Final Report

Low-Dose Repeat-Application Dispersant Testing

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Table of Contents

Executive Summary

The objective of the work was to investigate the effectiveness of chemical dispersants applied to crude oils in low-dosages and with repeated application.

Small-scale testing was completed in SL Ross's in-house wind-wave tank using Alaska North Slope (ANS) crude, Endicott crude, Ewing Bank crude, IFO 30 fuel oil, Oseberg Blend crude, and Rock crude. The oils were treated by successive applications of dispersant at low DOR (1:500 or 1:1000) with 5 minutes of energetic mixing between applications. Each 1:500 application is equivalent to a typical aircraft spray application to a 4 mm thick oil slick.

The small-scale test results suggest that each low-dose application of dispersant causes some dispersion of oil. There is no indication that dispersant accumulates in the oil until a threshold is reached and the dispersant starts to have an effect. The net effect of multiple low-dose applications of dispersant appears to be similar to a single equivalent high-dose application based on the final dispersant effectiveness (DE) measurements. The one exception to this was for the more viscous Rock crude oil where the multiple low-dose applications resulted in a better overall dispersion than an equivalent single dose. This may be due to the poor initial mixing of the dispersant with this viscous oil and the wash-off of the larger quantity of dispersant applied in the single application, high-dose test. The multiple low-dose applications may have succeeded in getting more net dispersant into the oil through the multiple exposures or contacts.

Large-scale DE testing was completed at the Ohmsett test tank in the week of May 4^{th} through 8^{th}, 2009 using the standard DE test protocol developed for dispersant testing at Ohmsett over the past several years.

The dispersant coverage applied in each pass during the test program was approximately 0.0094 mm. This spray thickness was somewhat thicker than the estimated value from a typical aircraft spray system (0.0075 mm). Up to 5 spray passes were used in each run. Dispersant application was stopped when no significant patches of thick oil could be located on the water surface. The final DE for all tests was high (83 to 95%). This suggests that multiple, low-dose applications of dispersant can be effective.

A Sequoia Scientific LISST 100X particle size analyzer (LISST) was used to record data on oil drop sizes and in-water oil concentrations. A Turner Cyclops C3 *in-situ* fluorometer (C3) was also deployed to measure in-water oil concentrations.

In the only high-dispersant-dose experiment completed the oil drop sizes in the zones of high oil concentrations were relatively small with average volume median diameters (VMDs) or d50's of 45 microns. In the low-dose, repeat-application experiments, the d50's were somewhat larger ranging from 65 to 159.

The C3 device identified the same concentration peaks and valleys as the LISST system but the calibration-adjusted C3 concentration values were consistently lower than the LISST values in five of the nine tests. For the heavier oils (Rock and IFO 180) the concentrations as determined by the C3 were similar to those as measured by the LISST. For the lighter oils (Endicott and ANS) the C3 measured concentrations were lower by factors between 3 and 50. The C3 measurement may be sensitive to the oil drop size distribution. This problem has been reported for similar *in-situ* fluorescence measurement systems. These apparent inconsistencies in concentration measurements between the LISST and calibrated C3 merit further investigation.

The behavior of the surface oil was observed after each application of dispersant to determine if the dispersant was effective on the oil remaining or returning to the surface over the life of the test. The initial low-dose dispersant application resulted in a partial dispersion of the oil in all tests and also resulted in a drastic spreading of the oil over a broad area of the tank. "Café-au-lait"- colored dispersions of the remaining thick surface oil patches were also observed on each subsequent low-dose application. Based on these observations it appears that each single, low-dose application of dispersant will be effective in dispersing some of the surface oil. As in the small-scale tests in the SL Ross wave tank, each low-dose dispersant application created a partial dispersion of the oil slick rather than accumulating in the oil until a threshold was reached before starting to have an effect.

Low-Dose Repeat-Application Dispersant Testing

1. Objective

The objective of the work was to investigate the effectiveness of chemical dispersants applied to crude oils and fuel oils in low-dosages and with repeated application.

2. Background

Common practice for the application of dispersant to large oil spills is through large fixed wing aircraft spraying. However, the dispersant application rate for a single pass from such spray systems typically is only about 0.0075 mm thick and can treat a slick of only about 0.15 mm thick at the normal design application ratio of one part dispersant to 20 parts of oil. Thick oil patches accounting for 80 to 90 % of the total oil volume can easily be 10 to 100 times thicker than this. The dispersant dose rate from an aircraft application hitting the thick oil could be in the range of 1:200 to 1:2000 under such conditions. The question to be answered in this project was: “Does dispersant applied in very low doses (1:1000 to 1:200) disperse a small fraction of an otherwise dispersible oil or is it simply ineffective until a minimum threshold concentration of dispersant in the oil is achieved, possibly through repeated spray passes?” The answer to this question has significant ramifications with respect to operational decisions in dispersant application on thick oil slicks. For example, if a test spray were completed on a thick oil slick and no dispersion was observed the dispersant might be considered to be ineffective whereas multiple applications of the dispersant might be necessary to achieve a dosage sufficient to generate dispersion. This work was completed at two test scales. Initial work was completed at a laboratory test tank scale to assess the effect of low-dose application on a number of oils. Once trends were determined in the laboratory, testing was completed at Ohmsett - The National Oil Spill Response Test Facility to verify similar behavior at full-scale.

3. Small Scale Tests

3.1 Methods

Small-scale tests were completed in April of 2009 in SL Ross's in-house wind-wave tank using the test protocol that has been established over several years (SL Ross 2003). The dimensions of this tank are 11m x 1.2m x 1.2 m. It is filled to a depth of 0.85 m with salt water for the testing. A photograph of the test tank is provided in Figure 1. Oil is contained in the center of the tank using an air bubble curtain barrier. Waves are introduced to the tank using a wave paddle positioned at one end of the tank and are dissipated by a beach at the other. In the present project, dispersant was applied to the surface oil by syringe in this test program for precise control of the application rate. The water temperature throughout the testing was 14.5 ºC and the water salinity was 32 ppt.

Small-scale tests were completed using the following six oils known to be chemically dispersible at recommended dispersant-to-oil ratios (DOR); Alaska North Slope (ANS) crude, Endicott crude, Ewing Bank crude, IFO 30 fuel oil, Oseberg Blend crude, and Rock crude. These oils were also available in large quantities at the Ohmsett facility for use in the full-scale testing.

In the low-dose, repeat application tests the oils were treated by successive applications of dispersant at low DOR with 5 minutes of energetic mixing between applications. In some runs a 1:1000 DOR was applied in the first application and this was followed by a number of 1:500 applications. Each 1:500 application is equivalent to a typical ADDS pack application to a 4 mm thick oil slick. Dispersant was applied until the entire slick dispersed or the equivalent of a 1:20 dispersant dosage has been achieved. Up to 10 separate dispersant applications were applied. A high dose test was also completed with each oil. In the high-dose tests the same total amount of dispersant was administered to the slick in one application as had been applied in the corresponding repeat-application test. The behavior of the oil slicks was documented after each application to track the effect of each dispersant application.

Figure 1. SL Ross Indoor Wave Tank

3.2 Results

A summary of the dispersant application schemes used for each test and the observed behavior of the treated oils are provided in Table 1. The oil remaining on the surface after the completion of each test was collected, measured and compared with that initially spilled to determine the final dispersant effectiveness (DE) for the test. These DE values are provided in Table 1.

Table 1. Dispersant Dosing Schemes and Effectiveness Observations

					Observations
1	Endicott	10 @ 1:500	1:50	84	Each application of dispersant generated some dispersion. There did not appear to be an accumulation of dispersant in the oil that subsequently led to a more significant dispersion. Initial application of dispersant caused the slick to fragment and cover wider portion of containment area. Over the 5 minutes between applications the slick returned to a more continuous shape. Café-au-lait dispersion not observed in any application.
2	Endicott	1 @ 1:50	1:50	84	Rapid café-au-lait -colored dispersion of oil within 30 seconds of application of dispersant.
3	ANS	1 @ 1:1000 4 @ 1:500	1:125	86	As in test 1, each application generated small amounts of dispersion. No café-au-lait type dispersion was observed. By last application the small quantity of oil on the surface and its patchiness made it difficult to target with dispersant.
4	ANS	1 @ 1:1000 4 @ 1:500	1:125	26	Dispersant was applied at 5-minute intervals with no wave action. Waves were started 5 minutes after the last application and run for 5 minutes. The early applications resulted in little or no dispersion of oil. Surface activity changed but there was little dispersion. Dispersion was poor once the waves were started. The applied dispersant may have leached from the oil slick during the no-wave action periods. The air-bubble induced current from the containment barrier may have been responsible for the dispersant stripping.
5	ANS	1 @ 1:125	1:125	80	Rapid café-au-lait dispersion of oil slick but not a complete dispersion of oil. The incomplete dispersion may be due to the drop-wise application of dispersant rather than a spray application.
6	IFO 30	2 @ 1:500	1:250	87	Significant largish-drop dispersion after each application. High density of this oil may be reason for good dispersion with low dosage.
7	IFO 30	4 @ 1:1000	1:250	90	Surface activity and significant large and small drop dispersion was observed on each application. Most of oil was dispersed by end of third application and mixing cycle. The ease of dispersion of this oil may make it unsuitable for testing at full-scale.
8	IFO 30	1 @ 1:250	1:250	90	Rapid, early and complete small drop dispersion of the oil with the single application.
9	Oseberg	1 @ 1:1000 2 @ 1:500	1:200	97	Initial surface activity and significant moderately sized oil drop dispersion on first application. Second application created more dispersion but still not café-au-lait coloring. It was hard to target the remaining oil in the third application that resulted in final dispersion of oil. Not a good candidate for large-scale testing due to easy dispersion with small dosage.

					Observations
10	Oseberg	1 @ 1:200	1:200	96	Early rapid dispersion with some café-au-lait coloring. Complete dispersion after 10 minutes of mixing.
11	Rock	5 @ 1:500	1:100	69	Oil stringers and fine drop dispersion occurred in early applications. The surface effect of dispersant and formation of stringers and fine oil drops lasted for about 5 minutes and then the remaining oil reformed a cohesive slick. By 5th application dispersant effect seemed to be diminishing.
12	Rock	1 @ 1:100	1:100	37	Dispersant wash-off was clearly visible when first applied. There was early café-au-lait dispersion but not complete dispersion. Multiple low-dose applications appears to work better with this heavy oil as less dispersant may be lost to the water phase if it is applied in smaller multiple applications.
13	Ewing Bank	2 @ 1:500	1:250	79	Good café-au-lait dispersion observed with initial 1:500 application. Most oil appeared to be dispersed after the first application. Not a good candidate for large-scale testing due to easy dispersion with small dosage.
14	Ewing Bank	1 @ 1:250	1:250	65	Good early dispersion but not complete. Visual estimate of dispersion higher than recorded. Possibly due to light oil coloring / density.

3.3 Discussion

The small-scale test results suggest that each low-dose application of dispersant causes some dispersion of oil and there is not an accumulation of dispersant in the oil until a threshold is reached and the dispersant starts to have an effect. This was common with all of the oils tested. The net effect of multiple low-dose applications of dispersant appears to be similar to a single equivalent high-dose application based on the final dispersant effectiveness measurements made for the two types of application. The one exception of this would appear to be for the more viscous Rock crude oil where the multiple low-dose applications resulted in a better overall dispersion than an equivalent single dose. This may be due to the poor initial mixing of the dispersant with this viscous oil and the wash-off of the larger quantity of dispersant applied in the single application, high-dose test. The low-dose applications may have succeeded in getting more dispersant into the oil through the multiple exposures or contacts. The low-viscosity, low density Oseberg and Ewing Bank oils and the IFO 30 fuel oil do not appear to be good candidates for the large-scale tests as they are too dispersible at low-dosages to permit observation of effects of multiple low-dose applications.

4. Large-Scale Ohmsett Testing

4.1 Methods

Large-scale DE testing was completed at the Ohmsett test tank in the week of May 4^{th} through 8^{th}, 2009. An overhead view of the Ohmsett facility is provided in Figure 2. The standard DE test protocol developed for dispersant testing at Ohmsett over the past several years was used in this testing with the exception that multiple low-dose dispersant applications were applied to the surface oil slicks. Detailed descriptions of the test protocol, and its development, and equipment used in the testing can be found in previous publications (SL Ross et al 2000, 2003, 2004, 2006).

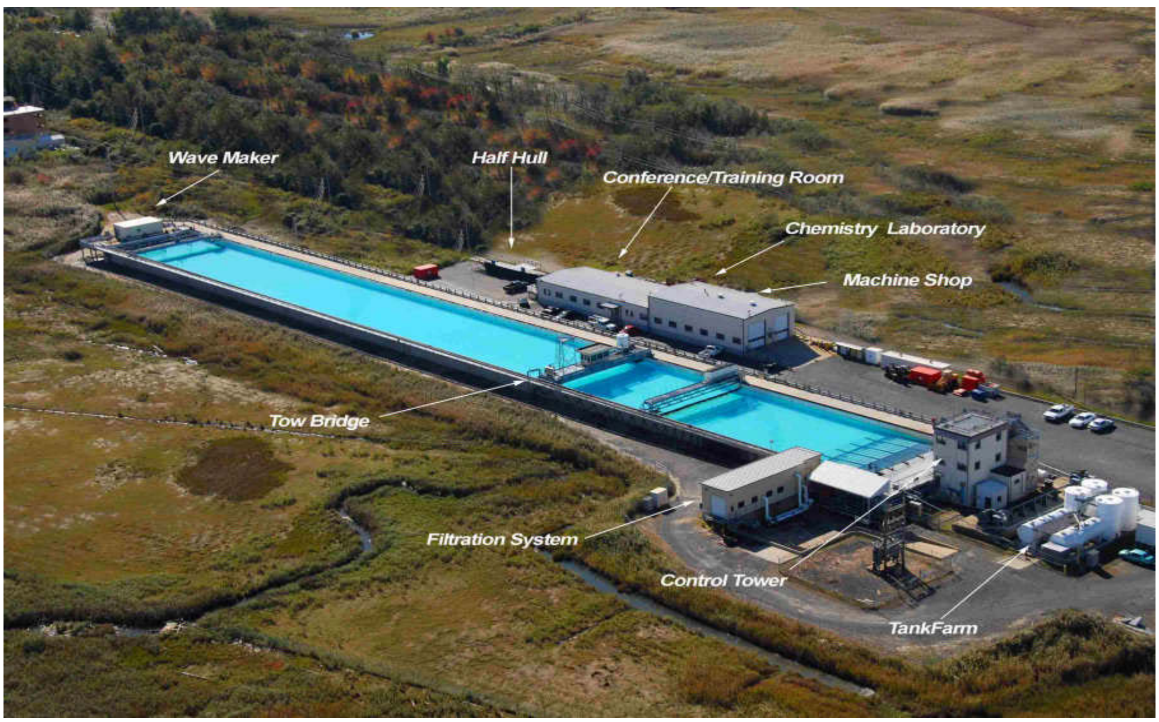

Figure 2. Ohmsett - The National Oil Spill Response Test Facility

The basic test procedure used for the dispersant effectiveness tests in this project was as follows.

1. The oil containment area was established by placing booms across the north and south ends of the Ohmsett tank.
2. The oil and dispersant were loaded into their respective supply tanks on the main bridge deck.

3. The main bridge was positioned at the southern quarter point within the boomed area. The wave paddle was started and the waves were allowed to develop to a stage just prior to the formation of breaking waves.
4. The wave paddle settings used in all of these tests were a 3.5-inch stroke and 34 to 35 strokes per minute.
5. The bridge was moved south at the required speed to achieve proper slick dimensions and dispersant application dosage (one knot or 0.5 m/s for this test series).
6. The oil was pumped at the required rate onto the surface through the discharge manifold mounted on the south side of the bridge (nominally 40 gpm for 1/2 minute in this test program).
7. The dispersant was applied to the oil slick from the spray bar system mounted on the north side of the bridge in the same pass.
8. The behavior of the treated oil was observed as the bridge was moved over the treated slick.
9. Additional low-dose applications of dispersant were made to the thickest oil patches remaining on the surface on subsequent passes down the tank. If necessary the spray bar was moved along the width of the tank so the dispersant spray would contact the thicker oil patches.
10. The behavior of the treated oil was observed after each application of dispersant.
11. Slicks were agitated by the breaking wave-field for 30 minutes after which waves were stopped.
12. Surface water currents developed by the water spray from the bridge fire monitors was used to sweep any surface oil remaining on the water surface at the end of the test to a common collection area at one corner of the containment boom.
13. The oil was then removed from the water surface using a double-diaphragm pump and suction wand or a hand ladle and placed in a collection drum or a 20 L pail.
14. The collected oil and water were allowed to stand at least overnight to allow the oil and water to separate before most of the free water was drained from the bottom of the collection container.
15. The remaining oil and water were well mixed and a sample was taken for water content and physical property determination.

16. The quantity of remaining liquid was measured and the amount of oil determined by subtracting the amount of water as determined using the water content analysis.
17. The effectiveness of the dispersant is reported as the volume of oil discharged minus the amount collected from the surface all divided by the amount discharged.
18. Each test was video taped for future visual reference.

The physical properties of the four oils tested are provided in Table 2. The more viscous IFO 180 was selected for use in the large-scale tests as it was believed that the IFO 30 oil was too easily dispersed in the small-scale test series. The ANS, Endicott and Rock crude oils were considered good candidates for the large-scale work based on the small-scale test results. The four oils provide a range of oil viscosities from 30 to 4300 cP and densities from 0.889 to 0.964. Spraying Systems Company 800050 and 650025 flat fan nozzles were used to achieve the low-dose dispersant application required in these tests. An attempt to use smaller orifice nozzles (650017) was not successful as the dispersant did not form a proper spray pattern with these small orifice nozzles because the dispersant is more viscous than water. The spray boom was made up of 11 nozzles mounted with a 2-foot spacing. All tests were conducted using Corexit 9500 dispersant. The tank water temperature varied between 16 and 17 ºC over the test program. Air temperatures ranged from 11 to 23 ºC. The tank water salinity was 32 ppt.

Table 2**.** Physical Properties of Oils Used in Large-Scale Tests

		Measured Density (g/cm^3 at 20°C)
Alaska North Slope (ANS)	30	0.889
Endicott	375	0.936
Rock	2450	0.964
IFO 180	4300	0.962

4.3 Results

4.3.1 Dispersant Effectiveness

The test conditions and estimated Dispersant Efficiencies (DE) for all of the large-scale tank tests are summarized in Table 3. The DE values in the table were determined using the following formula: DE= (oil volume spilled – oil volume collected from the surface) / oil volume spilled * 100. In one set of experiments with Rock oil, effectiveness of a single pass of a relatively high dose rate (Test 5) was compared to multiple passes of with lower dose rates (Tests 4 and 3). In Test 4, four passes at a lower dose produced similar level of effectiveness to a single high dose pass, demonstrating that multiple passes at low dosage can produce high levels of effectiveness. Overall, the final DE values for all tests were high (64% to 95 % with most values in the range of 83 to 95%). This shows that that for fresh oils with viscosities less than 4300 cP, multiple, low-dose applications of dispersant can be effective.

The dispersant coverage applied in each pass during the test program was approximately 0.0094 mm (based on the average of the initial spray thicknesses calculated for each run). This spray thickness was somewhat thicker than the estimated value from a typical aircraft spray system (0.0075 mm as indicated in the discussion section). Up to 5 spray passes were used in each run. Dispersant application was stopped when no significant patches of thick oil could be located on the water surface.

Hypertext links are provided in Table 3 to video clip segments of each of the tests. The video records can be viewed by double-clicking on a link when accessing this document digitally. The clips are in order from the start of the test progressing through to the end of each test and each dispersant application pass is labeled in the video record. The video clips provide a record of the behavior of the oil in each of the tests completed and it is recommended that they be viewed to get a full appreciation of the test program and the behavior of the oil after each low-dose treatment.

Table 3. Ohmsett Tank Dispersant Effectiveness (DE) Test Results Summary

			-							**Test #**
Endicott	18	13	375	71	3.03	1:315	4	88	VideoT1	1
Endicott	17	11	375	67	4.09	1:376	5	90	VideoT2	2
Rock	17	12	2450	77	7.83	1:730	5	64	VideoT3	3
Rock	17	12	2450	69	3.74	1:437	4	83	VideoT4	4
Rock	17	18	2450	71	4.21	1:103	1	86	VideoT5	5
IFO 180	16	17	4300	71	2.53	1:257	4	84	VideoT6	6
IFO 180	17	18	4300	78	3.44	1:415	4	95	VideoT7	7
ANS	17	18	30	77	1.64	1:176	3	91	VideoT8	8
ANS	17	23	30	78	1.69	1:229	3	95	VideoT9	9

1. Estimated DOR in first pass

4.3.2 Dispersed Oil Concentrations and Drop Size Distributions

Up to ten passes were made down the length of the test tank with the main bridge after the oil was discharged to measure in-water oil concentrations and drop size distributions. A Sequoia Scientific LISST 100X particle size analyzer (LISST) recorded data on oil drop sizes and in-water oil concentrations. A Turner Cyclops C3 *insitu* fluorometer (C3) was also deployed to measure in-water oil concentrations. These measurements were made to confirm the presence of oil in the water column and to characterize the form of the oil (drop size distribution). Graphs of the oil drop size distributions and concentrations are provided in Appendix A. Hypertext links to these graphs are provided in Table 4.

The "continuous" traces on these plots are from the LISST and C3 instruments that were towed back and forth through the water. The high concentration zones correspond to the times that the sensors were in the dispersed oil cloud. In the single control experiment test #5 (one application of dispersant at full dose rather than multiple low-dose applications), elevated oil concentrations (50 to 125 ppm peak concentrations) were recorded by the LISST under the slick, and the oil drop sizes in the zones of high oil concentrations were relatively small (average volume median diameters (VMDs) or d50's of 45 microns). In the low-dose, repeat-application cases, the oil drop sizes were somewhat larger (average d50's between 65 to 159 microns) in the high oil concentration zones (34 to 341 ppm peak concentrations). Dispersed oil drops less than 70 to 100 microns in diameter are generally considered permanently dispersed in a typical offshore environment (Lunel 1993, Neff 1990). The drop-size results from these low-dose tests suggest that the dispersant was effective in generating a significant portion (between 40 and 67%) of the dispersed oil in small enough drops to be permanently dispersed. The in-water oil characterizations qualitatively support the measurements of oil lost from the surface that are used to determine dispersant effectiveness.

In-water oil concentration was also measured using a Turner Cyclops-3 (C3) submersible sensor that measures the fluorescence of the oil in the water column. Rough calibrations of the C3 were completed for the four oils tested to permit the reporting of oil concentrations rather than raw fluorescence. The calibration data is provided in Appendix B. The calibration-adjusted fluorescence values acquired by the C3 are plotted along with the LISST data in Figures A1 through A9 after applying an adjustment factor described below. The C3 device identified the same concentration peaks and valleys as the LISST system but the calibration-adjusted C3 concentration values were consistently lower than the LISST values in five of the nine tests. For the heavier oils (Rock and IFO 180) the concentrations as determined by the C3 were similar to those as measured by the LISST. For the lighter oils (Endicott and ANS) the C3 measured concentrations were lower by factors between 3 and 50 as shown in Table 4. The C3 measurement may be sensitive to the oil drop size distribution as has been reported for similar *in-situ* fluorescence measurement systems (SL Ross 2003, Lambert 2001). However, the drop size data collected in these tests do not provide any conclusive evidence to support this in this study. The C3 system was recently acquired by MMS to provide an additional in-water oil concentration measurement capability at Ohmsett that will be compatible with the new equipment being put into service by the U.S. Coast Guard Strike Teams. The Cyclops data provides confirmation of the presence of oil in the water since it detects oil through fluorescence at oil specific wavelengths. However, the use of the C3 to accurately determine oil-in-water concentration values may be problematic as discussed above.

Table 4. In-Water Oil Characterization and Graph Hypertext Links

									DE (%)
Endicott	1:315	FigureA1	1	92	62	21	341	10x	88
Endicott	1:376	FigureA2	2	137	40	16	218	10x	90
Rock	1:730	FigureA3	3	107	42	44	119	50x	64
Rock	1:437	FigureA4	4	65	67	16	34	1x	83
Rock	1:103	FigureA5	5	45	72	33	116	1x	86
IFO 180	1:257	FigureA6	6	101	44	32	62	1x	84
IFO 180	1:415	FigureA7	7	159	41	27	104	1x	95
ANS	1:176	FigureA8	8	118	56	40	63	3x	91
ANS	1:229	FigureA9	9	93	56	42	127	10x	95

4.3.2.1 Oil Drop Size Analysis

The oil drop size data collected for each experiment have been analysed to determine 1) the average VMD drop size, 2) the volume percent of the oil present in the form of oil drops less then 70 microns in diameter, 3) the average elevated oil concentration, and 4) the peak oil concentration measured (see Table 4). The VMD drop size for test 5, the only test where a single, high-dose application of dispersant was made, was the smallest of all tests. The highest percentage of oil in the form of drops less than 70 microns in diameter was also recorded for this test. These results would be expected due to the larger amount of dispersant applied to all of the oil present on the first pass in this test compared to the remaining tests. The “volume percent less than 70 micron” values were computed for each test to provide an indication of the likely permanence of the dispersions generated. The only apparent trend in the drop size data for the low-dose tests appears to be that the ANS crude oil tests had the highest values for the Volume of Oil present in drops < 70 microns and the average elevated concentrations. This would be expected since ANS crude was the lightest oil tested.

4.3.3 Visual Observations

The behavior of the surface oil was observed after each application of dispersant to determine if the dispersant was effective on the oil remaining or returning to the surface over the life of the test. The initial dispersant application resulted in a partial dispersion of the oil in all tests. The initial low-dose application also resulted in a drastic spreading of the oil over a broad area of the tank. This behavior has not been prevalent in previous tests at Ohmsett where single, full dose applications of dispersant have been made. The early spreading of the oil to cover much of the width of the tank made it impossible to spray all of the oil remaining on the surface in one-pass in subsequent spray passes since the spray bar used was only wide enough to span about 1/3 of the tank width. The spray bar was moved along the width of the tank to target the heaviest zones of surface oil on each pass after the initial dispersant application. In all applications, for all of the oils tested, café-au-lait colored clouds of dispersed oil were visible when breaking waves passed through freshly treated surface oil. Dispersed oil clouds with this appearance are known to contain small oil droplets and thus are a good indicator of permanently dispersed oil. The size of the dispersed oil cloud depended on the amount of surface oil present when dispersant was applied but each low-dose application was effective in at least partially dispersing oil that remained on the surface even after the slick had been treated several times. The video records that can be accessed via the hypertext links in Table 3 provide some evidence of this dispersion. Unfortunately the overcast weather during much of this test program resulted in low-light levels and somewhat poor video recordings of some of the tests.

Based on these observations alone it can be concluded that, low-dose applications of dispersant at DORs of as little as 1:200 to 1:400 can be effective in dispersing some of the surface oil in oils with viscosities <4300 cP. Oil that is not dispersed in one pass can be effectively dispersed in subsequent passes. There is no evidence that dispersant accumulates in the oil and builds up to a sufficient concentration on subsequent application passes to then create an oil-in-water dispersion but rather creates a partial dispersion of the oil slick on each application. The low dose application also caused all of the oils tested to quickly spread over the width of the entire tank as has been observed in offshore dispersant application programs.

5. Summary of Key Results and Recommendations

The small-scale test results suggest that each low-dose application of dispersant causes some dispersion of oil and there is not an accumulation of dispersant in the oil until a threshold is reached and the dispersant starts to have an effect. The net effect of multiple low-dose applications of dispersant appears to be similar to a single equivalent high-dose application based on the final dispersant effectiveness (DE) measurements made for the two types of application. The one exception of this would appear to be for the more viscous Rock crude oil where the multiple low-dose applications resulted in a better overall dispersion than an equivalent single dose. This may be due to the poor initial mixing of the dispersant with this viscous oil and the wash-off of the larger quantity of dispersant applied in the single application, high-dose test. The low-dose applications may have succeeded in eventually getting more dispersant into the oil through the multiple exposures or contacts.

Future large-scale testing at Ohmsett could be completed using difficult to disperse oils such as IFO 380 or other viscous crude oils to determine if low-dose, multiple-pass dispersant operations can be more effective at dispersing these difficult oils than single-pass high-dose applications.

The final DE for all tests conducted in the large-scale Ohmsett test tank was high (83 to 95%). This suggests that multiple, low-dose applications of dispersant can be effective.

The C3 device identified the same concentration peaks and valleys as the LISST system but the oil-specific calibration-adjusted C3 concentration values were consistently lower than the LISST values in five of the nine tests. The C3 measurement may be sensitive to the oil drop size distribution. This problem has been reported for similar *in-situ* fluorescence measurement systems.

The use of the C3 system to accurately quantify the concentration of dispersed oil should be investigated more fully using a range of oils under differing dispersion conditions (drop size distributions) to improve the utility of this system in field monitoring programs.

The behavior of the surface oil was observed after each application of dispersant to determine if the dispersant was effective on the oil remaining or returning to the surface over the life of the test. The initial dispersant application resulted in a partial dispersion of the oil in all tests. The initial low-dose application also resulted in a drastic spreading of the oil over a broad area of the tank. Café-au-lait colored dispersions of the remaining thick surface oil patches were also observed on each subsequent low-dose application. Based on these observations it appears that each single, low-dose application of dispersant will be effective in dispersing some of the surface oil. The dispersant does not appear to stay with the oil and build up to a sufficient concentration on subsequent application passes to then create an oil-in-water dispersion but rather creates a partial dispersion of the oil slick on each application.

If low-dose dispersant application tests are carried out at Ohmsett in the future the spray bar system should be expanded to permit spraying over the full width of the tank in one pass to ensure that all surface oil is contacted with dispersant on each application. This would be a relatively minor modification to the existing system.

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Appendix A: Oil Drop Size and Concentration Graphs

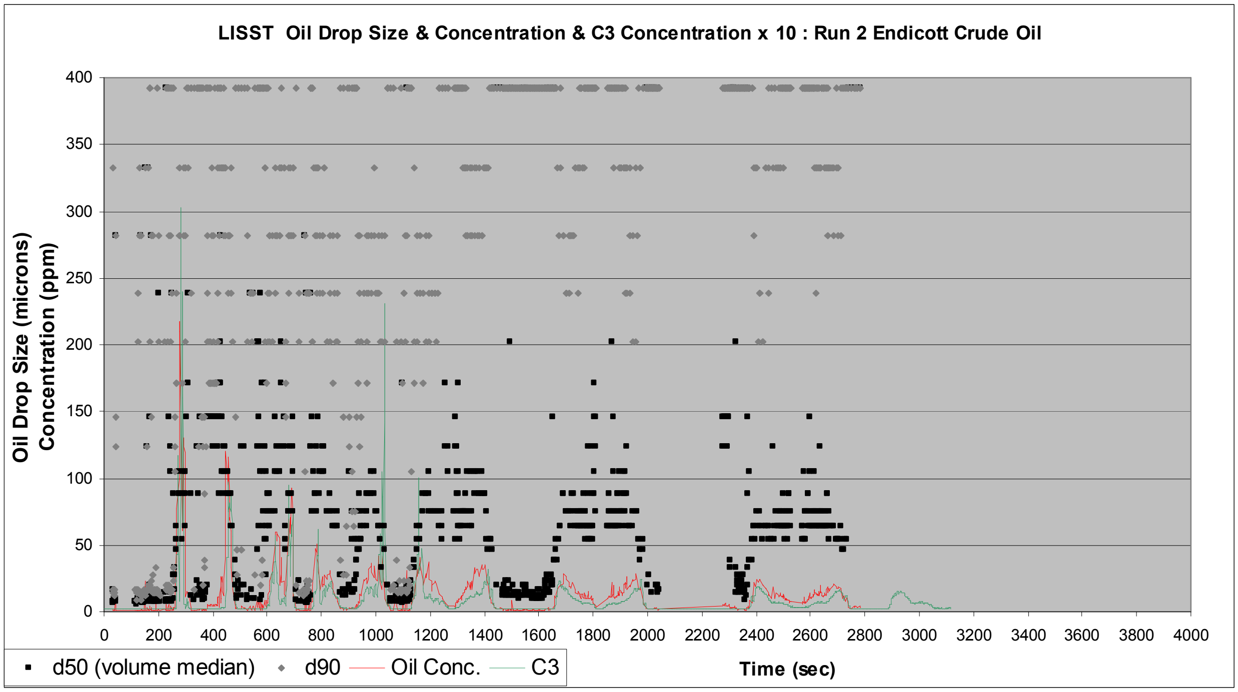

Figure A1: Oil Drop Size and Concentration Data: Test #1, Endicott Crude Oil

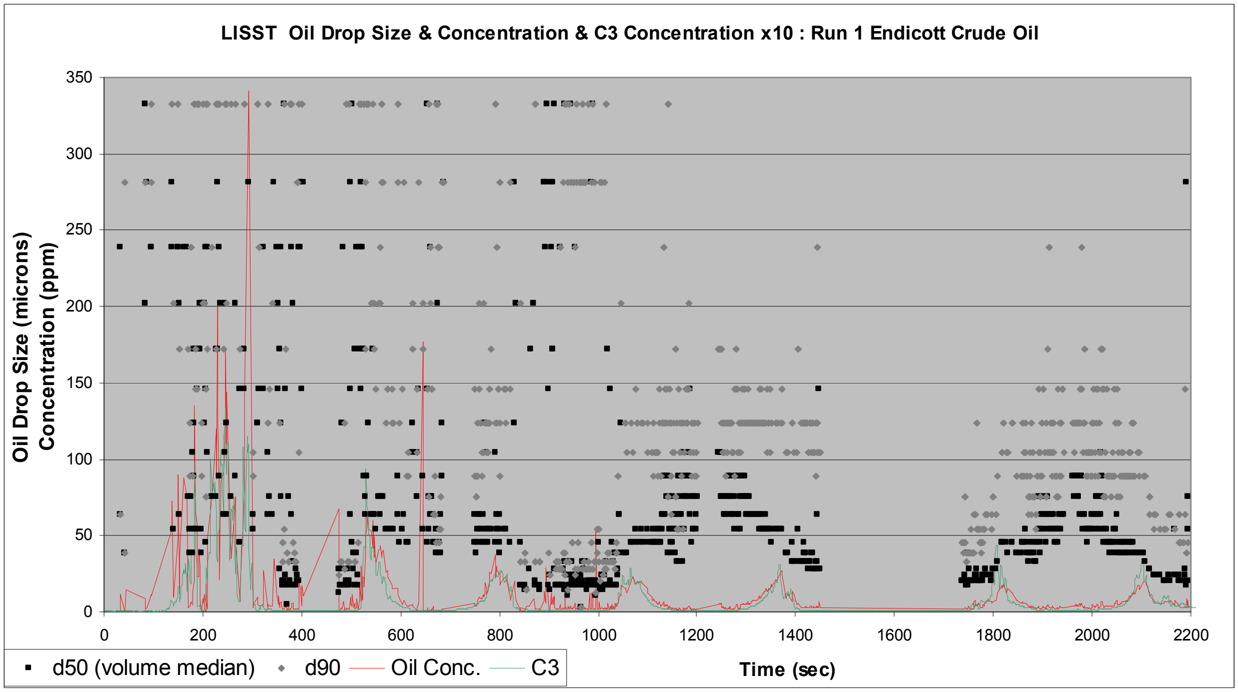

Figure A2: Oil Drop Size and Concentration Data: Test #2, Endicott Crude Oil

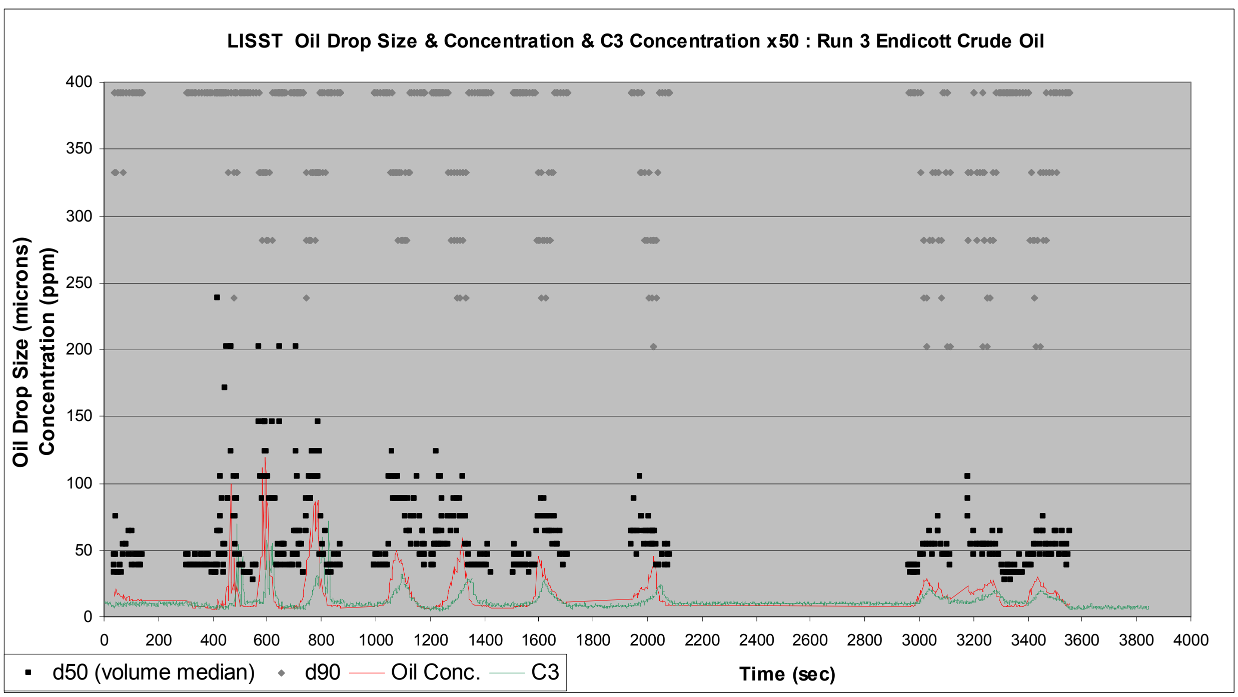

Figure A3: Oil Drop Size and Concentration Data: Test #3, Endicott Crude Oil

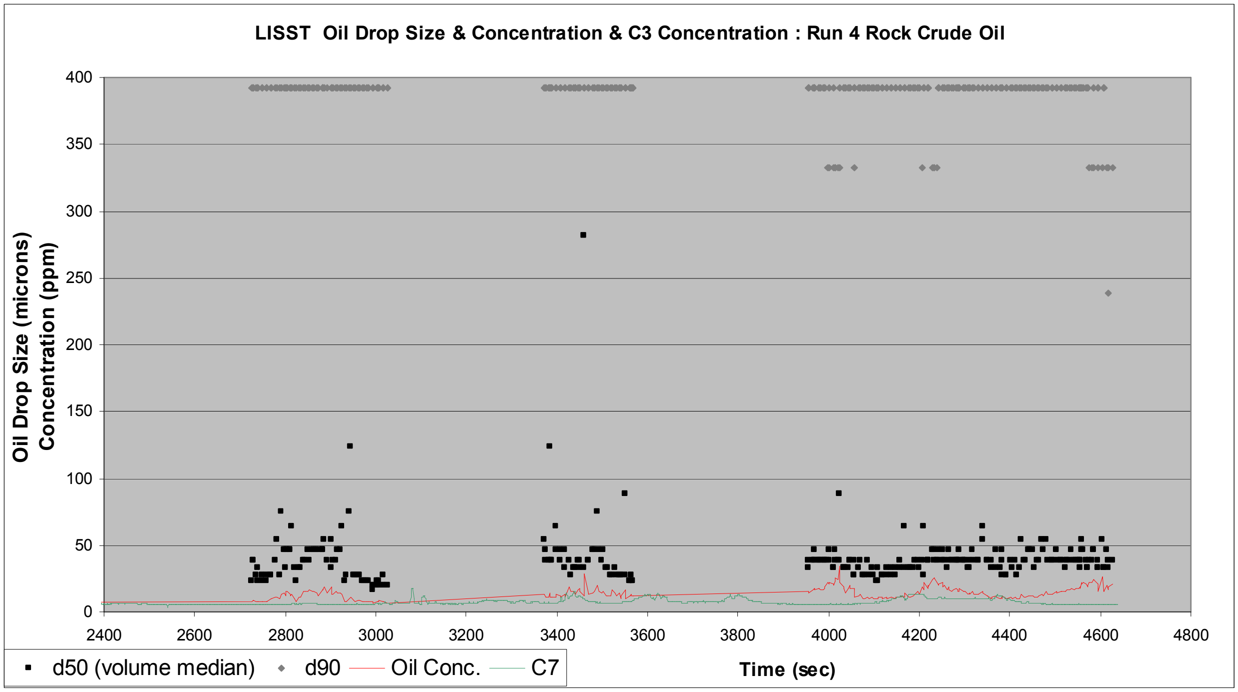

Figure A4: Oil Drop Size and Concentration Data: Test #4, Rock Crude Oil

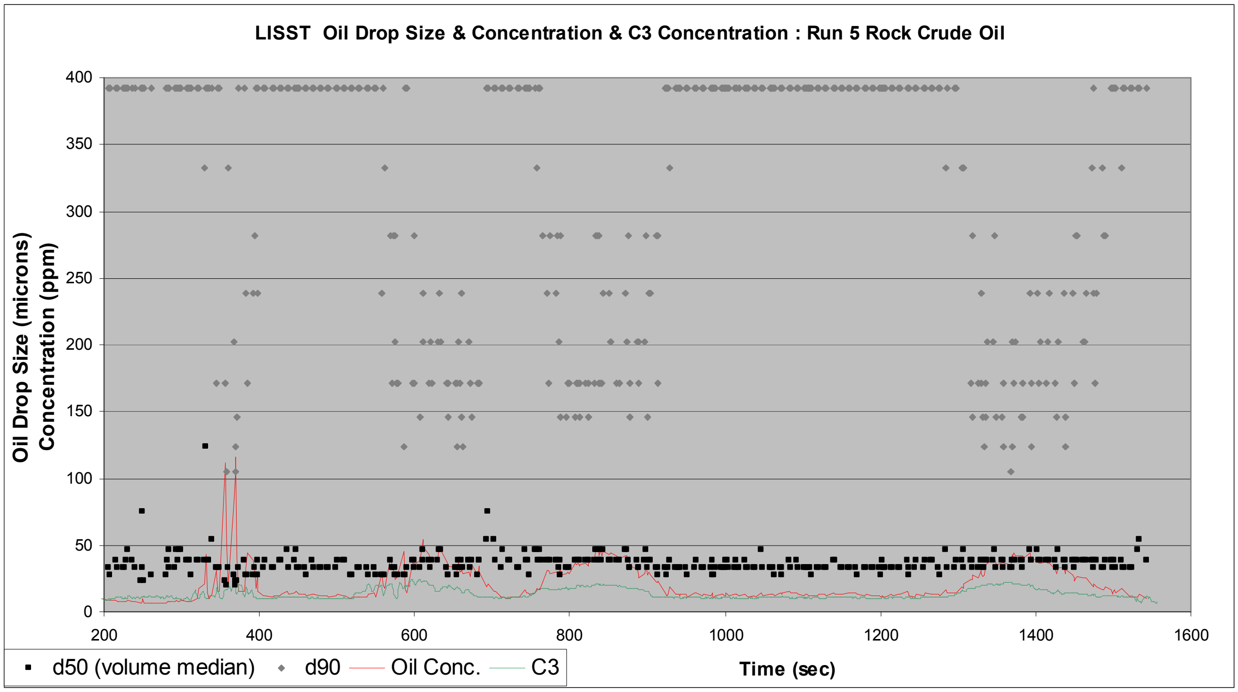

Figure A5: Oil Drop Size and Concentration Data: Test #5, Rock Crude Oil

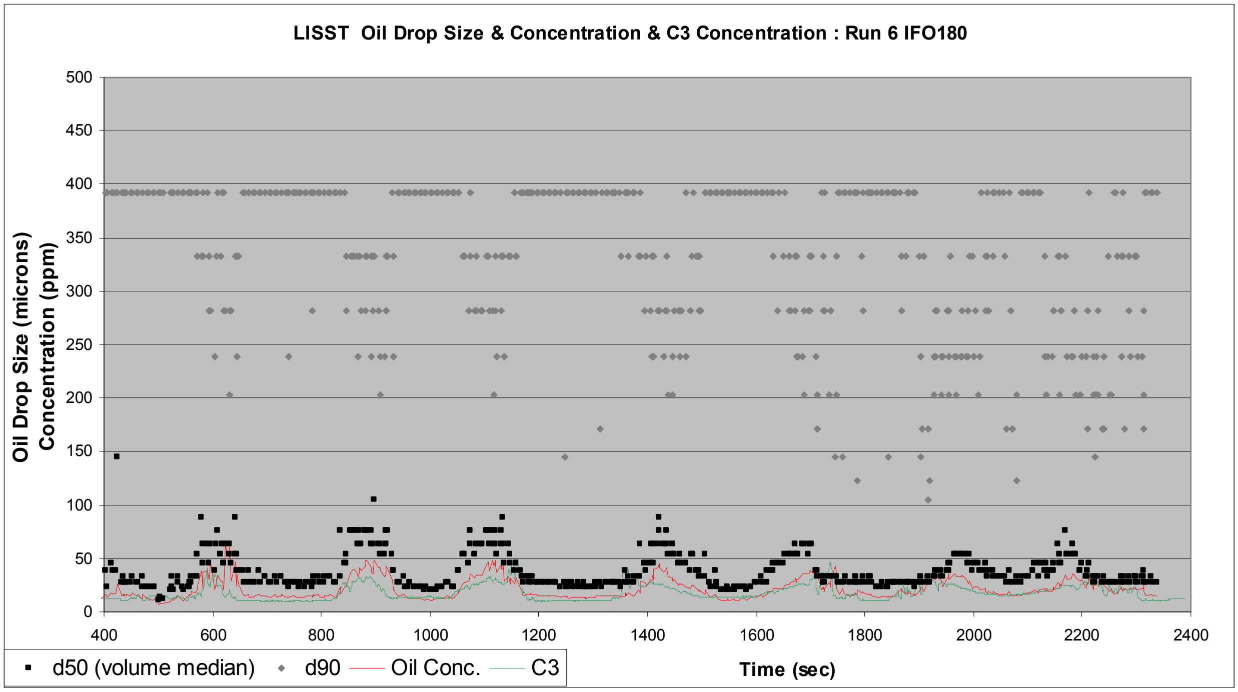

Figure A6: Oil Drop Size and Concentration Data: Test #6, IFO 180

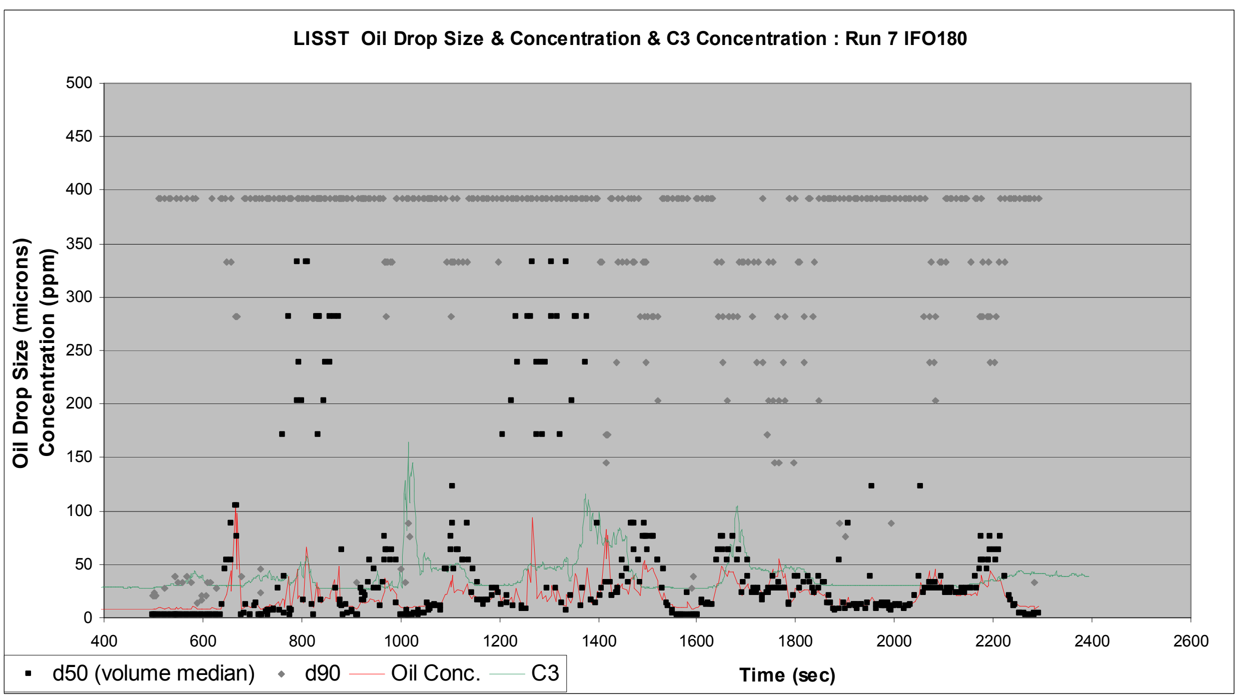

Figure A7: Oil Drop Size and Concentration Data: Test #7, IFO 180

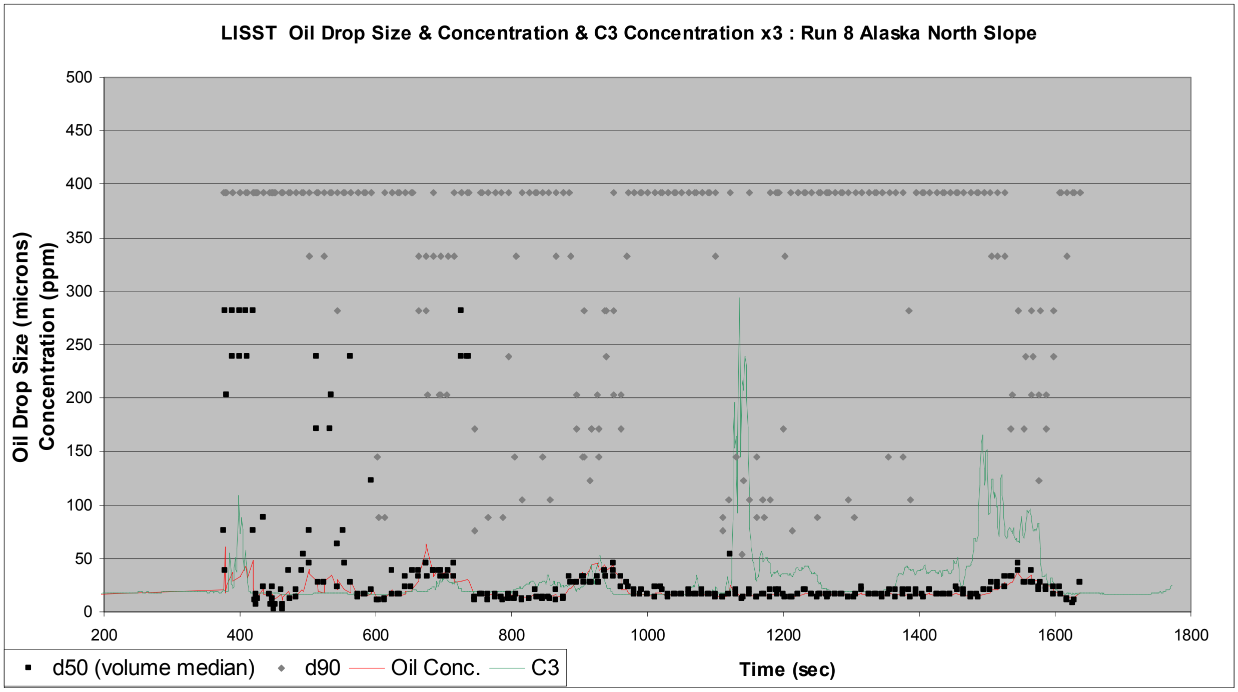

Figure A8: Oil Drop Size and Concentration Data: Test #8, ANS Crude Oil

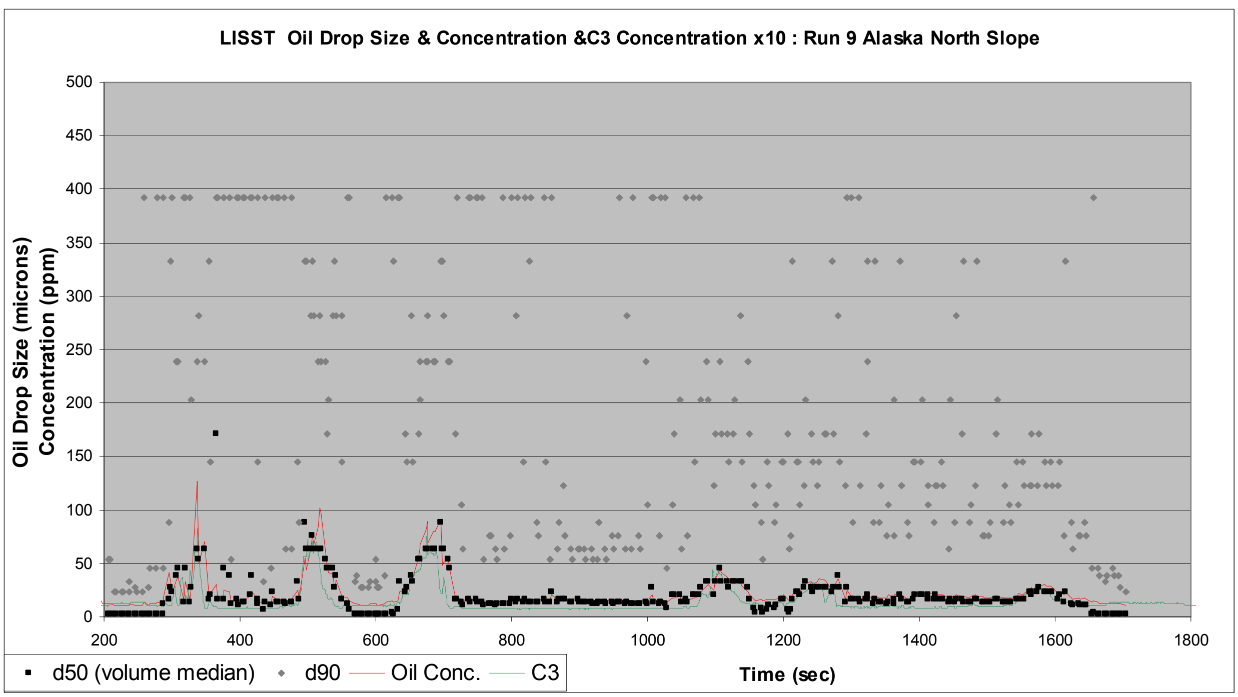

Figure A9: Oil Drop Size and Concentration Data: Test #9, ANS Crude Oil

Appendix B: Cyclops C3 Calibration Curves for Test Crude Oils

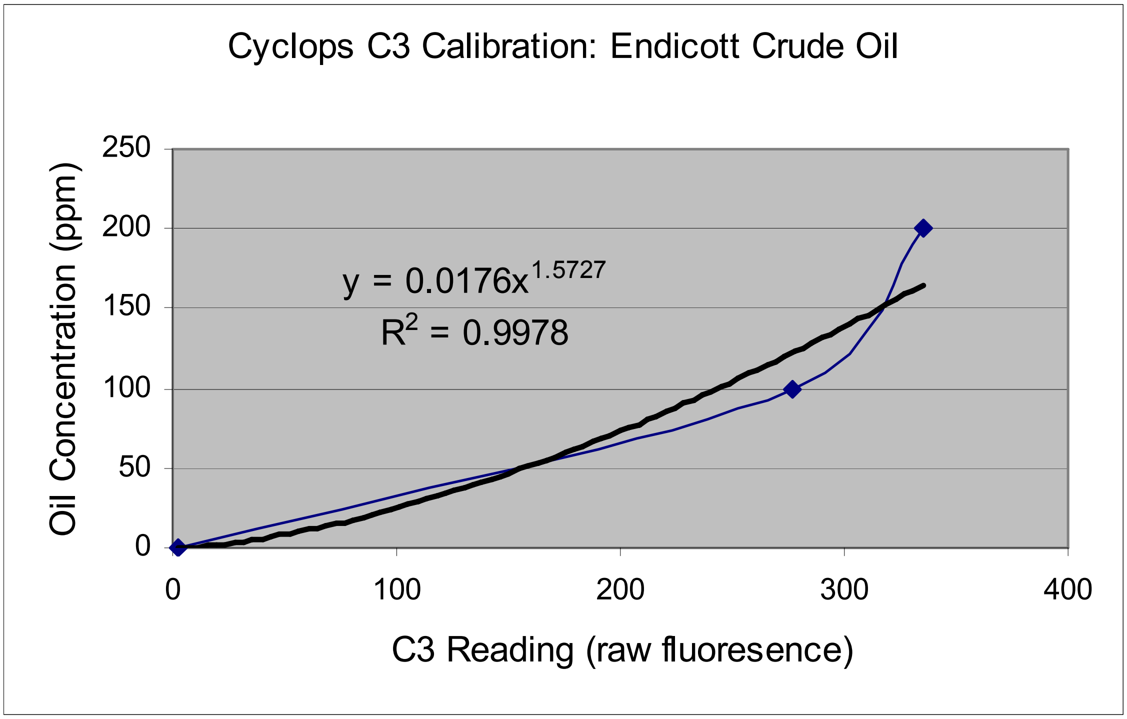

Figure B1. C3 Calibration for Endicott Crude

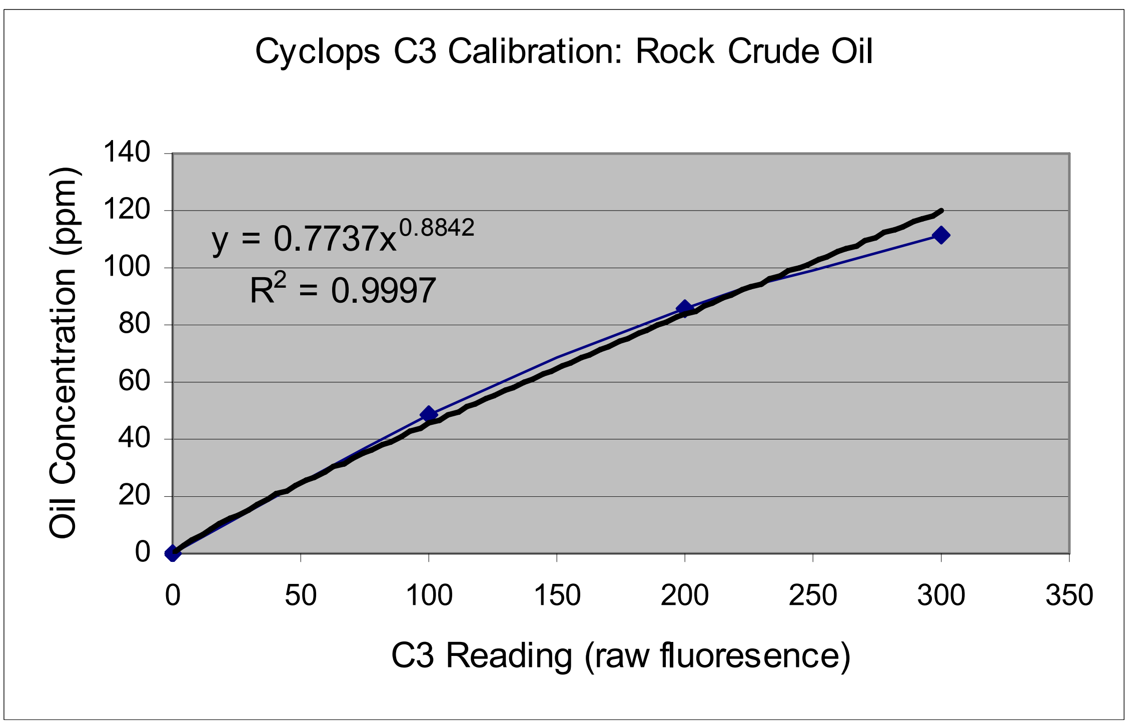

Figure B2. C3 Calibration for Rock Crude

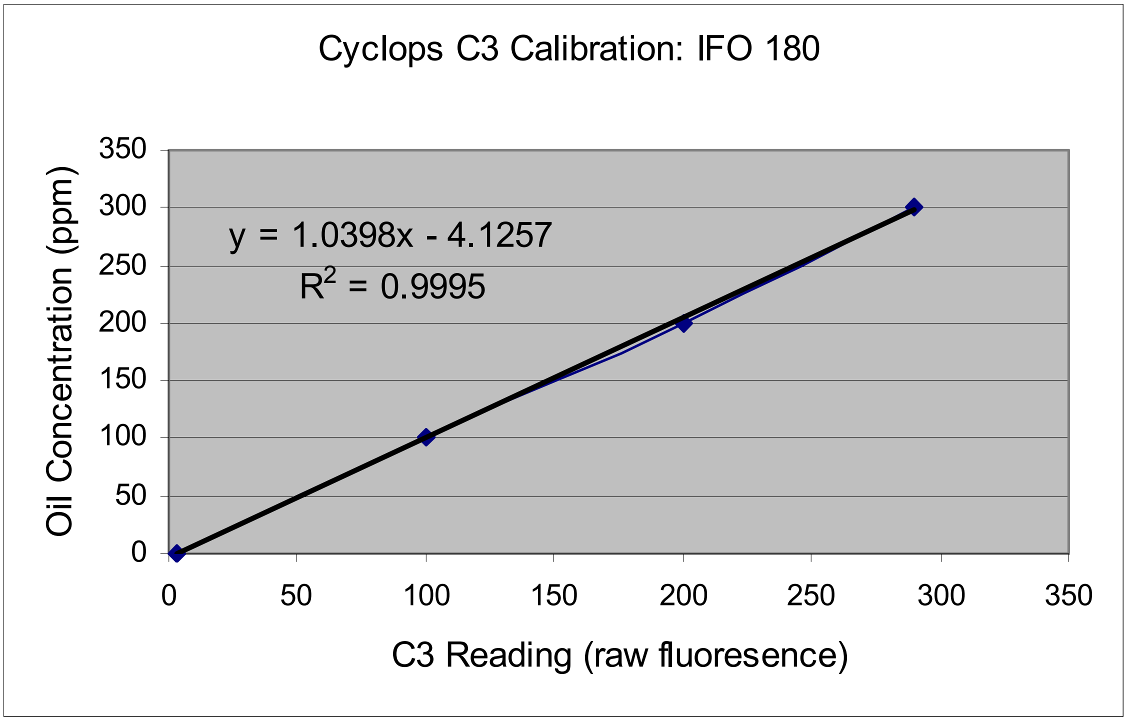

Figure B3. C3 Calibration for IFO 180

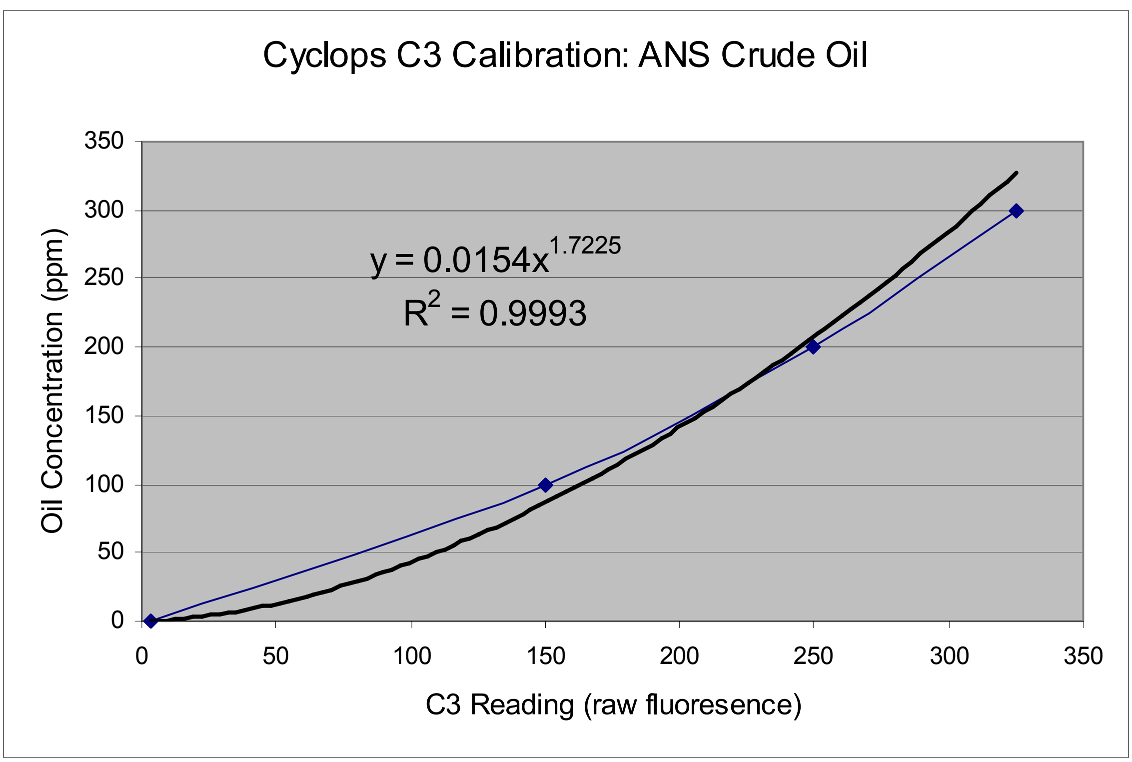

Figure B4. C3 Calibration for ANS Crude Oil