140-150 psi range were used. Figure A-10 shows the oil droplet size distribution for diesel over a 20 minute time frame. The duration of spraying was three minutes after which the water/oil was mixed for three minutes to equally distribute the dispersed oil within the water column. Concentrations for droplets sizes at approximately 50 µm and below appeared to remain relatively consistent whereas above 50 µm there appeared to be changing concentrations. Figure A-11 illustrates the percent by droplet size sprayed at 100 and 140 psi within the water column after 20 minutes. The effect of adding dispersant at a DOR of 1:5 was explored and the resulting droplet distribution is shown in Figure A-12.

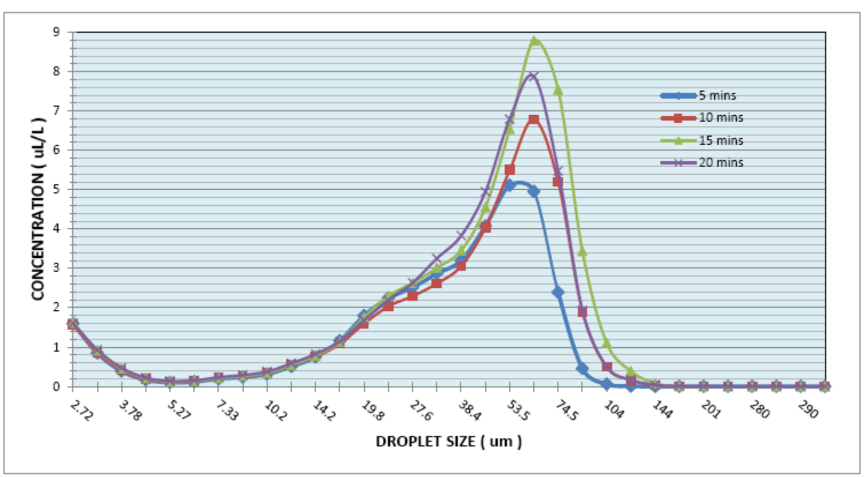

Figure A-10. Particle size distribution vs. concentration for diesel with 0.016 inch nozzle @ 140 psi.

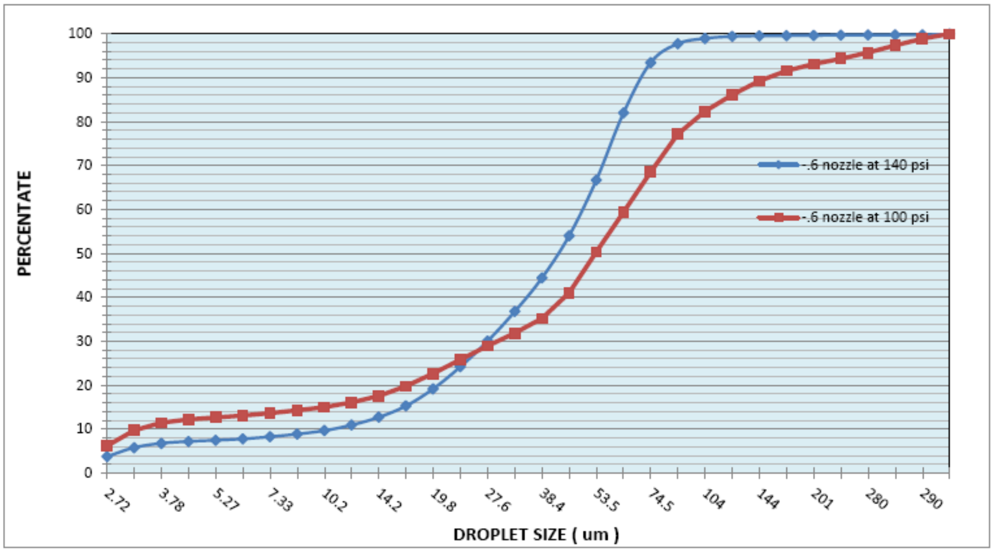

Figure A-11. Cumulative concentration after 20 minutes for diesel, 0.016 inch nozzle @100 & 140 psi.

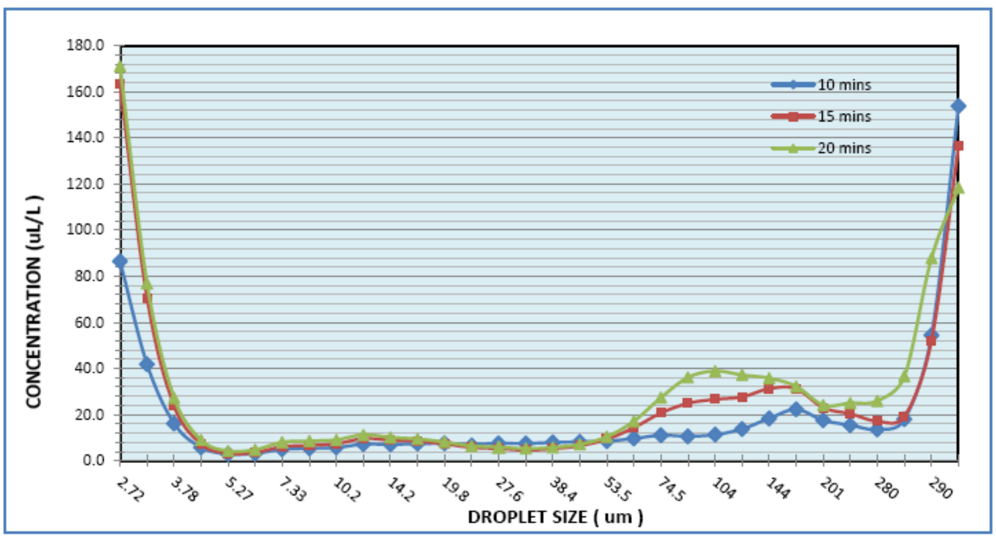

Figure A-12. Particle size distribution vs. concentration for diesel with dispersant. (0.016 inch nozzle@140 psi and DOR 1:5)

A significant portion of the diesel plume was comprised of very small droplets with a low overall concentration in the range of 20 - 70 µm as in the untreated diesel graph. The water appeared “milky,” a known indication of very small dispersed droplets (see Figure A-13).

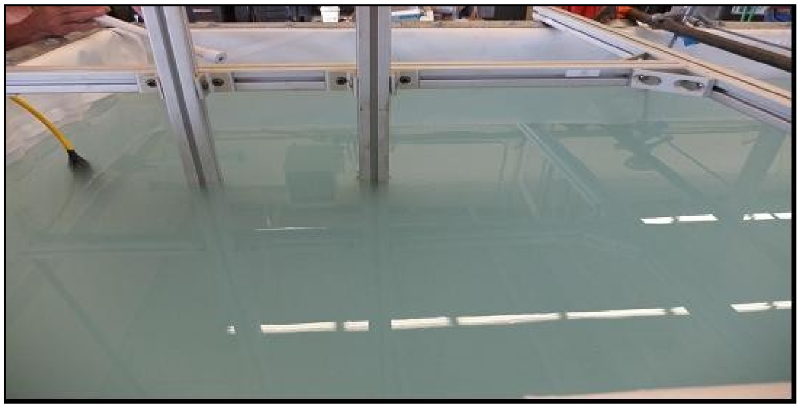

Figure A-13. Diesel dispersed.

Use of a second oil was explored to create a plume with different initial properties. The next oil tried was Hydrocal 300, an Ohmsett stock test oil. It was quickly determined during preliminary flow measurements that the nozzle and pressure combination was inadequate to atomize the oil in air and therefore would not be successful. It was apparent that the viscosity was too high (200 centipoise (cP) at 20 ^{o}C) and would require higher pressures. The next alternative oil chosen was Northstar Crude. Its viscosity was approximately 15 cP at 20 ^{o}C with a density of 0.91. The resulting distribution was unique in that there are two distinct ranges in which droplets formed. A significant portion of oil surfaced during the spraying; apparently the droplets measured after 20 minutes were still in the water column.

Using the same nozzle and line pressure, the effects of adding COREXIT 9500 at a DOR of 1:5 to the Northstar Crude were explored. Of interest is the fact that concentrations of formed droplets did not change over the 20-minute time frame. Although small droplets formed, a significant portion of oil surfaced immediately after being sprayed. Since a large fraction of oil surfaced, Northstar Crude was eliminated as an option for use in the large tank.

Anadarko Crude was tested next for possible use. Figures A-14 and A-15 illustrate the droplet size distribution and the percentage versus droplet size of Anadarko Crude using the 0.016 inch nozzle sprayed at 150 psi.

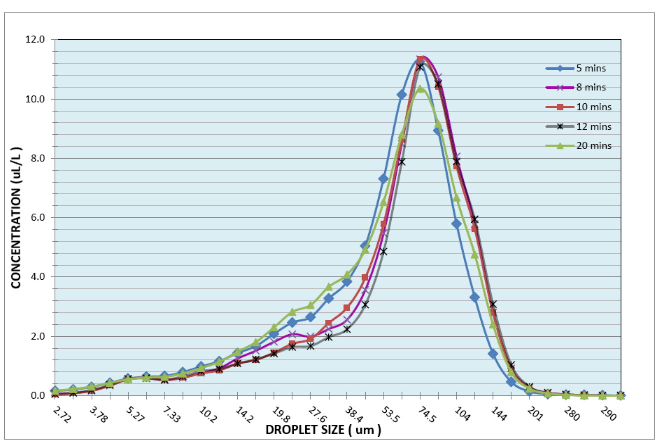

Figure A-14. Anadarko Crude particle size distribution vs. concentration.

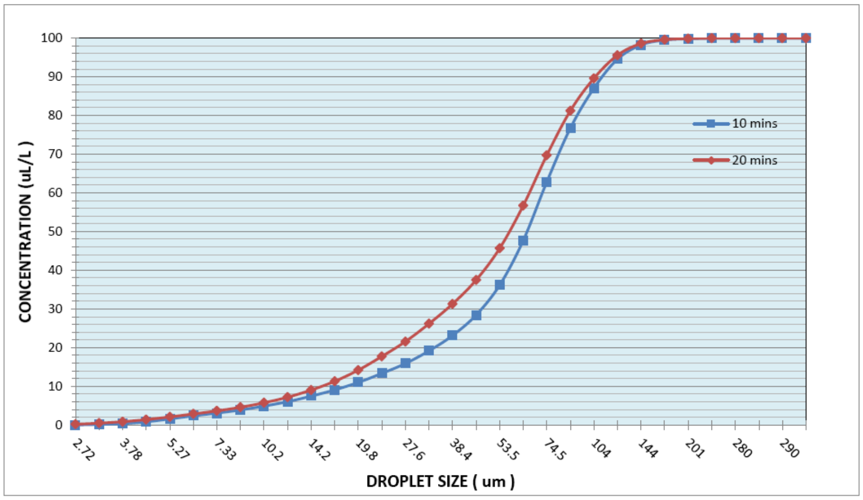

Figure A-15. Anadarko Crude concentration vs. droplet size.

Anadarko Crude was also evaluated after being treated with COREXIT 9500 with a DOR of 1:20. As shown in Figure A-16, the Anadarko Crude oil droplet size distribution is primarily at 70 µm and below. These results provided the narrowest range of droplets size all below the targeted 70 µm and less.

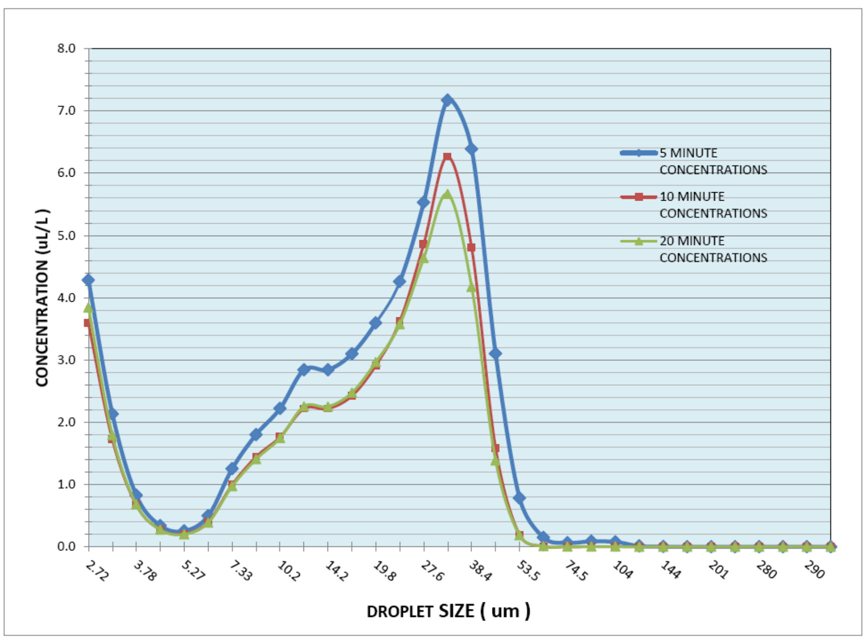

Figure A-16. Particle size distribution vs. concentration, Anadarko Crude with dispersant.

An attempt was made to determine if stratification of oil droplets was occurring during the experiments which would not have been visible to the eye. Following test number 28 (diesel, 0.016 inch nozzle at 145 psi), an additional data set was recorded with the LISST in which the depth of the sensor was incrementally positioned from seven inches below surface to the bottom to the test tank. Figure A-17 shows the droplet size comparison based on depth 40 minutes after the test start. The graph shows a slight drop off in concentration of the larger particles and consistent concentrations at approximately 20 µm and less.

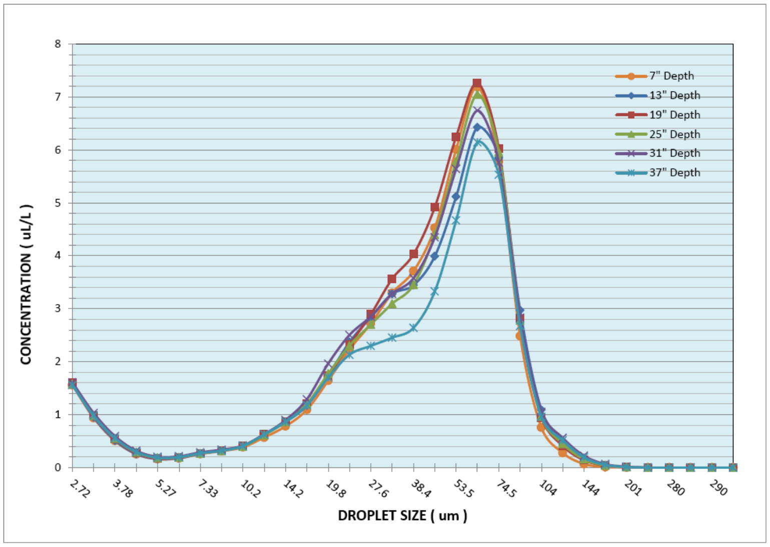

Figure A-17. Diesel particle size distribution vs. concentration, depth comparison.

Also interesting to note is the oil droplets above the targeted 70 μm range that were still present at the 40 minute mark.

A.7 Conclusions and Recommendations

Based on these preliminary experiments, where pressures were varied and nozzle sizes were explored, researchers concluded that using the smallest orifice nozzle and highest available pressure provided the most desirable droplet size distribution. For subsequent tests in which oil type comparisons were performed, the 0.016 inch nozzle and spraying pressures in the 140-150 psi range was used.

Concerning the selection of oils for use in the subsequent testing, based on the objectives to identify two oil types for use to create plumes in their raw form and treated with dispersant, diesel and Anadarko Crude produced the most desirable oil droplet distributions.

Related to further work in this area, the available combination of orifice sizes and pressures were found to produce oil droplet size distributions in the realm desired to meet the test objectives; however, investigating the effects of higher pressures with higher viscosity oils would be beneficial to potentially replicate plumes released from offshore wells.

When performing lab sized experiments as in this effort, alternative and redundant measurement techniques may be beneficial to explore. Such methods may include a submersible holographic microscope and turbidity measurements.

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APPENDIX B. TEST PROCEDURES

B.1 Planned Procedures

Ohmsett personnel created a preliminary test plan for each contractor to collect data in relatively clean tank water (background data), followed by Ohmsett's staff creating a suspended oil plume and the contractor acquiring additional data to determine if their equipment could detect the plume.

The test plan was modified to reflect the fact that the two systems acquire data differently. In general, the NORBIT system collects data at various distances outside the plume while the WET Labs system collects data while transiting through the plume.

As the water in the test basin is relatively quiescent compared to the ocean, small oil droplets created in the test basin tend to rise faster than they would in a more turbulent environment. Initially, the test procedure was identical for both contractors, but the time the oil was expected to remain suspended in the water column, on the order of minutes, required adjusting the test method so that each contractor would have sufficient time to acquire data.

B.1.1 NORBIT

The information in this section is from USCG internal references Eriksen (2013) and MAR, Inc. (2013b).

Optimum Test Scenario

NORBIT equipment uses the reflections of sound to gather information of objects under water. Generally speaking, harder objects generate a stronger return signal than softer objects. This information is used to determine the type of object. For this particular test the object, i.e. oil, is an object with characteristics very close to that of water. So in order to detect and characterize oil as the purpose of this test, it is very important that other strong reflectors are not present within the acoustic field. Generally the boundaries, e.g., the seabed and/or the sea surface, are the limiting factors for successful detection. In particular with the very low reflectivity targets as an oil plume, the reverberation from the seabed is significantly higher than that of a volumetric low concentration plume.

An optimum setup for NORBIT would be open calm sea, or in a very big test tank, where the test would not be limited by walls/bottom. That way all other interferences could be eliminated and pure data on oil obtained. As the objective of this project is detection of oil plumes near those boundaries (e.g., bottom/ surface) it is optimal to have as a realistic bottom reverberation as possible.

Planned Equipment Setup

The plan is for the WBMS sonar with rotator to be mounted on a pole which will be affixed to the bridge. The pole will be long enough to move vertically from water surface to just above tank bottom, making it possible to scan the full water column. Mid-column scan is the primary setup, as a secondary test setup the sonar can be placed in the water surface and angled downwards looking at the plume as it rises to the surface. Sonar will be connected to survey computer and will be powered from the bridge. Figure B-1 shows the recommended test set-up.

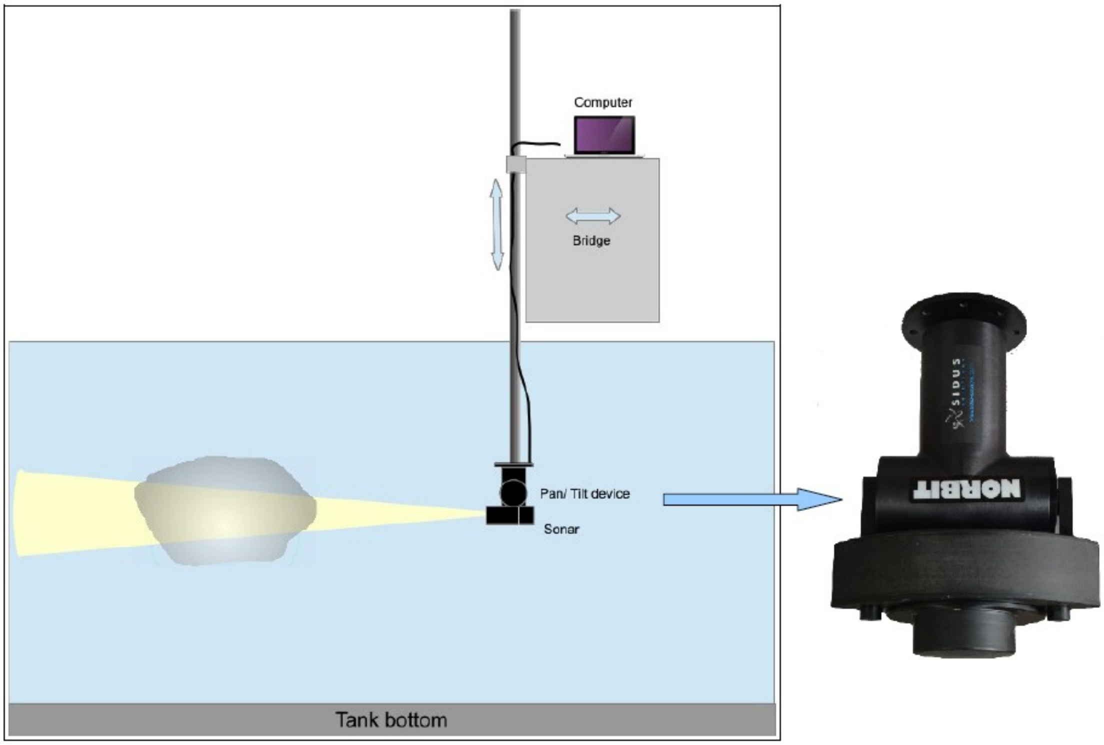


Figure B-1. WBMS recommended test set-up.

Planned Procedure

The WBMS acquires data from outside the plume. For this test series, the plan is to create discrete plumes in the tank and allow NORBIT to collect data at different distances from the plume: approximately 6, 16, 33, 66, and 98 ft (2 m, 5 m, 10 m, 20 m, and 30 m). As the plumes dissipate over time, it is unlikely that data from all the distances will be acquired from the same plume due to the time it takes to move the main bridge into position and for NORBIT to acquire data. While NORBIT will use the nozzle assembly support shaft as a target to initially aim their sonar prior to the release of oil, they requested that the oil spray nozzle assembly be removed from the water after creating the plume so it does not interfere with their data.

Prior to the start of the test, the main bridge will be positioned near the north end of the tank, yet allow an additional 98 ft (30 m) of north travel during the test. The spray nozzles will be deployed in the tank 23 ft (7 m) off the west wall, at a depth that will be determined during NORBIT's preliminary/practice runs, but likely near the bottom at a depth of ~ 7.3 ft (2.24 m). Pressurized oil will flow to the spray nozzles for 30 seconds to 3 minutes, depending on the results of NORBIT's preliminary/practice runs. NORBIT requested starting with higher oil concentrations (longer durations) and finishing with lower concentrations (shorter duration). At the end of the time, flow to the nozzles will cease, the nozzle assembly will be pulled from the water using the main bridge crane and the main bridge will move north until the WBMS is the correct distance from the plume. NORBIT requested starting with the closest distance. When NORBIT has gathered sufficient data at that position, the main bridge will move to the next position (2 m to 5 m, 5 m to 10 m, etc.) and NORBIT will again collect data. This will continue until NORBIT has acquired data at each position or until the plume has dispersed and is no longer detectable by NORBIT's equipment.

The main bridge will reset to the same north/south position as before, but the nozzles will be deployed in the tank 7 m off the east wall. Staggering the plumes will minimize the suspended oil from one test interfering with subsequent tests. The next test will repeat the process described above.

Once the data have been collected, the test will be repeated twice (three tests total) for each oil. Once the sequence is complete, it will be repeated for the next oil in the matrix. See Table B-1 for the proposed test matrix.

Table B-1. WBMS proposed test matrix.

Day	Run	Oil	Dispersant	Nozzle size (inch)	Pres	Duration	Surface	Notes
Mon	1-6	Diesel	No	0.016	140psi	3 min	calm	Setup & preliminary (practice) runs
Mon	7	Diesel	No	0.016	140 psi	3 min	calm	Discrete plumes
Tues	8	Diesel	No	0.016	140 psi	3 min	calm	Discrete plumes
Tues	9	Diesel	No	0.016	140 psi	3 min	calm	Discrete plumes
Tues	10	Anadarko	No	0.016	140 psi	3 min	calm	Discrete plumes
Wed	11	Anadarko	No	0.016	140 psi	3 min	calm	Discrete plumes
Wed	12	Anadarko	No	0.016	140 psi	3 min	calm	Discrete plumes
Wed	13	Anadarko	9500	0.016	140 psi	3 min	calm	Discrete plumes
Thurs	14	Anadarko	9500	0.016	140 psi	3 min	calm	Discrete plumes
Thurs	15	Anadarko	9500	0.016	140 psi	3 min	calm	Discrete plumes
Thurs	16	Diesel	9500	0.016	140 psi	3 min	calm	Discrete plumes
Fri	17	Diesel	9500	0.016	140 psi	3 min	calm	Discrete plumes
Fri	18	Diesel	9500	0.016	140 psi	3 min	calm	Discrete plumes
Fri	19	tbd	tbd	Variable	Variable	Variable	calm	Optional tests
Fri	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Derig and decon

If time permits, an optional test may be conducted. For this test, either a small stream of oil, or individual drops of oil, will be released near the bottom of the tank to simulate an underwater pipe that is leaking. To dispense the oil, the nozzle manifold will be disconnected from the support shaft and the nozzles will be replaced with threaded plugs. One of the plugs will be not fully tightened (approximately one turn past hand tight in preliminary tests) to allow pressurized oil to seep past the threads, enter the water column and rise. The spacing between the oil drops is changed by varying the oil pressure. The manifold assembly will be deployed into the tank and rest on the bottom of the tank. The oil supply lines will be paid out along the bottom of the tank towards the walkway so they do not interfere with NORBIT's data acquisition. The support stalk will be temporarily positioned just over the manifold assembly on the bottom of the tank so NORBIT can pre-aim their sonar. NORBIT will position their instrument approximately 6 ft (2 m) away from the oil supply manifold. Once NORBIT's instrument is aimed, the support stalk will be lifted from the water as in earlier tests. The oil line will be pressurized; trace quantities of oil will seep past the plug threads, into the water column and rise. NORBIT will attempt to detect either individual drops and/or a small stream of oil. If they are successful, NORBIT"s instrument will be relocated to a distance 5m from the oil supply manifold and the test will be repeated. The instrument will be moved farther from the oil to determine the maximum distance the instrument can detect the oil.

NORBIT also requested a test of their vertically oriented instrument, which would either look up at a plume from underneath, or down at a plume. If time permits, these may be attempted. To maximize the time the plume remains suspended, and minimize interference between the plume, the oil dispensing nozzles and the

WBMS, only oil with dispersant will be used and it will be dispensed for a short burst, on the order of 5-10 seconds.

To provide a soft bottom and minimize bottom sonar reflection, an 8 ft x 8 ft (2.5 m x 2.5 m) aluminum tray filled with sand may be positioned on the bottom of the tank. The spray nozzles would be positioned on top of the sand, with the oil lines arranged as in the oil stream test. NORBIT's equipment would be positioned directly above the sand tray and acquire data before, during, and after the release of oil. It is likely the WBMS will become engulfed by the plume. If possible, the scenario will be repeated, but this time the WBMS will be moved into position below the plume after it the plume is created and has risen sufficiently.

Droplet and Plume Sizes

The understanding was that the Anadarko Crude and diesel oils were chosen for their ability to stay suspended in the water column for about 2 minutes before moving to the surface. This would provide a time long enough time for NORBIT to record test data. NORBIT will only need a timespan of seconds to record data, but longer time gives the ability to record more data, or move the trolley while recording.
Plume size is not very important but NORBIT suggested the plume to be bigger than one square foot.

Concentration should be varied from test to test, starting with the higher concentration. Concentration has been discussed with OHMSETT and further tests will provide a more specific suggestion before the tests starts.

Advantages of Testing at Ohmsett

- An important advantage of testing at Ohmsett is the ability to fairly easily, and in a short time, perform several tests, and by that gather a good amount of data.
- Conditions are known, i.e., we will know the flow direction, temperatures, waves etc., and all tests can be performed in a very similar matter, which is important for test comparison.
- Tests can be recreated if needed and oil concentrations can easily be changed; i.e., we can learn as we go and change or perform extra tests if needed.
- Droplet sizes can be generated in a reliable manner with known variation of sizes.
- Different oil types can be tested relatively easily.

Disadvantages of Testing at Ohmsett

- One important disadvantage is the enclosed space the test tank provides. Reflections from side walls and/or bottom/surface disturb measurements. This particularly becomes a problem when testing at longer distances, and will be a limiting factor for how far away from the oil tests can be performed.
- The amount, type, and duration of contamination of the tank is unknown. It is known that microspheres in hybrid dispersants stay in the water column for a very long time.
- There is no natural "false" alarm generation possible in Ohmsett, e.g., fish, plankton, or other contaminations that would be present in the real scenarios

Test Description

The plan is for the plume to be released mid-water column, and the nozzle and equipment used for the release to be removed from the tank immediately after oil release in order to avoid any acoustic reflections from the equipment. It is expected that removing the equipment should only take about 10 seconds. NORBIT will use the nozzle to align sonar during the plume creation phase.

Sonar will then record data as the plume is suspended and rises to the surface (or drops to the seafloor), utilizing the rotator to keep the sonar pointing in the right direction as well as creating the 3D raw dataset. The rotator can be controlled from the sonar survey computer, directly in the user interface of the sonar. The raw data files will have the angular information.

The bridge can be moved during testing in order to measure different distances to the plume during the same release. NORBIT suggests that the first test be performed at a short distance with the highest concentration; this will provide a reference point for future tests. Following each test, equipment should be moved against the flow direction in order to test in clear water for every new plume release.

Comments on Proposed Test Schedule

NORBIT suggests that day 2 is used to focus on range test with various plume sizes. Test to be performed with diesel and Anadarko. It is desirable to establish a good understanding of the detectability of different volumes of oil at different ranges. Investigations of different droplet size distributions in the plumes generated would be desirable; hopefully some of those tests can be conducted already day 1. Tests with auto detection and false alarm will be incorporated during day 2 and 3.

NORBIT suggests testing with dispersants is done with ranges from almost full dispersion to no dispersion, to cover the range. We suggest dispersant is added to the oil as it reaches the surface to see the effect of the dispersant when the oil enters the oil column again.

It might also be beneficial to test dispersant alone to observe the effect of dispersant being applied to the surface. It is anticipated that waves influences the detectability of the plumes, this can be investigated as well during these tests. The first days could be focused on “free” field tests and then later tests with surface movements can be added.

B.1.2 WET Labs

The information in this section is from USCG internal references MAR, Inc. (2013b), Twardoswki (2013), and Twardoswki and Zhang (2014).

Pre-test Simulations

Simulations were carried out to assess the factors determining initial oil concentrations and the temporal-spatial dispersion of oil over time. Full discussion of the simulations can be found in Twardoswki (2013). Conclusions from the simulation results are as follows:

- For a 6 minute total time of release for the entire E-W slab of oil, 7.5 gal total oil release is optimal, as the peak initial concentration at the first measurement time would be approximately 22.5 ppm, very near the saturation point for the scattering sensors.
- Residual dispersed oil in the tank will be a problem for all releases after the first release due to dispersion of the oil in the tank and the slow velocity of water movement down the tank. For the second release ~ 328 ft (100 m) from the south end of the tank, 5 hours after release of the plume ~ 328 ft (100 m) from the N end of the tank, background oil concentrations will be near the

detection limit at the site of release, but north of that location will be detectable background oil. As oil continues to disperse, substantial residual is expected the following day (up to 1 ppm). The background can be resolved before a subsequent release of oil, but the background will continue to disperse, so that concentration gradients will not be static.

Equipment Set-up

As the main bridge will be moved during the test, WET Labs will setup their equipment on the main bridge. 110V, 220V, and 480V electrical power is available to them, as is a wireless internet connection should they need to upload/download data or software. For most of the tests, the top of the WINDOW package will be suspended about 1.5 ft (0.46 m) below the air-water interface using the bridge platform crane, stabilized with guy wires. The Ohmsett LISST device will be attached horizontally to the side of the WINDOW package.

Planned Procedure

Prior to the release of oil, the WINDOW will transit the entire length of the tank to acquire background levels. Following this run, a 33 ft (~10 m) long oil plume will be created that is oriented west to east. WET Labs has requested a 66 ft (~20 m) long plume (nearly the width of the tank) to aid in their modeling the plume. During WINDOW preliminary/practice runs, a 66 ft (20 m) plume may be created and compared with a 33 ft (~10 m) plume. At that time, USCG RDC representatives will determine which plume to use.

To create the plume, the spray nozzle assembly will be fastened to a trolley on the north edge of the main bridge. The spray nozzles will be set at a certain depth in the tank, likely near the bottom of the tank at a depth of ~ 7.3 ft (2.24 m). The trolley will be staged near the west wall of the tank, with the bridge stationary while the plume is created. As soon as oil flow begins, the trolley will be manually pulled from west to east while oil flowing through the submerged nozzles continues. After transiting ~ 33 ft (10 m), oil flow to the nozzles will cease while the trolley continues east as far as possible and is staged out of the way.

With an oil plume approximately 33 ft (10 m) long, oriented west to east, the main bridge will transit north approximately 16 ft (5 m) until it is over visually clean water. WINDOW, which is mounted in a cage, will be lowered into the water on the northwest side of the main bridge, using the main bridge crane, to a depth selected by WET Labs' personnel. The main bridge will transit south at a speed chosen by WET Labs and their instruments will acquire data as it is towed through the plume. Transiting will continue south until the instruments are in visually clean water. The main bridge will come to a stop and standby while WET Labs personnel process and save the data.

Only one data pass through a section of the plume will be made because instrumentation moving through the plume disturbs the plume. After each pass, the instrumentation will be moved to allow it to pass through an undisturbed portion of the plume. As the first pass is performed near the west wall, the crane boom will be extended to move the instrumentation east approximately 8 ft (2.5 m). Once WET Labs is ready for another run, the main bridge will transit from south to north, again going from visually clean water, through the plume, and into clean water. The runs will continue until the entire plume has been sampled, at approximately 8 ft (2.5 m) intervals, or until the plume has dissipated and is no longer detected by WINDOW. WET Labs may also draw water samples, examine the sample using a WET Labs' supplied bench top holographic microscope, and compare the results with their other data.

Once the data have been collected, the test will be repeated twice (three tests total) for each oil. Once the sequence is complete, it will be repeated for the next oil in the matrix (Table B-2). If time permits, a stationary plume will be created. The nozzles will be positioned near the bottom of the tank, likely at a depth of 7.3 ft (2.24 m). With the trolley and main bridge stationary, oil will flow through the nozzles for 3 minutes. When the oil flow stops, the main bridge will travel away from the plume into clear water so the nozzle assemble can be moved out of the way so that it does not disturb the plume. WINDOW will be deployed into visually clean water and, using the main bridge, will transit through the plume to map it.

Table B-2. WINDOW proposed test matrix.

Day	Run	Oil	Dispersant	Nozzle size (inch)	Pres	Duration	Surface	Notes
Mon	1-3	Diesel	No	0.016	140 psi	3 min	calm	Setup & preliminary (practice) runs
Mon	4	Diesel	No	0.016	140 psi	3 min	calm	West-East plume
Mon	5	Diesel	No	0.016	140 psi	3 min	calm	West-East plume
Tues	6	Diesel	No	0.016	140 psi	3 min	calm	West-East plume
Tues	7	Anadarko	No	0.016	140 psi	3 min	calm	West-East plume
Tues	8	Anadarko	No	0.016	140 psi	3 min	calm	West-East plume
Wed	9	Anadarko	No	0.016	140 psi	3 min	calm	West-East plume
Wed	10	Anadarko	No	0.016	140 psi	3 min	calm	West-East plume
Wed	11	Anadarko	9500	0.016	140 psi	3 min	calm	West-East plume
Thurs	12	Anadarko	9500	0.016	140 psi	3 min	calm	West-East plume
Thurs	13	Diesel	9500	0.016	140 psi	3 min	calm	West-East plume
Thurs	14	Diesel	9500	0.016	140 psi	3 min	calm	West-East plume
Fri	15	Diesel	9500	0.016	140 psi	3 min	calm	West-East plume
Fri	16	tbd	tbd	0.016	140 psi	3 min	calm	Stationary plume
Fri	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Derig and decon

Testing Recommendations

Simulations show background oil in the tank will be present after the first release and will build up through the week based on the slow N-S velocity of water advection. Background measurements should be taken before each oil release, but the background concentration gradients will not be static, as they will continue to diffuse. Furthermore, the Ohmsett test plan starts with diesel, then Anadarko, then Anadarko plus dispersant, and then diesel plus dispersant, so that the final diesel plus dispersant test will include a residual mixture of oils from all the previous tests. While this plan has interesting aspects, as WET Labs' measurement and inversion algorithm should be able to individually discriminate the size distributions of each type of oil droplets in the mixture, these residual oils could significantly complicate the primary goal of retrieving the concentration, size distribution, and density of the oil that was just released as accurately as possible.

WET Labs' simulations assumed all oil droplets were neutrally buoyant and conservatively mixed as a passive tracer. Oil droplets will have some buoyancy component, and there thus may be less oil over time than modeled as oil may collect at the surface. Coatings of dispersant and/or particulate material on the droplets dampen buoyancy, providing conditions more closely aligned with simulations. For oil droplets with appreciable buoyancy, large droplets rise faster than small droplets, so that size distributions can be expected to markedly change over time, providing a challenging test for our measurement and inversion technique. Furthermore, any oil reaching the surface will not be included in the total oil volume estimate, compromising the validation method.

From the results of the simulation, WET Labs recommended 7.5 gal of oil be released at a constant rate across the entire E-W distance of the tank in approximately 6 minutes, requiring a 75 gph release rate. This would provide optimal initial concentrations for the first set of measurements of about 23 ppm. These parameters are not specified in Ohmsett's test plan. The plan does state that the oil will be dispersed across a 33 ft (~10 m) E-W distance instead of the full 66 ft (~20 m) width of the tank. WET Labs requests the 66 ft (~20 m) because interpolation and modeling of the oil plumes will be significantly easier if the release is equivalent over the full width of the tank.

With respect to the validation method, the LISST provides an estimate of the size distribution for all particles, not just the oil droplets, so that resultant size distributions are useful as an upper bound for the suspensions of oil droplets. WET Labs has also found persistent problems with fouling of the optical windows of the LISST, limiting its use as a validation method.

B.2 Actual Procedures

B.2.1 NORBIT

The typical test for NORBIT's WBMS was performed in the following manner (MAR, 2013c):

- The distance from the sonar to the spray nozzle was predetermined and the spacing adjusted between each stalk (center to center of spray nozzle and sonar stalk). Distances are documented within the Ohmsett test log.
- The type of oil for use was loaded into the pump skid reservoir. An initial and final reservoir depth was recorded to quantify the volume dispensed. Analysis of the oil properties was performed and is provided within the analysis section of the Ohmsett test log.
- The plume was created by dispensing the test oil for a specific amount of time at a specified depth below waterline. Times varied based on the desired plume size.
- NORBIT operated their sonar, viewed the plumes real-time, and captured the corresponding data (typically stationary).
- Post-test, the Ohmsett main bridge was typically repositioned to a new area in the test basin to avoid a contaminated water column background.

A total of sixty-nine tests were performed, sixty-five in which the sonar instrument recorded data and four in which LISST data was collected for plume property data comparison (tests #266-269). The following parameters were varied for the series of tests performed:

- **The number of nozzles and orifice size** was decided and installed in the spray manifold prior to each test. The variation in orifice size and number of nozzles used allowed for varying oil droplet distributions and concentrations.
- Two **oil types** were used: diesel and Anadarko Crude. Each was used straight and after being premixed with COREXIT 9500 dispersant at a DOR of 1:20.
- The **distance from sonar to plume** was varied from zero to 36 ft (11 m).

- The operational **depth of the sonar** ranged from near the test basin floor (approximately 7.5 ft (2.3 m) below the waterline) to one foot (0.3 m) below the surface. The majority of the tests were performed at the 2-ft (0.6-m) depth.
- **Depth of plume creation** – plumes were created primarily at two depths: 7.3 ft (2.2 m) and 4 ft (1.2 m) below the waterline.

Additional information provided on Ohmsett's data log spreadsheet includes: volume dispensed, flow rate through nozzles, Ohmsett test number, nozzle configuration, oil type, date and time of day, and notes describing the test.

Oil plume property data was collected using the LISST 100X for diesel oil, with COREXIT 9500 dispersant and without. The plume was created using 3x0.020 inch nozzles and dispensing for one minute. The LISST was then slowly passed through the plume at 0.2 kts repeatedly until the oil concentration diminished. Three forms of photo-video information were recorded: still photos, underwater video, and video from the test basin observation windows. Table B-3 gives the WBMS actual test matrix from Eriksen, et al. (2014).

Table B-3. WBMS actual test matrix.

Test No	Activity	Notes
2013 Dec 09, preparation of the sonar mount, initial testing		
1	Preparation of the sonar mount. Mounting of the two sonars on the rotator.	Decision was made to mount the sonar and the plume dispenser on the same bridge.
2	Update FW in both sonars to the: 82004-devel68.rbf 82004-devel68.rbf.md5 uImage-228_2013-12-06_09-51-11.gz uImage-228_2013-12-06_09-51-11.gz.md5	The FW has been changed later.
	Preliminary testing of the frequency response of the Diesel oil	Wrong sonar setting, results not conclusive.
2013 Dec 10, Oil Type **Diesel**, Nozzle 3x-0.6, discharge rate 0.2 l/min Sonar mid water depth		
3	13_55_52, Range: 2m, 3min spill	Plume detected, Real-time detection: Throughout the spill and 1 minute after stop spill. Occasional detections for the next 2 min. Manual detection: Throughout the spill and 4minutes after stop spill
4	14_13_18, Range: 4m, Similar experiments: 5,6,7 3min spill	Real-time detection: N/A Manual detection: Throughout the spill and .5 minute after stop spill
3b)	02_07_36, Range: 5m	No Plume detected
2013 Dec 10, Oil Type **Diesel**, Nozzle 3x-1 Sonar mid water depth		
14	16_35_37, Range: 1m	Real-time detection: Throughout the spill and 1minute after stop spill. Manual detection: Throughout the spill and 6minutes after stop spill. The reminisce of the leakage from pipe is observed as well.

Table B-4. WBMS actual test matrix (cont.).

Test No	Activity	Notes
13	16_25_55, Range: 2.5m, narrow beam	Real-time detection: Throughout the 3 min spill and 20sec after stop spill. Manual detection: Throughout the spill and 1 minute after stop spill.
11	16_14_44, Range: 2.5m, wide beam	Plume detected, automatic detection OK.
9	15_56_18, Range: 5m	Real-time detection: Not suitable for automatic real-time detection. Manual detection: barely detected.
8	15_45_29, Range: 7m	Real-time detection: Not suitable for automatic real-time detection. Manual detection: barely detected.
2013 Dec 10, Oil Type **Diesel**, Nozzle 1x-0.6, discharge rate 0.06 l/min Sonar mid water depth, Nozzle at 1ft from the bottom		
17	17_17_08, Range:1m, 5 sec discharge @100psi	Plume detected, automatic detection OK.
2013 Dec 10, Oil Type **Anadarko**, Nozzle 3x-0.6, discharge rate 0.2 l/min Sonar mid water depth @4ft, Nozzle at 2ft from the bottom		
20	19_21_16, Range: 3m,	Real-time detection: Throughout the spill and at least 30 sec after stop spill. Manual detection: Throughout the spill and 30 sec after stop spill (file ends).
21	19_35_58, Range: 6m	No detection due to strong reverberations.
2013 Dec 11, Oil Type **Diesel with Dispersant**, Nozzle 3x-0.6, discharge rate 0.2 l/min Sonar at 2ft from bottom, applying shading to the sonar and anechoic mat, Nozzle at 2ft from the bottom Rotator fixed, positive pitch looking up toward the surface Firmware in Sonar: 82004-devel68.rbf, 82004-devel68.rbf.md5, uImage-226_2013-12-05_12-34-33.gz, uImage-226_2013-12-05_12-34-33.gz.md5		
23	14_53_36, Range: 2m, 3min spill	Plume detected, automatic detection OK. Manual detection: Throughout the spill and 180 sec after stop spill. Automatic detection: TBD, estimated to 2min after spill
24	15_14_14, Range: 2m, scanning vertically, 3min spill	Plume detected, automatic detection OK Manual detection: Throughout the spill and 90 sec after stop spill Automatic detection: TBD, estimated to 1min after spill.
32	19_18_17, Range: 2m, scanning vertically	Automatic detection and 3D visualization Manual detection: Throughout the spill and 120 sec after stop spill
26	15_36_14, Range: 6m, scanning vertically, 3min spill	Nozzles moved out of the way after spill, Plume detected. Manual detection: Throughout the spill and 180 sec after stop spill. Automatic detection: TBD, estimated to 1min after spill. Not so clear detection, possibility for false alarm during automatic detection.

Table B-5. WBMS actual test matrix (cont.).

Test No	Activity	Notes
27	15_56_20, Range: 6m, static	Plume detected, automatic detection OK. Manual detection: Throughout the spill and 60 sec after stop spill. Automatic detection: TBD, estimated difficult to detect. Not so clear detection, possibility for false alarm during automatic detection.
30	16_54_04, Range: 7.5m, scanning vertically	Some plume detected but it is believed that there are two phenomena creating two plumes, one with actual small droplets as expected and one resulting from a leakage from the pipe with high reflectivity and large droplets. That should be verified with the camera view. It is noticeable that at small pitch of e.g. 3deg. the plume has a distinct stripy character and appears in place where the nozzle has been. For larger pitch, e.g. 8 and looking into the surface the plume has less reflectivity and more cloudy character. Manual detection: Throughout the spill and 60 sec after stop spill. Not so clear detection, possibility for false alarm during automatic detection.
28	16_19_39, Range: 8m, scanning vertically	No detection.
2013 Dec 12, Oil Type **Anadarko with Dispersant**, Nozzle 3x-1, discharge rate 0.3 l/min Sonar position has changed to 6ft from bottom, Nozzles at 2ft from the bottom but changed orientation of the manifold toward the sonar. Positive pitch looking up toward the surface		
37	2013-12-12-15_47_27 Range: 2m, scanning vertically, 3 min	Manual detection: Throughout the spill and 20 sec after stop spill
38	2013-12-12-15_59_55 Range: 2m, scanning vertically Moving nozzle out after spill, 3 min.	Manual detection: Throughout the spill and 40 sec after stop spill
39	2013-12-12-16_07_23 Range: 2m Stationary, 3min spill – tilting manually similar test: 40, 30 sec. spill	Real-time detection: Not performed due to manual tilting. Manual detection: Throughout the spill and 3 min after stop spill. For test 40 and 30sec spill similar result.
Nozzles changed orientation of the manifold 90 deg parallel to the sonar, i.e. nozzles face sonar.		
41	2013-12-12-16_54_11 Range: 2m 30sec spill	Real-time detection: Throughout the spill and 1 min after the spill. Manual detection: Throughout the spill and 2 min after stop spill.

Table B-6. WBMS actual test matrix (cont.).

Test No	Activity	Notes
42	2013-12-12-17_01_13 Range: 5m 30 sec spill	Real-time detection: Not performed. Plausible due tostrong signal and observed effect. 3D detection off line - pending Manual detection: Throughout the spill and 40sec after stop spill. Important NOTE: a clear proof for existence of the pipe reminiscence seen in previous tests. The real plume is separate phenomena than a leakage plume from the pipe.
43	2013-12-12-17_08_49 Range: 7m 30 sec spill	Manual detection: Throughout the spill and 10sec after stop spill. Again, the two plumes are clearly visible: one generated by the nozzle and one by a leakage from the pipe.
44	2013-12-12-17_14_52 - background 2013-12-12-17_16_32 – plume Range: 9m 30 sec spill	Manual detection: Throughout the spill and 20sec after stop spill. Two plumes visible, actual and leakage.
47	2013-12-12-17_37_30 - background 2013-12-12-17_38_02 - plume Range: 12m 30 sec spill	Manual detection: Throughout the spill and 1min after stop spill. Two plumes visible, actual and leakage. **3D visualization - pending**
2013 Dec 12, Oil Type **Diesel** alone, Nozzle 3x-1, discharge rate 0.3 l/min Sonar at 6 ft from bottom, Nozzles at 2ft from the bottom facing the sonar. Positive pitch looking up toward the surface		
51	2013-12-12-19_42_45 Range: 1m 30 sec. Spill Similar test: 52	Manual detection: Throughout the spill and 1 min 10 sec after stop spill. Plume development visualization.
55	2013-12-12-21_10_07 Range: 1m 30 sec.	Low bandwidth test for BSS purposes.
55	2013-12-12-21_19_40 Range: 1m 30 sec. Spill	Low bandwidth test for BSS purposes. AutoGain 10kHz sweep.
54	Range:1m Frequency sweep test TP2 data	High bandwidth data has been collected for further analysis of the frequency response of the plume.
49	2013-12-12-19_24_08, Range: 5m 30 sec. spill	Manual detection: Throughout the spill and 1-2min after stop spill. 3D visualization very clear and distinct.

Table B-7. WBMS actual test matrix (cont.).

Test No	Activity	Notes
50	2013-12-12-19_33_18 Range: 11m 30 sec. spill	Manual detection: Throughout the spill and 30sec after stop spill. 3D visualization very clear and distinct.
2013 Dec 13, Oil Type **Diesel with Dispersant**, Nozzle 3x-1, discharge rate 0.3l/min Sonar **6ft** from bottom, Nozzles at 2ft from the bottom facing the sonar. Positive pitch looking up toward the surface		
57	2013-12-13-14_20_42 Range: 1m 30 sec. Spill	Manual detection: Throughout the spill and 1 min 5 sec after stop spill. Plume development visualization pending
58	2013-12-13-14_34_36 Range: 6m 30 sec. Spill	Manual detection: Throughout the spill and 3min after stop spill. Plume development visualization showing development and detection of 2x2m plume over 3min period
60	Range: 6m 30 sec. Spill, FLS test	Using bathy after FLS shows the plume was visible 6 min after stop spill.
61	2013-12-13-15_02_35 Range: 11m 30 sec. Spill	Manual detection: Throughout the spill and 3 min after stop spill. Plume development visualization showing development and detection of 3x3m plume over 3 min period.
64	2013-12-13-16_04_35 Range: 11:50m	Long-range tests are not conclusive due to large reverberations and multipath in the tank.

B.2.2 WET Labs

In general, there were four different test scenarios (MAR, 2013c):

- **Stationary** – the instrument package was above the oil spray manifold and positioned to sample the plumes as they rose, expanded, and dissipated.
- **Transect** – the defined plume was created then the main bridge and instrumentation package traveled north and south repeatedly through the plume. The instruments started in clean water (out of the plume), traveled through the plume until it reached clean water again then changed direction. The process was repeated until the plume concentration diminished.
- **Mapping** – a 30 ft (~ 9.2 m) long plume was created across the test basin in the east-to-west direction. While continually dispensing, the trolley nozzle manifold was guided at a constant rate along the trolley rail. Once the plume was created, the WINDOW instruments intersected the plume near the east end of the plume traveling north. Once in clean water, the instruments were jogged toward the west 5 ft (~ 1.5 m) then traveled south intersecting the plume. A minimum of five transects were performed.

- **High Speed Tow** – the instruments were towed at speeds up to 3.5 kts while passing through a plume.

The parameters for each test are provided on the Ohmsett data log spreadsheet. The information includes: the date and time, Ohmsett test number, nozzle configuration, oil type, dispensing rate, and volume dispensed. Three forms of photo-video information were recorded: still photos, underwater video, and video from the test basin observation windows.

Table B-4 gives the WINDOW actual test matrix from Twardoswki and Zhang (2014).

Table B-8. WINDOW actual test matrix.

DATE	TIME OF DAY	OHMSETT TEST #	OILTYPE	NOZZLE CONFIG Qty/size	NOZZLE DEPTH (FEET)	NOZZLE LOCATION (FROM WEST WALL)	SENSOR DEPTH (BELOW WATER LINE)	VOLUME of OIL DISPENSED (gallons)	DISPENSE RATE (Gal/hr)	OIL SPRAY DURAT. (min)	NOTES	WET Labs oil conc figs	WET Labs density figs	WET Labs conc and number dist figs	WET Labs DHM number dist figs
12/2/2013	11:22am	101	Diesel	3/-.6	7'-4"	~ 25'	~ 2'	0.168	3.35	3.0	Plume created below Instruments/stationary	7.101.1	7.101.1	1.101.2	
12/2/2013	1:22pm	102	Diesel	3/-.6	7'-4"	~ 25'	~ 2'	0.117	2.33	3.0	Plume created below Instruments/stationary; 1 of 3 nozzles clogged	7.102.1	7.102.1	7.102.2	7.102.2
12/2/2013	1:56pm	103	Diesel	3/-.6	7'-4"	~ 25'	~ 2'	0.185	3.70	3.0	Created plume then transects thru plume until low detection	7.103.1	7.103.1	7.103.2	
12/2/2013	2:23pm	104	Diesel	3/-.6	7'-4"	~ 25'	~ 2'	0.201	4.02	3.0	Created plume then transects thru plume until low detection	7.104.1	7.104.1	7.104.2	
12/2/2013	2:50pm	105	Diesel	3/-.6	7'-4"	~ 25'	~ 2'	0.168	3.35	3.0	Created plume then transects thru plume until low detection	7.105.1	7.105.1	7.105.2	
12/3/2013	9:59am	106	Anadarko	3/-.6	7'-4"	~ 25'	~ 2'	0.168	3.35	3.0	Created plume then transect thru; 1 nozzle partially clogged; created large droplets	7.106.1	7.106.1	7.106.2	7.106.2
12/3/2013	10:33am	107	Anadarko	3/-.6	7'-4"	~ 25'	~ 2'			3.0	aborted-clogged nozzles				
12/3/2013	11:05am	108	Anadarko	3/-.6	7'-4"	~ 25'	~ 2'	0.201	4.02	3.0	Transects thru plume until low detection, raised instruments to ~18" at 11:13	7.108.1	7.108.1	7.108.2	
12/3/2013	11:25am	109	Anadarko	3/-.6	7'-4"	~ 25'	~ 2'	0.201	4.02	3.0	Transects thru plume until low detection, raised instruments to ~18" at 11:30	7.109.1	7.109.1	7.109.2	
12/3/2013	1:35pm	110	Anadarko w/Dispersant	3/-.6	7'-4"	~ 25'	~ 2'	0.201	4.02	3.0	Transects thru plume until low detection, raised instruments to ~18" at 11:45	7.110.1	7.110.1	7.110.2	7.110.2

Table B-4. WINDOW actual test matrix (cont.).

12/3/2013	2:20pm	111	Anadarko w/Dispersant	3/-.6	7'-4"	~ 25'	~ 2'	0.168	3.35	3.0	Transects thru plume until low detection, raised instruments to ~18" at 2:38	7.111.1	7.111.1	7.111.2	
12/4/2013	9:49am	112	none	N/A	N/A	5' - 15' - 25'	~ 2'	N/A	N/A	N/A	3 pass transects for background				
12/4/2013	10:17am	113	Anadarko w/Dispersant	5/-.6	7'-4"	~ 25'	~ 2'	0.436	4.36	6.0	30' East-West Plume; instrumts pass thru in 5' increments across plume	7.113.1	7.113.1	7.113.2	7.113.2
12/4/2013	12:46pm	114	Diesel w/Dispersant	5/-.6	7'-4"	~ 25'	~ 2'	0.201	4.02	3.0	Transects thru plume until low detection, raised instruments to ~18" at 12:56	7.114.1			7.114.2
12/4/2013	1:23pm	115	Diesel w/Dispersant	5/-.6	7'-4"	~ 25'	~ 2'	0.134	2.68	3.0	Transects thru plume until low detection	7.115.1	7.115.1	7.115.2	7.115.2
12/4/2013	2:11pm	116	Diesel w/Dispersant	5/-.6	7'-4"	~ 25'	~ 2'	0.369	3.40	6.5	East to West Plume; -2 of 5 nozzles clogged-added to duration				
12/5/2013	9:31am	117	Diesel w/Dispersant	2/.6, 2/1, 1/2,1/6	7'-4"	~ 25'	~ 2'	0.771	24.99	1.9	Transects thru plume until low detection,	7.117.1	7.117.1	7.117.2	7.117.2
12/5/2013	11:25am	118	Diesel w/Dispersant	N/A	7'-4"	~ 25'	~ 2'	N/A	N/A	N/A	traveled up to 2kots -adjust rigging; passed thru previous plume				
12/5/2013	11:35am	119	Diesel w/Dispersant	N/A	7'-4"	~ 25'	~ 2'	N/A	N/A	N/A	traveled up to 3.5knots -adjust rigging; passed thru previous plume				
12/5/2013	11:50am	120	Diesel w/Dispersant	2/.6, 2/1, 1/2,1/6	7'-4"	~ 25'	~ 2'	1.005	24.12	2.5	traveled at 3.5knots - thru fresh plume	7.120.1			

APPENDIX C. ADDITIONAL RESULTS DISCUSSION

C.1 NORBIT

In addition to the results discussed in the body of the report, NORBIT conducted other calculations that could not be verified due to the limitations of the experimental set-up.

Concentration Measurements

Since one of the government requirements was to detect dispersed oil at levels of 0.5 ppb or lower, NORBIT tried to develop a way to measure the concentration of the plume over time using LISST. They conducted four tests with the LISST for this purpose. Unfortunately, during most of the scans the instrument was outside the main volume of the plume (see Figure C-1 for an example occurrence).

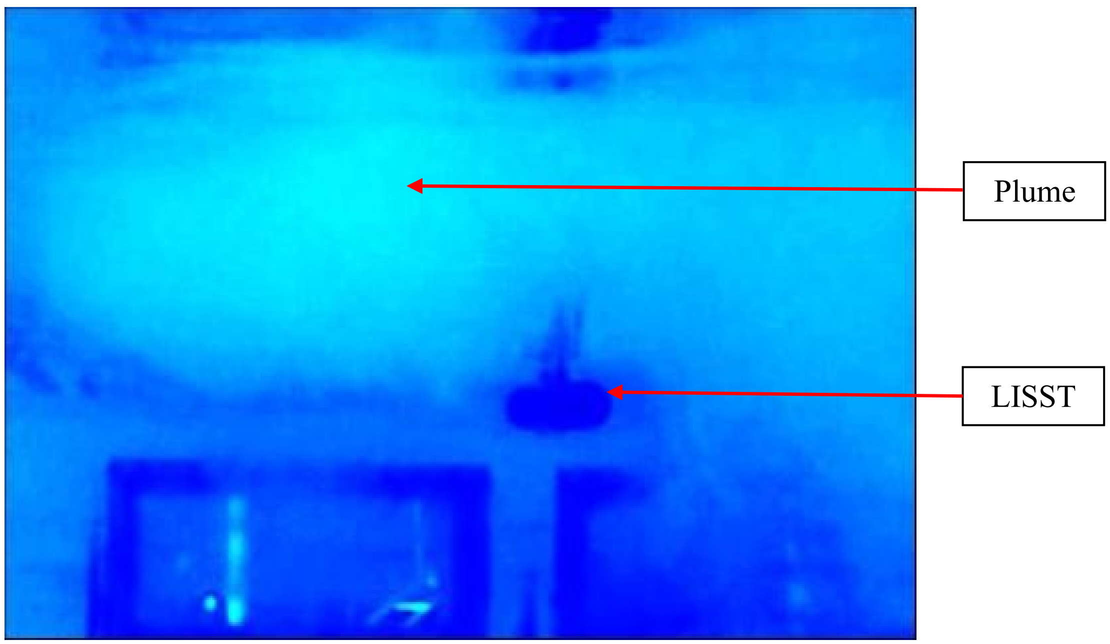


Figure C-1. Example of LISST taking measurements outside the plume.

Example rough LISST results are shown in Figure C-2 for Test #266, diesel with dispersant (normalized results can be found in APPENDIX D). The increasing "Row" numbers indicate increasing times (see Table C-1). Assuming speed of 0.18 kts (0.1 m/s) and the time stamp in the data files, NORBIT derived the total concentration over the traveled distance as shown in Figure C-3.

They tried to calculate the ppm using the shape and dimensions of the plume and the volume of oil released. There was a big discrepancy between these numbers and LISST so they used the LISST number of ~ 100 ppm average concentration 30 seconds after the spill and estimated minimal detections based on that. Table C-2 shows the ppm estimates added to their summary results (shown in Table 1 in the body of the report).

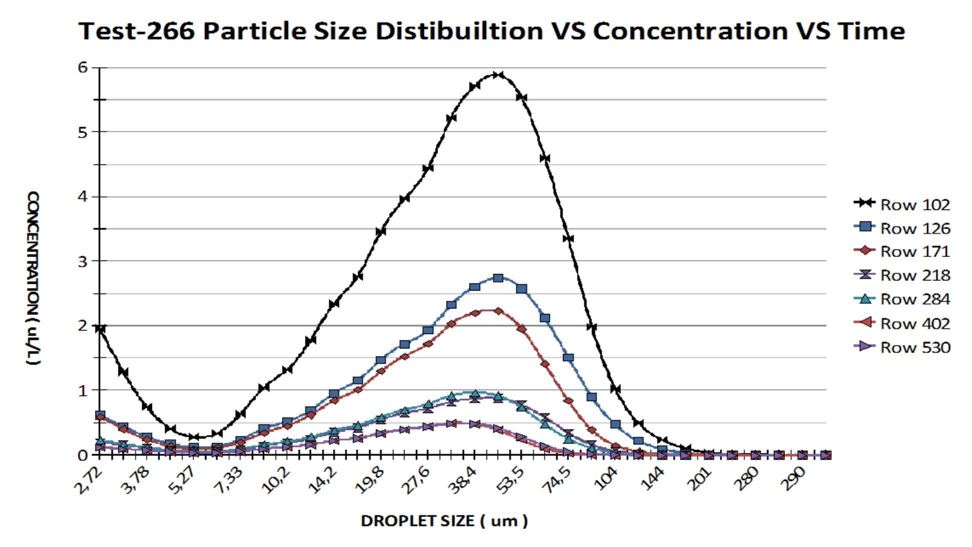


Figure C-2. LISST results for diesel with dispersant (Test #266).

Table C-1. Legend for Test #266 LISST results

Row number	Time from start (in minutes)
102	0.0
126	0.5
171	1.5
218	3.0
284	4.5
402	7.5
530	10.5

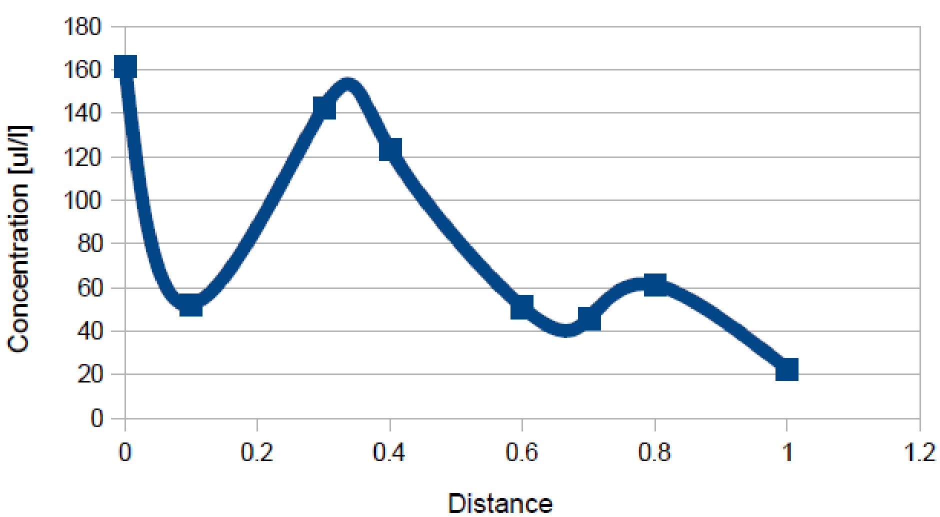


Figure C-1. Concentration vs distance for diesel with dispersant.

Table C-2. Summary of WBMS results (with ppm estimate).

Oil type, nozzle configuration (#xsize (inch)) and spill duration	Test no.	Spill range (m)	Automatic detection duration [sec] N/A – not performed N/D – no Detection	Supervised detection duration after spill stops [sec] N/A – not performed N/D – no Detection	Estimated minimal concentration for detection [parts per million (ppm)]
Diesel, 3x0.016, 3 min	3	2	60	120	20
	4, 5, 6	4	N/A	300	10
	3b	5	N/A	N/D	
Diesel, 3x0.020, 3 min	14	1	60	360	10
	13	2.5	20	60	80
	9	5	N/D	5	160
	8	7	N/D	1	160
Diesel, 3x0.020, 30 sec	51	1	N/A	70	80
	49	5	N/A	60	80
	50	11	N/A	30	100
Anadarko, 3x0.016, 3 min	20	3	30	30	100
	21	6	N/D	N/D	
Diesel + dispersant, 3x0.016, 3 min	23, 24, 32	2	N/A	120	20
	26, 27	6	N/A	60	80
	30	7.5	N/A	60	80
	28	8	N/D	N/D	
Diesel + dispersant, 3x0.020, 30 sec	57	1	N/A	65	80
	58	6	N/A	300	10
	61	11	N/A	180	20
Anadarko + dispersant, 3x0.020, 3 min	37, 38	2	N/A	20	120
Anadarko + dispersant, 3x0.020, 30 sec, nozzle change	41	2	N/A	180	20
	42	5	N/A	40	70
	43	7	N/A	10	150
	44	9	N/A	20	120
	47	12	N/A	60	80

The summary of the plume detection listed in Table C-2 is graphically represented in Figures C-4 (without dispersant) and C-5 (with dispersant). According to NORBIT, the detection capabilities outlined here should be treated with some reservations. The detection conditions changed throughout the test; the sonar and nozzles were repositioned several times to compensate for the strong multipathing in the tank and find a suitable location.

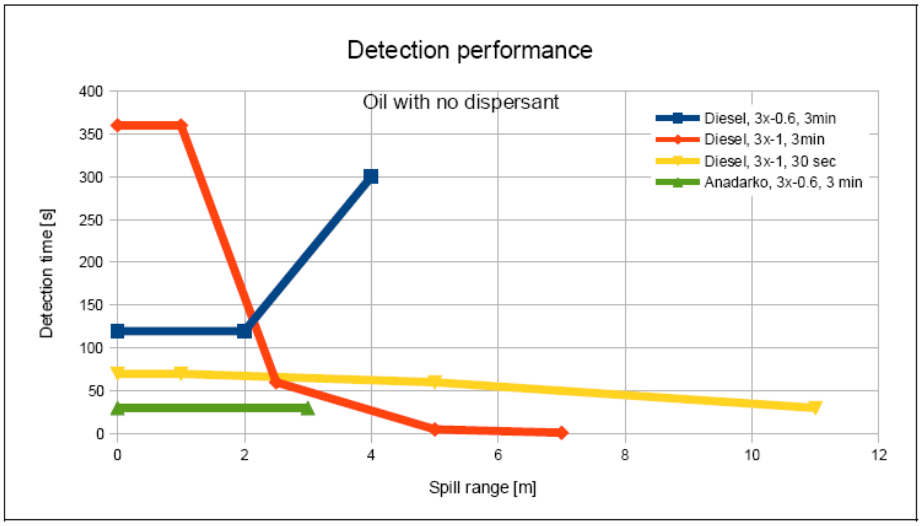


Figure C-2. WBMS detection with no dispersant.

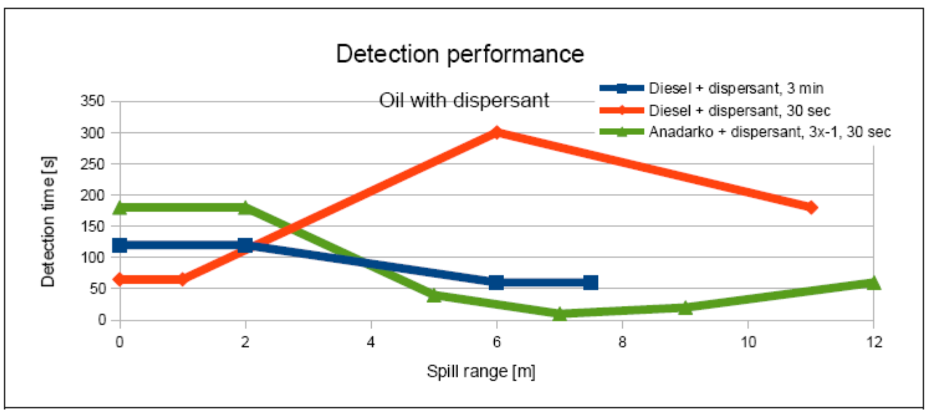


Figure C-3. WBMS detection with dispersant.

Frequency Response of the Plume

In order to determine droplet sizes, NORBIT tried to look for resonances in the backscatter from the plume. The theory for whether oil droplets will have any resonance phenomena is split, and they assumed that any resonance is only possible if there is gas involved. Even if there are no resonances in the droplets, interference phenomena may occur due to the distance between the droplets, combining that information with the backscattering strength could give an indication of the droplet size.

There were several attempts to investigate this theory. The frequency analysis at the chosen frequencies do not show any significant resonances or other nonlinear effects. This may indicate either that such phenomena do not occur or that the selection of frequencies did not correspond to the resonant frequencies of the droplets. Results were somewhat inconclusive, but droplet sized distribution is not expected to be possible with a system operating in this frequency band.

Table C-3 gives NORBIT's report of their compliance with the BAA requirements.

Table C-3. NORBIT requirements matrix.

Capability	WBMS
1. Provides results in near real time (less than 1 hour)	In setups with full bandwidth to the surface it will be real time data, in situations with storage on e.g. gliders data must be retrieved and processed. During trials real time detection of plumes were conducted, also automatic detection of plumes were observed in real time. All 3D visualizations were done in post processing, further work to improve automatic detection utilizing 3D information is still pending implementation and was not shown in real time.
2. Calibrates easily for different oils	No calibration is needed other than a secondary verification of the oil as the sonar is an indirect attenuation, density measurement. Minimal difference between different oil types were observed during the trials.
3. Detects oil at depths up to 200 feet	No limitations, the technology will work from surface to 4000 m water depth, performance depends on the reflectivity from the plume.
4. Works in currents or tow speeds up to 5 knots	Acoustic processing will not be affected by currents up to 5 kt.
5. Reports minimal false alarms	A verification of the plume is needed and the false alarm should be 0, if the acoustic tool is used without verification there will naturally be a risk of detecting other substances with different impedances. The BAA calls for a volumetric measurement, single fish targets should not particularly affect it, and typically fish schools have different reflectivity over time (When fish turns), which a plume does not have. Significant experience with 3D processing have been gained and hardware is in production to achieve a good classification/alarm generation with minimal false alarms. Still the high probability plumes must we verified by a point sensor, but it is expected that many of the typical false alarm scatters in the water column can be successfully rejected utilizing acoustic means.
6. Allows smooth data flow from field to command center	Full data from several sensors have been demonstrated over a single 100MB/S link so many systems will be possible with conventional technologies
7. Detects dispersed oil at levels of 0.5 ppb or lower	The sensor will be able to detect dispersed crude oil, during test we successfully detected 20 ppm; probably 0.5 ppb is not realistic. Further test on various concentrations is needed in order to clarify this. Significant uncertainty on concentration levels were observed during the test period. Typically oil will tend to collect in bigger balls and start to mix into the ocean layers. Therefore the results will to some extend depend on when, in the dispersant cycle, the sonar visualized the water volume.
8. Sweeps an area of water column 3 ft by 3 ft	Multibeam technology can sweep a significantly bigger area; tens of meters are realistic. If there are dispersed oil plumes, it is anticipated that plumes can be detected in up to 50-100m from the sensor depending of size and composition. Small droplets will naturally be detectable at much shorter ranges.
9. Provides digital readout or measured values and digitally logs field data	Visualization on the user interface is done so it is geometrical corrected thus a user gets fast visualization of the plume structure directly on the screen. Automatic detection have been shown directly in the user interface. All raw data can be stored for further analysis and data representation e.g. 3D visualization
10. Is field rugged	The system is designed as a field rugged system for general offshore utilization, system have successfully been integrated on many different platforms.

Table C-3. NORBIT requirements matrix (cont.).

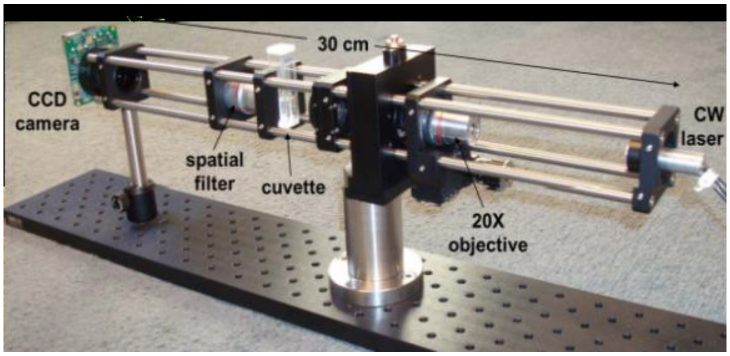
Capability	WBMS
11. Is portable	One of the main advantages of this system is its portability; wet end weighs less than 2 kg. Battery operation from a battery box of less than 4kg for a workday. Wireless transfer of data to computer or storage in head or battery box
12. Compatible with fresh and salt water	Designed for both fresh and salt water
13. Determine droplet size, density (specific gravity) and/or kinematic viscosity	At close ranges the droplet can be characterized (Within the 3 feet), at longer ranges with many small droplets (Down to a few mm) the average backscatter will be measured not the individual droplets. When droplets gets significantly smaller than the wavelength (Approximately 4mm) the test results in this report shows we cannot reliably determine droplet sizes. Further work is needed in order to answer if this is possible at all, probably a much wider frequency is need in order to determine the very small droplet sizes tested during this project
14. Adapts to various depths (deep vs. shallow)	No difference from an acoustic standpoint
15. Operates from vessel in variety of conditions	Sonar operates in a variety of weather conditions, it is clearly an advantage to have the sonar mounted on a platform which is as stable as possible e.g. AUV or ROV's. Norbit have solutions to correct for vessel introduced motion, this is currently not tested with the oil detection functionality but is certainly technical feasible.
16. Deploys quickly and easily	NORBIT sonar is very compact and designed for easy and quick deployment; actual deployment time will vary depending on the platform.

C.2 WET Labs

Validation Methods

Several forms of possible validation were attempted for the Ohmsett tests. Plume characteristic data were recorded using Ohmsett's Sequoia LISST 100X multi-parameter system for in-situ observations of particle size distribution and volume concentration. It also recorded the optical transmission, pressure, and temperature. Ohmsett personnel provided raw LISST data as well as graphs. The LISST sampling window was located approximately 8 inches (0.2 m) from the WET Labs sensors, oriented horizontally and attached to the same structural frame through the series of tests.

In addition to the LISSST instrument used by Ohmsett, WET Labs employed a bench top digital holographic microscope (Figure C-6, left) for validating undisturbed oil droplet size distributions and concentrations using image particle analysis techniques such as watershedding and thresholding. The MATLAB Image Analysis toolbox was used for this processing. A 2-D representation of a holographic image of an oil droplet suspension is shown in Figure C-12, right. This image is constructed by combining several hundred imaged planes within the 3-D holographic image. Image analysis software automatically provides sizes, particle contrast (related to particle density), and aspect ratio for every particle imaged. Image width is about 120 µm. Oil particles are nominally spherical with aspect ratio 1, so that their specific distributions may be approximated even when mixed within a complex aquatic particle assemblage, as the vast majority of naturally occurring particles are nonspherical. Several images can be averaged to obtain excellent counting statistics, even for relatively large particles (>100 µm).



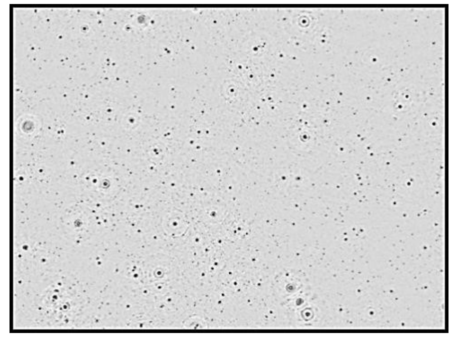


Figure C-6. Digital holographic microscope and sample image.

Additional Results

In addition to the concentration plots discussed in the body of the report, WET Labs also produced:

- Density plots showing the volume scattering function at 60 degrees measured by the sensor (blue line) and the calculated density (green and red lines) (see Figure C-7). The green line is the raw calculation of density, based on every sensor data point. The red line shows the results of a running 10-point median filter applied to the green line to smooth statistically insignificant spiking and allow for a more meaningful result.
- Volume concentration (particle volume in µL, per L sample volume, per µm size bin) and number size distribution (PSD; particle number, per m^{-3} sample volume, per µm size bin), calculated through the inversion technique at specific times corresponding to the large blue points in the volume scattering function (see Figure C-8).
- Number size distribution (for some of the experiments) analyzed by the digital holographic microscope (DHM) of the discrete water sample taken after the oil release (see Figure C-9).

Derived densities for diesel and Anadarko Crude were consistently around 0.83 kg/L and 0.87 kg/L, respectively, consistent with published values. In some cases inversion results were not entirely consistent with expectations or similar experiments, which may be an indication of air bubbles or some other confounding factor. In some cases towards the end of the testing, when residual background oil was present from previous experiments, densities would switch between the two different types. While a background measurement was made at the starting location, this did not resolve the edges of the experimental area, including instances where the current plume mixed with previous releases within the tank. This resulted in measurements of different co-occurring oil masses with different respective concentrations and densities.

Volume concentration distributions of oil droplets typically peaked in the range of 20 to 100 µm, but in some cases bimodal distributions were observed with an additional subfraction of relatively small droplets peaking around 7-8 µm. Number size distributions, also known as particle size distributions (PSDs), typically peaked in the 5-10 µm range. These distributions were in general agreement with distributions collected with the DHM. Note that like the LISST, DHM distributions represent all particles, not just oil droplets, so that continued increases in PSDs with decreasing particle size is common, as these particles are naturally abundant in very high concentrations and can readily pass through filtration systems. Note also that the unit conversion between the DHM PSDs and the PSDs obtained from scattering inversions is 10^6.

In some cases, PSDs seemed to shift to smaller droplets over time, likely reflecting that larger, more buoyant droplets were rising to the surface at a faster rate. In other cases, however, PSDs seemed to shift to larger droplets over time, which may be an indication of droplet coalescence over time and/or droplets scavenging other particulate material from the water column.

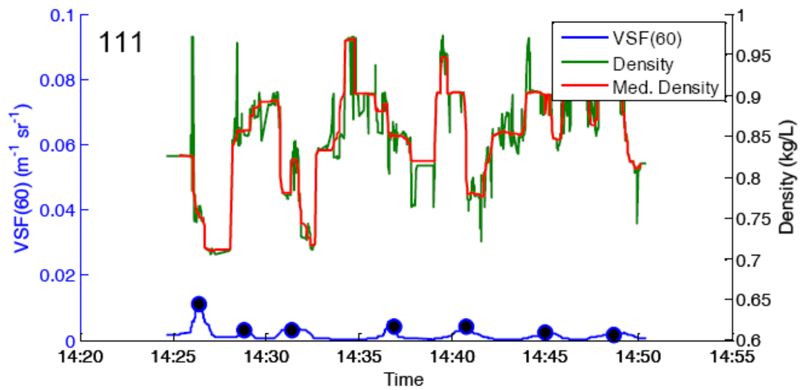


Figure C-7. Example volume scattering function and derived oil density for WINDOW transect experiments.

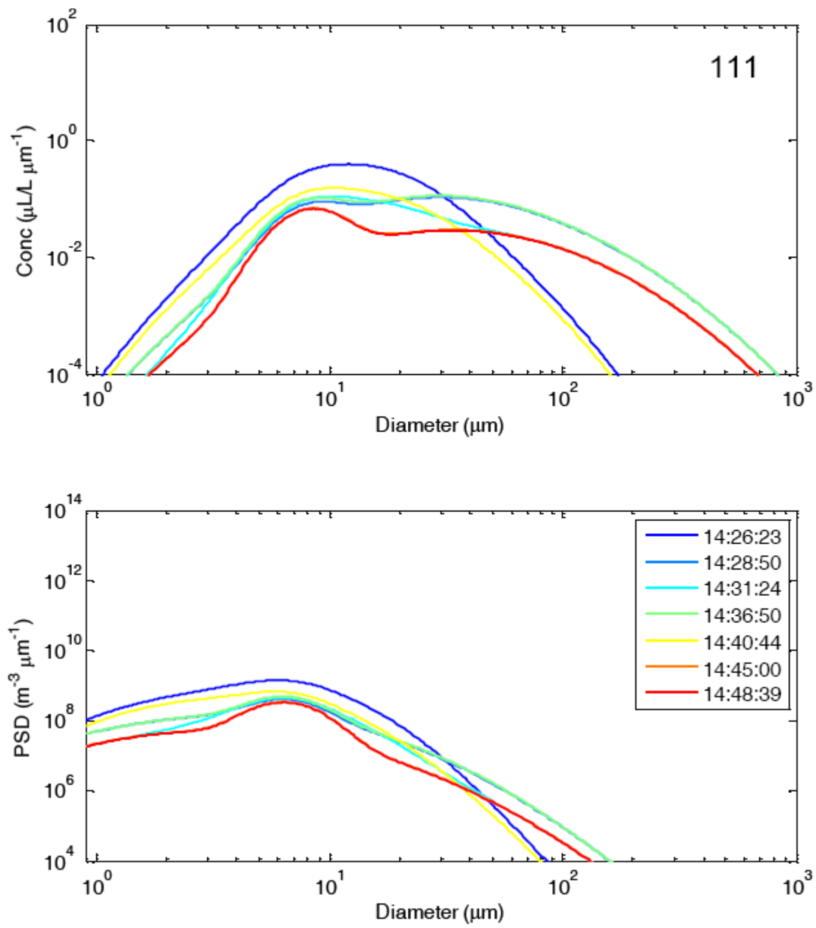


Figure C-8. Example volume concentration and number size distributions at chosen times. (corresponding with the large blue points in Figure C-7).

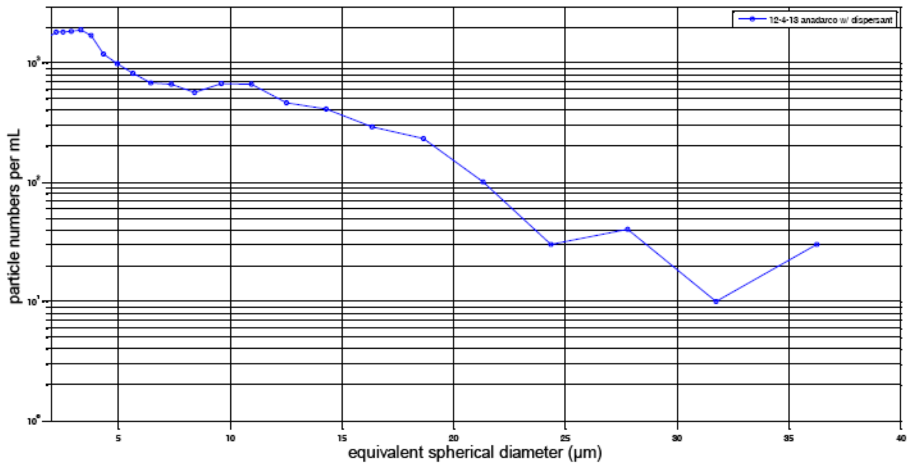


Figure C-9. Example of number size distribution analyzed with the DHM system.

The last measurement taken (Figure C-10) showed a strong signal pulse traversing through the plume at a speed of 3.5 knots. This was the fastest speed attempted during the testing because there was concern about the stability of the package suspended with wires and about the cabling on the package, which can be vulnerable to failure if exposed to substantial stress from passing water.

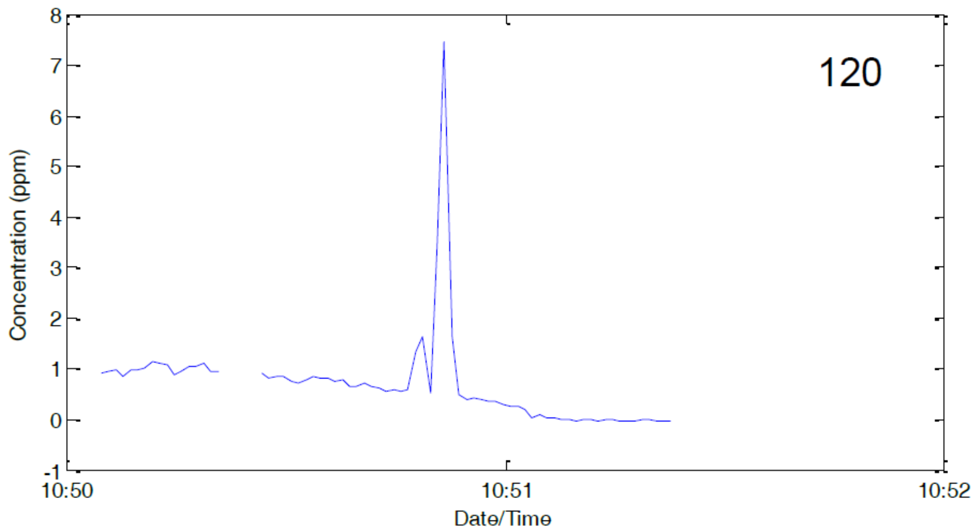


Figure C-10. Oil concentration as a function of time for high-speed run.

The ability to demonstrate other capabilities developed for WINDOW such as spatial mapping of plumes in Google Earth through distributed kmz files was relatively limited. Figure C-11 shows an example of these results. The study area in the tank was small enough that the wander on the GPS, up to 33 ft (10 m), provided significant bias error in the maps. In some cases where the platform moved significantly, mapping was more useful (Figure C-12). Table C-4 gives WET Labs' report of their compliance with the BAA requirements.

Figure C-11. Mapped oil concentration in Google Earth with GPS wander.

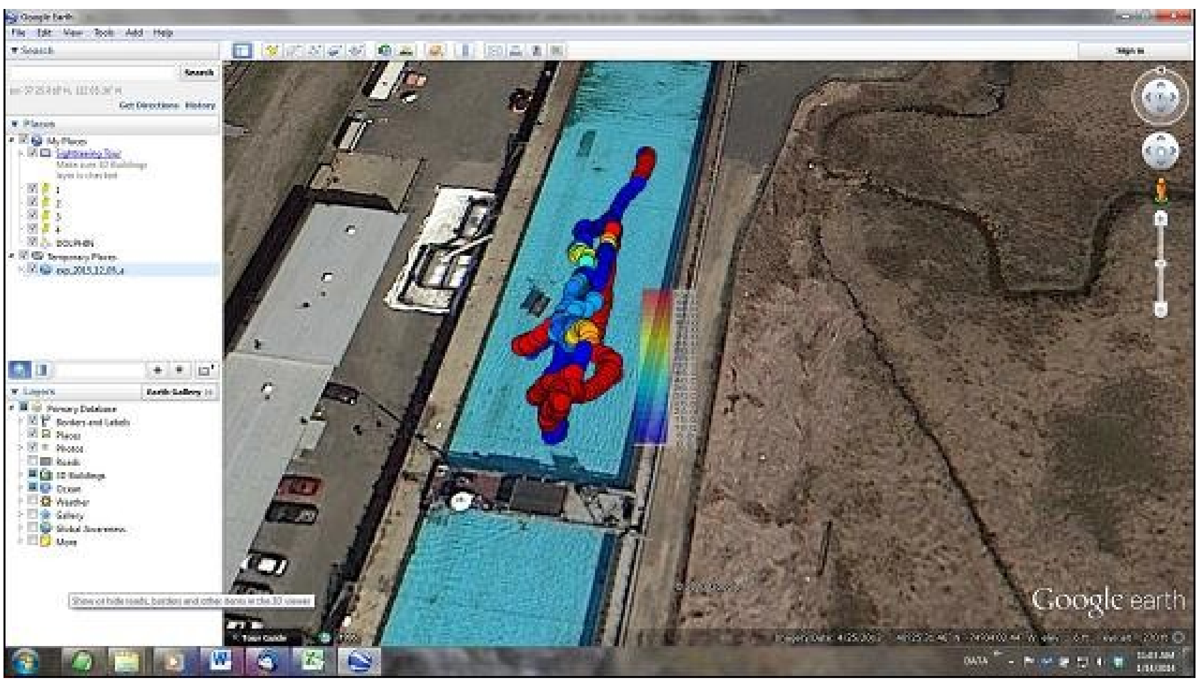


Figure C-12. Mapped oil concentration in Google Earth when measurements covered significant portions of the tank.

Table C-4. WET Labs requirements matrix.

Capability	WBMS
1. Provides results in near real time (less than 1 hour)	Results were provided in < 1 min
2. Calibrates easily for different oils	• The only calibration that is required is standard factory calibration to absolute volume scattering function units (m^{-1} sr^{-1}, where "sr" is the SI unit for steradian) once per year. • Calibration of 530 nm ECOs has shown to be stable within 2% over all natural environmental conditions (0-40 ^{o}C) for 1 year. • No on-site calibration is needed – a background measurement in unpolluted water is desirable for implementing the "background subtraction" inversion method • Sensors can be retuned for different oil detection sensitivity during annual factory calibration.
3. Works in currents or tow speeds up to 5 knots	• Sensors have been towed at speeds greater than 5 knots previously. • Sensors were towed at up to 3.5 knots at Ohmsett with no adverse effects to data quality.
4. Reports minimal false alarms	• Inversion algorithm keys off unique angular scattering shapes associated with spherical oil droplets that are not present in particle types seen in natural waters; this makes the algorithm very sensitive and uniquely specific to the presence of oil droplets. • There was no evidence of reports of false positives or false negatives during Ohmsett testing.

5. Detects dispersed crude oil	• After gain modifications to the scattering sensors for the Ohmsett experiment, our detection range was about 80 ppb to 80 ppm; detection range and sensitivity are both a function of gain settings, which can be tuned for specific applications
	• The detection limit of the ECO can be enhanced to at least 5 ppb and perhaps as low as 1 ppb simply by increasing the gain of the detector, which has been done in the past for measurements in very clear oceanic environments
	  o Note that increasing gain results in a decreased ability to resolve high concentrations of oil (greater than about 50 ppm) because sensor saturation will occur at lower concentrations.
	  o One possibility would be to use combinations of sensors with different gains or a gain switch to resolve a wider dynamic range

6. Sweeps an area of water column 3 ft by 3 ft	• Sample volume is on the order of mL, but towing the sensors provided 3D resolution of oil concentrations throughout the water column • Vertical variability in hydrography is typically 1-2 orders of magnitude greater than horizontal variability in the coastal ocean, so that extrapolation of a point measurement to 3 ft in the horizontal dimension may be assumed with excellent accuracy.
7. Provides digital readout or measured values and digitally logs field data	Digital results were demonstrated with readouts and maps in the operator GUI as well as maps disseminated to interested parties via smart phone or similar wireless devices.
8. Is field rugged	• Ruggedness of ECO sensors and other sensors in the proposed system have already been proven through field work for more than a decade and was also demonstrated at Ohmsett. • The ECO is remarkably robust, with a fully potted head, 2-3 percent drift per year, and no apparent environmental sensitivity in the temperature range of 0-40 oC.

Table C-4. WET Labs requirements matrix (cont.).

Capability	WBMS
9. Is portable	• Ohmsett demonstration showed the in-water sensor package is < 20 lbs and field deployable by a single operator. • The preferred commercial embodiment of the sensor package is a completely integrated sensor system with no individual sensor cables; such a sensor would be even more compact.
10. Determines droplet size, density (specific gravity) and/or kinematic viscosity	• Droplet size quantification with 1-2 μm precision, and density derived with better than 2 percent accuracy, was demonstrated in lab work. • At Ohmsett, droplet size distributions from the in-water sensor were consistent with size distributions measured with a bench top digital holographic microscope, even though the samples for bench top analysis were discretely collected. • At Ohmsett, derived oil densities were consistent with published values. • With estimates of mass concentration and density, oil recovery capability amounts for different recovery systems may be computed.
11. Deploys quickly and easily	Already proven with proposed technology; demonstrated at Ohmsett.
12. Grabs water samples for further laboratory testing	We collected samples for laboratory holographic imaging validation using hydrophilic tubing; the sensor system itself does not collect discrete samples.

APPENDIX D. LISST NORMALIZED GRAPHS

This is the collection of all the LISST normalized plots created by the Ohmsett team. They show what the instruments measured in the submerged oil plume at certain times. Generally, it is noted that the concentration significantly attenuates within a few minutes. Tests #266 to #269 capture oil plumes released during NORBIT's test trials while Tests #103 to #117 represent oil plumes released during WET Lab WINDOW's test trials.

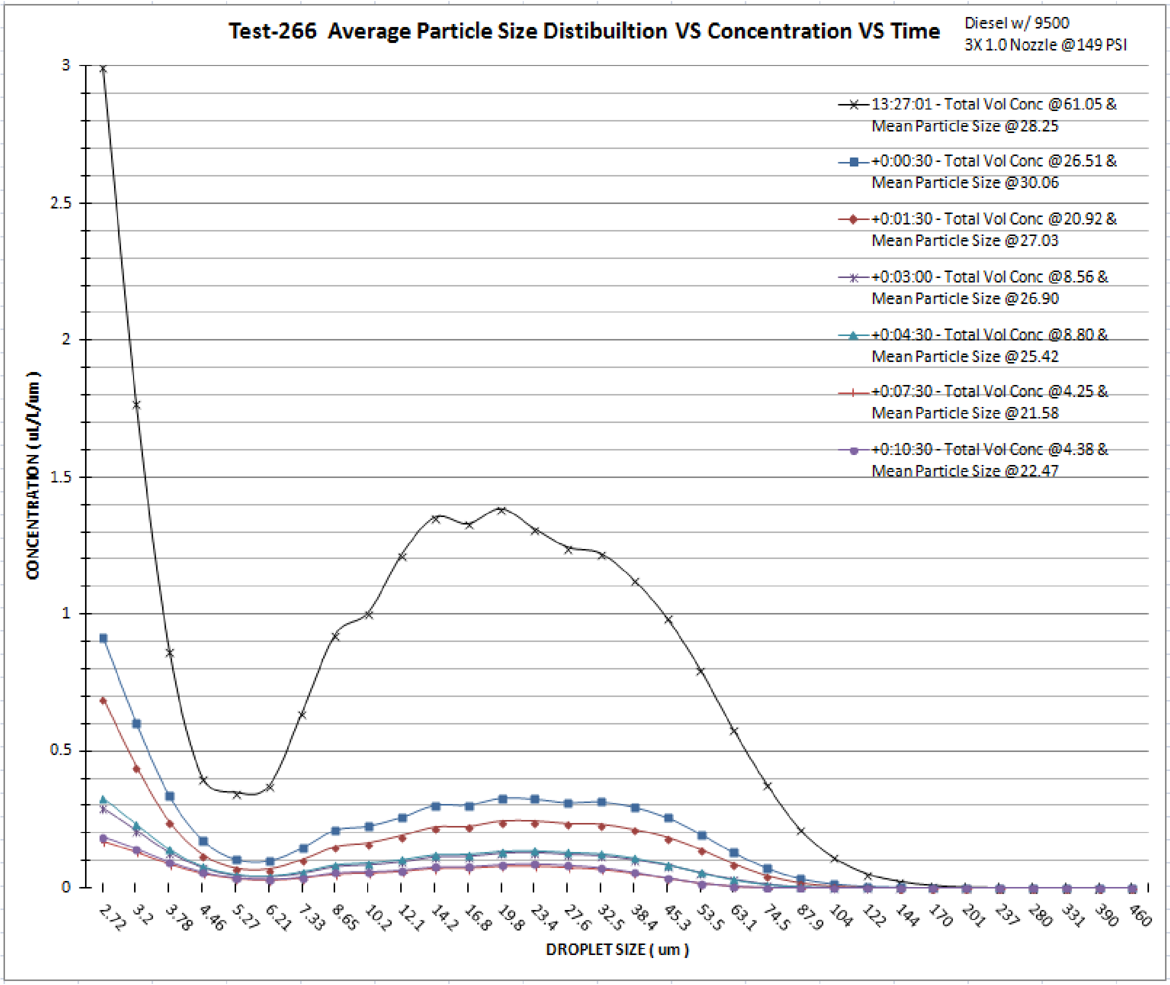


Figure D-1. WBMS Test #266 average particle size distribution.

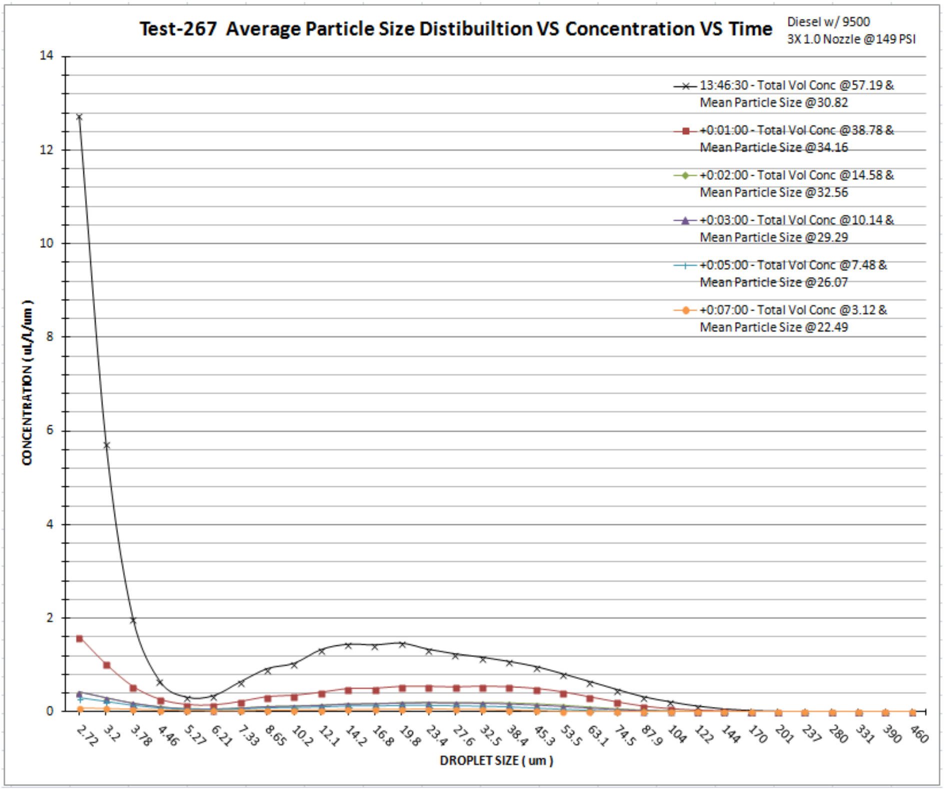


Figure D-2. WBMS Test #267 average particle size distribution.

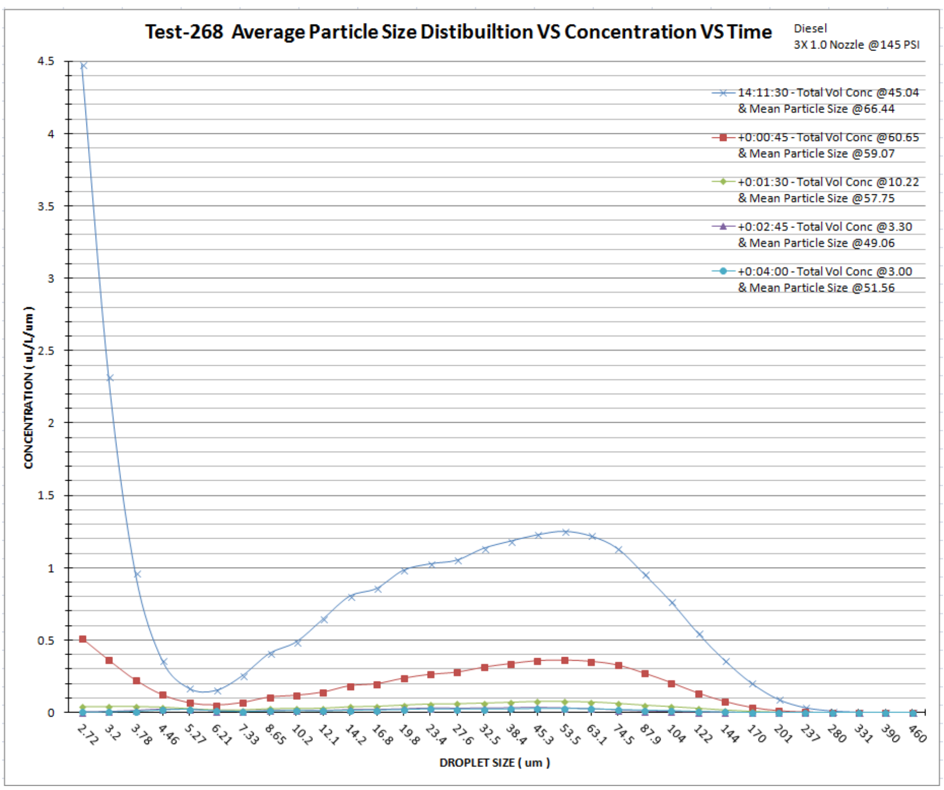


Figure D-3. WBMS Test #268 average particle size distribution.

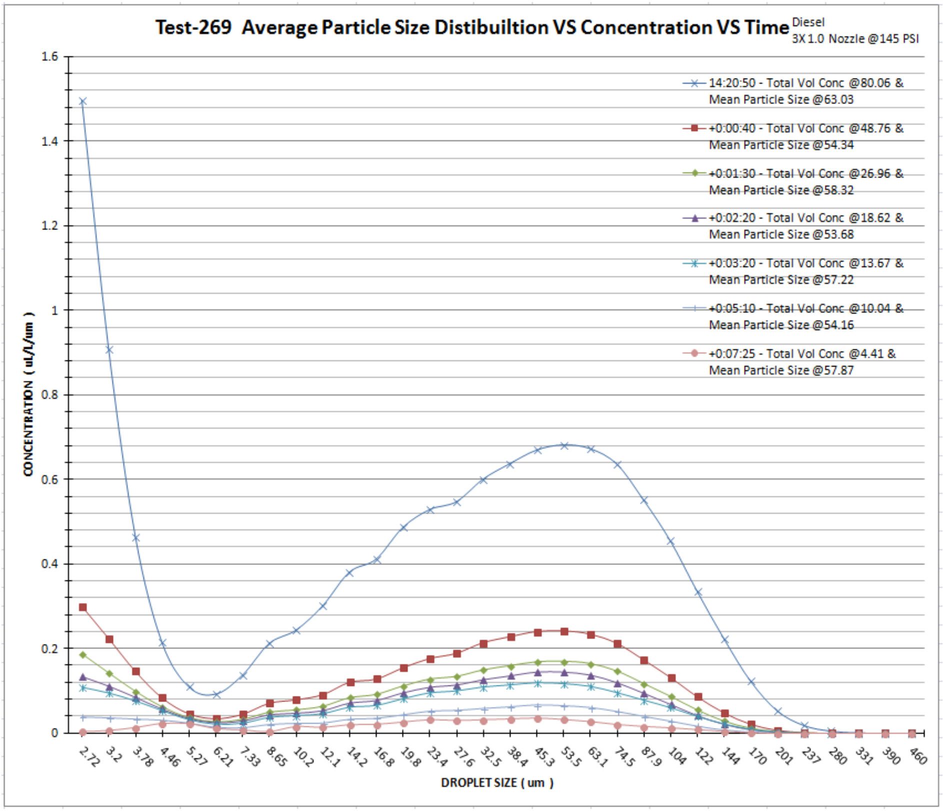


Figure D-4. WBMS Test #269 average particle size distribution.

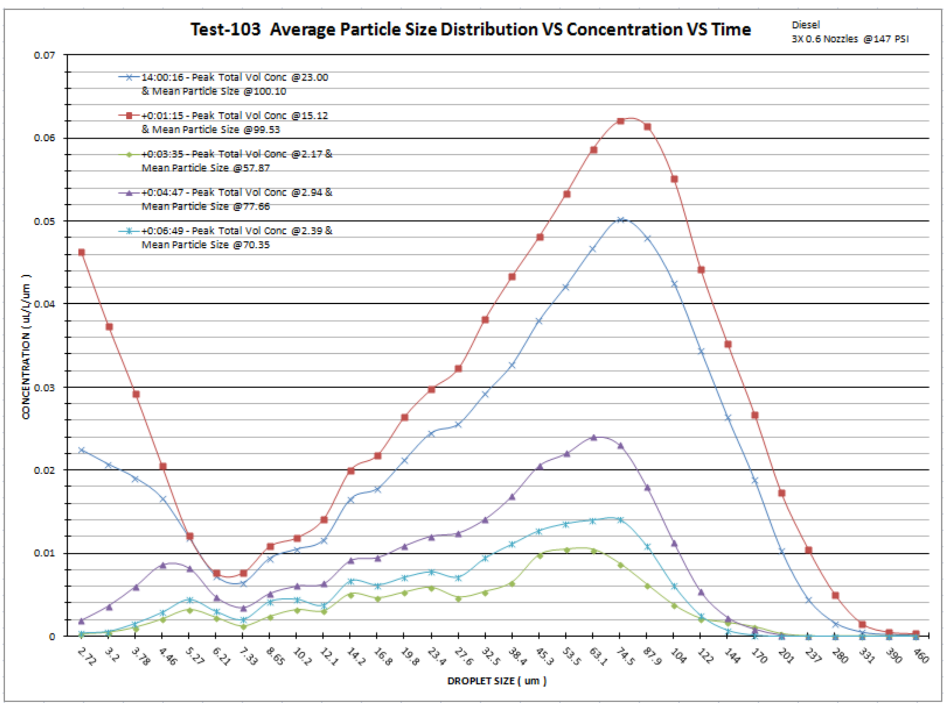


Figure D-5. WINDOW Test #103 average particle size distribution.

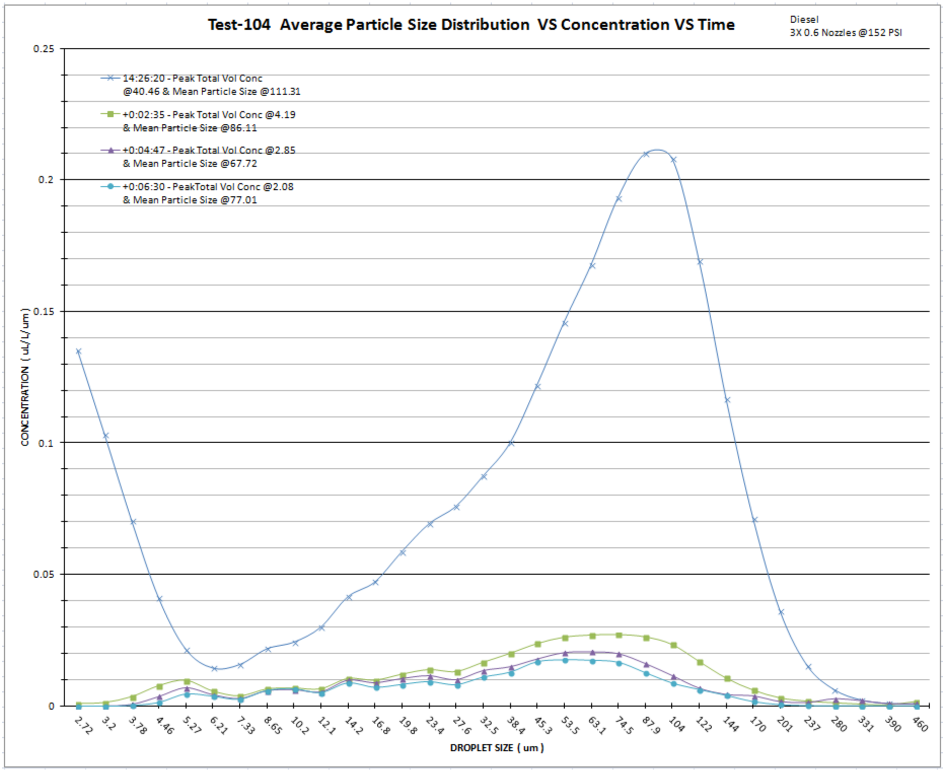


Figure D-6. WINDOW Test #104 average particle size distribution.

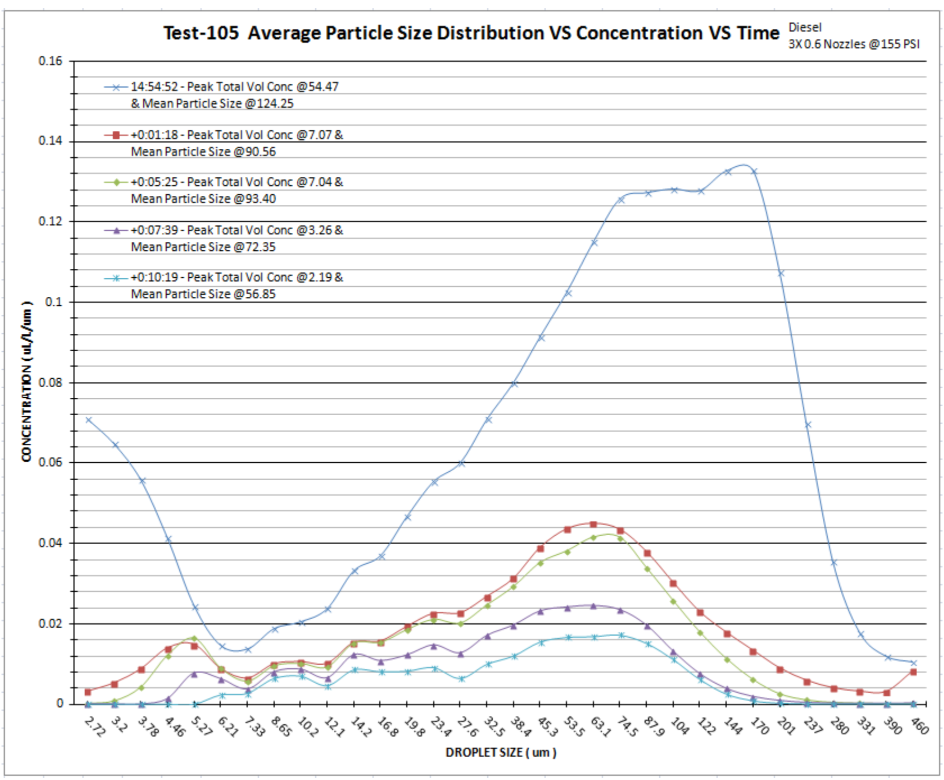


Figure D-7. WINDOW Test #105 average particle size distribution.

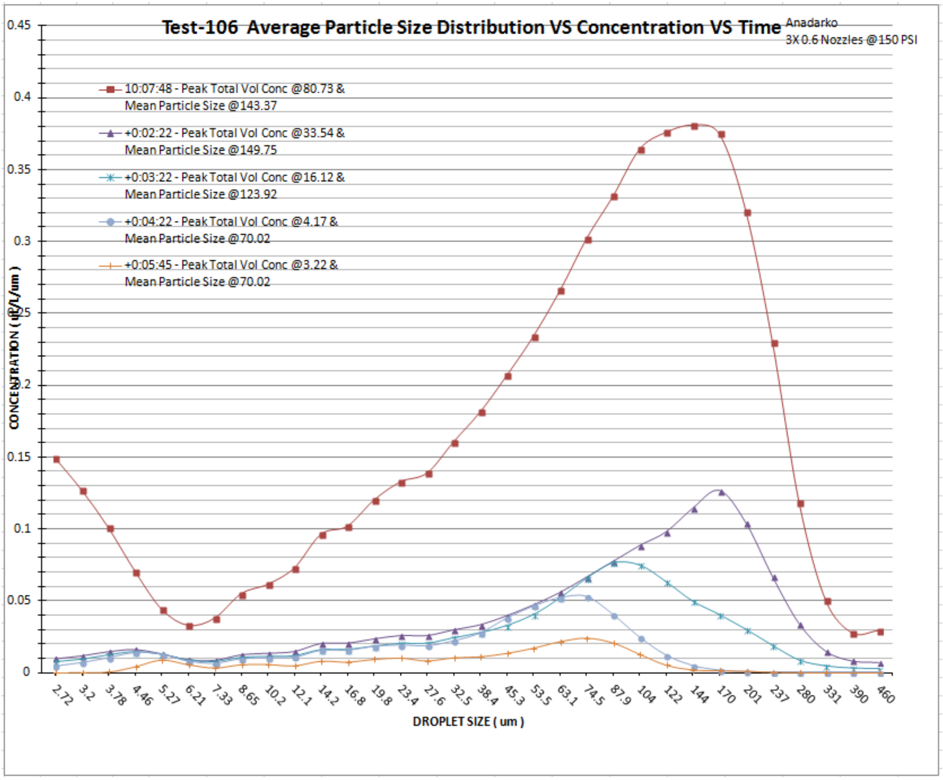


Figure D-8. WINDOW Test #106 average particle size distribution.

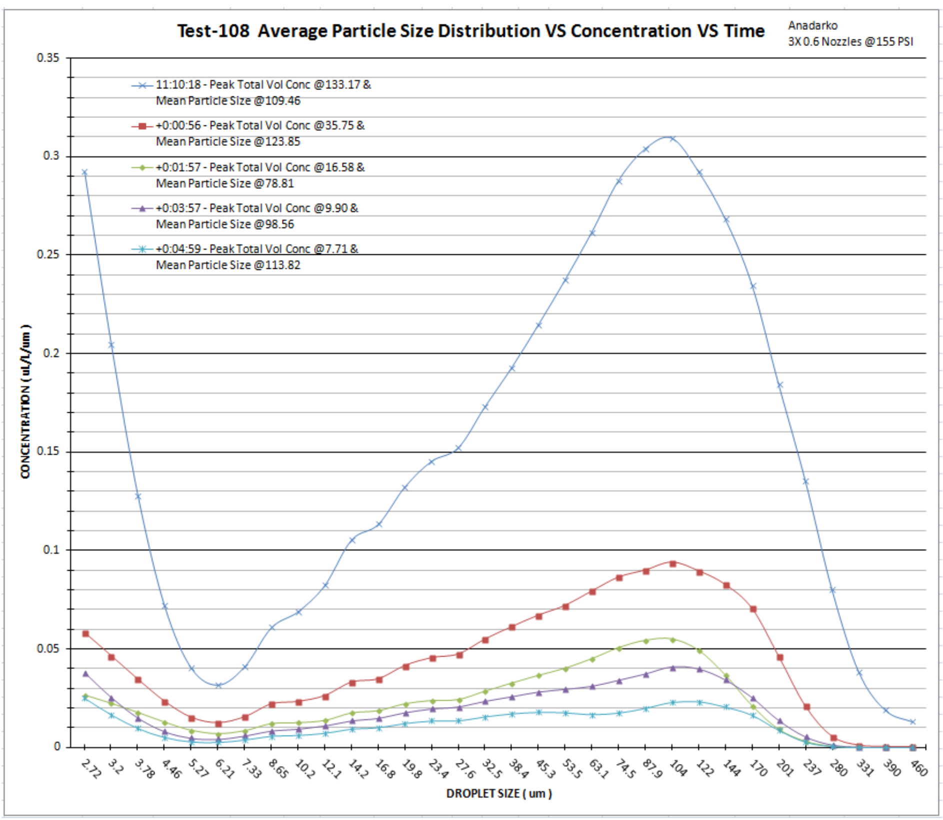


Figure D-9. WINDOW Test #108 average particle size distribution.

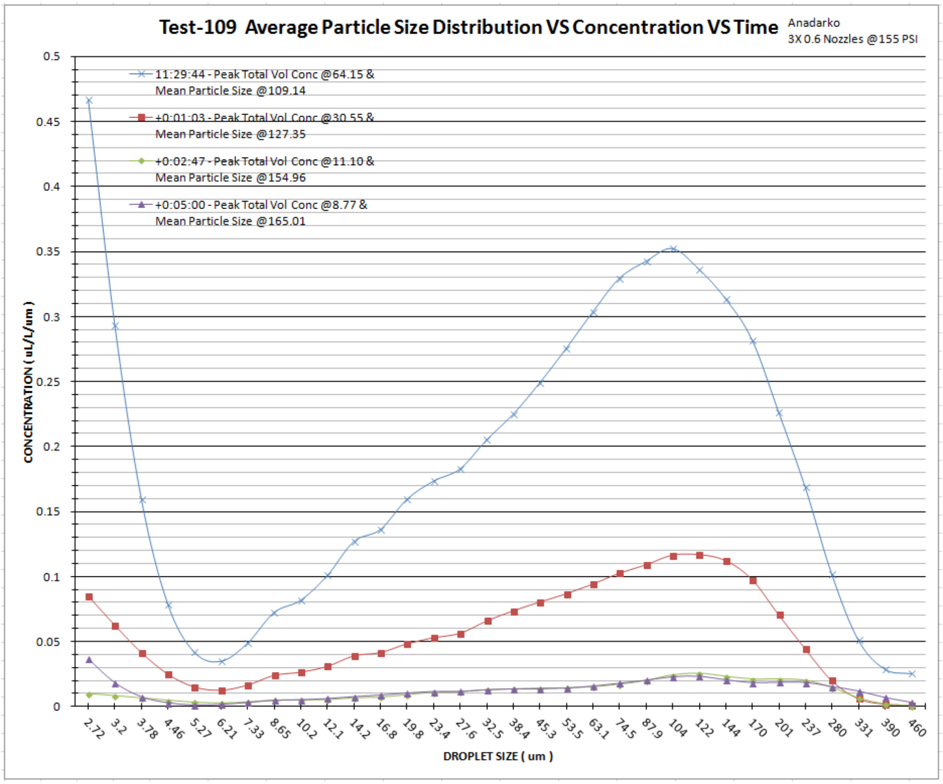


Figure D-10. WINDOW Test #109 average particle size distribution.

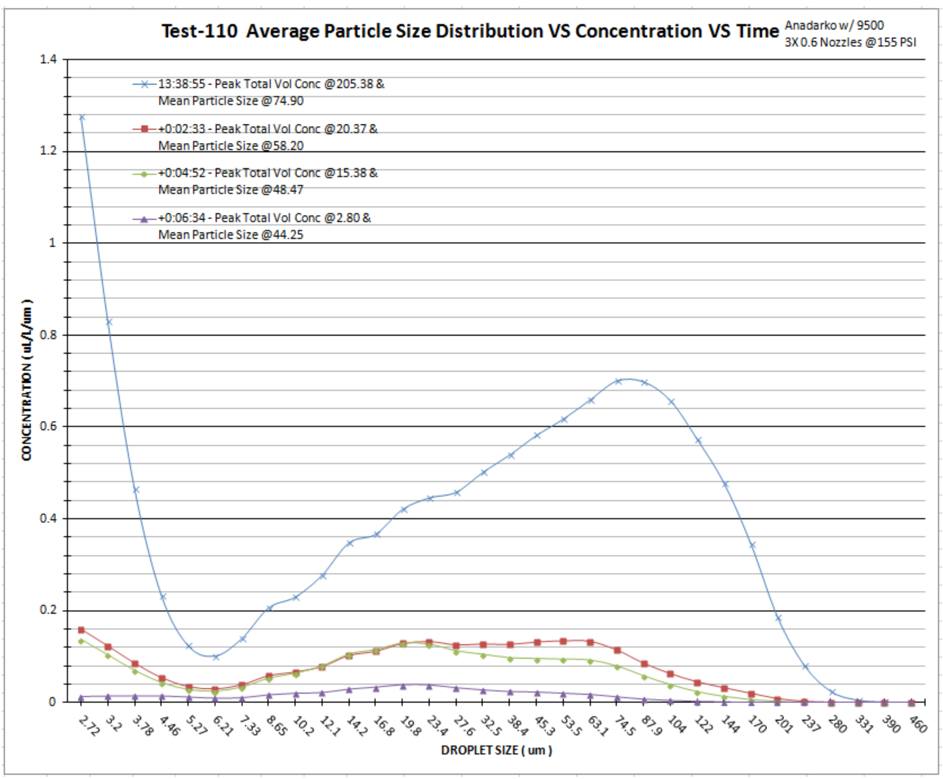


Figure D-11. WINDOW Test #110 average particle size distribution.

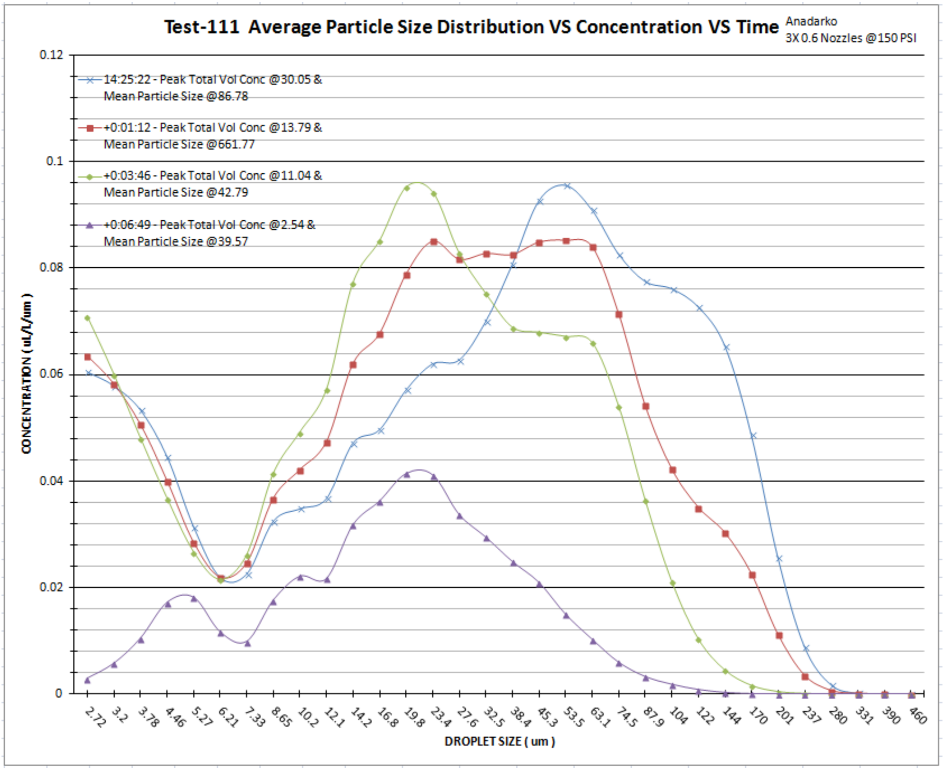


Figure D-12. WINDOW Test #111 average particle size distribution.

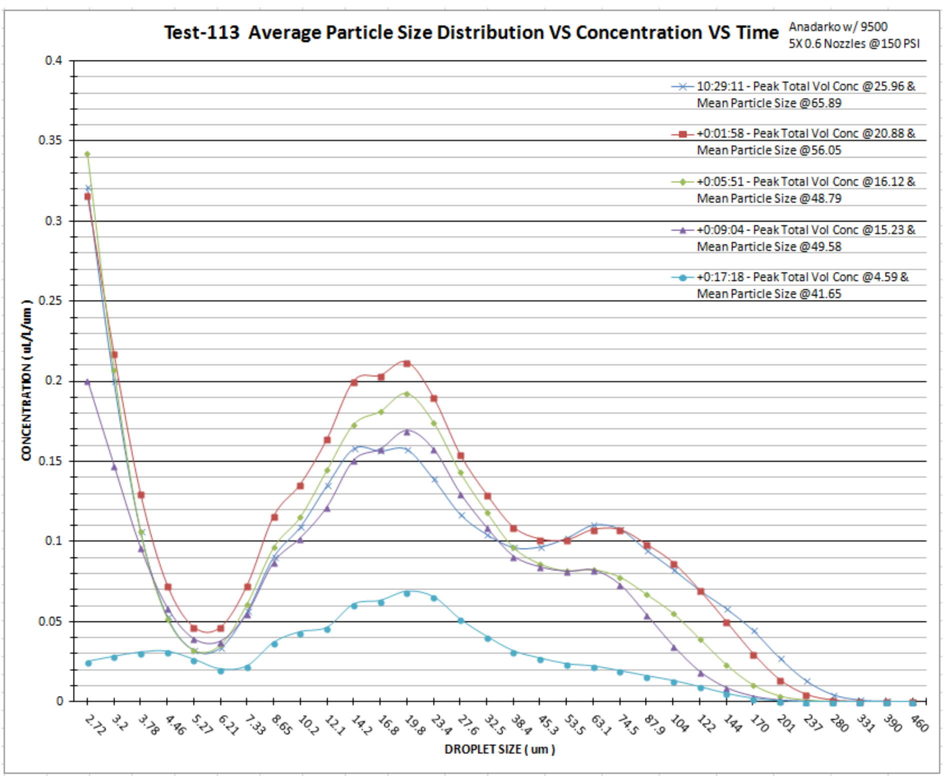


Figure D-13. WINDOW Test #113 average particle size distribution.

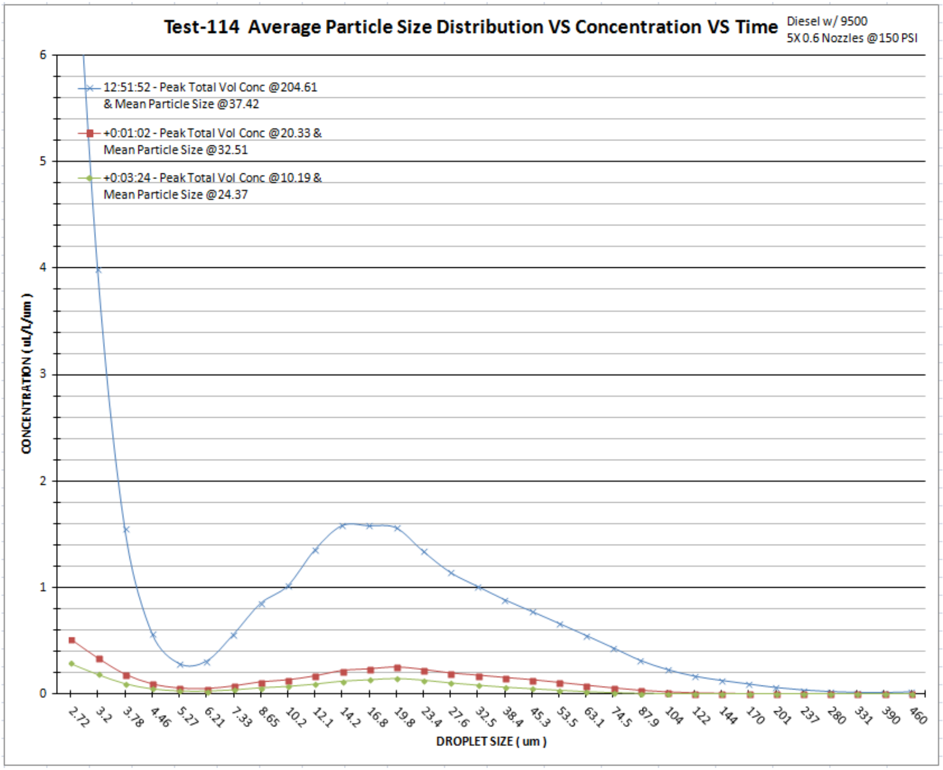


Figure D-14. WINDOW Test #114 average particle size distribution.

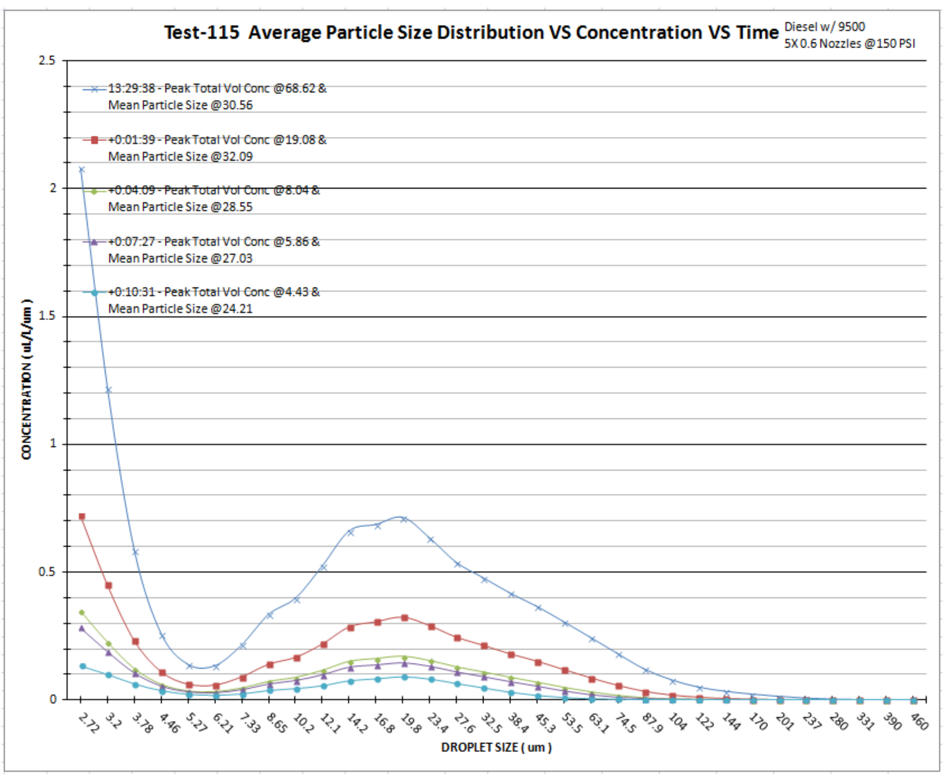


Figure D-15. WINDOW Test #115 average particle size distribution.

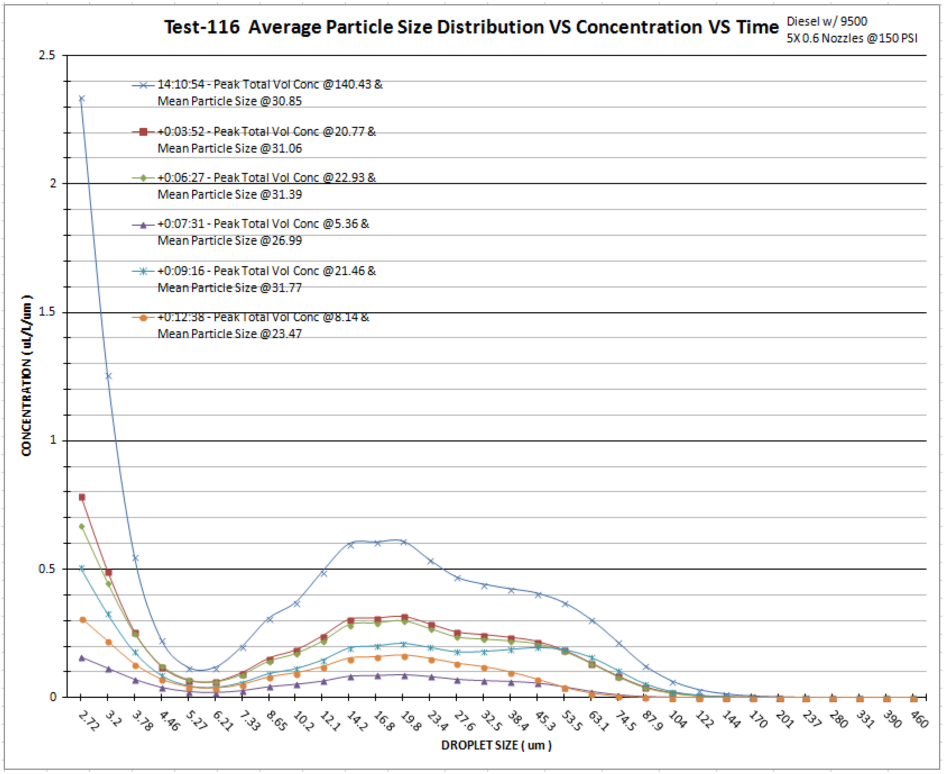


Figure D-16. WINDOW Test #116 average particle size distribution.

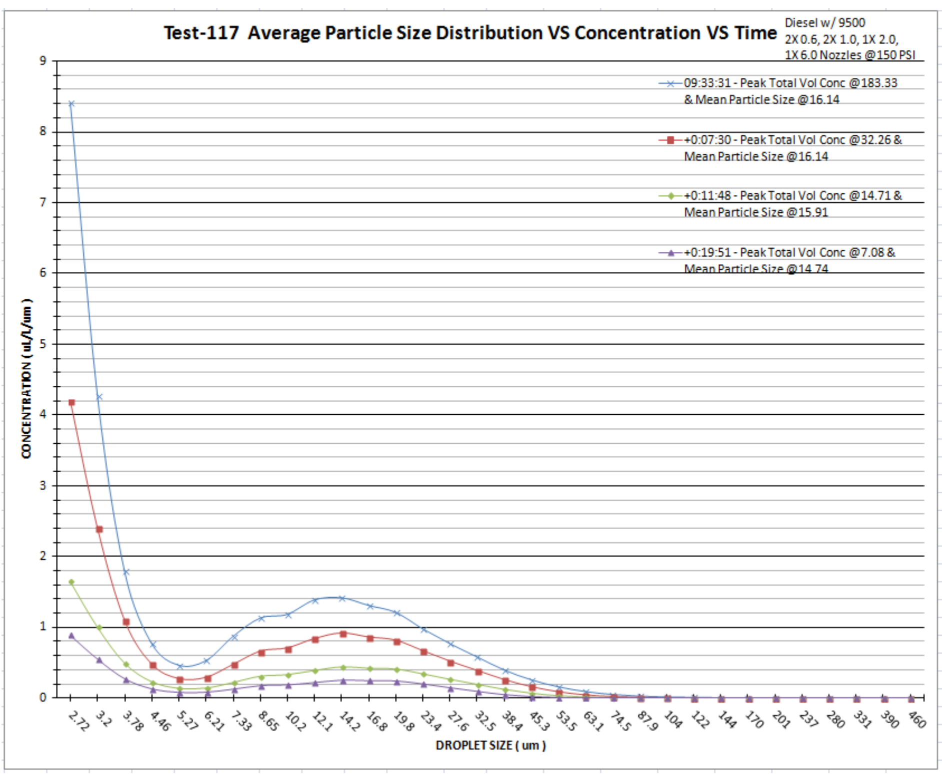


Figure D-17. WINDOW Test #117 average particle size distribution.

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