SUBSEA CHEMICAL DISPERSANT RESEARCH

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Disclaimer

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Executive Summary

The BP Macondo subsea blowout in the Gulf of Mexico was the first oil spill response that included the injection of chemical dispersants into a subsea oil and gas plume. The effect of this countermeasure on the ultimate fate of the oil was difficult to quantify during the spill event, but the operation generally was deemed to be effective in breaking the oil into smaller drops that resulted in less oil reaching the surface and an increase in the rate of bio-degradation of the oil. As such, there is considerable interest by both spill response organizations and regulatory agencies to 1) develop methods to measure the characteristics of the oil and gas plumes generated before and after chemical injection, 2) confirm that the injection of dispersants in a subsea plume is indeed effective, and 3) develop equipment and procedures to maximize the potential of the countermeasure under various spill and environmental conditions.

Because this is a very new approach to the use of chemical dispersants, there are many questions that need to be answered before a full understanding of the processes will be gained. Many of these questions include the development of plume measurement methods, nozzle design, study of injection location effects, application rates, the effects of temperature and pressure and the presence of gases and sediments. Our approach has been to expand upon work that is already underway elsewhere, on the most basic issues, in hopes of making cost-effective, incremental gains in the understanding of the feasibility and potential effectiveness of subsea dispersant injection. The research conducted in this project investigates the issue of the effect of natural gas, oil type, dispersant to oil ratio, and gas to oil ratio on the subsea chemical dispersion process.

The primary objective of this work was to determine if the presence of natural gas or methane in a subsea oil and gas discharge would reduce the effectiveness of a dispersant injected into the gas-oil mixture. The underlying concern was that some of the dispersant might be attracted to the hydrocarbon gas bubble-water interface and not be available to attach to the oil-water interface and thus reduce the effectiveness of the applied dispersant. Tests were conducted with air (non-hydrocarbon) or methane (hydrocarbon) with all other parameters kept constant and the resulting
drop size distributions compared. The significance of dispersant to oil ratio (DOR), location of dispersant injection, gas to oil ratio (GOR), oil type and orifice diameter were also evaluated in the test program. The size of the oil drops generated in the subsea release, specifically the volume medium drop diameter (VMD) metric of the oil drop size distribution, was used as the criteria for comparison of dispersant effectiveness.

Tests were conducted both at the SL Ross laboratory facilities in Ottawa and at the BSEE operated National Oil Spill Response Research & Renewable Energy Test Facility (Ohmsett) in Leonardo, New Jersey. The small scale work at SL Ross provided convenient and cost-effective test environments to evaluate methods for liquid and gas delivery to the underwater nozzle and methods for the measurement of the resulting oil and gas plumes. Two small scale test setups were used. One utilized a 6 inch diameter by 5.6 foot high clear acrylic column and the other a 4 foot wide by 33 inch deep by 30 feet long tank. The vertical column provided optimal test conditions for digital imaging of the oil and gas plume, but did not permit the use of an in-situ particle size analyzer for convenient oil drop size measurement. The tank tests allowed the deployment of the in-situ particle size analyzer, but were not as conducive to the digital imaging of the oil and gas plume. The tank tests utilized a horizontal jet release to successfully evaluate the ability to segregate the rising oil drops and gas bubbles to allow direct measurement of the oil drops using the laser in-situ particle size analyzer (LISST). Pressurized supply tanks and precision needle valves for flow control were implemented for the oil and dispersant delivery systems in both of the small scale test setups. Gas flow was controlled using a rotameter flow meter. The liquid and gas delivery systems developed and tested in the small scale testing were then successfully implemented in the larger scale tests conducted at Ohmsett. The laser in-situ particle size analyzer was the primary tool used to measure the dispersed oil drop sizes in the discharge plume in the small scale tank tests at SL Ross and in the large scale tests at Ohmsett. The processing of digital video imagery for the measurement of the larger oil drops present in the untreated oil and gas plumes was investigated but a suitable method was not identified and further work in this area is required.
The test results indicate that there may be a reduction in dispersant effectiveness when methane as opposed to air is present for some oil types, but not all, under the flow and low pressure conditions studied. This study did not address the issue of deep water releases, gas properties under high pressure, complex natural gas mixtures, or hydrate formation under high pressure conditions and is applicable only to shallow well blowout situations. A reduction in effectiveness, as measured by an increase in the oil drop distribution VMD by about 20 to 30 microns, was identified for two of the oils: Terra Nova crude oil, Figure 17, in the small orifice tests conducted at SL Ross and Endicott crude oil in the large orifice tests conducted at Ohmsett, Figure 74 and Figure 75. It is also instructive to note that an increase in gas flow in the tests with Endicott crude oil did not result in a greater loss in effectiveness in the methane tests when compared to the tests that used air (compare Figure 76 and Figure 74 and Figure 77 and Figure 75). For the Dorado oil there was no significant loss in effectiveness when methane was present in the discharge as seen in Figure 34 to Figure 43 for the small orifice tests and Figure 62 to Figure 70 for the large orifice tests. The average VMDs for the tests with air were generally slightly smaller than the methane VMDs for the Dorado crude oil tests, but the standard deviations of the measured drop size distributions overlapped suggesting that the difference is not appreciable.

The dispersant to oil ratio (DOR) had a significant effect on dispersant effectiveness in all of the tests conducted, as would be expected. In the large orifice (4.5 mm) tests at Ohmsett a DOR of 1:50 was adequate to achieve dispersions with oil drop VMDs of less than about 70 microns for both the Dorado (Figure 86 and Figure 87) and Endicott (Figure 88 and Figure 89) crude oils. In the small orifice (1.5 mm) tests at Ohmsett higher dispersant doses were required to achieve small oil drop dispersions than those used in the large orifice tests. For the Dorado crude oil (Figure 58 and Figure 59) the 1:50 DOR only achieved dispersions with VMDs of 80 to 140 microns and for the Endicott crude a 1:50 DOR generated dispersions with VMDs of 200 to 230 microns (Figure 60 and Figure 61). In the small orifice tests at Ohmsett with Endicott, DORs of 1:10 were necessary to achieve oil drop VMDs of 50 microns. In the small orifice (1.5 mm) tests at SL Ross good dispersions (VMDs less than 70 microns) were achieved with DORs of 1:50 for both Endicott crude, Figure 25, and Terra Nova crude, Figure 26. The reason for the difference in
the Endicott results from the Ohmsett tests is not known. One possible explanation is that the oil used in the SL Ross test was not from the same batch as that used at Ohmsett.

The orifice size used in the testing appeared to have an effect on the dispersant effectiveness outcome as discussed above. Better dispersant efficiency was generally achieved in the larger orifice tests at Ohmsett where direct comparison to small orifice tests can be made.

The effect of gas to oil ratio (GOR) used in the tests on the dispersant effectiveness is inconclusive based on the Ohmsett test data where sufficient data is available for comparison. For the Dorado oil there appears to be minimal influence of GOR on the oil drop VMDs in the 4.5 mm orifice tests (Figure 86 and Figure 87) at all DORs. In the small orifice tests (Figure 58 and Figure 59) there was little influence of GOR on the oil drop size distribution at the high DORs tested for both the air and methane tests and no consistent difference at all DORs for the tests with methane (Figure 59). In the tests with air as the gas (Figure 58) the higher GOR resulted in smaller oil drops for the low dose applications. For the Endicott oil there was a consistent increase in the oil drop VMDs in the 4.5 mm orifice tests with an increase in GOR (Figure 88 and Figure 89) at all DORs. There is insufficient data to comment on the influence of GOR for Endicott crude and the small orifice.

The effect of dispersant injection location was studied in a separate series of tests conducted in late June, 2014 using Alaska North Slope crude oil (ANS). Sufficient quantities of Dorado and Endicott were not available for these tests. These additional tests indicate that the injection location within the pipe has some impact on the resulting dispersed oil drop size distribution depending on the flow conditions. Injection of dispersant in the pipe prior to exit from the discharge nozzle resulted in the best dispersant performance in the small orifice tests (see Figure 106 and Figure 107) but the location within the pipe did not result in a major difference in dispersant performance for the small orifice tests. In the lower velocity large orifice tests, dispersant performance was enhanced when the in-pipe injection location was moved further away from the exit (see Figure 114 and Figure 115). This was likely due to the longer mixing
times available in the pipe prior to exit from the nozzle and the overall reduced mixing in the larger diameter releases which had lower flow velocities than the small orifice tests. In both the small and large orifice tests the dispersant performance was reduced when the injection point was moved outside of the pipe and dispersant performance decreased as the injection location was moved further away from the exit.

Differences in dispersant effectiveness on the two primary test oils (Endicott and Dorado) have been noted above for the nozzle sizes, DORs, GORs and gas versus air conditions tested. Additional testing on a number of oils would be required before quantifiable relationships between oil properties, the above tests conditions and dispersant effectiveness could be made.
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SUBSEA CHEMICAL DISPERSANT RESEARCH

1 Background

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Because this is a very new approach to the use of chemical dispersants there are many questions that need to be answered before a full understanding of the processes will be gained. Many of these questions were identified in a solicitation published by BSEE and include the development of plume measurement methods, nozzle design, study of injection location effects, application rates, the effects of temperature and pressure and the presence of gases and sediments. Our approach expands upon work that is already underway elsewhere, on the most basic issues, in hopes of making cost-effective, incremental gains in the understanding of the feasibility and potential effectiveness of subsea dispersant injection.

Recent work conducted at Sintef (Brandvik et al., 2013; Johansen et al., 2013) studied oil drop size atomization from chemically treated submerged oil jets. The Sintef tests to date have used air and are not investigating the effect that natural gas might have on the dispersion process. The research conducted in this project investigates the issue of the effect of natural gas, oil type, dispersant to oil ratio, and gas to oil ratio on the subsea chemical dispersion process.
2 Project Description

Tests were conducted both at the SL Ross laboratory facilities in Ottawa, Ontario and at the BSEE operated National Oil Spill Response Research & Renewable Energy Test Facility (Ohmsett) in Leonardo, New Jersey. The small scale work at SL Ross laid the ground work for larger-scale testing conducted at Ohmsett.

The research focused on the following areas.

1. Work to develop and test techniques for the creation of representative oil and gas discharges with dispersant injection and the measurement of the resulting oil drop and gas bubble distributions in subsea oil and gas plumes.

2. Bench scale testing to study the effect that the presence of natural gas has on the effectiveness of dispersants when applied in a gas-oil-water system. The goal here was to determine if the presence of the natural gas significantly alters the effectiveness of the dispersant. If it does not then future tests, under similar low pressure conditions as studied in this program, can be conducted using air instead of natural gas thus making tests less expensive and less complicated.

3. Small-scale tank tests to further evaluate measurement techniques and the effect of natural gas on the dispersion process.

4. Larger-scale, longer term tests at the Ohmsett facility to expand the investigation of the effect of gas on the dispersion process using different oils, gas to oil flow rates and dispersant to oil ratios.
3 Small Scale Testing

Bench-scale and tank tests were completed in the SL Ross laboratory to investigate the role of natural gas in the gas-dispersant-water-oil system to determine if it is stripping away dispersant and significantly altering the amount of dispersant available to the oil. Small amounts of oil, methane (as an analogue for natural gas) and dispersant have been injected into the bottom of a small diameter vertical column of water and a large test tank and the behavior of the mixture monitored as it rises through the water. The tests have been repeated with oil, air and dispersant for comparison.

One of the objectives of the small scale laboratory tests was to evaluate techniques for the measurement of the oil drops and gas bubble plumes to determine which techniques might be the most appropriate for the larger Ohmsett tank tests. A LISST 100x particle size analyzer and digital imaging techniques were employed. We consulted with our contacts at Sintef to draw upon their experience to date in these types of measurements in their ongoing test program and discussed possible measurement techniques with researchers at the Canadian National Research Council’s (NRC) Institute for Chemical Process and Environmental Technology.

3.1 Vertical Column Tests

3.1.1 Apparatus

A vertical column up-flow test apparatus was custom built for the small-scale tests. Liquid (oil or water), gas (air or methane) and dispersant delivery systems were also developed as part of this bench scale testing component. The system permits the use of high definition video and digital still photography in close proximity to the liquid and gas interactions, the inclusion of high intensity lighting and test runs with relatively small amounts of test water and oil.

The base of the up-flow column is shown in Figure 1. The base houses the oil/gas/dispersant injection nozzle and the up-flow water intake. Figure 2 shows the upper portion of the column with the digital still and video camera mounts, lighting, upper water overflow collection, propane ignition source to burn exiting methane and overhead ventilation hood. The propane ignition and
ventilation at the top of the column were implemented to ensure that no flammable gasses were released into the confined space of the laboratory to eliminate any explosive hazards.

The column inside diameter is 5.75 inches (14.6 cm) and the column height is 5.6 feet (1.7 m). A 5 gallon pail was fitted over the top of the column to collect the water overflow from the top of the tube and direct it to waste storage. Figure 3 and Figure 4 show close-ups of the column base and top components, respectively. The up-flow water enters the column through the 3/8 inch holes drilled in the white plastic ring positioned within the column. The size of these holes was increased after initial testing to reduce the water turbulence in the vicinity of the oil/gas/dispersant nozzle release point. Water is pumped into the column using a sump pump and ¾ inch hose after passing through a pleated paper filter to remove particulates. The up-flow velocity used in all tests was 1 inch/sec (2.5 cm/s) with a flow rate of about 6.7 gallons per minute (gpm) (425 cm³/s). Each test used approximately 18.5 gallons (70 liters) of 35 parts per
thousand (ppt) salt water that was prepared prior to each test. The salt used to make the test water was a fine grained 97.5 % (minimum) sodium chloride.

The digital cameras were mounted on sliding tracks for ease of camera positioning. Frosted panels were placed in front of the backlights to soften the lighting (see Figure 5).

The plumbing arrangement shown in Figure 6 was used to deliver the oil, gas and dispersant to the discharge nozzle. The inside diameters of the pipes leading to this header were 1/8 inch. Gas entered the system at the point furthest from the nozzle, oil into the central port and dispersant at the post closest to the nozzle exit. The oil and dispersant were delivered to the nozzle using canisters pressurized by air shown in Figure 7 and Figure 8. Liquid flow rates were controlled using needle valves shown in Figure 7. A high precision Vernier needle valve was used for the low flow dispersant connection and a 5 turn needle valve was used to control the higher oil flows. Gas flow was controlled using the rotameter shown in Figure 7. A pressurized cylinder of methane was used as the gas supply. A gas regulator valve was also fitted to the cylinder for precise pressure control.

A sample video of the column in operation can be viewed by clicking on the following hypertext links: Gas and untreated oil  Gas and Treated oil. These video clips are from Run 11 shown in Table 1.

GasAndTreatedOil.avi
Figure 3 Column Base Showing Water Up-Flow Ports

Figure 4 Close-up of Water Over-Flow and Propane Ignition Source
Figure 5 Camera Mounts and Back Lighting

Figure 6 Plumbing to Discharge Nozzle: Gas (bottom fitting), Oil (middle) and Dispersant (top)
Figure 7 Dispersant Supply Tank (top left), Air/Methane Flow Meter (top right left photo), Dispersant and Oil Flow Needle Valves (right photo)

Figure 8 Oil Supply Canister (top right), Air or Gas Line Connection (left)
3.1.2. Oil Drop and Gas Bubble Measurements Methods Investigated

We consulted with researchers at the Canadian National Research Council who have experience in high speed measurement of drops in various flow situations to identify other possible cost-effective options for these types of measurements. They visited our lab and viewed the experimental setup. Their opinion is that high speed video may not be able to differentiate between oil drops and gas bubbles unless the gas flow is less than 10% of the total flow volume. They recommend using a phase Doppler anemometer or stereoscopic imaging methods for the multiphase flow measurements. These methods were not pursued as they could not be transferred to the Ohmsett large tank tests. We also reviewed the types of measurements made by Sintef (Norwegian Research Institute) scientists who are doing similar work. They reported using an under-water digital macro camera with green laser lighting, an in-line particle visual microscope (PVM) and a LISST-100x particle size analyzer (Brandvik et al, 2013). Their published work suggests that the LISST provided the best drop size data as this was the only data presented in the paper. Based on this review, digital video and still imagery and LISST-100x particle size measurements were used as the primary oil drop and gas bubble measurement tools in the project. For the column tests the LISST-100x was used in a bench mode rather than being placed in the flow field due to the small size of the test column.

3.1.3. Test Protocol

The initial tests conducted in the vertical column were used to test digital video and still camera mounting and placement, gas and liquid flow systems, and lighting configurations. Once these systems were in place the following basic test procedure was implemented for each test. The test was started with a flow of gas at the required flow rate. The gas bubbles were imaged for at least one minute. Oil or water flow was then initiated and imaged again for approximately 1 minute. Water was used as a flow replacement for oil in some tests to investigate if dispersant had a significant effect on the gas bubble size. Dispersant flow was then added for approximately one minute and digital images were captured during the dispersant application period and for an additional period following the shutdown of the nozzle flow while the column cleared. All tests were conducted using Corexit 9500 (C9500) dispersant.
3.1.3.1. **Test Summary: Vertical Column**

A summary of the tests completed in the vertical column is provided in Table 1. Four tests were completed with water as the discharge fluid rather than oil to determine if the air or methane bubble sizes would be altered with the addition of dispersants. The remaining column tests used Endicott crude oil (density of 0.92 g/cc at 15°C).

**Table 1 Vertical Column Test Summary**

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Gas Type</th>
<th>Gas Flow (ml/min)</th>
<th>Oil Type</th>
<th>Oil Flow (ml/min)</th>
<th>Disp. Flow (ml/min)</th>
<th>DOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>air</td>
<td>750</td>
<td>water</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>2</td>
<td>air</td>
<td>750</td>
<td>water</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>3</td>
<td>methane</td>
<td>750</td>
<td>water</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>4</td>
<td>methane</td>
<td>750</td>
<td>water</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>5</td>
<td>air</td>
<td>1350</td>
<td>Endicott</td>
<td>150</td>
<td>7.5</td>
<td>1:20</td>
</tr>
<tr>
<td>6</td>
<td>methane</td>
<td>1350</td>
<td>Endicott</td>
<td>150</td>
<td>7.5</td>
<td>1:20</td>
</tr>
<tr>
<td>7</td>
<td>air</td>
<td>1350</td>
<td>Endicott</td>
<td>150</td>
<td>7.5</td>
<td>1:20</td>
</tr>
<tr>
<td>8</td>
<td>methane</td>
<td>1350</td>
<td>Endicott</td>
<td>150</td>
<td>7.5</td>
<td>1:25</td>
</tr>
<tr>
<td>9</td>
<td>methane</td>
<td>750</td>
<td>Endicott</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>10</td>
<td>air</td>
<td>750</td>
<td>Endicott</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>11</td>
<td>methane</td>
<td>750</td>
<td>Endicott</td>
<td>750</td>
<td>7.5</td>
<td>1:100</td>
</tr>
<tr>
<td>12</td>
<td>air</td>
<td>1350</td>
<td>Endicott</td>
<td>150</td>
<td>2</td>
<td>1:75</td>
</tr>
<tr>
<td>13</td>
<td>methane</td>
<td>1350</td>
<td>Endicott</td>
<td>150</td>
<td>2</td>
<td>1:75</td>
</tr>
</tbody>
</table>

3.1.4. **LISST Data Collection**

An attempt was made to process the overflow water from the column through the LISST using the flow-through adapter kit. Unfortunately the oil concentrations in the water flow were too high and the LISST became saturated. When saturation occurs not enough light is transmitted by the laser to the receptor to permit a measurement.

A further attempt was made to sample the overflow water, dilute it and then measure the drop size distribution using the static sampling cell adapter. In this process the oil has the opportunity to quickly surface in the sampling cell and re-coalesce. The drop size data collected using this technique were not reliable and have not been reported. The use of the LISST in the column
testing was deemed inappropriate and abandoned. No attempt was made to mount the LISST through the column wall. The oil concentrations within the column would have been too high for a measurement based on the results from the flow-through adapter kit.

### 3.1.5. Oil Drop and Gas Bubble Sizes by Digital Image Processing

Both digital still and video images of the oil and gas rising through the column were taken. The cameras were mounted on rails that permitted accurate placement of the cameras close to the column as seen in Figure 5. The early tests demonstrated that the digital video records provided better feedback on the lighting and provided a better overall product for the imaging of the larger gas bubbles and oil droplets prior to dispersant application. Once dispersant was applied and the oil drop sizes were reduced to 10's of microns in diameter neither the digital video nor digital still setups deployed were successful in capturing the individual oil drops. This was not unexpected due to the resolution of the cameras and the close-up lenses used in the testing. With more elaborate lighting, specialized lenses and higher resolution cameras it would be theoretically possible to image oil drops of a few microns in diameter, over a very small viewing area, using the still and possibly even video cameras. However, applying this technology to Ohmsett testing would be very difficult. The cameras would have to be mounted in the water to be close enough to the dispersed oil cloud. The lighting would have to be adjusted for each dispersant cloud ‘density’ and only a very small field of view would be imaged at a given time (to enable high enough resolution images to be recorded). A large number of images would then need to be processed using automated image analysis software similar to that described below. For these reasons the use of digital still and digital video images is likely best suited for the measurement of the larger gas bubbles and oil droplets that are generated prior to the dispersant application. These larger oil drops and gas bubbles cannot be measured using the LISST due to its 2.5 to 500 µm measurement range.

Drop size distributions have been determined by analyzing the digital video images collected during the column tests using the image processing software ‘‘ImageJ’’ developed by the National Institutes of Health (http://rsb.info.nih.gov/ij/) and a methodology kindly provided by Frank Shaffer of NETL and customized for use in this project. Approximately 10 seconds of video image (about 300 frames) were extracted from each video for analysis of the oil drop sizes.
prior to dispersant application and while dispersant was applied. A sample video frame of the column from Run 12, prior to dispersant application, and the resulting drop size capture by imageJ are provided in Figure 9.

Comparison of the two screen captures in Figure 9 illustrates that the imageJ analysis of the oil drops did not identify a number of the larger oil drops in the frame. Two primary reasons for the inability of imageJ to identify these larger drops were identified. Because the large oil drops cover a larger part of the viewing area they more often overlap small drops at their edges. This results in a non-circular entity when the image is automatically analysed and the drop is rejected. The second problem is best described by close examination of the two large oil drops in the top-center of the upper image of Figure 9. There are small gas bubbles in front of the oil bubbles. These overlapping bubbles given the oil drop an uneven coloring which results in an un-even re-classification of the black oil drop when the image is processed and the drop is not captured as an oil drop in the automated processing. As a result of these problems in imaging and processing the oil drops, the drop size distributions as determined using the imageJ analysis are like skewed towards a smaller than actual drop size distribution.
Figure 9 Video Frame of Oil Drops and gas Bubbles (upper frame) and imageJ Oil Drop Analysis (lower frame): pre-dispersant
Cumulative oil drop size distributions measured using the video imagery and imageJ processing are summarized in Figure 10 for the up-flow column tests that used the common oil and gas flow rates of 150 ml/min and 1350 ml/min, respectively. Tests that used both air and methane are shown in this graph. Figure 11 shows the cumulative oil drop size distributions for the higher oil flow tests conducted in the column. In these tests oil and gas flows were both 750 ml/min resulting in the same overall flow as in the previous tests.

It should be stressed that the drop size distributions shown in Figure 10 and Figure 11 are likely skewed to smaller drop sizes than actual for the reasons outlined above. The primary piece of information to take away from these graphs is that the volume median drop diameters of the untreated oil discharges tested are greater than 700 µm and therefore these drop distributions could not be measured by the LISST. The detectable particle size range for the LISST 100x is 2.5 to 500 µm. The drop size distributions are also very similar for the high and low oil flow tests. This would be expected since the gas flow was increased in the low oil flow tests to maintain the same overall combined oil and gas flow through the discharge orifice to maintain similar oil atomization conditions at the nozzle exit.
Figure 10 Oil Drop Cumulative Volume Distributions by imageJ Analysis of Video Imagery

Figure 11 Oil Drop Cumulative Volume Distributions by imageJ Analysis of Video Imagery: High Oil Flow Tests
The video image provided in Figure 12 is for the same test run as Figure 9 but was taken after dispersant was injected. The oil drops become much smaller after the dispersant has been applied. The volume median diameter in chemically aided oil dispersion is often less than 50 microns. This has been observed in many tests conducted at the Ohmsett facility where the LISST has been used to measure the oil drop size distributions. Many of the oil drops are therefore smaller than the minimum resolution of the video camera; which for the camera, lens and zoom setting used in this study resulted in an image pixel size (or minimum resolution) of about 35 microns. This would suggest that half of the discharged oil could be in drops smaller than what the video camera could record. These small drops also drastically reduce the light transmittance and make imaging of the larger drops very difficult as well. As a result of these issues the digital imaging used in this work was inadequate to record the drop size distribution of the dispersed oil clouds. Fortunately, the LISST device is well suited to measuring the drop size distributions in these dispersed oil clouds and is the method of choice for these measurements when it can be deployed in the plume as intended. The column used in these tests was too small to allow in-situ placement of the LISST and oil concentrations in the column were too high to permit measurement by the LISST, as previously discussed.

The upper image in Figure 13 shows methane bubbles during dispersant injection with no oil present. The lower image shows the imageJ automated bubble identification results. The method was unable to successfully identify the medium and large gas bubbles due to the considerable glare on the bubble surfaces. This resulted in un-even classification of the bubble area and rejection as a bubble in the automated processing. The lower graphic in Figure 13 shows the gas bubbles identified by imageJ for this image. Only the very small gas bubbles were identified using the process and the gas bubble distributions identified using this method were deemed inaccurate and have not been reported.

Considerable time was spent trying to optimize the image processing steps to improve both the oil and gas bubble drop identification with little or no improvement over the processing scheme initially provided by Frank Shaffer of NETL. It is possible that alternative image processing methods could result in improved oil drop identification for the untreated oil conditions and for the gas only bubble detection but this is left for future in-depth assessment.
Figure 12 Video Frame of Oil Drops and gas Bubbles (upper frame) and imageJ Oil Drop Analysis (lower frame): post-dispersant
Figure 13 Video Frame of Methane Bubbles (upper frame) and imageJ Bubble Analysis (lower frame): post-dispersant
3.1.6. Column Tests Discussion

The primary purpose of the column tests was to evaluate methods for the measurement of oil drop and gas bubble sizes. The column tests also provided a convenient experimental platform to test oil, gas and dispersant delivery and flow measurement methods. The small diameter of the column permitted a close-up view of the rising oil and gas plume and the ability to video the process from close proximity. However, the small size of the column did not permit the use of the LISST particle size analyzer to measure the dispersed oil drop size distributions.

The use of video records for the analysis of oil drop distributions prior to dispersant application when the oil drops are relatively large (up to a few mm in diameter) shows promise. The analysis of the video data collected indicates that the untreated oil drop size distributions have volume median diameters (VMD) in the range of at least 800 to 1500 µm, and likely higher, since the method used in the analysis was not able to consistently capture the larger oil droplets imaged. Additional work is needed to establish an improved image enhancement methodology to enable the automated drop analysis to capture the full range of drop sizes generated. The digital video data was not able to measure the dispersed oil drop distributions but, because the LISST particle size analyzer is very good at this, further development of video methods for this purpose are not recommended.

3.2 Small Tank Tests

3.2.1. Apparatus

Tests were conducted in the SL Ross wind/wave tank following the column tests. See Figure 14 for an overview of this tank. The tank is 4 feet wide by 33 feet long with 33.5 inch water depth. The tank was filled with 35 ppt salt water that was filtered using sand and activated carbon filters. The quantity of dispersant used in the tests on a given day were insufficient to affect the dispersant effectiveness outcomes and any dispersant applied was removed through filtering overnight. A high capacity overhead fume hood was used to remove methane from the laboratory during the tests. Tests were conducted next to the side viewing widow in the center of the tank. The tank tests used the same oil, gas and dispersant delivery system developed during the column tests. Figure 15 shows the nozzle configuration used in the tank work. The same 1.5 mm diameter nozzle used in the Column tests was used in the tank tests. The cement brick held the
nozzle and supply lines on the tank bottom with the nozzle positioned horizontally. Figure 16 shows the lighting, GoPro and high definition video cameras and LISST setup used in the testing. The high definition video camera used was a Panasonic HDC HS900 and videos were recorded with a 1920 by 1080 pixel resolution and a 59.9 per second frame rate. The camera shutter was set to $1/3000^{th}$ of a second. The GoPro camera recorded with an 848 by 480 pixel resolution and a 120 per second frame rate.
Figure 14 SL Ross Wind Wave Tank

Figure 15 Nozzle Configuration Used in Horizontal Tank Tests

Figure 16 SL Ross Tank Setup (Video Cameras, Lighting and LISST Position in Water)
3.2.2. Test Procedure

In each test the methane or air flow was initiated first and flow rate established using the rotameter flow meter. Oil was then turned on and allowed to flow without dispersant to provide pre-dispersant video footage of the oil and gas drop sizes. Because the flow was controlled via shutoff valves at the liquid sources rather than next to the orifice there was an opportunity for a small amount of oil and dispersant to mix at the exit prior to pressurizing the oil and dispersant lines. This resulted in a short burst of dispersant laden oil at the initiation of each test. To remove the oil generated from this burst from the test measurements the nozzle was positioned in a separate location of the tank from where the measurements were made during the initial 10 to 20 seconds of oil flow. Once the discharge reverted to large, untreated oil drops the jet was moved into the field of view of the video cameras and the LISST. An overview video using a GoPro camera and a video close-up of the plume using a high definition Panasonic video camera were taken over the entire test period through the tank viewing window. The LISST was moved into the surface dispersed oil cloud once the chemically dispersed oil was present. The LISST was positioned so the rising gas bubbles did not pass by its optical sensors. The LISST optical sensor was positioned about 10cm below the water surface. Each test was run for approximately 5 minutes.

3.2.3. Tank Test Results

Tests with identical oil flow and dispersant dosage were run with air and then methane to determine if the methane scavenged any of the applied dispersant and thus reduced the effectiveness of the dispersant. The tests described in Table 2 were completed in the tank test program. An example video showing an overview of a typical plume can be accessed through the following link: Test Overview. This video was recorded using the GoPro video camera mounted outside of the tank looking through the viewing window. A close-up of the plume during the same test is provided through the following link: Plume Close-up. This video was taken using the HD video camera, also mounted outside the tank and looking through the viewing window.

Tests were conducted using dispersant to oil ratios of 1:50, 1:95 and 1:190 using both Endicott and Terra Nova crude oils and Corexit 9500 dispersant. The physical properties of these oils are provided in Table 3.
Table 2 Tests Completed in SL Ross Wave Tank

<table>
<thead>
<tr>
<th>Run Descriptor</th>
<th>Gas Type</th>
<th>Gas Flow (ml/min)</th>
<th>Oil Type</th>
<th>Oil Flow (ml/min)</th>
<th>Disp. Flow (ml/min)</th>
<th>DOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>END1 &amp; 7</td>
<td>Air</td>
<td>1350</td>
<td>Endicott</td>
<td>100</td>
<td>2</td>
<td>1:50</td>
</tr>
<tr>
<td>END10</td>
<td>Air</td>
<td>1350</td>
<td>Endicott</td>
<td>190</td>
<td>2</td>
<td>1:95</td>
</tr>
<tr>
<td>END4</td>
<td>Air</td>
<td>1350</td>
<td>Endicott</td>
<td>380</td>
<td>2</td>
<td>1:190</td>
</tr>
<tr>
<td>END2 &amp; 8</td>
<td>Methane</td>
<td>1350</td>
<td>Endicott</td>
<td>100</td>
<td>2</td>
<td>1:50</td>
</tr>
<tr>
<td>END9</td>
<td>Methane</td>
<td>1350</td>
<td>Endicott</td>
<td>190</td>
<td>2</td>
<td>1:95</td>
</tr>
<tr>
<td>END 3, 5 &amp; 6</td>
<td>Methane</td>
<td>1350</td>
<td>Endicott</td>
<td>380</td>
<td>2</td>
<td>1:190</td>
</tr>
<tr>
<td>TN 6</td>
<td>Air</td>
<td>1350</td>
<td>Terra Nova</td>
<td>380</td>
<td>7.6</td>
<td>1:50</td>
</tr>
<tr>
<td>TN3 &amp; 5</td>
<td>Air</td>
<td>1350</td>
<td>Terra Nova</td>
<td>380</td>
<td>4</td>
<td>1:95</td>
</tr>
<tr>
<td>TN1</td>
<td>Air</td>
<td>1350</td>
<td>Terra Nova</td>
<td>380</td>
<td>2</td>
<td>1:190</td>
</tr>
<tr>
<td>TN7</td>
<td>Methane</td>
<td>1350</td>
<td>Terra Nova</td>
<td>380</td>
<td>7.6</td>
<td>1:50</td>
</tr>
<tr>
<td>TN4</td>
<td>Methane</td>
<td>1350</td>
<td>Terra Nova</td>
<td>380</td>
<td>4</td>
<td>1:95</td>
</tr>
<tr>
<td>TN2</td>
<td>Methane</td>
<td>1350</td>
<td>Terra Nova</td>
<td>380</td>
<td>2</td>
<td>1:190</td>
</tr>
</tbody>
</table>

Table 3 Physical Properties of Test Oils Small Scale Tests

<table>
<thead>
<tr>
<th>Oil</th>
<th>Density @ 15°C (g/cc)</th>
<th>Viscosity @ 15°C (mPas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endicott Crude</td>
<td>0.920</td>
<td>205 @ 40 s⁻¹</td>
</tr>
<tr>
<td>Terra Nova</td>
<td>0.868</td>
<td>37 @ 100 s⁻¹</td>
</tr>
</tbody>
</table>

The average cumulative oil drop size distributions as recorded by the LISST from the Terra Nova crude oil tests for all DORs for both air and methane have been plotted in Figure 17. This plot is followed by separate figures (Figure 18(1:50), Figure 19(1:95) and Figure 20(1:190)) showing the average drop size distributions along with the drop size distribution variation recorded during each test (average diameter ± one standard deviation) for air and methane at each individual DOR.

These graphs compare the measured drop size distributions for the tests where air and methane were used at the different dispersant to oil ratios. The data for the Terra Nova crude shows a
consistent trend of slightly larger oil drops for the tests with methane when compared to the air tests. The volume median drop diameters were 20 to 30 microns larger in the methane tests for the higher DOR tests (1:50 and 1:95). Drop size also consistently increased with a reduction in applied dispersant amount. These two results would suggest that the methane may be stripping a small amount of dispersant from the oil-water system.

**Figure 17 Average Oil Drop Size Distributions all DORs: Terra Nova Crude Oil**

The plots showing the variation in the measured drop sizes throughout the experiments show that the variations between the air and methane tests cannot be explained due to test variability.
Figure 18 Oil Drop Size Distributions 1:50 DOR with StdDev: Terra Nova Crude Oil

Figure 19 Oil Drop Size Distributions 1:95 DOR with StdDev: Terra Nova Crude Oil
The average cumulative oil drop size distributions as recorded by the LISST from the Endicott crude oil tests for all DORs for both air and methane have been plotted in Figure 21. This plot is followed by separate figures Figure 22(1:50), Figure 23(1:95) and Figure 24(1:190)) showing the average drop size distributions along with the drop size distribution variation recorded during each test (average diameter + _ one standard deviation) for air and methane at each individual DOR.

In the Endicott tests the average drop size distributions recorded for the methane runs were actually slightly smaller than for the air tests. In the Endicott tests there is considerable overlap of the drop size standard deviations recorded in the air and methane tests at the same DOR. This would suggest that the differences between the air and methane tests may not be significant. For the Endicott crude oil there was no reduction in dispersant effectiveness due to the presence of the methane, unlike in the tests with the Terra Nova crude.
Figure 21 Average Oil Drop Size Distributions all DORs: Endicott Crude Oil

Figure 22 Oil Drop Size Distributions, 1:50 DOR with stdDev: Endicott Crude Oil
The volume median diameters of the oil drop size distributions for the Endicott and Terra Nova crude oil tests have been plotted against the dispersant to oil ratio (DOR) for each test in Figure 25 and Figure 26, respectively. It is apparent from these figures that the effectiveness of the
dispersant diminishes with a reduction in DOR and dispersant dosages greater than 1:100 would appear to be required to achieve an oil dispersion with oil drop distribution VMDs less than 70 microns. These plots also reinforce early observations that the presence of gas in the discharge did not alter the dispersant effectiveness (as measured by the oil drop VMD) in the Endicott tests and reduced the effectiveness only marginally for the Terra Nova crude.

![Figure 25 Oil Drop Volume Median Diameter vs Dispersant to Oil Ratio: Endicott Crude](image-url)
3.2.4. **Small Test Tank Discussion**

The testing conducted in the SL Ross wind wave tank provided an opportunity to conduct tests with the LISST deployed in-situ to evaluate its potential for monitoring the oil drop size from a submerged horizontal oil and gas discharge. The oil and gas released from the horizontal release did rise in laterally separated plumes that permitted the measurement of the oil cloud separate from the bubble plume by the LISST. The drop size data collected provided preliminary evidence of the potential effects of a hydrocarbon based gas (methane) in altering the effectiveness of a subsea dispersant application. The preliminary data suggests that the gas may reduce the dispersant effectiveness, but this may be dependent on oil properties. Additional testing with a range of oils would be needed to quantify the effect of specific oil properties on the dispersion process in the presence of methane versus air.
3.3 Small Scale Tests: Summary

The column tests provided a convenient test bed to develop the liquid and gas delivery systems and test out digital imaging and analysis options. However, future small scale work would best be completed in the larger tank where the LISST can be deployed for efficient dispersed oil drop size distribution measurement. The use of digital video and still imaging for drop size measurement requires significant data processing efforts when compared to the ease of acquiring this data with the LISST. One draw-back to the LISST is that it cannot differentiate between the oil and gas bubbles. The oil and gas discharge need to be oriented horizontally so the oil droplets separate from the gas bubbles. Differentiation between oil and gas bubbles is also difficult to do in an automated analysis of digital video or still imagery.

The results of the small-scale testing indicated that there may have been a small loss of dispersant to the methane gas for lighter of the two oils tested (Terra Nova crude). The results also indicate that the effectiveness of the dispersant diminishes with a reduction in DOR and dispersant dosages greater than 1:100 would appear to be required to achieve an oil dispersion with oil drop distribution VMDs less than 70 microns. Further investigation of these variables was undertaken in the large scale testing conducted at Ohmsett that is discussed in the following report section.
4 Large-Scale Ohmsett Testing

The second phase of testing was conducted at the Ohmsett facility in Leonardo New Jersey. A photo of the test tank is provided in Figure 27. The tank is 60 feet wide, 200 feet long with a water depth of 8 feet. The tests in this program were completed next to one of the viewing windows on the west side of the tank. All tests were completed with no wave action with water temperatures ranging from 24 °C to 27 °C. The salinity and interfacial tension of the water with mineral oil at the time of the tests were 31 ppt and 38.5 dynes/cm, respectively. The high interfacial tension value indicates that the test water was clear of surfactants at the time of the testing. The tests were conducted outdoors with relatively small methane flow rates that were allowed to dissipate under natural diffusion processes. The research participants on site were made aware of the use of the methane and precautions were taken to ensure that no ignition sources were present during the methane release.

Figure 27 Ohmsett - The National Oil Spill Response Research & Renewable Energy Test Facility
4.1 Test Apparatus

The experience and methods gained from the small-scale testing were transferred to the larger scale testing conducted at the Ohmsett facility. The dispersant, oil and gas delivery and measuring methods used in the small scale testing were deployed in the large scale work. One improvement to the setup was the implementation of underwater remotely activated solenoid valves in the dispersant, oil and gas flow lines placed near the discharge header to provide more precise control over the flow start and stop conditions. Figure 28 shows the equipment cage used to hold the LISST-100x drop size analyzers, video cameras, acoustic drop size measurement equipment and outlet nozzles. The acoustic equipment, high definition underwater camera and one of the GoPro cameras was deployed and managed by Applied Research Associates to gather data for further refinement of their oil drop size measurement system. Additional information on this initiative is provided in Appendix B. Two LISST devices were mounted directly above the horizontal discharge nozzle. The LISST devices were fitted with light path reduction modules (80 and 90%) to permit recording in high oil concentrations. One underwater GoPro camera (1440x864 pixel resolution and 30 frames per second) was mounted next to the bottom LISST to capture the oil plume passing by. A second underwater GoPro was mounted on the south-west corner of the equipment cage to capture an overview of the rising plume. Both GoPro cameras were operated with 1920 x 1080 resolution and 59.9 frames per second. The high definition underwater camera (1440x864 pixel resolution and 30 frames per second) was mounted on the east side of the cage to provide a view of the plume from discharge to surface. Figure 29 is a close-up of the discharge nozzle mounting arrangement. The discharge nozzle, flow control solenoids and liquid and gas feeder lines were mounted on a moveable platform. The nozzle position was adjusted during a test to ensure that oil only was passing by the LISST optical sensors.
Figure 28 Instrument Cage

Figure 29 Discharge Nozzle Cart
The oil and dispersant were loaded into separate pressure tanks that were pressurized using the compressed air supply available on the bridge. The liquid and gas flow rates were controlled and monitored using pressure control valves and rotameters mounted on the bridge. Methane (99.0% CH₄) was supplied from a ME 2.0 K sized cylinder with pressure control regulator.

### 4.2 Test Oils and Dispersant

All of the large scale tests conducted at Ohmsett used Corexit 9500 dispersant. The oils used in the testing were fresh Endicott and Dorado crude oils available in the Ohmsett oil inventory at the time of the testing. The Terra Nova crude oil used in the small scale tests at SL Ross was not available at Ohmsett but the Dorado crude oil physical properties are very similar to Terra Nova. Physical properties of the crude oils are provided in Table 4.

<table>
<thead>
<tr>
<th>Crude Oil</th>
<th>Density @ 15 °C (g/cc)</th>
<th>Viscosity @ 15 °C and (mPas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endicott</td>
<td>0.921</td>
<td>168 @ 100 s⁻¹ shear</td>
</tr>
<tr>
<td>Dorado</td>
<td>0.875</td>
<td>35 @ 1 s⁻¹ shear</td>
</tr>
</tbody>
</table>

### 4.3 Large-Scale Test Procedures

The following procedure was implemented for each test. The dispersant and oil flow control needle valves positioned next to the discharge nozzle were calibrated to the required flow rates for the test. The dispersant and oil supply canisters and gas supply were pressurized to 50 psi. The optics for the LISST particle size analyzers were cleaned. The GoPro video cameras were positioned and started. The equipment cage was lowered into position in front of the viewing window. The LISST devices were checked to ensure the optics were clean and zero readings were captured in clean water. Gas flow was initiated and the discharge nozzle position roughly oriented. The underwater HD video camera was started. The oil flow was then started by opening the solenoid control valve. The LISST devices were activated to record the rising oil drop distributions. The discharge nozzle position was fine-tuned to ensure that oil droplets were passing through the LISST sensor gaps, but the gas-bubble plume was not. Approximately 2 minutes after the start of the oil flow the dispersant solenoid valve was opened to start the
dispersant injection. The nozzle position was monitored throughout the test to ensure that the dispersed oil plume passed by the LISST sensors. The oil and dispersant flows were stopped after 2 minutes of dispersant injection. The LISST data files were terminated and stored for future analysis and the subsea HD video camera recording was stopped. A roaming video camera also took footage of the release from the bridge deck and through the viewing window. The water in the vicinity of the equipment cage was flushed with clean water using the main bridge fire monitor before beginning the next test. The LISST devices were operated to determine if their optics were still clean. If they were clean they would display low background particle concentrations (less than 5 ppm). If the lens were clean a second test was conducted. If the lenses required cleaning or if a change in the oil or dispersant flow was required the equipment cage was retrieved to the side deck and appropriate adjustments and cleaning were completed prior to re-deploying the cage for the next test.

Videos showing overviews of two of the Ohmsett scale tests can be viewed by clicking on the links in Table 5. These videos provide a good overview of a test that was very successful in dispersing the oil (1:50 DOR test 35 with Dorado crude oil) and a test where the dispersant was not as effective (1:200 DOR test 43 with Dorado crude oil). These clips show the oil discharge for a few seconds prior to dispersant injection followed by 10 to 20 seconds during the dispersion process. The one exception to this is the “Test 43 from Bridge” video that only shows the initial oil release period. The initial video section was chosen because the video does not show an appreciable difference with or without dispersant applied and this viewing period shows the surface behavior of the released oil.

<table>
<thead>
<tr>
<th>Video Contents</th>
<th>High Dispersant Dose (1:50) Dorado Oil Test 35</th>
<th>Low Dispersant Dose (1:200) Dorado Oil Test 43</th>
</tr>
</thead>
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<tr>
<td>Large Tank Test Overview (Overhead)</td>
<td><strong>Test 35 from Bridge</strong></td>
<td><strong>Test 43 from Bridge</strong></td>
</tr>
<tr>
<td>Large Tank Test Overview (Viewing Window)</td>
<td><strong>Test 35 Viewing Window</strong></td>
<td><strong>Test 43 Viewing Window</strong></td>
</tr>
<tr>
<td>Large Tank Test Overview (Subsea HD Video)</td>
<td><strong>Test 35 HD</strong></td>
<td><strong>Test 43 HD</strong></td>
</tr>
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<td>Large Tank Test Overview (Subsea GoPro at LISST)</td>
<td><strong>Test 35 Dorado</strong></td>
<td><strong>Test 43 Dorado</strong></td>
</tr>
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</table>
4.4 Large-Scale Test Results

Two LISST 100x particle size analyzers were deployed to provide the oil drop-size distributions for the dispersed oil plumes. The oil drop size distributions have been used to compare the effectiveness of the injected dispersant when applied with air versus methane. A GoPro underwater video camera was mounted next to one of the LISST devices to provide a visual of oil drops in the plume that were larger than those measureable by the LISST devices. A clear ruler was mounted in the GoPro field of view to provide a scale when viewing the dispersed oil. The tests conducted during the Ohmsett testing are summarized in Table 6.

Table 6. Large Scale Ohmsett Test Conditions

<table>
<thead>
<tr>
<th>Test #</th>
<th>Orifice ID (mm)</th>
<th>Oil Type</th>
<th>Oil Flow (ml/min)</th>
<th>Gas Type</th>
<th>Gas Flow (ml/min)</th>
<th>Dispersant Flow (ml/min)</th>
<th>Gas to Oil Ratio (GOR)</th>
<th>Dispersant to Oil Ratio (DOR)</th>
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</table>

*Note: The oil flow rates in tests 4 and 5 were incorrect and data from these two runs have not been analyzed.*
4.4.1. Dispersed Oil Drop Sizes by LISST 100x Particle Size Analyzers

Two LISST 100x devices were mounted vertically above the centerline of the discharge nozzle. For tests 1 through 19 the upper LISST was located 72 inches (1.83 m) above the nozzle and the lower LISST 54.5 inches (1.38 m) above. For the remainder of the tests the upper LISST was located 54.5 inches (1.38 m) above the nozzle and the lower LISST 39 inches (1.0 m) above. The LISST was lowered to minimize the amount of gas bubbles in the sensor zone. As the plume moved to the surface the gas bubbles diverged and were impacting on the upper LISST in its initial position. Average cumulative volume drop size distributions have been determined for both the pre- and post-dispersant application stages of each test. The average distributions were determined by selecting between 50 and 100 of the drop size measurements made by each LISST and averaging the measurements. The number of distributions selected for determination of the average value was based on a visual inspection of each data set to identify the distributions when the oil concentrations were high and thus the plume was in the path of the LISST. This varied from test to test because of the dynamic nature of the plume.

4.4.1.1. Pre-Dispersant Applied Drop Sizes

The oil drop size distributions measured using the LISST prior to dispersant application for the small nozzle releases of Endicott crude are summarized in Figure 30 (upper) and Figure 31 (lower) for the air releases and Figure 32 (upper) and Figure 33 (lower) for the methane releases. The oil release prior to dispersant application is in the form of relatively large oil drops (as seen in the sample GoPro videos shown in Table 5) with many oil drops that are greater than 0.5 mm, the maximum size recorded by the LISST devices. Because of this, the drop size distributions shown in Figure 30, Figure 31, Figure 32 and Figure 33 only show the distributions of oil drops below 500 microns and do not reveal the true drop size distributions generated pre-dispersant application. It is instructive to compare the distributions only to identify that the distributions of drops less than 500 microns for all of these tests have similar distributions, with Volume Median Diameters (VMDs) in the 190 to 260 micron range. Similar plots of pre-dispersant applied oil drop size distributions are provided in Appendix A for the Dorado crude oil releases with the small 1.5 mm nozzle and for both the Endicott and Dorado discharges with the larger 4.5 mm nozzles. The same conclusion can be drawn from the figures provided in Appendix A, that is, the pre-dispersant applied drop size distributions for all tests, at a specific nozzle diameter, are
similar for both the air and methane tests. The pre-dispersant applied oil drop size distributions for the larger nozzle releases have larger VMDs of approximately 350 microns for both the Endicott and Dorado crude oils.

Figure 30 Cumulative Oil Drop Size Distributions: Pre-Dispersant Application, Air, 1.5 mm Orifice (Air) Upper Lisst: Runs 6,7,10,13,14,16,18

Endicott Oil - Oil Drops Pre Dispersant Addition : 1.5 mm Orifice (Air) Upper Lisst: Runs 6,7,10,13,14,16,18

Figure 30 Cumulative Oil Drop Size Distributions: Pre-Dispersant Application, Air, 1.5 mm Nozzle, Upper LISST
Figure 31 Cumulative Oil Drop Size Distributions: Pre-Dispersant Application, Air, 1.5 mm Nozzle, Lower LISST

Figure 32 Cumulative Oil Drop Size Distributions: Pre-Dispersant Application, Methane, 1.5 mm Nozzle, Upper LISST
4.4.1.2. Post-Dispersant Drop Sizes

Average cumulative volume drop size distributions also have been determined for the post-dispersant application stages of each test. The average distributions were determined by selecting between 50 and 100 of the drop size measurements made by each LISST during the period of high oil concentration readings and calculating the average and standard deviation in each drop size bin recorded by the LISST. The average and the average plus and minus the standard deviations of the drop distributions are shown in the plots that follow. The oil drop size distributions provided below are representative of the full spectrum of drops present in the dispersion because the oil drops are much smaller and generally are within the range measureable by the LISST when dispersant is successfully applied. The oil drop distributions from the 1:200 DOR tests are likely missing some oil in the form of drops greater than 500 microns, since the dispersant was not as effective at this low dosage. However, the drop size distributions measured for the air and methane tests at these low dosages provide a measuring stick for comparison of the potential effect of methane on the dispersion process, the primary goal of the testing.
4.4.1.2.1. **Small Discharge Orifice LISST Data Results: Cumulative Volume Percent**

A comparison of the cumulative oil drop size distributions for the air and methane tests for the small diameter orifice tests for Dorado crude oil tests are provided in Figure 34 through Figure 45 for a range of dispersant to oil ratios (DORs of 1:50, 1:100 and 1:200) and gas to oil ratios (GORs of approximately 5:1 and 10:1). In these small orifice tests the VMD of the distributions for the 1:50 DOR and both GORs are consistently between 90 to 110 microns. (See Figure 34, Figure 35, Figure 36 and Figure 37). When the dosage was decreased to 1:100 the VMDs increased to between 170 and 210 microns, with slightly smaller drops measured for the higher GOR tests. (See Figure 38, Figure 39, Figure 40, and Figure 41). At the lowest DOR of 1:200, the VMD increased to between 200 to 250 microns. (See Figure 42, Figure 43, Figure 44 and Figure 45). The distributions for both the gas and methane tests are very similar for tests with otherwise identical conditions, with no appreciable difference in oil drop size distribution due to the presence of methane versus air in the system. For these tests with Dorado crude oil and Corexit 9500 dispersant at various DORs and GORs there appears to be no impact on the final dispersant effectiveness when methane is discharged with the oil versus air. The data from the upper and lower LISST devices were also very consistent throughout all of the tests.
Figure 35 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:50 DOR, 5:1 GOR (Lower LISST)

Figure 36 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:50 DOR, 10:1 GOR (Upper LISST)
Figure 37 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:50 DOR, 10:1 GOR (Lower LISST)

Figure 38 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:100 DOR, 5:1 GOR (Upper LISST)
Figure 39 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:100 DOR, 5:1 GOR (Lower LISST)

Figure 40 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:100 DOR, 10:1 GOR (Upper LISST)
Figure 41 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:100 DOR, 10:1 GOR (Lower LISST)

Figure 42 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:200 DOR, 5:1 GOR (Upper LISST)
Figure 43 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:200 DOR, 5:1 GOR (Lower LISST)

Figure 44 Oil Drop Size Distribution, Small Orifice, Dorado Crude, 1:200 DOR, 10:1 GOR (Upper LISST)
A comparison of the cumulative oil drop size distributions for the air and methane tests for the small diameter orifice tests for Endicott crude oil tests are provided in Figure 46 through Figure 57 for dispersant to oil ratios (DORs) of 1:10, 1:20 and 1:50 and gas to oil ratios (GORs) of 1:3 to 1:9. These small orifice tests with Endicott crude oil were the first ones conducted in the test program and the DOR and GOR values were adjusted during the early stages of the work to generate a range dispersant effectiveness outcomes. As a result of this the DORs and GORs were not as consistent in this array of tests as in others conducted later in the test program. In these small orifice tests the VMD of the distributions for the 1:10 DOR and 5:1 GORs were between 7 to 15 microns. This range does not include the data from the lower LISST Air test #14. Based on the significantly larger drop data for this test, it is likely that the lower LISST was positioned so that the air bubbles were being recorded at this location. (See Figure 46, and Figure 47). When the dispersant dosage was decreased to 1:20 the VMDs increased to between 150 and 200. (See Figure 48 and Figure 49). At the lowest DOR tested (1:50) with Endicott and the small orifice the VMD increased to between 200 to 250 microns. (See Figure 50, Figure 51, Figure 52, Figure 54, Figure 55, and Figure 55). Note that the lower LISST data for test #6 with AIR in Figure 53
was again likely measuring air bubbles based on the significantly larger drops shown. The LISST’s were repositioned so they were both closer to the discharge location to prevent this from occurring in the later tests. For these tests with Endicott crude oil and Corexit 9500 dispersant at various DORs and GORs there again appears to be no consistent or significant impact on the final dispersant effectiveness when methane is discharged with the oil versus air. The data from the early Endicott crude oil tests was not as consistent as those that followed using the Dorado crude oil, but the data does not indicate that there was a loss in dispersant effectiveness when methane was discharged with the oil.

Two tests were conducted with the dispersant injected into the exiting oil and gas plume outside of the discharge pipe. These tests were conducted primarily to determine if the dispersant was being delivered properly to the oil and gas stream during the in-pipe injection tests and not to conduct an evaluation of the influence of dispersant application location. The oil dispersions from the early in-pipe dispersant injection tests at Ohmsett were not as impressive as we had expected based on the small scale tests and these two tests were conducted in an attempt to determine why this was the case. The dispersant was injected a few mm from the oil and gas release point above the oil and gas nozzle in these tests. The results of these tests are shown in Figure 50 and Figure 51. There did not appear to be a significant difference in the dispersant performance in these tests when compared to those where the dispersant was injected inside the discharge piping (compare to Figure 52, Figure 53, Figure 54 and Figure 55). This suggested that the dispersant was being delivered to the oil and gas stream in the in-pipe injection tests.
Figure 46 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:10 DOR, 5:1 GOR (Upper LISST)

Figure 47 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:10 DOR, 5:1 GOR (Lower LISST)
Figure 48 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:20 DOR, 3:1 GOR (Upper LISST)

Figure 49 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:20 DOR, 3:1 GOR (Lower LISST)
Figure 50 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 5:1 GOR (Upper LISST) Dispersant Applied into Plume External to Discharge Header

Figure 51 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 5:1 GOR (Lower LISST) Dispersant Applied into Plume External to Discharge Header
Figure 52 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 4:1 GOR (Upper LISST)

Figure 53 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 4:1 GOR (Lower LISST)
Figure 54 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 5:1 GOR (Upper LISST)

Figure 55 Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 5:1 GOR (Lower LISST)
**Figure 56** Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 9:1 GOR (Upper LISST)

**Figure 57** Oil Drop Size Distribution, Small Orifice, Endicott Crude, 1:50 DOR, 9:1 GOR (Lower LISST)
4.4.1.2.2. Small Discharge Orifice LISST Data Results: Oil Drop VMD vs DOR

Plots of the oil drop VMDs against the dispersant dose rate (DOR), for each tested gas to oil ratios (GOR), are provided in Figure 58 through Figure 61 for the 1.5 mm orifice tests. In all of these tests a reduction in dispersant resulted in an increase in the oil drop VMD, as would be expected. For the Dorado crude oil tests (Figure 58 for air and Figure 59 for methane) the oil drop VMDs at the 1:50 DOR were in the 80 to 150 micron range suggesting that dispersant doses higher than 1:50 might be needed to achieve complete dispersion of this oil (assuming a minimum 70 micron VMD is required for successful dispersion, Lunel, 1993) under the conditions tested. The higher gas to oil ratio (GOR) tests generated consistently smaller oil drop size distributions at the low dispersant dosages but this was not as evident in the higher dose 1:50 DOR tests. This suggests that when significant dispersant is present its effect on the oil drop size distribution is more important than the hydrodynamic influence (additional drop shearing) of a higher gas flow.

For the small orifice, Endicott crude oil tests conducted at Ohmsett (Figure 60 for air & Figure 61 for methane) much more dispersant was needed than in the Dorado oil tests to achieve appreciable dispersion. DORs of 1:10 were necessary to achieve small oil drop dispersions with VMDs less than 70 microns. DORs of 1:20 and 1: 50 resulted in oil drop VMDs of around 200 microns. These results are surprising since the results from tests conducted at SL Ross using the same orifice and similar GORs with Endicott crude resulted in significant small oil drop dispersion at the much lower dispersant dosages of 1:50 and 1:100 (see Figure 25). This was noted during the Ohmsett test program and is the reason that higher dispersant dosages and an alternative dispersant injection location were investigated at Ohmsett for these tests with Endicott crude oil. We have not been able to identify any reason for the difference in results other than the Endicott crude oil used at Ohmsett did not come from the same sample batch as that used at SL Ross.
Figure 58 Oil Drop VMD vs DOR: Air & Dorado Crude, 1.5 mm Orifice

Figure 59 Oil Drop VMD vs DOR: Methane & Dorado Crude, 1.5 mm Orifice
Figure 60 Oil Drop VMD vs DOR: Air & Endicott Crude, 1.5 mm Orifice

Figure 61 Oil Drop VMD vs DOR: Methane & Endicott Crude, 1.5 mm Orifice
4.4.1.2.3. **Large Discharge Orifice LISST Data Results: Cumulative Volume Percent**

Data similar to that collected for the small orifice discharge were also collected for the large orifice (4.5 mm internal diameter) tests that also used Dorado and Endicott crude oil and Corexit 9500 dispersant. The oil drop VMD comparisons of the air and methane tests under otherwise identical conditions for the Dorado crude oil tests are shown in Figure 62 through Figure 73. As with the small orifice tests the VMD of the average drop size distributions increase with decreasing dispersant dosage, as would be expected. The difference in average drop size distribution with air versus methane and 1:50 DOR (all other factors the same) was minimal in the large orifice tests for the Dorado crude oil. In the 1:50 DOR tests (Figure 62, Figure 63, Figure 64 and Figure 65) the average oil drop size distributions for the air tests showed consistently smaller VMDs than for the methane tests but the difference was less than 10 microns. The variation in the measured drop size distributions was larger than this difference as seen in the plotted standard deviations. Note that the lower LISST data for the methane test results in Figure 59 are not available as the data file was corrupt and could not be analysed. At the lower DORs of 1:100 (Figure 66, Figure 67, Figure 68 and Figure 69) and 1:200 (Figure 70, Figure 71, Figure 72 and Figure 73) there were no appreciable differences in the recorded average drop size distributions when the air and methane tests are compared. The large scale large orifice test results with Dorado crude indicate that the presence of methane in the discharge had little or no effect on the resulting drop size distribution and did not alter the effectiveness of the injected dispersant when compared to tests conducted with air.
Figure 62 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:50 DOR, 5:1 GOR (Upper LISST)

Figure 63 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:50 DOR, 5:1 GOR (Lower LISST)
Figure 64 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:50 DOR, 9:1 GOR (Upper LISST)

Figure 65 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:50 DOR, 9:1 GOR (Lower LISST)
Figure 66 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:100 DOR, 5:1 GOR (Upper LISST)

Figure 67 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:100 DOR, 5:1 GOR (Lower LISST)
Figure 68 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:100 DOR, 9:1 GOR (Upper LISST)

Figure 69 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:100 DOR, 9:1 GOR (Lower LISST)
Figure 70 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:200 DOR, 5:1 GOR (Upper LISST)

Note: the air and methane data are essentially identical and at the scale shown the methane obscures the air data.

Figure 71 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:200 DOR, 5:1 GOR (Lower LISST)
Figure 72 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:200 DOR, 9:1 GOR (Upper LISST)
Note: again the air and methane data are essentially identical and at the scale shown the methane obscures the air data.

Figure 73 Oil Drop Size Distribution, Large Orifice, Dorado Crude, 1:200 DOR, 9:1 GOR (Lower LISST)
The comparisons of the air and methane tests under otherwise identical conditions for the Endicott crude oil tests are shown in Figure 74 through Figure 85. The VMD of the average drop size distributions of the Endicott crude also increase with decreasing dispersant dosage. The difference in average drop size distribution with air versus methane at 1:50 DOR (all other factors the same) was minimal in the large orifice tests for the Endicott crude oil. In the 1:50 DOR tests (Figure 74, Figure 75, Figure 76 and Figure 77) and the 1:100 DOR tests (Figure 78, Figure 79, Figure 80 and Figure 81) the average oil drop size distributions for the air tests showed consistently smaller VMDs than for the methane tests; the difference was 20 microns or less. The variation in the measured drop size distributions was smaller than this difference for the 5:1GOR tests (Figure 74, Figure 75, Figure 78 and Figure 79) but greater than the difference for the higher GOR of 9:1 (Figure 76, Figure 77, Figure 80 and Figure 81) as seen in the plotted standard deviations. Intuitively, a higher methane flow rate should have resulted in a greater difference in the average drop size distributions when compared to air at the same DOR if the methane were stripping dispersant away from the oil-water system but this was not the case in these tests. At the higher DORs of 1:200 (Figure 82, Figure 83, Figure 84 and Figure 85) there were no appreciable differences in the recorded average drop size distributions when the air and methane tests are compared. In summary, the large scale large orifice test results with Endicott crude also indicate that the presence of methane in the discharge had a very minor or no effect on the resulting average oil drop size distribution. The same results were found in the small scale tests with the Endicott crude oil. From an operational perspective the presence of methane in the discharge flow did not significantly alter the effectiveness of the injected dispersant in these tests.
Figure 74 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:50 DOR, 5:1 GOR (Upper LISST)

Figure 75 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:50 DOR, 5:1 GOR (Lower LISST)
Figure 76 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:50 DOR, 9:1 GOR (Upper LISST)

Figure 77 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:50 DOR, 9:1 GOR (Lower LISST)
Figure 78 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:100 DOR, 5:1 GOR (Upper LISST)

Figure 79 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:100 DOR, 5:1 GOR (Lower LISST)
Figure 80 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:100 DOR, 9:1 GOR (Upper LISST)

Figure 81 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:100 DOR, 9:1 GOR (Lower LISST)
Figure 82 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:200 DOR, 5:1 GOR (Upper LISST)

Figure 83 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:200 DOR, 5:1 GOR (Lower LISST)
Figure 84 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:200 DOR, 9:1 GOR (Upper LISST)

Figure 85 Oil Drop Size Distribution, Large Orifice, Endicott Crude, 1:200 DOR, 9:1 GOR (Lower LISST)
4.4.1.2.4. **Large Discharge Orifice LISST Data Results: Oil Drop VMD vs DOR**

Plots of the oil drop VMDs against the dispersant dose rate (DOR), for each tested gas to oil ratio (GOR), are provided in Figure 86 through Figure 89 for the 4.5 mm orifice tests. The Dorado crude oil was effectively dispersed at 1:50 DOR in both the air (Figure 86) and methane (Figure 87) tests with oil drop VMDs of approximately 50 microns. As the dispersant dosage was reduced the VMD of the oil drop distribution increased in a linear fashion with better results evident at 1:100 DOR than at 1:200, unlike in the earlier 1.5 mm orifice tests. In these 4.5 mm orifice tests the higher gas to oil ratio (GOR) did not result in smaller oil drops at all DORs.

![Figure 86 Oil Drop VMD vs DOR: Air & Dorado Crude, 4.5 mm Orifice](image)
The Endicott crude oil was effectively dispersed at 1:50 DOR in both the air (Figure 88) and methane (Figure 89) tests with oil drop VMDs of between 30 and 75 microns. The oil drop VMDs were significantly larger (200+ microns) and very similar at both the 1:100 and 1:200 DORs, much like the earlier small orifice results. The higher gas to oil ratio (GOR) resulted in smaller oil drops at all of the DORs in these 4.5 mm orifice tests with Endicott crude oil.
Figure 88 Oil Drop VMD vs DOR: Air & Endicott Crude, 4.5 mm Orifice

Figure 89 Oil Drop VMD vs DOR: Methane & Endicott Crude, 4.5 mm Orifice
4.4.2. Pre-Dispersant Applied Oil Drop Sizes by Video Analysis

The GoPro video camera mounted adjacent to the upper LISST was pointed at a ruler to provide a scale for oil drop size estimation prior to dispersant application. An example video from this camera can be accessed through the link in Table 5. These GoPro cameras have a very wide depth of field that makes the automated analysis of the drop sizes in the video image not reliable. Drops that are not positioned on the same plane as the ruler would be assigned either larger (drops closer to the camera than the ruler) or smaller (drops further away from the camera) diameters than their actual dimension in an automated drop analysis of the video. It is even difficult to distinguish the position of the drops relative to the ruler when viewing the video. The best we can conclude from these underwater views of the early dispersion is that there are oil drops present that are significantly larger than the minimum value recordable (500 microns) by the LISST 100x device during the periods of no dispersant injection and for many of the low dose tests conducted. The GoPro videos also show that drops larger than those measureable by the LISST were not present during tests where the dispersant was successful. The objective of this project was to compare the drop size distributions measured when methane was the test gas against the distributions when air was released with the oil. This was possible using the measurements made by the LISST 100x hardware. If the full oil drop size distributions pre- and post-dispersant application are required to meet the objectives of future projects additional research into practical methods to measure oil drops greater than 500 microns in diameter at Ohmsett will be required. The acoustic measurement methods being developed by ARA using data collected during this study and elsewhere may be one possible solution. More sophisticated underwater video cameras and lenses with limited depths of field and elaborate lighting setups could possibly be used but oiling of lenses and lighting equipment would result in short recording periods and time consuming cleanup for each test condition. The oil drop illumination also has to be ideal to allow the image to be processed so the full range of oil drops can be automatically detected, as was discussed in 3.1.5. The use of digital video for this purpose also requires considerable post-processing of the data to arrive at a final oil drop size distribution.
5 Phase II Large-Scale Ohmsett Testing: Investigation of Dispersant Injection Location

Time was not available during the first series of tests conducted at Ohmsett to study the effect of dispersant injection location on dispersant effectiveness. A second series of tests were conducted at Ohmsett in late June of 2014 to study the effect of this variable.

5.1 Test Apparatus

Tests were conducted using the same equipment cage, LISST particle size analyzers and dispersant and oil supply systems described in Section 4.1. The LISST devices were mounted at 1.5 m and 1.9 m from the orifice outlet. Water nozzles were mounted at the LISST optical light path surfaces to provide clean water flushing of the surfaces prior to testing to remove contaminants such as air bubbles and oil drops that would affect the drop size measurements. Figure 90 shows the equipment cage with the LIIST devices, cameras and water flushing hoses in place prior to a test.

Figure 90 Equipment Cage Being Deployed
The oil was released from vertically oriented nozzles in this series of tests to maximize the mixing potential of the injected dispersant in the rising oil plume. No air or methane was discharged within the oil stream in this series of tests to allow the direct measurement of oil drop sizes without the interference of gas bubbles. Three underwater video cameras and one video camera mounted in a side viewing window recorded all tests. Figure 91 to Figure 97 show the nozzle arrangements used in the testing. Figure 91 shows the small orifice nozzle (1.5 mm inner diameter) with the dispersant injection point 13 nozzle diameters from the nozzle exit inside the oil delivery pipe. This in-pipe injection location point was chosen to match an injection location at the bottom of a 20 foot BOP stack with an 18 inch pipe diameter as per the BP Macondo well. Figure 92 shows the small orifice with the dispersant injection point inside the pipe 1.5 nozzle diameters from the nozzle exit. Figure 93 shows the small orifice with the dispersant injection point 1.5 nozzle diameters from the nozzle exit outside the pipe. Figure 94 shows the small orifice with the dispersant injection point 13 nozzle diameters from the nozzle exit outside the oil delivery pipe. Figure 95 shows the large orifice nozzle (4.5 mm inner diameter) with the dispersant injection point 13 nozzle diameters from the nozzle exit inside the oil delivery pipe. Figure 96 shows the large orifice with the dispersant injection point inside the pipe 1.5 nozzle diameters from the nozzle exit. Figure 97 shows the large orifice with the dispersant injection point 1.5 nozzle diameters from the nozzle exit outside the pipe. A photo of the large orifice with the dispersant injection point 13 nozzle diameters from the nozzle exit outside the oil delivery pipe is not available.
Figure 91 Small Orifice (1.5 mm): Dispersant Injection 13 Diameters Inside Pipe
Figure 92 Small Orifice (1.5 mm): Dispersant Injection 1.5 Diameters Inside Pipe

Figure 93 Small Orifice (1.5 mm): Dispersant Injection 1.5 Diameters Outside Pipe
Figure 94 Small Orifice (1.5 mm): Dispersant Injection 13 Diameters Outside Pipe

Figure 95 Large Orifice (4.5 mm): Dispersant Injection 13 Diameters Inside Pipe
Figure 96  Large Orifice (4.5 mm): Dispersant Injection 1.5 Diameters Inside Pipe

Figure 97  Large Orifice (4.5 mm): Dispersant Injection 1.5 Diameters Outside Pipe
5.2 Test Procedures

The following procedure was implemented for each test. The dispersant and oil supply canisters were pressurized to the required pressure for the test. The dispersant and oil flow control needle valves positioned next to the discharge nozzle were calibrated to the required flow rates for the test. The optics for the LISST particle size analyzers were cleaned. The GoPro video cameras were positioned and started. The equipment cage was lowered into position in front of the viewing window. The LISST devices were checked to ensure the optics were clean and zero readings were captured in clean water. The underwater video camera was started. The LISST devices were activated to record the rising oil drop distributions. An air flow was established from a separate nozzle located about 25 cm north of the oil discharge nozzle. This air flow was added to create an upward flow of water in the vicinity of the oil plume to assist in moving oil droplets to the surface and to reduce the oil build-up in the vicinity of the LISST devices. The air bubbles from this release surfaced to the north of the LISST optical measurement zone and did not affect the oil drop size measurements. The oil flow was then started by opening the solenoid control valve. The horizontal position of the discharge nozzle was fine-tuned by moving the nozzle platform to ensure that oil droplets were passing through the LISST sensor gaps. Approximately 2 minutes after the start of the oil flow the dispersant solenoid valve was opened to start the dispersant injection. The nozzle position was monitored throughout the test to ensure that the dispersed oil plume passed by the LISST sensors. The oil and dispersant flows were stopped after approximately 2 minutes of dispersant injection. The LISST data files were terminated and stored for future analysis and the subsea video camera recordings were stopped. The water in the vicinity of the equipment cage was flushed with clean water using the main bridge fire monitor before beginning the next test. The cage was removed from the water and placed on the tank deck and a new nozzle arrangement was installed for the next test. The LISST optical surfaces were cleaned and the cage positioned in the tank for the next test. If the LISST devices did not show a clean signal prior to a test the water flush system was activated to clean the light path surfaces prior to testing.

Videos showing overviews of two of the Ohmsett scale tests can be viewed by clicking on the links in Table 7. The video links in column two of the table provide overviews of tests with the small 1.5 mm orifice and injection points 1 pipe diameter inside the pipe (test 3) and 13 pipe diameters outside (test 5). The visuals provided for the post-dispersant oil plume are dramatically
different than the pre-dispersant applied plume in these videos. In the third column of the table sample videos for the larger orifice are provided for dispersant injection points 13 diameters inside and outside of the oil supply pipe. These videos show the significantly larger pre-dispersant applied initial oil drops in the large nozzle release when compared to the small nozzle videos. The change in oil drop size distribution when the dispersant is turned on is also more evident in the window view and subsea overview video records for these large orifice tests.

Table 7 Sample Video from Ohmsett Phase II Tests: Dispersant Injection

<table>
<thead>
<tr>
<th>Video Contents</th>
<th>Small Orifice, High DOR (1:50) ANS Crude Oil (tests 3 &amp; 5)</th>
<th>Large Orifice ANS High DOR (1:50) ANS Crude Oil (tests 10 &amp; 13)</th>
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<td>Injection Point 13 dia In-Pipe</td>
<td></td>
</tr>
<tr>
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<td>Test3GoProPre-Disp</td>
<td>Test10GoProPre-Disp</td>
</tr>
<tr>
<td>Go Pro: Post-Dispersant Application</td>
<td>Test3GoProPost-Disp</td>
<td>Test10GoProPost-Disp</td>
</tr>
<tr>
<td>Subsea Overview</td>
<td>Test3SubSea</td>
<td>Not Recorded</td>
</tr>
<tr>
<td>Viewing Window Overview</td>
<td>Test3WindowView</td>
<td>Test10WindowView</td>
</tr>
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<td></td>
</tr>
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<td>Viewing Window Overview</td>
<td>Test5WindowView</td>
<td>Test13WindowView</td>
</tr>
</tbody>
</table>

5.3 Test Results: Injection Location

Dispersant was injected into the oil at four different locations. The injection points included two within the oil supply pipe and two outside the pipe in the oil plume after exiting the nozzle. In both cases the injections points were 13 and 1.5 pipe diameters from the nozzle exit as shown in section 5.1.
5.3.1. Pre-Dispersant Applied Drop Size Distributions

The LISST devices were operated for approximately 2 minutes prior to dispersant addition in all tests. Figure 98 shows example drop size distributions from the 1.5 mm diameter nozzle prior to dispersant application for three of the tests randomly selected from tests conducted on separate days. For the pre-dispersant applied case all other parameters are constant and the drop size distributions from the 1.5 mm orifice tests should be identical. In this case the flow parameters were such that the predicted drop size distribution generated were within the measurement range of the LISST devices (2.5 to 500 microns). The oil drop VMDs for these undispersed distributions are about 150 microns.

Figure 98 Oil Drop Size Distribution Pre-Dispersant Application for the 1.5 mm Nozzle

Figure 99 shows example drop size distributions from the 4.5 mm diameter nozzle prior to dispersant application. In this case the flow parameters were such that the predicted drop size distribution generated were not within the measurement range of the LISST devices. This is evident in the GoPro pre-dispersant applied videos for tests #10 and #13 shown in Table 7 where many of the oil drops are visibly greater than 0.5 mm. The oil drop size distributions in Figure 99
are not accurate representations of the actual oil drops generated prior to dispersant application for these tests and are included only to show that consistent oil drop sizes existed in the large orifice tests prior to dispersant application within the range detectable by the LISST.

![Figure 99 Oil Drop Size Distribution Pre-Dispersant Application for the 4.5 mm Nozzle](image)

5.3.2. **Post-Dispersant Applied Drop Size Distributions**

The oil drop size distributions presented in the following sections were determined using the same methods described in Section 4.4.1.2.

5.3.2.1. **Small Orifice Cumulative Volume Distributions**

A comparison of the cumulative oil drop size distributions for the various dispersant injection locations for the small diameter orifice tests using ANS crude oil are provided in Figure 100 through Figure 105 for a range of dispersant to oil ratios (DORs of 1:50, 1:100 and 1:200). In these small orifice tests the VMD of the oil drop distributions are consistently smaller for the two in-pipe injection locations across all DORs. The oil drop VMDs for the two in-pipe injection locations are not significantly different across all DORs. When the dispersant injection location was moved outside of the pipe the VMD of the oil drops increased as the distance away from the release point increased.
Figure 100 Oil Drop Size vs Injection Location (Small Orifice, 1:50 DOR: Upper Lisst)

Figure 101 Oil Drop Size vs Injection Location (Small Orifice, 1:50 DOR: Lower Lisst)
Figure 102 Oil Drop Size vs Injection Location (Small Orifice, 1:100 DOR: Upper Lisst)

Figure 103 Oil Drop Size vs Injection Location (Small Orifice, 1:100 DOR: Lower Lisst)
Figure 104 Oil Drop Size vs Injection Location (Small Orifice, 1:200 DOR: Upper List)

Figure 105 Oil Drop Size vs Injection Location (Small Orifice, 1:200 DOR: Lower List)
5.3.2.2. **Small Orifice VMD vs DOR and Dispersant Injection Location**

The volume median diameter (VMD) of the oil drop size distributions for the small orifice tests shown in section 5.3.2.1 have been plotted in Figure 107 and Figure 107. The general trend demonstrated by these plots is a smaller oil drop VMD for the higher DOR tests, as would be expected. For the in-pipe injection locations the VMD’s are quite similar for both the 1:50 and 1:100 doses. In the lowest DOR tests the VMD are smallest when the dispersant was injected inside the pipe furthest from the exit. The oil drop VMDs are largest when the injection point was outside of the nozzle. The poorest dispersant performance was seen when the dispersant was injected outside of the pipe in the oil plume13 nozzle diameters away from the exit point.

![Oil Drop VMD vs Injection Location: Small Orifice Upper Lisst](image)

*Figure 106 Oil Drop VMD for Small Orifice vs Injection Location and DOR: Upper Lisst*
5.3.2.3. **Large Orifice Cumulative Volume Distributions**

A comparison of the cumulative oil drop size distributions for the various dispersant injection locations for the large diameter orifice tests using ANS crude oil are provided in Figure 108 through Figure 113 for a range of dispersant to oil ratios (DORs of 1:50, 1:100 and 1:200). In these large orifice tests the VMD of the oil drop distributions are consistently smaller for the two in-pipe injection locations across all DORs. The oil drop VMDs for the in-pipe injection point the furthest from the nozzle exit (13 diameters) are consistently smaller than the 1 pipe diameter in-pipe results. This is likely due to the lower velocities, lower in-pipe mixing and lower shearing at exit in the larger orifice tests as compared to the small diameter tests. When the dispersant injection location was moved outside of the pipe the VMD of the oil drops increased as the distance away from the release point increased, as was the case in the small orifice tests.
Figure 108 Oil Drop Size vs Injection Location (Large Orifice, 1:50 DOR: Upper Lisst)

Figure 109 Oil Drop Size vs Injection Location (Large Orifice, 1:50 DOR: Lower Lisst)
Figure 110 Oil Drop Size vs Injection Location (Large Orifice, 1:100 DOR: Upper Lisst)

Figure 111 Oil Drop Size vs Injection Location (Large Orifice, 1:100 DOR: Lower Lisst)
Figure 112 Oil Drop Size vs Injection Location (Large Orifice, 1:200 DOR: Upper Listt)

Figure 113 Oil Drop Size vs Injection Location (Large Orifice, 1:200 DOR: Lower Listt)
5.3.2.4. **Large Orifice VMD vs DOR and Dispersant Injection Location**

The volume median diameter (VMD) of the oil drop size distributions for the large orifice tests shown in section 5.3.2.3 have been plotted in Figure 114 and Figure 115. The general trend demonstrated by these plots is the same as for the small orifice tests: a smaller oil drop VMD was measured for the higher DOR tests. For the in-pipe injection locations the VMD’s are smallest when the dispersant was injected inside the pipe furthest from the exit. There was a slightly different trend in the large orifice tests as compared to the small orifice results. In the large orifice test the oil drops were consistently smaller in the tests where the dispersant was injected into the pipe 13 diameters from the exit when compared to the injection location 1 nozzle diameter from the exit. This may be due to the reduced in-pipe mixing energy in the larger nozzle tests due to the lower fluid velocities in these tests. The oil drop VMDs were again the largest when the injection point was outside of the nozzle. The poorest dispersant performance was seen when the dispersant was injected outside of the pipe in the oil plume 13 nozzle diameters away from the exit point.

![Figure 114 Oil Drop VMD for Large orifice vs Injection Location and DOR: Upper Lisst](image)

**Figure 114 Oil Drop VMD for Large orifice vs Injection Location and DOR: Upper Lisst**
6 Discussion of Project Results

6.1 Comparison to Other Research

The authors are not aware of any previous research into the effects of the presence of methane or natural gas on the effectiveness of chemical dispersants when injected into a subsea oil and gas discharge. A search of the scientific literature and common oil spill conference proceedings (The Arctic and Marine Oil Spill Technical Seminar-AMOP or the International Oil Spill Conference Proceedings-IOSC) did not identify any publications studying this process. There are two recent publications by Sintef that describe subsea dispersant use, the oil drop size distributions generated and mathematical modeling of the drop formation process. The focus of this work by Sintef was to measure the oil drop size distributions from treated and untreated subsea discharges with various discharge characteristics and to develop a model to predict the oil drop sizes as a function of the discharge parameters. The Sintef references reported below do not present data on the effect of dispersant injection location on dispersant effectiveness but state that this will be a subject in future publications. The tests conducted by Sintef had a limited number of runs with both air and oil in the discharge stream and none with methane (or natural gas) and oil (see Figure 115 Oil Drop VMD for Large orifice vs Injection Location and DOR: Lower Lisst
Brandvik et.al., 2013) .The potential for the reduction of dispersant effectiveness due to the presence of a hydrocarbon gas that might strip away dispersant from the oil-water system could not be addressed with the Sintef data. It is however instructive to note that the data collected in this study could be used to verify the drop size predictor model developed by Sintef (see Johansen et. al., 2013). A quick assessment of the Sintef model has found that it predicted the VMD of the drops sizes produced prior to dispersant application in the column studies completed in this project, but over estimates the drop sizes for the high dispersant dosage tests completed both in the SL Ross tank and in the large scale tests at Ohmsett. The VMDs of the oil drop distributions in the column tests shown in Figure 10 and Figure 11, for cases prior to the application of dispersant, are on the order of 800 to 1500 microns. The Sintef model predicts VMDs of 1230 to 1290 microns for these oil property and flow conditions. It should be noted that the VMDs from Figure 10 and Figure 11 may underestimate the true VMD of the oil drops due to problems with the measurement technique as earlier described. The oil drop distribution VMDs recorded by the LISST for the high dispersant dose rate (1:50) tests at Ohmsett are between 40 and 90 microns (see Figure 62, Figure 63, Figure 64, Figure 65, Figure 74, Figure 75, Figure 76 and Figure 77). The Sintef drop size model predicts VMDs between 390 and 1900 microns when the flow conditions and oil properties from these tests are modeled, considerably larger than those measured. It was assumed that the interfacial tension (IFT) was reduced by a factor of 1000 when dispersant was applied in these calculations since oil-water interfacial tensions were not measured in this test program. This reduction in IFT is of the same order of magnitude as was recorded in the Sintef study. The Sintef model is not sensitive to interfacial tension reductions greater than 500 to 1000 times. It would appear that the Sintef model does not predict the oil drop size reduction that was measured with successful dispersant application in this project’s experiments. The authors of the Sintef paper recognized that their model is preliminary and could require parametric adjustment once additional test data becomes available. Sufficient data is presented in this report to assist in furthering the development of Sintef’s drop prediction model, but this exercise is outside the scope of this project.
6.2 Project Findings

The primary objective of this work was to determine if the presence of natural gas or methane in a subsea oil and gas discharge would reduce the effectiveness of a dispersant injected into the gas-oil mixture. The underlying concern was that some of the dispersant might be attracted to the hydrocarbon gas bubble-water interface and not be available to attach to the oil-water interface and thus reduce the effectiveness of the applied dispersant. Tests were conducted with air (non-hydrocarbon) or methane (hydrocarbon) with all other parameters kept constant and the resulting drop size distributions compared. The significance of dispersant to oil ratio (DOR), gas to oil ratio (GOR), oil type and orifice diameter were also evaluated in the test program. The size of the oil drops generated in the subsea release, specifically the volume medium drop diameter (VMD) metric of the oil drop size distribution, was used as the criteria for comparison of dispersant effectiveness.

The test results indicate that there may be a reduction in dispersant effectiveness when methane as opposed to air is present for some oil types, but not all, under the flow and low pressure conditions studied. This study did not address the issue of deep water releases, gas properties under high pressure or hydrate formation under high pressure conditions and is applicable only to shallow well blowout situations. A reduction in effectiveness, as measured by an increase in the oil drop distribution VMD by about 20 to 30 microns, was identified for two of the oils: Terra Nova crude oil, Figure 17, in the small orifice tests conducted at SL Ross and Endicott crude oil in the large orifice tests conducted at Ohmsett, Figure 74 and Figure 75. It is also instructive to note that an increase in gas flow in the tests with Endicott crude oil did not result in a greater loss in effectiveness in the methane tests when compared to the tests that used air (compare Figure 76 and Figure 74 and Figure 77 and Figure 75). For the Dorado oil there was no significant loss in effectiveness when methane was present in the discharge as seen in Figure 34 to Figure 43 for the small orifice tests and Figure 62 to Figure 70 for the large orifice tests. The average VMDs for the tests with air were generally slightly smaller than the methane VMDs for the Dorado crude oil tests, but the standard deviations of the measured drop size distributions overlapped suggesting that the difference is not appreciable.
The dispersant to oil ratio (DOR) had a significant effect on dispersant effectiveness in all of the tests conducted, as would be expected. In the large orifice (4.5 mm) tests at Ohmsett a DOR of 1:50 was adequate to achieve dispersions with oil drop VMDs of less than about 70 microns for both the Dorado (Figure 86 and Figure 87) and Endicott (Figure 88 and Figure 89) crude oils. In the small orifice (1.5 mm) tests at Ohmsett higher dispersant doses were required to achieve small oil drop dispersions than those used in the large orifice tests. For the Dorado crude oil (Figure 58 and Figure 59) the 1:50 DOR only achieved dispersions with VMDs of 80 to 140 microns and for the Endicott crude a 1:50 DOR generated dispersions with VMDs of 200 to 230 microns (Figure 60 and Figure 61). In the small orifice tests at Ohmsett with Endicott, DORs of 1:10 were necessary to achieve oil drop VMDs of 50 microns. In the small orifice (1.5 mm) tests at SL Ross good dispersions (VMDs less than 70 microns) were achieved with DORs of 1:50 for both Endicott crude, Figure 25, and Terra Nova crude, Figure 26. The reason for the difference in the Endicott results from the Ohmsett tests is not known. One possible explanation is that the oil used in the SL Ross test was not from the same batch as that used at Ohmsett.

The orifice size used in the testing appeared to have an effect on the dispersant effectiveness outcome as discussed above. Better dispersant efficiency was generally achieved in the larger orifice tests at Ohmsett where direct comparison to small orifice tests can be made.

The effect of gas to oil ratio used in the tests on the dispersant effectiveness is inconclusive based on the Ohmsett test data where sufficient data is available for comparison. For the Dorado oil there appears to be minimal influence on the oil drop VMDs in the 4.5 mm orifice tests (Figure 86 and Figure 87) at all DORs. In the small orifice tests (Figure 58 and Figure 59) there was little influence of GOR on the oil drop size distribution at the high DORs tested for both the air and methane tests and no consistent difference at all DORs for the tests with methane (Figure 59). In the tests with air as the gas (Figure 58) the higher GOR resulted in smaller oil drops for the low dose applications. For the Endicott oil there was a consistent increase in the oil drop VMDs in the 4.5 mm orifice tests with an increase in GOR (Figure 88 and Figure 89) at all DORs. There is insufficient data to comment on the influence of GOR for Endicott crude and the small orifice.
Differences in dispersant effectiveness on the two primary test oils (Endicott and Dorado) have been noted above for the nozzle sizes, DORs, GORs and gas versus air conditions tested. Additional testing on a number of oils would be required before quantifiable relationships between oil properties the above tests conditions and dispersant effectiveness could be made.

The dispersant injection location was shown to have a significant effect on the resulting oil drop size distribution for the Alaskan North Slope crude oil tests described in Section 5. Injection of dispersant in the pipe prior to exit from the discharge nozzle resulted in the best dispersant performance in the small orifice tests (see Figure 106 and Figure 107). In the lower velocity large orifice tests dispersant performance was enhanced when the in-pipe injection location was moved further away from the exit resulting in longer mixing times in the pipe prior to exit from the nozzle (see Figure 114 and Figure 115). In both the small and large orifice tests the dispersant performance was reduced when the injection point was moved outside of the pipe and dispersant performance decreased as the injection location was moved further away from the exit. The importance of DOR was also reinforced in the ANS tests where higher DOR tests resulted in improved dispersant performance.

7 References


Appendix A: Oil Drop Size Distribution Plots

8.1 Pre-dispersant Applied, Dorado Oil, Small Orifice (1.5 mm), Oil Drop Size Distributions

![Graph showing oil drop size distributions for Dorado Oil with pre-dispersant applied, 1.5 mm orifice, and 9:1 GOR (AIR).](image)

The graphs illustrate the cumulative volume percentage of oil drop sizes for different runs (22, 26, 31) indicating the effect of dispersant addition on drop size distribution.
Durado Oil - Oil Drops Pre Dispersant Addition :1.5 mm Orifice
5:1 GOR (AIR)       Upper List : Runs 20, 24, 29

Cumulative Volume %

Oil Drop Size (µm)

Run 20
Run 24
Run 29

Durado Oil - Oil Drops Pre Dispersant Addition :1.5 mm Orifice
5:1 GOR (AIR)       Lower List : Runs 20, 24, 29

Cumulative Volume %

Oil Drop Size (µm)

Run 20
Run 24
Run 29
Durado Oil - Oil Drops Pre Dispersant Addition : 1.5 mm Orifice
9:1 GOR (Methane)  Upper List : Runs 23, 27, 32

Cumulative Volume %

Oil Drop Size (µm)

Run 23
Run 27
Run 32

Durado Oil - Oil Drops Pre Dispersant Addition : 1.5 mm Orifice
9:1 GOR (Methane)  Lower List : Runs 23, 27, 32

Cumulative Volume %

Oil Drop Size (µm)

Run 23
Run 27
Run 32
Durado Oil - Oil Drops Pre Dispersant Addition : 1.5 mm Orifice
5:1 GOR (Methane)   Upper List : Runs 21, 25, 30

Cumulative Volume %

Oil Drop Size (µm)

Run 21
Run 25
Run 30

Durado Oil - Oil Drops Pre Dispersant Addition : 1.5 mm Orifice
5:1 GOR (Methane)   Lower List : Runs 21, 25, 30

Cumulative Volume %

Oil Drop Size (µm)

Run 21
Run 25
Run 30
8.2 Pre-dispersant Applied, Endicott Oil, Large Orifice (4.5 mm), Oil Drop Size Distributions

Endicott Oil - Oil Drops Pre Dispersant Addition : 4.5 mm Orifice
5:1 GOR (AIR) Upper Lisst : Runs 45, 49, 53

Endicott Oil - Oil Drops Pre Dispersant Addition : 4.5 mm Orifice
5:1 GOR (Methane) Upper Lisst : Runs 46, 50, 54
Endicott Oil - Oil Drops Pre Dispersant Addition : 4.5 mm Orifice
9:1 GOR (AIR)     Upper Lisst : Runs 47, 51, 55

Endicott Oil - Oil Drops Pre Dispersant Addition : 4.5 mm Orifice
9:1 GOR (Methane)     Upper Lisst : Runs 48, 52, 56
8.3 Pre-dispersant Applied, Dorado Oil, Large Orifice (4.5 mm), Oil Drop Size Distributions

Durado Oil - Oil Drops Pre Dispersant Addition : 4.5 mm Orifice
1:5 GOR (AIR)     Upper Lisst : Runs 33, 37, 41

Run 33
Run 37
Run 41

Durado Oil - Oil Drops Pre Dispersant Addition : 4.5 mm Orifice
5:1 GOR (Methane)     Upper Lisst : Runs 34, 38, 42

Run 34
Run 38
Run 42
9  Appendix B Data Collection and Analysis for Acoustic Drop Size Measurement Development

(double click on the following cover page to access entire report contents)
Final Report Contribution

Subsea Chemical Dispersant Research

For

U.S. Department of the Interior
Bureau of Safety and Environmental Enforcement (BSEE)

Submitted By:

Paul D. Panetta and Dale McElhone

The College of William & Mary, Virginia Institute of Marine Science

February 11, 2013

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DISCLAIMER

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