DISPERSANT EFFECTIVENESS TESTING: RELATING RESULTS FROM OHMSETT TO AT-SEA TESTS

For

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By

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Preface

The 2003 United Kingdom at-sea dispersant trials made possible a number of studies comparing performance of dispersants in wave tanks and laboratory apparatus with performance at sea. The testing at Ohmsett was just one of these studies; the others and their sponsors included: a) Exdet test sponsored by ExxonMobil; b) Baffled Flask Test and Swirling Flask Test by U.S. Minerals Management Service (MMS); and c) SL Ross wave tank by Canada Department of Fisheries and Oceans. Tests in the Warren Spring Laboratory apparatus had been conducted prior to the at-sea tests and were discussed in Lewis' technical report on the sea trials. Also, during the October 2003 Ohmsett test period certain important tests could not be accommodated in the test schedule. These "supplemental tests" were completed in April 2005. The supplemental tests and tests with other apparatus have been described individually elsewhere, but an overview of results of all testing is provided in this report.

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We also extend special thanks to the sponsors of the 2003 UK field trials International Tanker Owners Pollution Federation, Maritime and Coast Guard Agency, Oil Spill Response Limited, Department of Environment, Food and Rural Affairs for allowing Joe Mullin and Ken Trudel from the study team to observe the UK field trials.

Executive Summary

Questions have been raised concerning the effectiveness of dispersants on crude oils in cold waters, specifically Alaska North Slope and Hibernia crude oils. In the past, planners relied on bench-scale laboratory tests to address questions about dispersibility of oils, but these tests often yielded conflicting results. Tests in large wave tanks, like Ohmsett, may produce more realistic results because they reproduce at-sea operational and dispersion processes more realistically than laboratory apparatus. However, even tank tests have been criticized because their results have not been compared with at-sea tests. The present study compared results of dispersant tests conducted at the U.S. Minerals Management Service facility, Ohmsett, with tests performed at sea in the United Kingdom in 2003. Identical oils and dispersants were used in both tests. In parallel studies, these same combinations of oils and dispersants were tested in other apparatus currently used for regulatory purposes, including the Swirling Flask Test, Baffled Flask Test, Exdet Test, and S. L Ross Wave tank test. The results from all of these studies are summarized and discussed here.

The UK at-sea tests estimated the viscosity of oil that limits chemical dispersion. This was accomplished by testing a number of intermediate fuel oil (IFOs) spanning a range of viscosities, up to a maximum of 7000 cP (at 15º C). Those tests showed that the limiting oil viscosity might vary with mixing energy (i.e., wind speed, wave energy). At the lowest wind speeds tested (7 to 10 knots), the limiting oil viscosity in tests with the dispersant Corexit 9500 lay between the viscosities of IFO 180 (viscosity = 2075 cP at 15º C) and IFO 380 (viscosity = 7100 cP at 15º C). At slightly higher wind speeds (11 to 14 knots) dispersant effectiveness was near maximum with both oils and the limiting effect of oil viscosity was eliminated. This suggests that in winds of 7 to 10 knots the limiting viscosity lies in the range from 2075 to 7100 cP, but at higher wind speeds the limiting oil viscosity exceeds 7100 cP. Superdispersant 25 (SD 25) and Agma 379 (Agma) produced some dispersant effectiveness at sea, but neither produced the high levels of effectiveness shown by Corexit.

Those tests were repeated at Ohmsett to determine whether Ohmsett tests could predict the oil viscosity limitations of dispersion observed at sea. In Ohmsett tests, wave energy also influenced dispersion performance. Preliminary tests were conducted under a range of wave conditions at

Ohmsett. Tests conducted at 35 wave cycles per minute (cpm) produced far greater dispersant effectiveness than at sea and were discontinued. Tests in 33.3 cpm waves resulted in effectiveness that was similar to at sea, but subsequently proved to be slightly higher than at sea. Tests in 30 cpm waves produced no evidence of chemically augmented dispersion with any combination of oil, dispersant and DOR. Tests with Corexit in 33.3 cpm waves produced high levels of dispersion in both IFO 180 and IFO 380, showing that in 33.3 cpm waves, oil viscosity did not limit chemical dispersion at Ohmsett in the same way that it had at sea at the lower wind speeds (7 to 10 knots). Rather the 33.3 cpm results were more consistent with at-sea results in winds of 11 to 14 knots, where the oil viscosity limiting dispersion was clearly greater than that of IFO 380, 7100 cP. In general, Ohmsett tests in 33.3 cpm waves appeared to produce somewhat higher levels of effectiveness than at sea for most combinations of dispersants and oils.

These Ohmsett tests were used successfully to verify and demonstrate the limitations of the visual and UV fluorescence methods used to monitor dispersant effectiveness in the US and UK.

The Ohmsett study was one of five in which the oils, dispersants and DORs tested in the 2003 UK sea trials were retested in laboratory effectiveness tests and wave tank tests. The objectives were to compare results from different test methods with effectiveness data gathered at sea. It had been assumed that a potential advantage of wave tank tests for predicting dispersant performance at sea was that wave tank testing could reproduce many of the at-sea operational and dispersion processes that cannot be reproduced in small-scale lab tests. One of the objectives of this work was to attempt to verify this assumption. Tests were completed using bench-scale laboratory apparatus, including: a) Swirling Flask Test (SFT) (EPA standard, Environment Canada standard), b) Baffled Flask Test (BFT) (developed by EPA to replace the SFT), c) Exxon Dispersant Effectiveness Test (EXDET), and d) Warren Spring Laboratory Test (WSL Test) (UK standard), as well as in the SL Ross intermediate scale wave tank and the large scale Ohmsett wave tank. In short, most laboratory and wave tank tests produced high levels of effectiveness in tests with combinations of oil, dispersant and DOR (O/D/DOR) that yielded high levels of effectiveness at sea. The exception was the Swirling Flask Test (SFT), which produced very low estimates of effectiveness under conditions that produced the highest levels of dispersant performance at sea even under conditions of relatively low mixing energy at sea. The potential usefulness of the SFT is not considered further here. All other test methods produced moderate to high levels of effectiveness for IFO 180 and IFO 380. None of the tests in this study predicted the oil viscosity limitation on dispersion observed in the at-sea tests at low wind speeds. That is, none predicted both a high level of dispersibility for the IFO 180 and the almost complete lack of dispersion observed in the IFO 380 at low wind speeds at sea. On the other hand, all methods showed IFO 180 to be more dispersible than the IFO 380. Hence, all methods produced results more consistent with the at-sea tests with Corexit in winds of 11 to 14 knots. Both wave tanks and most laboratory methods ranked the performance of the dispersant products in the same order as at sea, but some did not.

The key recommendations from this study are the following.

a) Studies should be completed at Ohmsett and at-sea to characterize and quantify wave environments so that wave conditions at Ohmsett (and the dispersant results produced at these conditions) can be related to wave conditions at sea in ways that are useful for dispersant research and testing.
b) The unique capability of Ohmsett should be used to establish the limits of dispersant performance on viscous Outer Continental Shelf oils and relate these to potential dispersant performance at sea.
c) The unique capability of the Ohmsett wave tank should be used to elucidate the process(s) by which oil viscosity, wave energy, dispersant type and DOR interact to limit the chemical dispersibility of viscous oils, so that the limitations of dispersant performance at sea can be more reliably predicted.
d) The capability of the Ohmsett wave tank should be used to assess the limits of dispersibility of oils in non-breaking waves, as well as in breaking waves.
e) The wave energy setting to be used in standard dispersant effectiveness tests at Ohmsett should be re-assessed in light of the present work.
f) The visual scale used to describe dispersant effectiveness that was developed in the UK field trials and used in this study is an effective and valuable tool for quantifying dispersant performance in actual spills and for research purposes. The system should be revised based on the experience gained at Ohmsett in this and other studies. The system

should also be standardized and more fully documented to improve its usefulness by less experienced practitioners.

g) In future studies, replicate control runs should be completed with all oils tested in order to more gain a better understanding of the oil losses that occur during the tests by natural and method-related means.

1 Introduction

1.1 Objectives

The objectives of this study were:

a) To compare the results of dispersant effectiveness tests completed at Ohmsett with those completed under actual at-sea conditions during sea trials in the UK in June 2003.
b) To assess the reliability of visual and in-situ fluorescence methods for determining the effectiveness of dispersant applications.
c) To compare test results from existing laboratory (four) and wave-tank (two) effectiveness tests with dispersant performance at sea using the same oils and dispersants.

1.2 Background

Government regulators and spill responders have questioned the potential effectiveness of dispersants on several specific crude oils in cold waters, including Alaska North Slope and Hibernia crude oils. Ideally, effectiveness testing should be done at sea, under real-world conditions, but this is seldom feasible or economical. In the past, planners conducted bench-scale laboratory studies to assess potential dispersant performance on these oils, but tests often yielded conflicting results (e.g., Daling and Lichtenthaler 1986). Larger scale tests in wave tanks like Ohmsett show promise in producing more consistent and realistic results because they reproduce some of the at-sea dispersion processes better than laboratory tests (SL Ross 2000a, 2000b, 2002, SL Ross and MAR 2003). However, tank tests too have been criticized because results have not been compared with at-sea tests. The present study addressed the above concerns by comparing results of dispersant tests conducted at the U.S. Minerals Management Service wave tank facility, Ohmsett, with tests performed at sea in the United Kingdom in 2003 (Colcomb et al. 2005, Lewis 2004). Identical oils and dispersants were used in both tests. The present study prompted other authors to test these same oils, dispersants and dispersant-to-oil ratio using other dispersant effectiveness tests currently in use (e.g., Swirling Flask Test (SFT), Baffled Flask Test (BFT), Exdet Test (Exdet), SL Ross Wave Tank Test (SLR)) and compare their results with the 2003 United Kingdom at-sea trials. The collective results of these studies are summarized and discussed here, as well.

Previous authors have attempted to relate dispersant performance in laboratory effectiveness tests and performance at sea, commonly with limited success (e.g., Daling and Lichtenthaler 1986; Desmarquest et al. 1985, Nichols and Parker 1985, Mackay and Chau 1987). Their approaches ranged from providing an overview of lessons learned from laboratory tests at-sea tests to comparing numerical estimates of dispersant performance in paired lab and field tests. The present project differs from this early work in that it focuses not on correlating numerical estimates of dispersant effectiveness made in the lab and field, but rather on the problem of using laboratory tests and at-sea trials to distinguish between undispersible oils and dispersible ones.

Demarquest et al. (1985) and Daling and Lichtenthaler (1986) both compared numerical results of laboratory dispersant effectiveness with results of sea tests. Daling and Lichtenthaler, tested crude oils and dispersants at sea and in the lab. They found that no single laboratory test method correlated well with at-sea tests, but that the averaged results from several lab methods improved agreement between lab and sea test results. Desmarquest et al. compared results obtained with the Warren-Spring Laboratory (WSL) Test and Institut-Francais de Petroleum (IFP) Tests, with results obtained at sea. They concluded that results of certain lab tests correlated somewhat with results of sea trials, while those of others did not. More importantly, the latter found that all tests showed clearly the negative effect that high oil viscosity had on dispersant performance. The present study focused on using lab and sea tests to distinguish between undispersible oils and dispersible oils, a key question for responders and planners. The UK at-sea trials aimed at determining the limiting oil viscosity for chemical dispersion, that is, the oil viscosity at which dispersant performance was reduced to nil. Details of the 2003 UK at-sea experiments are reported elsewhere (Lewis 2004, Colcomb et al. 2005). In short, heavy marine fuel oils, spanning a broad range of viscosities were tested at sea under “real world” conditions. Small amounts of intermediate fuel oils (IFOs) were spilled at sea, sprayed with dispersants and effectiveness was assessed. Two grades of heavy fuel oil were used in most tests, IFO 380 (viscosity = 7100 cP at 16°C) and IFO 180 (viscosity = 2075 cP at 16°C) in the expectation that the less viscous oil might be dispersible, while the more viscous oil might not. Dispersion was assessed visually using a semi-quantitative four-point scale developed for this trial (Table 1-1). The study investigated the aspects of the dispersion process visible to the trained observer, namely the shattering of the dispersant-treated slick into oil droplets by cresting waves. An important consideration in this study is that for safety reasons tests could be conducted only under relatively light winds: the wind speed window was 7 to 14 knots. The results are summarized in Table 1-2. Results showed that the less viscous oil, IFO 180, dispersed readily with the dispersant product Corexit 9500. The more viscous oil, IFO 380 did not disperse at lower wind speeds (7 to 10 knots), but dispersed well at higher wind speeds (11 to 14 knots). The break point viscosity between the dispersible and undispersible oils lay between the IFO 180 and IFO 380 at lower wind speeds at least, but apparently shifted to above the viscosity of IFO 380 at the higher wind speed.

The Ohmsett work repeated the tests using identical oils and dispersants to verify that oils that were undispersible at sea were similarly undispersible at Ohmsett, and that those that were dispersible at sea were dispersible at Ohmsett. The objectives of test in other apparatus were:

a) To verify that oils that were clearly dispersible at sea were dispersible in these apparatus;
b) To determine whether oil-dispersant combinations produced little or no dispersion at sea were undispersible in the lab tests or, if dispersible, to determine the level of dispersant performance produced in the lab tests by oils that were undispersible at sea.

The main set of Ohmsett tests were conducted in October 2003, with supplemental tests conducted in April 2005. Tests in Exdet, SFT, BFT and SLR tank were completed from January to September 2004.

Another subject that requires study is the monitoring of effectiveness of dispersant applications in the field. Well thought-out, practical protocols, such as United States Coast Guard’s SMART (USCG et al. 2001) and UK’s dispersant effectiveness protocols (Davies 2000) are currently in place, but practical experience with them is limited. These methods use both visual and in-situ fluorescence for quantifying dispersant performance. The present study compared the results of visual and in-situ fluorescence methods with the direct measurements of effectiveness made in all test runs in order to verify their usefulness and to identify any possible limitations of these techniques.

Table 1-1: Method for Assessing Dispersant Effectiveness in UK At-Sea Trials 2003

Rank [a]	Standard Phrase	Description
1	No obvious dispersion	Dispersant being washed off the black oil as white, watery solution leaving oil on surface. Quantity of oil on sea surface not altered by dispersant.
2	Slow or partial dispersion	Some surface activity (oil appearance altered). Spreading out of oil. Larger droplets of oil (1 mm in diameter or greater) seen rapidly rising back to sea surface, but overall quantity appears to be similar to that before dispersant spraying.
3	Moderately rapid dispersion	Quantity of oil visibly less than before spraying. Oil in some areas being dispersed to leave only sheen on sea surface, but in other areas still some oil present.
4	Very rapid and total dispersion	Oil rapidly disappearing from surface. Light brown plume of dispersed oil visible in water under the oil and drifting away from it.
a) For purposes of the Ohmsett tests the dispersion effectiveness categories will be identified as follows: 1 = none; 2 = slight; 3 = moderate; 4 = high.		

Table 1-2: Summary of Results of 2003 At-Sea Dispersant Trial

Test No.	Test Oil	Dispersant and Nominal DOR	Wind Speed, Knots	Averages of Observer Effectiveness Assessments		
				2 minute	5 minute	10 minute
24	IFO 380	Corexit 9500 / 1:25	8.5	1	1	1
24a	IFO 380	Corexit 9500 / 1:25	8	1.1	1.2	1.2
24f	IFO 380	Corexit 9500 / 1:25	14	3	2	2
25	IFO 380	Corexit 9500 / 1:50	8	1.7	1.7	1.7
18	IFO 380	Superdispersant 25 / 1:25	7.5	2	2	2.32
18a	IFO 380	Superdispersant 25 / 1:25	7.5	2	2	2
18fa	IFO 380	Superdispersant 25 / 1:25	13	2.7	1.2	1.2
19	IFO 380	Superdispersant 25 / 1:50	8	1.4	1.6	1.4
23	IFO 380	Agma DR 379 / 1:25	9	1.6	1.6	1.5
23f	IFO 380	Agma DR 379 / 1:25	11	1.7	1.2	1.2
10	IFO 180	Corexit 9500 / 1:25	12	4.0	4.0	4.0
10a	IFO 180	Corexit 9500 / 1:25	7	3.0	3.2	3.0
10f	IFO 180	Corexit 9500 / 1:25	8	3.0	3.0	3.0
11	IFO 180	Corexit 9500 / 1:50	12	3.2	2.7	2.3
12	IFO 180	Corexit 9500 / 1:100	11	2.3	2.2	1.8
17	IFO 180	Superdispersant 25 / 1:25	9	1.7	2	1.8
17f	IFO 180	Superdispersant 25 / 1:25	8	2	2	2
15	IFO 180	Superdispersant 25 / 1:50	8	1	1	1
14	IFO 180	Agma DR 379 / 1:25	10	1.5	1.8	1.4
14f	IFO 180	Agma DR 379 / 1:25	10	2.2	2.8	2.5

2 Methods

The tests at Ohmsett were completed under conditions that were as identical as possible to those in the at-sea tests. The oils that were used, IFO 180 and IFO 380, were drawn from the same batches as those used in the at-sea trials. However, all of the oil acquired for testing was consumed in the October 2003 tests; for the April 2005 supplemental tests, replacement oils were blended to produce similar viscosities to the original oils. Details of blending are described in SL Ross and MAR 2005b.

Tests were conducted using the same three dispersant products used in the UK sea trials, namely Corexit 9500, Superdispersant 25 and Agma 379. The same nominal dispersant-to-oil ratios (DORs) were used, and tests were completed in similar water temperatures (16 to 17ºC) as in the at-sea tests.

Tests were conducted at three wave-maker settings 30, 33.3 and 35 wave cycles per minute (cpm); in each case the paddle stroke length was 3 inches (7.6 cm). A comparison of these wave-maker settings with the at-sea conditions is discussed in 4.1.

The Ohmsett dispersant effectiveness test protocol has been documented fully in a variety of technical reports and publications (Belore 2003, SL Ross 2000a; 2000b, 2002, SL Ross and MAR 2003). This protocol was used in all tests with the exception of the following.

a) Waves were started and allowed to fully develop before the oil was discharged and sprayed with dispersant to more closely simulate dispersant application in field situations.
b) Three different wave energy conditions were used in the testing in an attempt to match wave energy conditions at Ohmsett to those present in the UK dispersant field trials.

Abbreviated descriptions of the equipment and test methods used in this study are provided in the following sections.

2.1 Major Test Equipment Components

A detailed description of the test protocol and equipment used in the testing in October 2003 and April 2005 can be found in previous publications (SL Ross et al 2000a, 2000b, 2002, 2003, 2005a). The main equipment components of the dispersant effectiveness (DE) test procedure include the Ohmsett tank, the wave-making system, the main equipment bridge, the oil distribution system, the oil containment boom, and the dispersant spray system. Photos of the Ohmsett facility, oil and dispersant discharge booms used in the October 2003 testing are provided in Figures 2.1 through 2.3. Significant improvements to the oil delivery system were implemented for the April 2005 study to facilitate the discharge of viscous oils. In earlier studies, problems had been encountered in delivering viscous oils and these modifications successfully addressed the problem. The oil discharge system introduced for the April 2005 tests includes a progressing cavity pump, a pump speed control system, a gravity fed oil hopper supply, three-inch oil supply lines and a stainless steel oil discharge manifold. Oil is pumped into the hopper from drums or other supply tanks using the progressive cavity pump in reverse. A digital control module is used to control pump flow rate. The pump generates 0.19 gallons per minute per revolution of the pump. The quantity of oil discharged from the hopper is measured using a sonic probe mounted above the oil supply. Photographs of the oil supply system and oil discharge header are provided in SL Ross 2005.

Figure 2-1: Ohmsett Test Tank with Containment Boom, October 2003.

Figure 2-2: Oil Distribution System, October 2003.

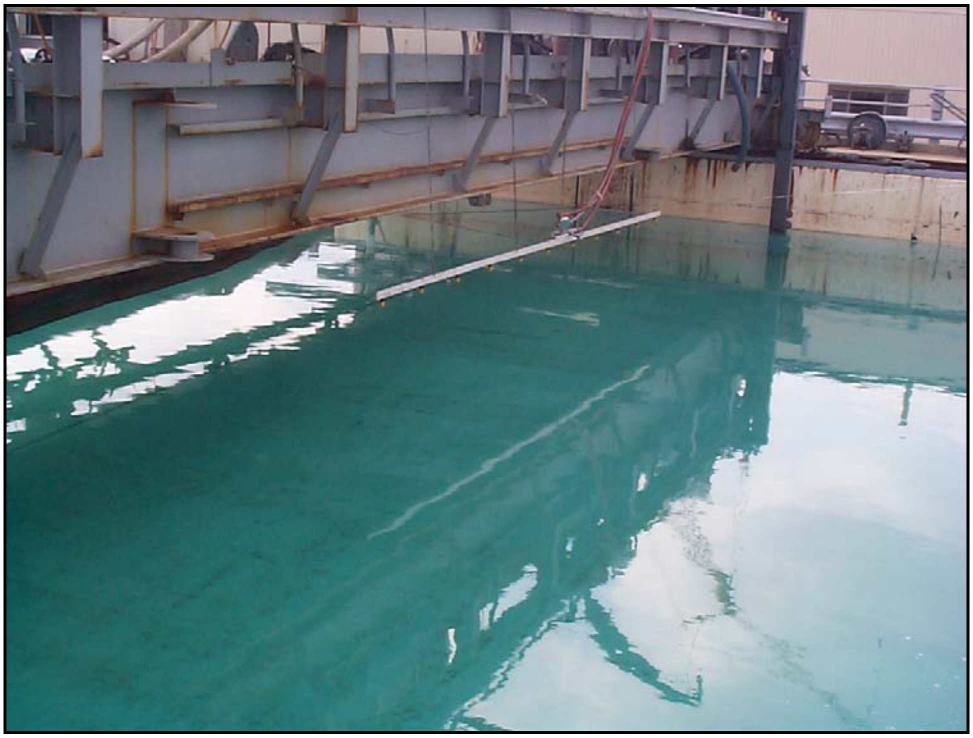

Figure 2-3: Dispersant Spray Bar, October 2003 and April 2005.

2.2 Test Procedure

The following test protocol was implemented for each test. The protocol has been refined through experience gained over the past three years of dispersant effectiveness testing at Ohmsett.

A large rectangle of containment boom is tied off in the tank between two stationary bridges and remains in place throughout the testing program. For each test:

1. The test oil is transferred to the delivery hopper on the Main Bridge and the oil transfer pump’s suction line placed into the oil supply.
2. The oil distribution system is charged with oil.
3. The dispersant supply tank is filled, the spray bar is operated for a short period outside of the boomed area, and the control solenoid is closed so dispersant re-circulates back to the supply tank until the spray operation commences.
4. The Main Bridge is positioned inside the north end of the containment boom rectangle.
5. Data acquisition and video recording of the test is started.

6. Waves are initiated at the required setting and time is allowed for the waves to fully develop.
7. Fluorometer recording is started to establish background oil levels in the tank.
8. The bridge is accelerated to the required speed.
9. When Main Bridge oil distribution system is approximately central to the rectangle of boom, the test slick discharge is started by opening the air-actuators. The duration of the oil discharge is timed.
10. The oil is discharged over a 20-metre travel distance. The air actuators are closed at end of the oil discharge.
11. When the dispersant spray bar is 1 metre from the beginning of the test slick, the solenoid valve is opened to begin the spray and is held open until the spray bar is 1 metre past the end of the test slick.
12. The oil and dispersant pumps are turned off.
13. The fluorometer data for the background pass is stored on computer and the fluorometer and data acquisition computer are prepared for subsequent passes through the tank.
14. The main bridge is moved quickly (1 knot) over the slick shortly after the oil discharge is complete to allow observation of the initial behavior of the surface oil and dispersant.
15. The main bridge is moved slowly (0.25 knots) over the slick at approximately 1 to 3 minutes, 4 to 9 minutes and 10 to 19 minutes after discharging the oil with the fluorometer pumps positioned in the water so they travel through the center of any visible dispersed oil cloud.
16. The fluorometer readings are recorded at 5-second intervals during each pass.
17. Water grab samples are taken for background and high oil concentration events. The samples are later analysed for total petroleum hydrocarbon (TPH) concentration for use in fluorometer result ‘calibration’.
18. The quantities of dispersant and oil discharged in the test are measured.
19. Visually observe the dispersion and record the event with still photos and video.
20. After 35 to 40 minutes stop the waves and allow surface to calm.
21. Herd any remaining surface oil to downwind end of rectangle of boom for recovery and volumetric/water content measurements.

Figure 2-4 shows a typical test shortly after the oil was discharged and the onset of the first wave cresting. The photo provides a good indication of the intermediate wave energy used in the tests.

Figure 2-5 shows oil being collected after a test in which only a portion of the discharged oil was dispersed. Oil was herded to a boom corner using fire monitor spray and then pumped to collection drums using a double-diaphragm pump and pickup tube.

Figure 2-4: Oil Slick Shortly After Discharge, Cresting Wave in Center of Photo

Figure 2-5: Oil Collection at End of Test

3 Test Results

A total of twenty tests were completed in October 2003 with various combinations of oil type, dispersant type, and dispersant-to-oil ratios (DORs). An additional seven supplemental tests were completed in April 2005. Table 3-1 summarizes the tests that were completed, including environmental conditions at the time of each test, arranged by order of test completion.

3.1 DOR Measurements

Three dispersant-to-oil ratio (DOR) values are referred to throughout the report. The target DOR (DOR_T) refers to the nominal DOR that was to be applied in the Ohmsett test in order to match the actual DORs used in the UK at-sea trials. The nominal DOR (DOR_N) is defined as the average oil thickness divided by average dispersant thickness applied. The measured DOR (DOR_M) is the estimate of the ratio of volume (or thickness) of oil treated per volume (or thickness) of dispersant applied. These dispersant-to-oil ratios have been calculated based on the following information and assumptions. The daily test logs and the Microsoft Excel spreadsheet DORcalcs.xls containing raw data used in these calculations are available on request.

The volume of oil discharged (column 9 in Table 3-1) was determined by measuring the depth of oil in the supply drum prior to and after discharge and using a volume per unit depth calculation. The quantity of dispersant sprayed was determined by measuring the depth of dispersant in the supply tank prior to and after spraying. The oil pumping time was recorded, the discharge width is known to be 5 metres, and the bridge was moved at a speed of 0.5 m/s (1 knot). The oil did not always form a continuous slick over the 5 metre wide swath so an estimate of the percent of water covered with oil over the oil discharge width was made using digital photos of the surface slick taken at a location just before the addition of dispersant. The oil coverage varied from 10 to 70% and was a strong function of the type of oil released. IFO 380 oil generally covered about 25% of the spill swath surface; IFO 180 covered about 35%; IFO 120 covered between 45 and 65%.

Local Disk (C:)**Table 3-1: Summary of Ohmsett Heavy Fuel Oil Dispersant Effectiveness Tests**

Test #	Oil Type	Disp. Type	Wave Freq (cpm)	Air Temp °C	Water Temp °C	Oil Temp °C	Disp. Temp °C	Oil Volume (litres)	Nominal Oil Thickness (mm)	Target DOR_T	Nominal DOR_N	Measured DOR_M	DE (%)	Links to Video Segments
1	IFO 380	none	35	15	16	23	-	70.78	0.76	0	control	control	30	R1s1, r1s2, r1s3, r1s4
2	IFO 380	9500 [c]	35	18	17	24	27	98.13	1.09	1:50	40	180	58	R2s1, r2s1, r2s3, r2s4, r2s5
3	IFO 380	9500 [c]	33.3	18	17	16	24	17.70	0.46	1:50	20	195	34	r3s1, r3s2, r3s3, r3s4, r3s5
4	IFO 380	9500 [c]	30	19	16	22		99.74	1.10	1:50	47	153	26	r4s1, r4s2, r4s3, r4s4, r4s5, r4s6
5	IFO 380	Super 25[s]	30	21	17	24	21	71.58	0.79	1:50	32	144	18	r5s1, r5s2, r5s3, r5s4
6	IFO 380	Super 25[s]	30	21	17	24	22	61.93	0.68	1:25	17	67	20	r6s1, r6s2, r6s3, r6s4, r6s5
7	IFO 380	9500 [c]	30	16	16	22	20	32.17	0.35	1:25	16	65	13	r7s1, r7s2, r7s4
8	IFO 380	Agma [a]	35	17	17	24	18	78.82	0.91	1:50	25	100	16	r8s1, r8s2, r8s3
9	IFO 380	Super 25[s]	33.3	17	17	23	18	82.85	1.03	1:50	43	171	29	r9s1, r9s2
10	IFO 180	none	33.3	16	18	19	-	76.81	0.85	0	control	control	2	r10s1, r10s2, r10s3
11	IFO 180	Agma [a]	30	17	16	20	18	85.26	0.83	1:50	36	105	17	r11s1, r11s2, r11s3
12	IFO 180	Agma [a]	33.3	18	17	23	21	86.06	0.83	1:50	40	148	24	r12s1, r12s2, r12s3, r12s4, r12s5, r12s6
13	IFO 180	Super 25[s]	30	16	17	17	16	83.65	0.81	1:50	40	129	21	r13s1, r13s2, r13s3, r13s4
14	IFO 180	9500	30	18	17	17	19	77.62	0.85	1:50	35	101	21	r14s1, r14s2, r14s3, r14s4
15	IFO 180	Super 25[s]	33.3	18	17	22	19	75.61	0.84	1:50	34	106	45	r15s1, r15s2, r15s3, r15s4, r15s5
16	IFO 180	9500 [c]	33.3	18	17	21	17	78.82	0.87	1:50	35	106	84	r16s1, r16s2, r16s3, r16s4, r16s5, r16s6
17	IFO 120	9500 [c]	30	15	16	16	15	83.25	0.92	1:50	43	63	39	r17s1, r17s2, r17s3, r17s4, r17s5
18	IFO 120	9500 [c]	33.3	17	16	18	18	81.24	1.09	1:50	46	106	66	R18s1
19	IFO 180	9500 [c]	30	13	15	15	8	80.83	0.78	1:25	21	63	36	r19s1, r19s2, r19s3, r19s4, r19s5, r19s6
20	IFO 380	Super 25[s]	33.3	17	15	22	14	52.28	0.57	1:50	26	104	53	r20s1, r20s2, r20s3, r20s4, r120s5

a - Agma DR 379 dispersant s- Superdispersant 25 c- Corexit 9500 DOR_M – measured DOR calculated using % water surface covered by oil and quantity of dispersant sprayed

The approximate thickness of the actual patches of oil on the water surface in each test ("actual oil thickness") was determined using the flow rate of oil, oil spray swath width, bridge speed, discharge time, and the fraction of surface area covered by oil. The "thickness" of dispersant sprayed by the spray bar was estimated in a similar fashion. The time that the spray boom was in operation was recorded. The dispersant spray swath was 6 metres and the deck speed was 0.5 m/s. The dispersant flow rate divided by the spray swath and bridge speed provides an estimate of the thickness of dispersant reaching the surface.

The average oil thickness (total oil volume of oil discharged divided by the oil swath width and swath length) divided by the dispersant thickness gives the nominal DOR_N. The "actual oil thickness" divided by the dispersant thickness gives the measured DOR_M.

The nominal DORs achieved in the tests were somewhat larger (therefore more dispersant was applied than intended) than the target DORs, in most cases. Nominal DORs of between 1:20 and 1:46 were achieved for the targeted DORs of 1:50. Nominal DORs of between 1:16 and 1:25 were achieved for the 1:25 target DORs. The measured DORs, which provide the most accurate estimate of the amount of dispersant, actually contacting the oil, were much smaller than the nominal DORs due to the spotty nature of the oil slicks (therefore much less dispersant actually reached the oil than indicated by either the target or nominal DORs). The measured DORs for the 1:50 target tests ranged from about 1:100 to 1:195 (i.e., 1/2 to 1/4 of the target amount). The measured DORs for the 1:25 target tests ranged from about 1:65 to 1:100 (about 1/3 to 1/4 of the target amount).

The water temperature ranged between 15 and 18°C throughout the testing. Air temperatures ranged between 13 and 21°C. Detailed air temperature, wind velocity, wave height, wave frequency and bridge speed data were collected during each test. These data are available are available from the authors on request.

3.2 Wave Characterization

Wave amplitude and period were recorded during each test. These records were analyzed for average wave amplitude and period and the results are shown in Table 3-2.

Table 3-2: Measured Average Wave Amplitudes and Periods

Run Identifier	Wave Paddle Setting (cpm)	Average of All Bridge Data for Run		Analysis of Wave Height Data							
				Data Early in Test				Data Late in Test			
		CPM	Period (s)	Amplitude		Wave Period		Amplitude		Wave Period	
				Ave. (cm)	Std. Dev. (cm)	Period (s)	Std. Dev. (s)	Ave. (cm)	Std. Dev. (cm)	Period (s)	Std. Dev. (s)
1	35	34.6	1.73	19.4	2.1	1.83	0.12	14.1	7.5	1.89	0.23
2	35	34.4	1.75	18.4	4.3	1.98	0.14	15.4	8.6	1.88	0.21
3	33.3	32.4	1.86	16.8	3.1	1.77	0.01	17.3	6.2	1.84	0.12
4	30	29.1	2.06	16.4	3.8	2.09	0.17	11.1	1.5	2.04	0.10
5	30	28.7	2.09	14.4	1.7	2.07	0.11	6.5	1.4	2.06	0.18
6	30	28.9	2.08	11.8	4.4	2.01	0.14	17.6	2.1	2.07	0.10
7	30	29.2	2.05	13.6	3.2	1.85	0.13	13.6	4.0	1.95	0.12
8	35	32.9	1.82	17.8	4.6	1.65	0.11	20.3	5.9	1.88	0.12
9	33.3	33.1	1.81	17.0	6.9	1.76	0.11	14.7	5.8	1.78	0.16
10	33.3	32.6	1.84	22.8	2.7	1.82	0.08	20.8	5.6	1.83	0.09
11	30	28.7	2.09	10.1	2.8	2.09	0.12	10.8	2.0	2.09	0.18
12	33.3	33.0	1.82	15.0	5.6	1.60	0.12	20.6	3.8	1.80	0.09
13	30	29.2	2.06	13.2	2.0	1.96	0.14	13.2	4.3	2.05	0.18
14	30	28.8	2.09	13.0	3.6	2.03	0.11	12.2	2.0	2.08	0.10
15	33.3	33.3	1.80	14.0	6.4	1.82	0.19	16.0	4.1	1.72	0.10
16	33.3	33.4	1.80	16.3	5.1	1.72	0.12	16.5	4.6	1.70	0.10
17	30	29.1	2.06	14.4	5.3	1.94	0.15	15.7	4.8	1.99	0.13
18	33.3	32.9	1.82	17.0	7.1	1.63	0.13	16.0	5.8	1.76	0.16
19	30	29.1	2.06	10.2	3.0	2.06	0.21	10.7	4.5	2.05	0.26
20	33.3	33.5	1.79	15.6	5.1	1.85	0.21	16.7	5.3	1.74	0.13

The bridge operator set the wave paddle to the value shown in the second column of Table 3-2. Three settings were used during the tests: 30 cycles per minute (cpm), 33.3 cpm, and 35 cpm. In all cases the paddle stroke length was 3 inches (7.6 cm). The wave paddle frequencies recorded by the bridge data acquisition system were averaged over the length of each test. The average frequency and wave period determined from this data are recorded in columns 3 and 4 of Table 3-2. The wave height data recorded by the data acquisition system were also analyzed to determine the average wave heights and wave periods. The water height data includes considerable noise so only small segments of the data sets were analyzed in each run. Wave amplitude and period estimates were made using data segments from the beginning of each test and from the middle or end of each test. Noise in the data did not allow this analysis to be done at consistent elapsed times from test to test. The wave period data as recoded by the bridge (column 4) and as analyzed from the wave height data (columns 7 and 11) are very similar. Wave amplitude data varied considerably throughout each run and the values shown in Table 3-2 provide only a partial picture of the nature of the waves in each run. A detailed analysis of the waves is beyond the scope of this study, but some general observations can be made based on the basic wave data.

The wave amplitudes and periods reported in Table 3-2 have been further averaged for each of the three wave energy settings used in the testing. Table 3-3 shows these results. The average wave heights increase from 12.7 cm at the 30 cpm paddle setting to 17.1 cm for the 33.3 cpm setting. No breaking waves were present at the 30 cpm setting and occasional breaking waves existed at the 33.3 cpm setting. When the paddle frequency was increased to 35 cpm, the average wave amplitude only increased to 17.6 cm, but at the increased setting, breaking waves were common. A review of the wave data (see data sheets for run 1, 3 and 8 in bridgeData) for the tests where the high frequency waves were used shows a much wider variation in wave height than for the lower frequency tests. The high amplitude breaking waves are followed by much lower height waves. This results in an average wave height that is only marginally larger than the average value for the 33.3 cpm wave paddle setting. The wave period data, as calculated from the wave height data, is reasonable for the lower wave energies, but is quite different than the wave paddle setting for the high wave energy condition.

Table 3-3: Wave Heights and Periods at Used in Testing

Wave Paddle Setting		Average Wave Amplitude	Average Wave Period
(cpm)	period (s)	(cm)	(s)
30	2.0	12.7	2.03
33.3	1.80	17.1	1.76
35	1.71	17.6	1.85

3.3 Properties of Oils Used in Testing

Three fuel oils were used during the test program. IFO 380 and IFO 180 were the primary oils used in these experiments, as these were the oils used during the offshore trials in the UK. The IFO 120 tests were completed on the second visitor's day in wind conditions that normally would be considered too high for testing (the wind was gusting to 50 knots). The tests were completed primarily to show the attendees a successful dispersion. Additional amounts of IFO 180 and 380 were blended from locally available IFO380 and marine gas oil for the April 2005 supplemental tests. Basic physical properties of the test oils are shown in Table 3-4.

Table 3-4: Physical Properties of Fuel Oils

Oil Type	Density (kg/m^3) @20°C	Viscosity, Pa.s (cP)			
		@ 16°C		@ 50°C	
		@ 10 s^{-1}	@ 100 s^{-1}	@ 10 s^{-1}	@ 100 s^{-1}
IFO 380 (original)	0.983	7100	Na	314	324
IFO 380 (new)	0.988	6515	Na	296	344
IFO 380 (suppl. 2005)	0.954	7025	Na	Na	Na
IFO 180 - original	0.970	2075	1925	134	146
IFO 380 (new)	0.972	1645	1580	121	139
IFO 380 (suppl. 2005)	0.950	2410	NA	NA	NA
IFO 120 (original)	na	1145	1145	87.5	87.5

NA – not available

Two batches of the IFO 180 and IFO 380 oils were used in these tests. The original volumes prepared for the UK trials were not sufficient for both the sea trials and Ohmsett tests. The Exxon Mobil Fawley refinery prepared second batches of IFO 180 and 380 (new), using the same procedures as for the originals, to provide sufficient quantities for the Ohmsett work. Only the original oils were used in the at-sea tests. At Ohmsett the original oils were used for the early tests. Seven supplemental tests were completed in April 2005, using replacement oils blended for this purpose from locally obtained IFO 380 and marine gasoil. Properties of the custom-blended replacement oils (suppl. 2005) are also reported in Table 3-4.

3.4 Experimental Results: IFO 380: Tests #1 to #9 and #20

3.4.1 Control (No Dispersants)

The first test completed using IFO 380 (viscosity of 7100 cP at 16°C) was a control test with no application of dispersants. The purpose of the test was to evaluate the ability of the containment boom to hold oil in the test area and to establish how much of the oil would evaporate and naturally disperse over the test period. The basic test parameters and dispersant effectiveness estimates (measured, visual and UV fluorometry) for this, and all other tests, are provided in Table 3-5. Approximately 71 litres of oil were discharged in the test. The waves were set to the high energy or 35 cycles per minute (cpm) frequency. It was obvious from the absence of a visible cloud of oil in the water column that no significant natural dispersion of oil occurred at this wave energy over the duration of the test. The dispersant performance during this test was rated as 1.0 on the visual assessment scale. This behavior is clear in the video record that can be accessed via the following hyperlinks (r1s1, r1s2, r1s3, r1s4). At the end of the 35-minute test period, 51.5 litres of emulsion, with water content of 3.6%, was collected from within the boomed area. A total of 49.6 litres of oil was recovered or 70% of the oil initially spilled. No oil was seen exiting the boomed area or dispersing into the water column in this test. The fluorometry data taken during the tests, and shown in the following hyperlinks (1mRun1, 2mRun1), also did not detect an increase in hydrocarbons in the water column over the duration of the test. The 20 litres of oil unaccounted for in this control test is attributed to retention of the viscous oil on the containment boom that was not completely recovered at the end of the test. The quantity of oil unaccounted for in this control run was higher than the 0 to 20% loss experienced in control runs during previous studies (SLRoss and MAR 2003) where lighter oils were used. Retention of oil on the containment boom appeared to be more significant in this test due to the more viscous nature of the fuel oil.

Figure 3-1 provides a sequence of photos that show the initial oil slick, oil on the surface in the presence of breaking waves (no significant dispersion seen), and the use of fire monitors to herd oil to a collection zone at the end of the test.

3.4.2 IFO 380 Treated with Dispersants

A complete summary of the test conditions for all of the 2003 tests discussed in this section is provided in Table 3-1. Results of the 2003 tests are summarized in Table 3-5.

In test #2 the waves were set to 35 cpm, and Corexit 9500 dispersant was applied at 1:40 nominal DOR_N (1:50 $DOR_{T,}$ 1:180 DOR_M). This wave setting resulted in a steady occurrence of breaking waves through the test tank. The IFO 380 oil appeared to disperse quickly with the onset of breaking waves after the dispersant was applied. The following video links provide an overview of the test progression (r2s1, r2s1, r2s3, r2s4, r2s5). The observation team felt that this was a much better dispersion than was seen during the UK field trials (visual = 4.0 at Ohmsett versus 1.7 at sea) for the same oil-dispersant combination. It was concluded that the 35 cpm wave setting was generating considerably higher mixing energy than that encountered during the UK fieldwork. As a result, all but one of the subsequent tests was completed at lower wave energies.

Table 3-5: Summary of Ohmsett Test Results

Test #	Oil Type	Dispersant Type	Wave Frequency: Nominal, min^{-1}	Wave Frequency: Measured, min^{-1}	Volume of Oil Spilled, litres	Target DOR	Measured DOR	Dispersant Performance, Visual Method (a)			Dispersant Performance, Direct Measurement (b)	Dispersant Performance, UVF (c)	
								1 to 3 min	4 to 9 min	10 to 19 min		1 metre depth	2 metre depth
1	IFO 380	no disp.	35	34.6	70.8	no disp.	0	1.0	1.0	1.0	30	0	0
2	IFO 380	9500	35	34.4	98.1	1:50	1:180	1.2	3.0	4.0	58	18	8
3	IFO 380	9500	33.3	32.4	17.7	1:50	1:195	2.3	2.7	3.0	34	4	-5
4	IFO 380	9500	30	29.1	99.7	1:50	1:153	1.5	1.3	1.2	26	-4	0
7	IFO 380	9500	30	29.2	32.2	1:25	1:65	1.0	1.4	1.4	13	2	3
20	IFO 380	SD25	33.3	33.5	52.3	1:50	1:104	2.5	3.3	3.5	53	15	10
9C	IFO 380	SD25	33.3	33.1	82.9	1:50	1:171	2.0	2.3	2.3	29	5	3
5	IFO 380	SD25	30	28.7	71.6	1:50	1:144	1.2	1.0	1.0	18	1	1
6	IFO 380	SD25	30	28.9	61.9	1:25	1:67	1.1	1.2	1.1	20	0	0
8	IFO 380	Agma	33	32.9	78.8	1:50	1:100	1.7	2.0	2.0	16	5	5
10	IFO 180	no disp.	33.3	32.6	76.8	no disp.	0	1.0	1.0	1.0	2	0	0
16	IFO 180	9500	33.3	33.4	78.8	1:50	1:106	2.3	3.5	4.0	84	50	50
14	IFO 180	9500	30	28.8	77.6	1:50	1:101	1.0	1.0	1.2	21	2	1
19	IFO 180	9500	30	29.1	80.8	1:25	1:63	1.0	1.1	1.4	36	4	5
15	IFO 180	SD25	33.3	33.3	75.6	1:50	1:106	1.0	3.4	3.8	45	40	25
13	IFO 180	SD25	30	29.2	83.7	1:50	1:129	1.0	1.0	1.0	21	0	0
12	IFO 180	Agma	33.3	33.0	86.1	1:50	1:148	2.7	2.2	2.2	17	25	20
11	IFO 180	Agma	30	28.7	85.3	1:50	1:105	1.0	1.2	1.0	24	0	0

a. Visual dispersant effectiveness assessment method described in Table 1-1
b. Oil remaining on the water surface at the end of the tests is measured
c. By in-situ fluorescence at depths of 1 and 2 metres below the water surface based on difference in fluorometry output between third fluorometry pass and background pass.

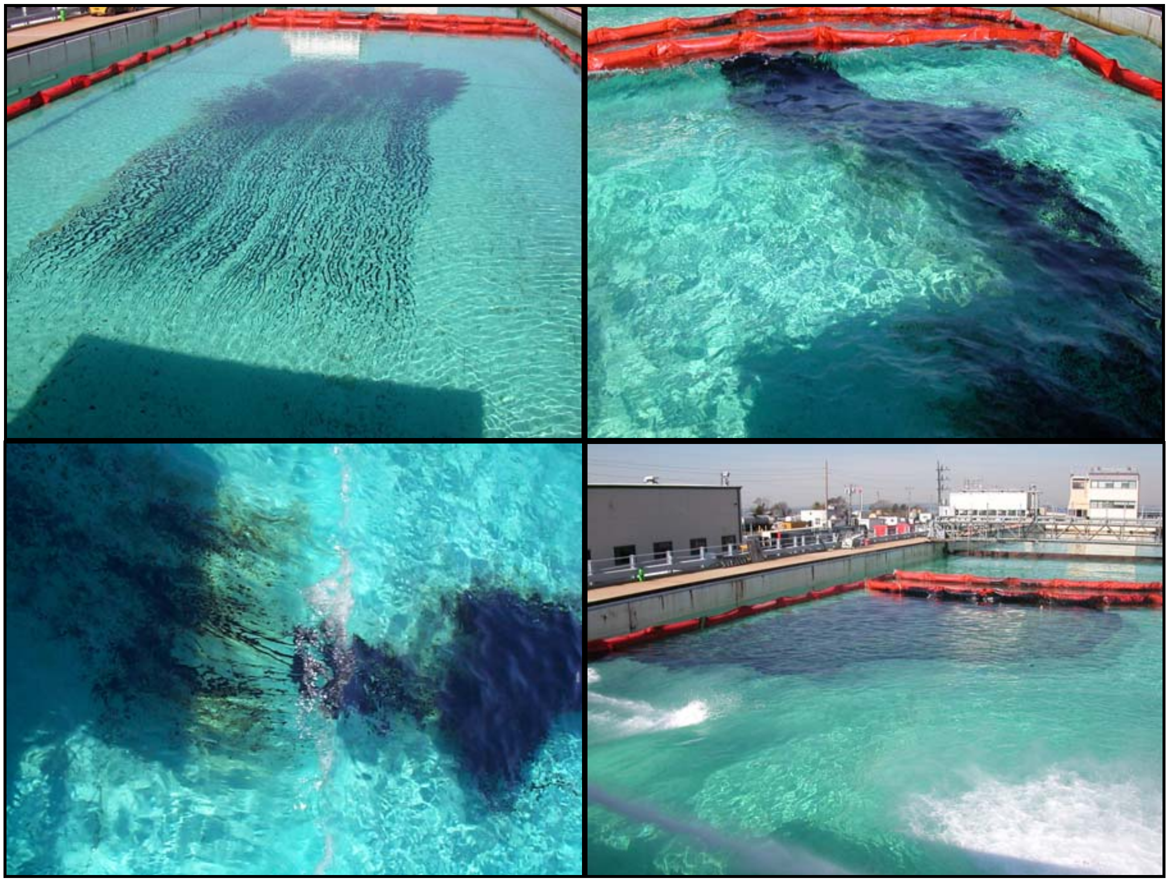

Figure 3-1: Photo Sequence for IFO 380 Control Test

In test #2, 98 litres of oil were spilled and 42 litres were recovered (after accounting for the 9.5% water content of the collected product). This indicates that about 58% of the oil dispersed. Observations made during the test and the video records, which show a very significant dark cloud of dispersed oil, would seem to indicate a more efficient dispersion, but the collection of a sizeable amount of oil at the end of this test indicates that the dispersant was not completely effective in dispersing the heavy fuel oil even in a high energy situation. The fluorometry data confirm the presence of oil in the water column, as seen in the following plots of the raw fluorometry readings at 1 and 2 metre water depths (1mRun2, 2mRun2). The limited amount of oil seen at the 2-metre depth may be because inadequate time had passed for the oil to disperse to the lower level. The concentration at the 1-metre level increased from pass three to pass four and the oil concentration was just starting to build at the 2-metre level on the fourth pass. The presence of significant oil in the water column and the 58% dispersion estimate does however show that IFO 380 oils can be dispersed at relatively low dispersant dosages (1:40 nominal, 1:180 measured) if the seas are relatively rough. Figure 3-2 shows still photos of early dispersion and final dispersed oil cloud for test #2.

Figure 3-2: Test #2 Early Dispersion and Dispersed Oil Cloud at End of Test

In tests 3, 9 and 20 the wave energy was lowered to the 33.3 cpm setting and dispersant was applied with the intention of achieving a nominal dispersant application of about 1:50.

In test #3 a small amount of oil was released (17.7 litres) due to the failure of the oil delivery pump. Because the oil appeared to completely disperse early on in the test (visual = 3.0), the run was carried out to completion. The raw fluorometry data for this run can be accessed via the following links (1mRun3, 2mRun3). A significant increase of dispersed oil was recorded at the 1 metre depth in this run, thus confirming the observed dispersion. The oil concentrations recorded at 2 metres show a steady decrease over the run duration.

In test # 9 the pump failed on two initial attempts and small amounts of oil were discharged and treated. The third attempt was successful and 82.8 litres of oil was discharged and sprayed. For this test the reported DORs and fluorometry data are based on the third oil discharge and spray conditions. The reported dispersant effectiveness estimate is based on the total amount of oil discharged in the three attempts and the amount of oil collected at the end of the overall test.

At the 33.3 cpm wave energy level, both Corexit 9500 (test #3, $DOR_{N\ 1:20}$; DOR_M 1:195) and Superdispersant 25 (test #9, DOR_N 1:43; DOR_M 1:171 and test #20, DOR_N 1:26; DOR_M 1:104) visually appeared to be effective in dispersing the IFO 380 to varying degrees (visual = 2.8 and 3.5, respectively). However, the estimated DE based on recovered oil quantities did not exactly match the observed behavior. In test #3 the Corexit 9500 dispersed 34% of the oil. Superdispersant 25 dispersed 30% in test 9 and 53% in test 20. The reduced effectiveness of Superdispersant 25 in test 9 versus test 20 could be due either to the smaller amount of dispersant reaching the oil in test 9 or a slightly less energetic wave energy during the early stages of test 9. In either event it would appear that the energy level – dispersant dosage combination for the IFO 380 oil was critical in these tests. More dispersant or a little more mixing was all that was needed to generate an improved outcome in test #20. The following hyperlinks provide visual records of the dispersion process in these three tests (test #3: r3s1, r3s2, r3s3, r3s4, r3s5; test #9: r9s1, r9s2; test #20: r20s1, r20s2, r20s3, r20s4, r120s5). The crow's nest video record for test 9 is not available due to a camera failure. The video clips for tests 3 and 20 clearly show dispersed oil in the water column. The presence of reddish-brown dispersed oil clouds in the video clips of test #20 is evidence of a smaller oil drop size distribution in this test and helps to confirm the better DE estimate for this test. The following hyperlinks show the fluorometry records for the three runs (1mRun3, 2mRun3, 1mRun9, 2mRun9, 1mRun20, 2mRun20). The fluorometry traces support the relative DE measurements in these three runs. Much more oil was detected in the water column in run # 20 when compared with Runs #3 and #9.

Figure 3-3 shows still photos of the final dispersed oil clouds for tests 3, 9 and 20. The quantity of oil discharged in test #3 was considerably less than in the other tests due to a malfunction of the pump during discharge. The surface oil seen in the test #9 photo is further evidence that the dispersant was not as effective in this test compared with the other two tests in this grouping.

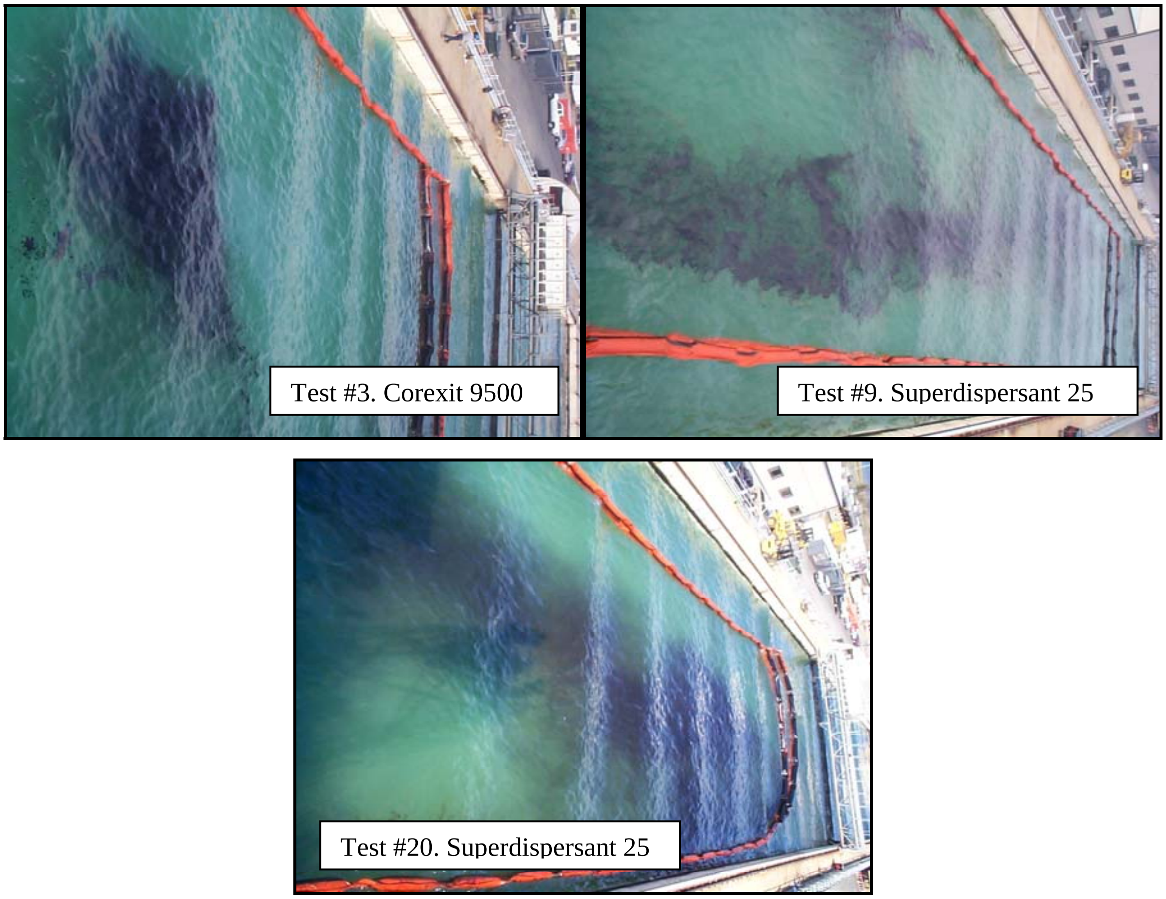

Figure 3-3: Photos of Tests 3, 9 and 20 at Ends of Tests

In tests #4 and #5 the wave energy was lowered to the 30 cpm setting and dispersant was again applied in an attempt to get a nominal dispersant application of about 1:50. Neither Corexit 9500 (test #4, DOR$_M$ 1:135) nor Superdispersant 25 (test #5, DOR$_M$ 1:127) achieved significant dispersion of the IFO 380 at this wave energy. The visual rankings for these tests were 1.2 and 1.0, respectively, indicating little or no dispersion. Based on the surface oil collected at the end of these tests dispersion efficiencies for test #4 and #5 were only 26% and 18%, respectively. The fluorometry results for these two tests can be seen using the following links (1mRun4, 2mRun4, 1mRun5, 2mRun5). These results confirm that no significant amounts of oil were dispersed into the water in these two tests. The reduced effectiveness is attributed to the lower wave energies used in these tests. The following hyperlinks provide visual records of the dispersion process in these two tests (test #4: r4s1, r4s2, r4s3, r4s4, r4s5, r4s6; test #5: r5s1, r5s2, r5s3, r5s4). Figure 3-4 shows still photos of the final slicks for tests #4 and #5.

Figure 3-4: Photos of Slicks at Ends of Tests 4 and 5

Tests #6 and #7 were completed with the same wave settings and dispersants as in tests #4 and #5, but the target dispersant dosage was doubled to 1:25. The purpose of these two tests was to determine if an increase in dispersant dosage would overcome the lack of mixing energy. Superdispersant 25 (test #6, DOR_M 1:67) dispersed 20% of the surface oil. This is not significantly different (DE 20% vs. 18%) when compared with the lower dose rate dispersion efficiency, which indicates that increasing the dispersant dosage did not improve the performance of the dispersant at this mixing level. Corexit 9500 (test #7, DOR_M 1:65) dispersed about 13% of the surface oil. Again, the higher dose rate did not improve the dispersant efficiency at this mixing level. The visual effectiveness assessments for these two runs were 1.1 and 1.3, respectively. The fluorometry records for these runs can be viewed using the following links (1mRun6, 2mRun6, 1mRun7, 2mRun7). These hyperlinks provide visual records of the dispersion process for these two tests (test #6: r6s1, r6s2, r6s3, r6s4, r6s5; test #7: r7s1, r7s2, r7s3, r7s4). Figure 3-5 shows still photos of the slicks for tests #6 and #7.

Figure 3-5: Photos of Slicks Near Ends of Tests 6 and 7

Figure 3-6: Surface Slick in Test # 8

A single test (test #8) was completed on IFO 380 oil with Agma DR 379 dispersant. The waves were set to 33.3 cpm and the dispersant was applied with a target DOR of 1:25. Even at this high energy and high DOR (nominal DOR_N of 1:25 and calculated actual DOR_M of 1:100) the IFO 380 was not dispersed in this test. Based on the amount of surface oil collected at the end of the test only 16% of the oil was dispersed. The oil appeared to break into large drops that quickly resurfaced and formed a thin slick that covered a large portion of the boomed area. This is evident in the following video clips and the photo of Figure 3-6 (r8s1, r8s2, r8s3). The fluorometry results shown in the following links show more oil in the water column than would be expected for this run based on the final DE estimate (1mRun8, 2mRun8). The high oil concentration may be due to the presence of large transient oil drops that quickly re-surfaced once the waves were stopped and oil collection began.

3.4.3 Summary

Results of tests with IFO 380 (viscosity = 7100 cP at test temperature of 16^{o} C) are summarized in Table 3-5. The control test with IFO 380 (no dispersant) at wave energy 35 CPM showed no obvious dispersion (visual effectiveness rank = 1.0). Seventy percent of the spilled oil volume remained on the water’s surface and was collected at the end of this test. Most of the 30% of the original oil that was not accounted for was likely attached to the containment boom and not recovered in the collection process. This amount of loss from the control was higher than the 0 to 20% losses from control runs in previous Ohmsett tests involving crude oil (SL Ross and MAR 2003). This higher degree of loss may be due to the more viscous oil used in these tests resulting in larger amounts of oil sticking to the containment boom.

Treating IFO 380 with Corexit 9500 at a DOR_T of 1:50 at a wave frequency of 35 CPM yielded a high level of effectiveness. The IFO 380 appeared to disperse completely and rapidly (visual effectiveness rank = 4.0). However, at the end of the test 40% of the spilled oil was collected for an overall DE estimate of 60%. Dispersion of IFO 380 with Corexit 9500 and 33.3 CPM wave setting appeared to be moderately rapid, but only partially complete (visual = 3.0), which was consistent with the lower measured effectiveness (measured DE = 34%). A further reduction in wave energy to 30 CPM resulted in very little visibly detectible dispersion (visual = 1.2) and measured dispersion similar to the control (measured DE = 26%).

Treatment with Superdispersant-25 (SD-25) at 33.3 CPM produced levels of dispersion that could not be distinguished from that of Corexit 9500 either visually (visual = 3.5 and 2.8) or by direct measurement (measured DE = 53% and 29%). The somewhat higher performance of SD-25 in run #20 than in run #9C may have been due to the higher DOR in run #20. Treatment with Agma DR 379 (Agma) at 33.3 CPM produced some apparent dispersion (visual = 2.0), but less than with Corexit 9500 or SD-25. Direct measurements showed that Agma was markedly less effective (DE = 16%) than Corexit 9500 or SD-25. Indeed the measured DE value for the Agma run was lower than for the control run, suggesting that, contrary to the visual appearance of dispersion, little or no actual dispersion took place.

At 30 CPM, SD-25 produced little dispersion visually (visual = 1.0) and by direct measurement (measured DE = 18%). Agma was not tested at 30 CPM.

3.5 Experimental Results: IFO 180: Tests #10 to #16

3.5.1 Control (No Dispersants)

The first test completed using IFO 180 (viscosity of 2075 cP at test temperature of 16°C) was a control test with no application of dispersants. The purpose of the test was to evaluate the ability of the containment boom to hold oil in the test area and to establish how much of the oil would evaporate and naturally disperse over the test period. Approximately 77 litres of oil were discharged in the test. The wave paddle was set to 33.3 cycles per minute (cpm) and 3 inch (7.6 cm) stroke. It was obvious, based on the absence of a visible cloud of oil in the water column that significant natural dispersion of oil did not occur at this wave energy over the duration of the test. The visual assessment of dispersant effectiveness for this test was 1.0. This behavior also is clear in the video records that can be accessed via the following hyperlinks (r10s1, r10s2, r10s3). At the end of the 35 minute test period about 57 litres of emulsion with a 0.8% water content was collected from within the boomed area. A total of 56.7 litres of oil were recovered or 74% of the oil initially spilled. Figure 3-7 shows the initial oil slick and the oil after being subjected to wind herding and waves (no significant dispersion seen). The fluorometry data collected during this run confirms that little or no oil dispersed in this run (1mRun10, 2mRun10). Although the waves appear to be quite calm in these photos and video clips the average wave amplitude in this test was the highest of all of the tests that used the 33.3 wave setting.

Figure 3-7: IFO 180 Control Slick (Test #1)

3.5.2 IFO 180 Treated with Dispersants

As was the case for the IFO 380 oil, the ability to chemically disperse IFO 180 was affected primarily by the level of wave energy applied during the test and less so by the type and amount of dispersant applied. Refer to Table 3-1 for a complete summary of the test conditions for all of the tests discussed in this section. Table 3-5 provides summarizes of the dispersant effectiveness estimates for the tests.

In tests #11, #13 and #14 dispersant was applied at a 1:50 DOR_T and the waves were set to the low energy level (30 cpm). In test #19 dispersant was applied at a target DOR_T of 1:25. None of the three dispersants effectively dispersed the IFO 180 oil at this wave energy. The visual effectiveness estimates for these 4 tests were 1.0, 1.0, 1.2, and 1.1, respectively. The video clips accessible via the following links illustrate the absence of dispersed oil in these runs with the exception of the r14S3 clip and the video clips for test #19 (test #11:r11s1, r11s2, r11s3; test #13: r13s1, r13s2, r13s3, r13s4; test #14: r14s1, r14s2, r14s3, r14s4; test #19: r19s1, r19s2, r19s3, r19s4, r19s5, r19s6). The small amount of dispersed oil visible in r14S3 was the result of the fluorometer hoses passing through the surface slick during the bridge transit and creating enough mixing to disperse the oil in the vicinity of the hoses. The dispersed oil seen in test #19's video clips is also due to the effect of the fluorometer hoses as well as the movement of the containment boom when the oil was herded to the east side of the tank. The localized dispersion due to turbulence caused by the instrument hoses did not occur at all in Run #11 with the Agma DR 379 dispersant, was observed only in the early stages of Run #13 with Superdispersant 25, and was evident throughout tests #14 and #19 with the Corexit 9500 dispersant. When collecting the oil at the end of these tests the oil from Runs #14 and #19 was easily dispersed if it was disturbed or mixed during collection. The oil at the end of tests #11 and #13 did not disperse when disturbed during the collection process. From these observations it would appear that Corexit 9500 was the only dispersant that maintained an influence on the dispersibility of the oil over the full duration of the test, but even with this dispersant not enough mixing energy was applied by the waves at the 30 cpm setting to cause significant dispersion. Doubling the dispersant dosage in test #19 did not appear to improve the dispersion process, but the movement of the containment boom at the side of the tank did disperse a considerable amount of oil in this test. This is likely the reason for the higher DE estimate for test #19 (36%) versus test #14

(21%). Figure 3-8 shows digital photos of the surface oil in these four tests after dispersant application and wave action.

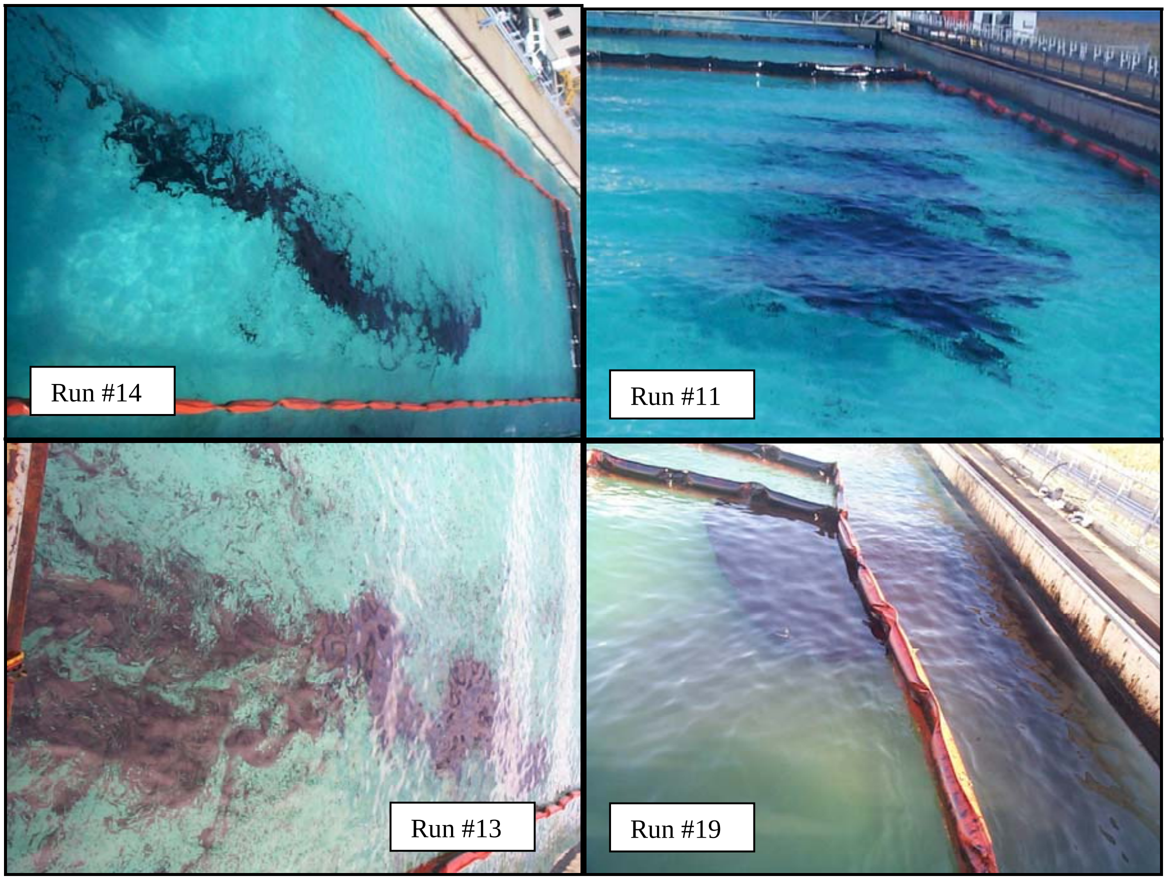

Figure 3-8: Surface Slicks in Runs #11, #13 and #14

The measured DOR$_M$ for these runs ranged from about 1:101 to 1:129 (1:63 for test #19) and the dispersant effectiveness estimates ranged from 17% to 21% (36% for test 19 with dispersion along containment boom) confirming the poor dispersion observed in all of these tests.

The fluorometry data for these runs can be accessed via the following links (1mRun11, 2mRun11, 1mRun13, 2mRun13, 1mRun14, 2mRun14, 1mRun19, 2mRun19). These data provide further support to the comments made above. With the exception of run #19 very little dispersed oil was detected by the fluorometers in these runs. The fluorometer data from run #19 confirms the higher DE estimate that has been attributed to additional mixing energy added by the side containment boom.

Tests # 12, #15, and #16 were repeats of the previous runs with the exception that the wave energy was increased to 33.3 cpm. Target DORs were again 1:50 in these runs. Measured DORs ranged from 1:148 to 1:101, so the amount of dispersant applied was very similar to the previous series of tests. A number of video clips of these runs can be accessed via the following hyperlinks (Agma: Run #12:r12s1, r12s2, r12s3, r12s4, r12s5, r12s6; Superdispersant: Run #15: r15s1, r15s2, r15s3, r15s4, r15s5; Corexit: Run #16; r16s1, r16s2, r16s3, r16s4, r16s5, r16s6). In all three of these tests significant amounts of the IFO 180 oil appeared to be dispersed. Visually it appeared as though Corexit 9500 dispersed the oil somewhat more completely that Superdispersant 25 and both of these products gave considerably better results than the Agma DR 379. Agma appeared to generate an initial dispersion of large drops that resurfaced and formed a large thin surface slick over most of the containment area (r12s4). These observations are confirmed by the measured dispersant effectiveness based on the collected oil. The Corexit 9500 run (test #16) had the highest measured effectiveness at 84%, followed by Superdispersant 25 with 45% and Agma DR 379 with 24%. The visual assessments also confirmed this trend with effectiveness assessments of 4.0 for Corexit, 3.8 for Superdispersant 25, and 2.2 for Agma.

The fluorometer data for these runs show a similar trend to the DE measurements. These data can be viewed via the following links (1mRun12, 2mRun12, 1mRun15, 2mRun15, 1mRun16, 2mRun16). The highest dispersant oil readings were recorded for the Corexit run #16, followed by the Superdispersant 25 run #15 and Agma DR379 run #12.

Figure 3-9 provides digital photos of these three tests near the end of each run.

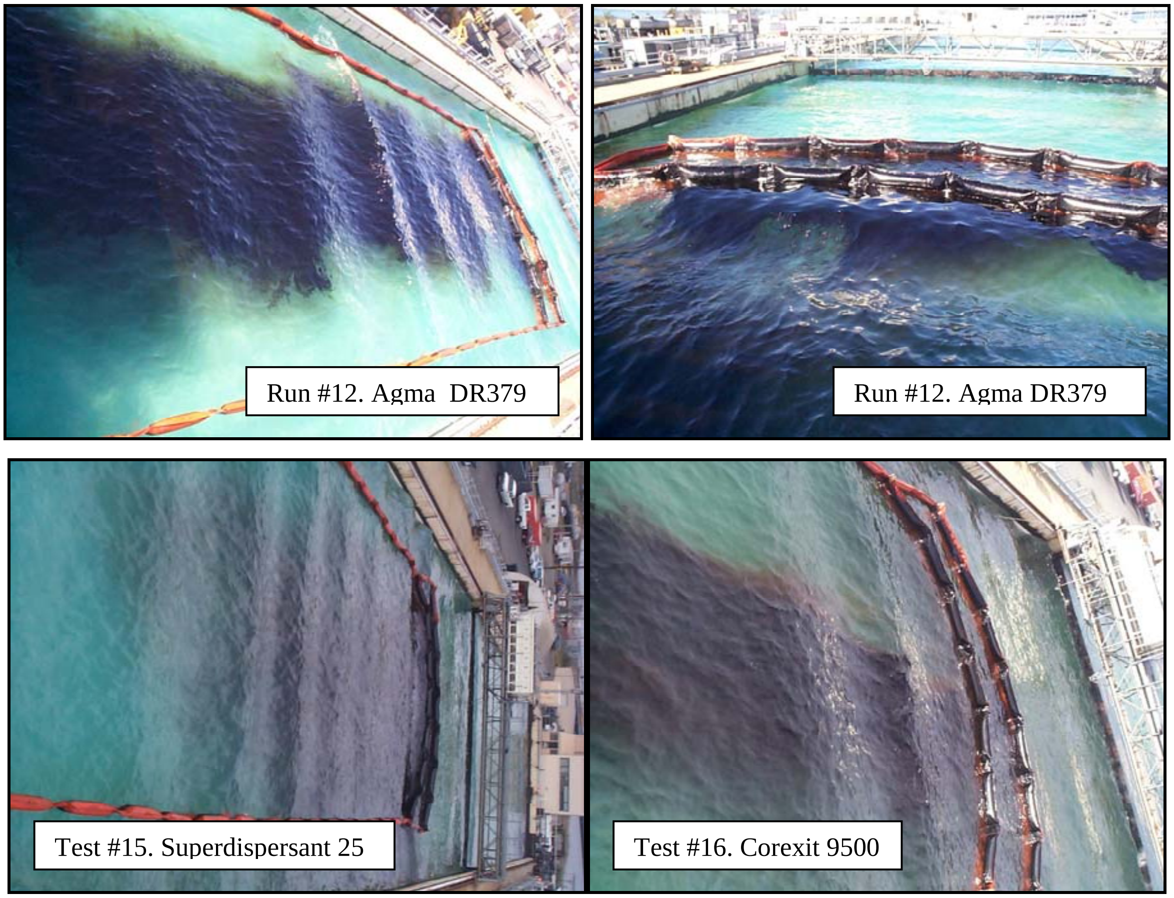

Figure 3-9: Tests #12, #15 and #16

3.5.3 Summary

Results of tests with IFO 180 (viscosity = 2075 cP at test temperature of 16^{o} C) are summarized in Table 3-5. No visible dispersion took place in the control test (no dispersant) completed with IFO 180 at 33.3 CPM (visual = 1.0), but direct measurement showed a measured loss of 24% of the originally spilled oil. As was the case with the control test with IFO 380, this oil loss in the control test is slightly higher than the values observed in earlier Ohmsett tests involving less viscous crude oils (SL Ross and MAR 2003). It is recommended that, whenever circumstances permit in future test programs, several replicate control runs be completed in order to better quantify these losses.

No testing was completed on IFO 180 at 35 CPM. At 33.3 CPM, treatment with Corexit 9500 at a nominal DOR of 1:50 produced apparent complete and rapid dispersion (visual = 4.0) and a measured DE of 84%. This showed that the IFO 180 was more dispersible than the IFO 380 at Ohmsett. This was consistent with the results of the at-sea tests (Lewis 2004). Reducing the wave frequency to 30 CPM resulted in a clear reduction in the performance of Corexit 9500 on IFO 180, with very little dispersion being detectable either visually (visual = 1.2) or by direct measurement (measured DE = 21%). Visually, SD-25 appeared to produce almost complete and rapid dispersion of IFO 180 at 33.3 CPM (visual = 3.8), but direct measurement showed that dispersion was less effective than the visual estimates suggested (measured DE = 45%). Effectiveness of SD-25 on IFO 180 could not be differentiated from effectiveness on IFO 380 based on these observations, due at least in part, to the large between-run variability in the SD-25/IFO 380 tests. Effectiveness of SD-25 could not be distinguished from that of Corexit 9500, based on visual observations, but measured levels showed that SD-25 was markedly less effective than Corexit 9500 in dispersing IFO 180. At 30 CPM the SD-25 test yielded no evidence of chemical dispersion either visually (visual = 1.0) or by measurement (measured DE = 21%), results that were similar to those with IFO 180 treated with Corexit 9500.

Based on direct measurement, treatment of IFO 180 with Agma produced no increase in effectiveness over the control run and no more dispersion when compared with the IFO 380 results. However, treatment of IFO 180 with Agma produced oil behaviour that observers identified as “slow and partial dispersion” as had been observed in the IFO 380 tests. Apparently, under test conditions, Agma produces little actual dispersion in either IFO 180 or 380. However, the visual appearance of the treated slick suggested to observers that dispersion was taking place. It is clear Agma performed less well than the other two products since both Corexit 9500 and SD-25 produced considerable levels of measurable oil dispersion at wave energies of 33.3 CPM.

3.6 Experimental Results: IFO 120: Tests #17 and #18

IFO 120 oil was used in Tests #17 and #18. These tests were completed under very high wind conditions and were included in the test program primarily so observers at the facility could see the test facility in use for dispersant effectiveness testing. Both tests had target DORs of 1:50 with Corexit 9500 dispersant. Test #17 was completed using the low wave setting of 30 cpm.

The 33.3 cpm wave setting was used in test #18. Video clips for these tests can be accessed via the following hyperlinks (Test #17: r17s1, r17s2, r17s3, r17s4, r17s5; test #18: r18s1). Video footage from the crow's nest was not taken during test #18 due to the extremely high and gusting winds during this test (gusts up to 50 mph were recorded). The IFO 120 oil was readily dispersed in both the low and moderate wave conditions. DE values of 39% for test #17 and 66% for test #18 were measured. At the moderate wave setting (test #18) the oil was herded to the east containment boom and dispersed near the boom. The final DE estimate for this run may not be reliable due to the additional mixing imparted by the boom movement. However, the DE for Run #18 should be as good or better than test #17 due to the higher wave energies in this test. The fluorometry data collected during these tests can be seen via the following links (1mRun17, 2mRun17, 1mRun18, 2mRun18). These data follow the same trend as the DE results with significantly higher dispersed oil readings in run #18.

Figure 3-10 shows a photo of the successful dispersion of the IFO 120 in the low wave energy conditions (first photo) and the dispersion of the oil at the east boom in test #18.

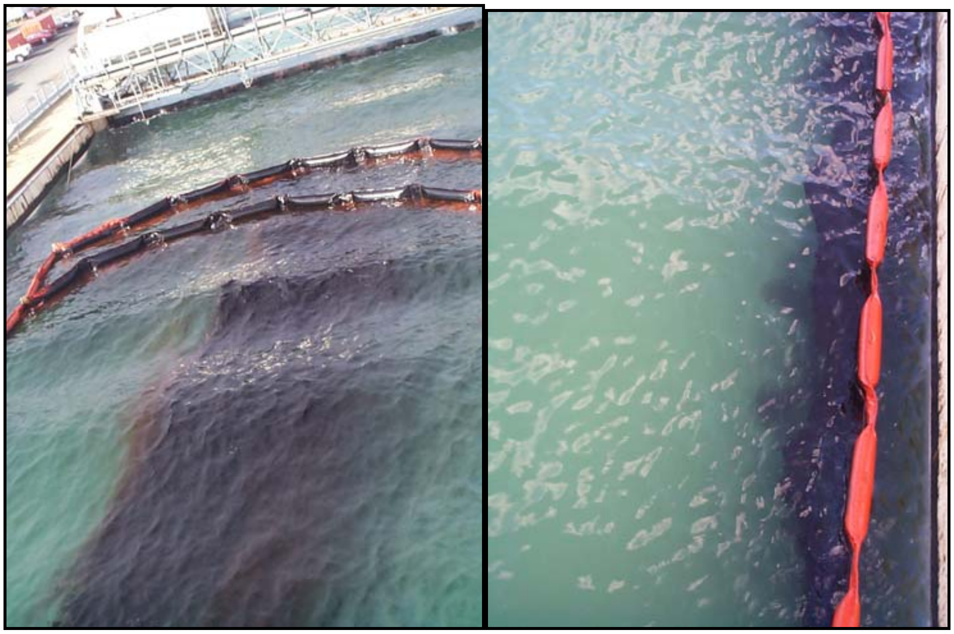

Figure 3-10: Photos of Dispersion in Tests #17 and #18

3.7 Oil Residue Properties

The oil remaining in the containment boom at the end of each test was collected for volume and density determination. Table 3-6 summarizes these data.

Table 3-6: Change in Oil Properties During Tests

Test #	Fresh Oil			Collected Oil				
	Oil Type	Density (kg/m^3)		DE (%)	Volume of Emulsion (litres)	Water Content of Emul. (%)	Volume of Oil (litres)	Density @ 26°C (kg/m^3)
		@ 20°C	@ 26 °C					
1	IFO 380	985	970	30	51.48	3.6	49.63	981
2	IFO 380	985	970	58	45.05	9.5	40.77	979
3	IFO 380	985	970	34	12.87	9.5	11.65	980
4	IFO 380	985	970	26	74.95	1.6	73.75	975
5	IFO 380	985	970	18	60.19	2.4	58.74	977
6	IFO 380	985	970	20	49.97	1.1	49.42	973
7	IFO 380	985	970	13	28.01	0.3	27.93	972
8	IFO 380	985	970	16	68.51	3.6	66.05	973
9	IFO 380	985	970	29	82.90	5.05	78.71	975
10	IFO 180	971	957	26	57.16	0.8	56.70	964
11	IFO 180	971	957	17	73.06	2.7	71.08	965
12	IFO 180	971	957	24	69.27	5.8	65.25	967
13	IFO 180	971	957	21	67.76	2.8	65.86	966
14	IFO 180	971	957	21	61.32	0.2	61.20	963
15	IFO 180	971	957	45	46.56	10	41.90	na
16	IFO 180	971	957	84	14.38	14	12.37	966
17	IFO 120	na	na	39	51.48	0.6	51.17	na
18	IFO 120	na	na	66	30.66	9	27.90	na
19	IFO 180	971	957	36	51.48	0.2	51.38	960
20	IFO 380	985	970	53	27.25	9	24.80	974

na- not available

As would be expected, the densities of the oils increased over the duration of the tests. Complete fresh and weathered property data are not available for these oils so an estimate of the amount of oil lost through evaporation cannot be made.

3.8 Results of Supplemental Tests (April 2005)

Seven supplemental tests were completed in April 2005, using replacement oils blended for this purpose from IFO 380 and marine gasoil. Test conditions and results are reported in Table 3-7 and are reported with results of 2003 tests in Table 3-8.

Replicate control (no dispersant) runs with IFO 180 in 33.3-cpm waves produced no visual evidence of dispersion. When the oil remaining at the end of the tests was collected, approximately 96 and 84 percent of the discharged oil was recovered, leaving 4 and 16 percent of the discharged oil unaccounted for. IFO 180 tested with Corexit 9500 at a DOR of 1:25 at a wave frequency of 33.3 cpm produced high levels of effectiveness based on both visual assessment methods (visual 3 to 4) and direct measurement (only 5 and 14% of oil remained at the end of the test.) IFO 380 tested with Corexit 9500 (DOR of 1:25) in 33.3-cpm waves yielded a high level of effectiveness both visually (visual = 3 to 4) and in terms of oil recovered (15% oil recovered at the end of the test). IFO 180 treated with Corexit 9500 and tested in non-breaking waves (waves at 30 cpm) yielded little or no visual evidence of dispersion in the central parts of the slick at any time during the test. The amounts of oil collected at the end of the tests (50 and 69% of the oil recovered) appear to be significantly less than in the controls.

Table 3-7: Supplemental Dispersant Effectiveness Tests on Heavy Fuel Oil at Ohmsett [a]

Test #	Oil Type	Disp. Type	Wave Freq (cpm)	Water Temp °C	Oil Temp °C	Disp. Temp °C	Oil Volume (litres)	Target DOR_T	Measured DOR_M	DE (%)	Visual Assessments of Dispersant Effectiveness [b]		
											0 to 4 min	4 to 10 min	11 to 20 min.
S6	IFO 380R	1:25	33.3	56F	65F	55F	72.7	1:25	1:21	85	1	4	2
S1	IFO 180R	Control	33.3	54F	68F	na	74.6	0	0	4	1	1	1
S2	IFO 180R	Control	33.3	54F	62F	na	82.7	0	0	16	1	1	1
S5	IFO 180R	1:25	33.3	57F	69F	54F	84.5	1:25	1:7	95	3	4	1
S7	IFO 180R	1:25	33.3	55F	53F	52F	74.3	1:25	1:23	86	4	3	3
S3	IFO 180R	1:25	30	54F	54F	54F	82.3	1:25	1:9	31	1	1.5	1
S4	IFO 180R	1:25	30	55F	60F	57F	80.2	1:25	1:9	50	1.5[c]	1.5	1.5

a. All tests used reblended IFO 180 or 380 (referred to as IFO 180Ror IFO 380R) as described in the text. All dispersant tests used Corexit 9500 at stated dispersant-to-oil-ratios.
b. Based on Lewis four-point scale (Lewis 2004)
c. At least some of the visible dispersion was due to turbulence caused by interactions with waves and boom and boom connectors.

Table 3-8: Summary of Ohmsett Tests in 2003 and 2005 [a]

Test #	Oil Type	Dispersant Type	Wave Frequency: Nominal, min^{-1}	Wave Frequency: Measured, Min^{-1}	Volume of Oil Spilled, litres	Target DOR	Measured DOR	Dispersant Performance, Visual Method [b]			Dispersant Performance, Direct Measurement [c]
								median	min	max	
1	IFO 380	no disp.	35	34.6	70.8	no disp.	0	1	1	1	30
2	IFO 380	9500	35	34.4	98.1	1:50	1:180	4	4	4	58
3	IFO 380	9500	33.3	32.4	17.7	1:50	1:200	3	2	4	34
2005-6	**IFO 30**	**9500**	**33.3**	**34**	**72.7**	**1:25**	**1:21**	**3**	**3**	**4**	**84**
4	IFO 380	9500	30	29.1	99.7	1:50	1:150	1	1	1.5	26
7	IFO 380	9500	30	29.2	32.2	1:25	1:65	1	1	2	13
20	IFO 380	SD25	33.3	33.5	52.3	1:50	1:100	3.5	3	4	53
9C	IFO 380	SD25	33.3	33.1	82.9	1:50	1:170	2.75	2	3.5	29
5	IFO 380	SD25	30	28.7	71.6	1:50	1:140	1	1	1	18
6	IFO 380	SD25	30	28.9	61.9	1:25	1:65	1	1	1.2	20
8	IFO 380	Agma	33	32.9	78.8	1:50	1:100	2	2	2	16
10	IFO 180	no disp.	33.3	32.6	76.8	no disp.	no disp.	1	1	1	26
2005-1	**IFO 180**	**no disp**	**33.3**	**34**	**74.6**	**no disp**	**no disp**	**1**	**1**	**1**	**4**
2005-2	**IFO 180**	**no disp**	**33.3**	**34**	**82.7**	**no disp**	**no disp**	**1**	**1**	**1**	**16**
16	IFO 180	9500	33.3	33.4	78.8	1:50	1:100	4	4	4	84
2005-5	**IFO 180**	**9500**	**33.3**	**34**	**84.5**	**1:25**	**1:7**	**4**	**4**	**4**	**94**
205-7	**IFO 180**	**9500**	**33.3**	**34**	**74.34**	**1:25**	**1:23**	**4**	**4**	**4**	**86**
2005-3	**IFO 180**	**9500**	**30**	**30**	**82.3**	**1:25**	**1:9**	**1**	**1**	**1.5**	**31**
2005-4	**IFO 180**	**9500**	**30**	**30**	**80.2**	**1:25**	**1:9**	**1.5**	**1**	**1.5**	**50**
14	IFO 180	9500	30	28.8	77.6	1:50	1:100	1.2	1.2	1.2	21
19	IFO 180	9500	30	29.1	80.8	1:25	1:60	1	1	1.25	36
15	IFO 180	SD25	33.3	33.3	75.6	1:50	1:100	3.5	3.5	4	45
13	IFO 180	SD25	30	29.2	83.7	1:50	1:130	1	1	1	21
12	IFO 180	Agma	33.3	33.0	86.1	1:50	1:150	2	2	2.5	24
11	IFO 180	Agma	30	28.7	85.3	1:50	1:100	1	1	1	17

a. Supplemental tests (2005) are labeled and printed in bold.
b. Visual dispersant effectiveness assessment method described in Lewis (2004).
c. Oil remaining on the water surface at the end of the tests is measured

4 Discussion

4.1 Initial Scoping Tests

Given the apparent influence of mixing energy on dispersant performance in the UK trials (Lewis 2004), initial scoping tests were performed at Ohmsett at three wave energy settings, 35-cpm, 33.3 cpm and 30 cpm, to identify the wave frequency that yielded the effectiveness most similar to the at-sea tests. Scoping tests used a combination of oil (IFO 380), dispersant (9500) and DOR (nominal DOR of 1:50) that had produced low to moderate dispersant performance at sea (visual = 2.0, see Test 25 in Table 1-2). Effectiveness was assessed visually, as in the at-sea tests. The three wave settings used in these tests were selected because they are commonly used in other Ohmsett testing. Asher (2005) characterized these wave conditions in a separate study. The 35-cpm wave setting was used in this study because the setting had been used routinely in earlier dispersant tests (e.g., SL Ross 2000b, SL Ross and MAR 2003, 2005). This setting produced frequent breaking waves. The 33.3 cpm wave setting produced less frequent breaking waves than did 35 cpm. The 30-cpm wave setting produced smooth, regular waves that did not break.

The 35-cpm test produced a much higher level of dispersion (visual = 4.0) (Test 2, Table 4-1) than had been observed at sea (See test 25 in Table 1-2.) The test at 33.3 cpm produced less dispersion than 35 cpm (visual = 3.0), but dispersion was still greater than at sea. The 30 cpm-test produced no visually detectible effectiveness (visual = 1.0), a result that was less than at sea. Clearly the 35-cpm waves used routinely in dispersant testing at Ohmsett produced levels of dispersion that were greater than in at-sea in winds of 7 to 14 knots. The Ohmsett wave frequency that would produce effectiveness levels similar to at sea for IFO 380/9500/DOR=1:50 appeared to be less than 33.3 cpm, but greater than 30 cpm. Based on the results of these scoping tests, all subsequent tests in the project were completed at both 30 and 33.3 cpm, in order to bracket the apparent at-sea conditions. In addition, due to the apparently high level of effectiveness produced at the DOR of 1:50, most subsequent tests in October 2003 used a nominal DOR of 1:50 or less rather than the 1:25 DOR used at sea, in order to minimize the contamination of tank water with dispersant. Tests using a DOR of 1:25 were completed in April 2005.

Table 4-1: Results of Scoping Tests on IFO 380 at a Nominal DOR of 1:50

Test Location	Dispersant Type	Measured DOR	Ohmsett Wave Frequency, cpm	Dispersant Performance (Visual Method)		
				Median	Min.	Max.
At Sea	Corexit 9500	1:110	Na	2.0	1.0	2.0
Ohmsett	Corexit 9500	1:180	35	4.0	4.0	4.0
Ohmsett	Corexit 9500	1:195	33.3	3.0	2.0	4.0
Ohmsett	Corexit 9500	1:150	30	1.0	1.0	1.5
Ohmsett	No dispersant	No	35	1	1	1
Standard conditions at Ohmsett include 75 to 100 litres of oil, laid down as a slick 5 m wide by 20 m long, sprayed immediately with dispersant at a known application rate, then agitated for up to 40 minutes.						

4.2 Overview of Results

The results of both the October 2003 and April 2005 tests are reported in Table 3-8.

4.2.1 Control Tests

In these and other recent Ohmsett tests, the difference between the amount of oil discharged and collected was termed dispersant effectiveness (DE), though it is recognized that this difference is actually made up of oil lost by natural dispersion, evaporation, clingage on the boom, and inefficiencies in the collection process, as well as by chemically augmented dispersion. The control tests (no dispersant) provide an estimate of amounts of oil lost by “natural dispersion”, evaporation, clingage to the boom, etc. and provided a useful baseline against which chemically augmented dispersion can be compared. In the October 2003 tests, the control with IFO 180 at wave energy 33 cpm produced no dispersion visually (visual = 1.0), as had been observed at sea. At the end of the test, 74% of the original oil volume was recovered. The test with IFO 380 tested at 35 cpm yielded visual = 1.0 and a recovery efficiency of 70%. Recovery rates in controls for other studies have been variable, ranging from 78 to 120% in one earlier (SL Ross and MAR 2003) and 70 to 89% in more recent work (SL Ross and MAR 2005). Replicate control tests with IFO 180 completed in April 2005 also produced no dispersion visually, but oil recovery amounts were somewhat higher (96% and 84%) than in earlier studies.

4.2.2 Experimental Tests with IFO 180

In general, of the three dispersants tested, Corexit 9500 produced the highest level of dispersion in the at-sea tests and in Ohmsett tests (based on direct measurement). For this reason results with Corexit are generally presented first here and results with other products are compared with it.

Corexit 9500 applied at a nominal DOR of 1:50 and tested in 33.3 cpm waves produced complete and rapid dispersion of IFO 180 (visual = 4.0). At the end of the test only 16% of the oil was recovered, far less than in controls (DE = 84%) (Table 3-9.) Replicate tests with a higher DOR of 1:25 in April 2005 produced identical results visually and recovery rates of only 6 and 14% (DE values of 94 and 86%.) These results were consistent with those of the at-sea tests that produced moderate to rapid dispersion (visual = 3 to 4). Effectiveness declined to near control levels at a wave frequency of 30 cpm (visual = 1.0 to 1.2). However, in some tests the amounts of oil lost from the slick during the tests in 30-cpm waves were slightly higher than in controls (DE = 21% and 36%), suggesting that some chemically augmented dispersion was occurring. Replicate tests in April 2005 confirmed that there was no visible evidence of dispersion, even though DE values (DE = 31 and 50%) were somewhat greater than in controls. The inconsistency between visual observations and direct measurements in these tests may be due to an artifact of the test apparatus. After treatment with dispersant, no dispersion whatsoever was visible where the slick was agitated gently by the regular, non-breaking waves. Clearly, however, the oil was highly susceptible to dispersion: dispersion was commonly observed during the test in areas of turbulence created by sampling apparatus being drawn through the slick, and again after the test where patches of treated, but undispersed oil (evidently still containing much dispersant) were agitated with tools during the post-test collection process. These dispersion losses may account for the discrepancy between visual observations and oil recovery in these low-energy tests.

Visually, the dispersant product Superdispersant 25 (SD 25) produced higher levels of dispersant performance at Ohmsett than at sea. At Ohmsett, SD 25 appeared to produce almost complete and rapid dispersion of IFO180 at 33.3 cpm (visual = 3.5) and direct measurements too showed significant effectiveness (DE = 45%.) Effectiveness of SD-25 could not be distinguished from 9500 by visual means, but direct measurement suggested it to be somewhat less effective than 9500 as had been observed with IFO 180 at sea. The Agma dispersant product appeared to produce some effectiveness visually at 33 cpm (visual = 2.2), as had been observed at sea, but direct measurements showed no increase in dispersion over the control (DE = 17). At 30 cpm neither SD-25 nor Agma yielded any apparent dispersion either visually (visual = 1.0) or by measurement.

4.2.3 Experimental Tests with IFO 380

Results with IFO 380 contrasted somewhat with IFO 180. The control test (no dispersant) with IFO 380 in 35 cpm waves showed no dispersion (visual = 1.0, DE = 30%) (Table 3-9.) The DE in the control test was consistent with the DE with IFO 180 in this project and with other oils in other projects (SL Ross and MAR 2005). Corexit 9500 applied at a nominal DOR of 1:50 and tested in 35 cpm waves appeared to produce “very rapid and complete dispersion” visually (visual = 4.0) and effectiveness much higher than in controls based on direct measurement (DE = 60%). The test at 33.3 cpm with 9500 yielded somewhat ambiguous results in that “moderately rapid dispersion” was observed visually (visual = 3), but direct measurement suggested that little dispersion was actually occurring (DE = 34%). Post-test analysis showed that the actual amount of oil discharged in this test was considerably less than in other tests (only 17.7 litres rather than 75 to 100 litres) and the actual DOR was also low, approximately 1:200 rather than 1:50, so the test was repeated in April 2005. In the 2005 test, dispersion performance was high, both visually (= 3 to 4) and by measurement, with only 14% of the oil recovered at the end of the test. As discussed below, this dispersant performance was higher than in the at-sea tests conducted at the lower wind speeds of 7 to 10 knots, but consistent with results of the at-sea test at higher wind speed, 11 to 14 knots. As in the IFO 180 tests, effectiveness of 9500 on IFO 380 declined to control level (visual = 1.2, DE = 26%) at 30 cpm.

The product SD 25 produced higher levels of dispersant performance at Ohmsett than at sea with the IFO 380. SD 25 produced moderately rapid dispersion at 33.3 cpm (visual = 3.5 and 2.8, DE = 53% and 29%) even at relatively low doses of 1:100 to 1:170. Performance of SD 25 could not be distinguished from 9500 either visually or by direct measurement. Agma appeared to produce some dispersion visually with IFO 380 at 33.3 cpm (visual = 2.0), but direct measurements showed little dispersion (DE = 16%). SD 25 was ineffective at 30 cpm (visual = 1.0, DE = 18%). Agma was not tested at 30 cpm.

4.3 Comparison of Visual, Fluorescence and Direct Measurement Methods

4.3.1 Comparison of Visual and Direct Measurements

Dispersant effectiveness measurements made by visual means were compared with direct measurements for all of the October 2003 tests in Figure 4-1. At Ohmsett, the designation “no obvious dispersion” or visual = 1 was applied to tests in which there was no visible evidence whatsoever of slick shattering into droplets by cresting waves. As described above, all control runs produced no visual evidence of dispersion (visual = 1.0). In these controls, measured losses ranged from 4 to 26% in IFO 180 tests and the one IFO380 control was 30%. These are within the range of control values for other recent Ohmsett tests with crude oils (11 to 30%, SL Ross and MAR 2003, 2005). In general, dispersant tests that produced little effectiveness visually (visual = 1.0 to 1.4) also produced DE values (DE = 13 to 26) similar to the controls, with the exception of two tests that produced losses of 36 and 50%. As discussed above, elevated DE values in these tests may result from the fact that the treated oil was highly susceptible to dispersion by handling during collection. As a rule, however, tests yielding visual effectiveness ratings of 1.0 to 1.4 produced levels of measured dispersion that were similar to controls.

The designation “slow and/or partial dispersion” or visual = 2 was applied to tests in which dispersant spraying produced little apparent change in the behavior of the oil slick or the amount of oil in it, even though dispersed oil droplets were occasionally observed caused by cresting waves. Tests ranked as visual = 1.5 to 2.4 by observers produced measured DE values of 18 to 26%, values that were indistinguishable from runs ranked as visual = 1 to 1.4. Apparently, the limited dispersion observed in these tests was very minor indeed and/or temporary. This suggests that the visual = 2 category, as applied at Ohmsett (and perhaps in at-sea tests), is prone to false positive errors.

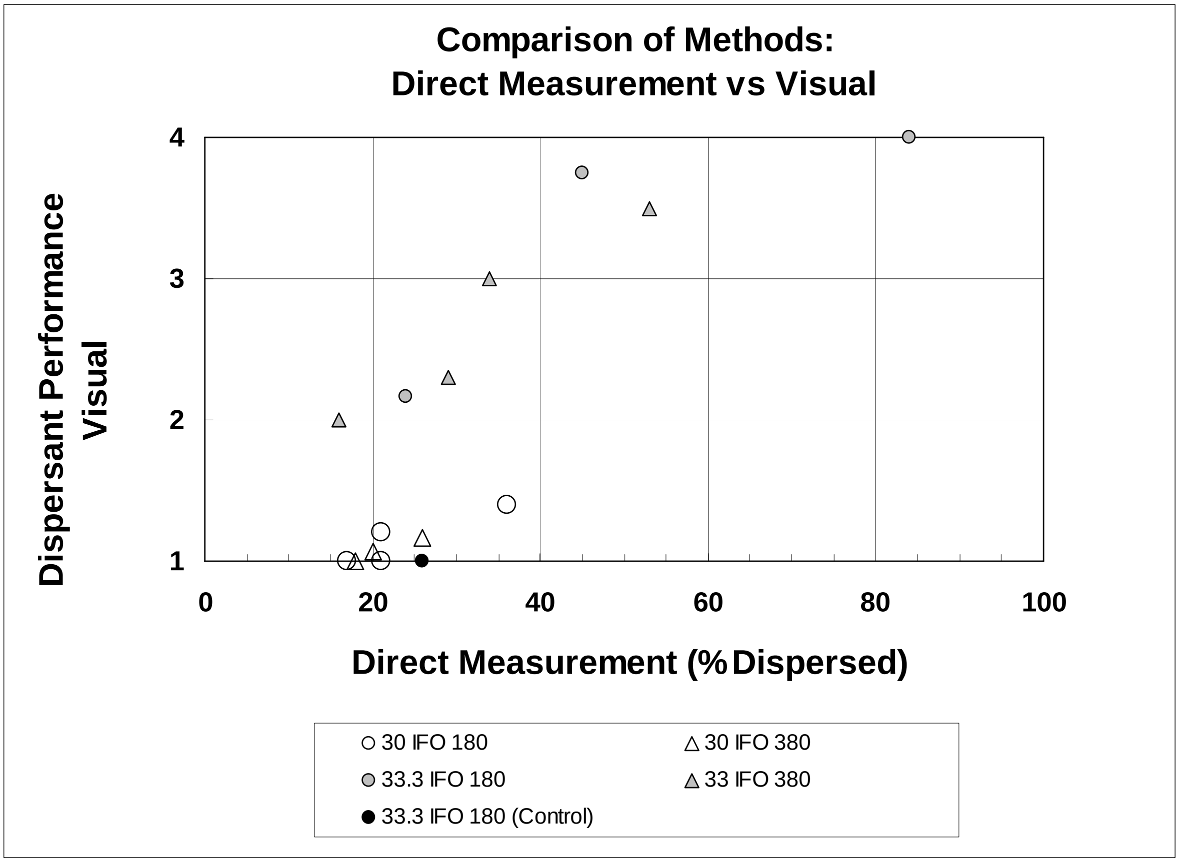

Figure 4-1: Comparison of Effectiveness Assessment Methods in Ohmsett Tests

Tests ranked "moderately rapid dispersion" or visual = 3, were characterized by extensive shattering of slicks into fine droplets by breaking waves and appearance of extensive brown-black clouds of dispersed oil droplets in the water column, while large sections of thick oil slicks remained clearly visible throughout the test. Tests ranked as visual = 2.5 to 3.4 produced measured DE values in the 30 to 40% range, slightly higher than the controls and former two dispersant performance categories.

Finally, "rapid and complete dispersion" or visual = 4 was used to describe tests in which slicks were apparently quickly and completely shattered into brown-black clouds of fine dispersed oil droplets by the first few cresting waves passing through the slicks, leaving no patches of thick oil apparent on the surface. Visual = 3.5 to 4 tests produced DE values ranging from 45% to 95% and therefore clearly reflected high levels of dispersion performance. However, the descriptor “complete dispersion” was not accurate for some of the spills in this category. In some tests, although dispersion appeared (visually) to be rapid and complete early in the test, as the test progressed small amounts of undispersed oil reassembled into patches of thick oil and accumulated on the boom, showing that dispersion was not complete. A ranking 3.5 to 4.0 always reflected a high level of dispersion effectiveness, but it also corresponded to a broad range of measured levels of effectiveness (DE = 45% to 94%) and it was not possible to visually distinguish different levels of dispersion within this range.

4.3.2 Fluorometry Assessments versus Direct Measurements

Raw fluorescence results were compared with measured dispersant performance in Figure 4-2. Four fluorometry passes were completed during each control and dispersant test. One “background pass” was completed as the oil slick was discharged and sprayed with dispersants, but before any dispersion had a chance to occur. Following the “background pass” three operational passes were completed at: 2 to 5 minutes, 5 to 10 minutes and 10 to 15 minutes into the test. Water was sampled continuously at depths of 1 and 2 metres below the surface and monitored for concentrations of fluorescing hydrocarbons. Results of all runs are reported in Appendix 2. These data were summarized to simplify the task of correlating the fluorometry output with direct measurements. For each test the fluorometry curves during the third pass for both depths were evaluated and the average levels of fluorescence were determined for the period when the sampler was clearly in the main part of dispersed oil cloud. The difference between the two-metre depth-average value and the background fluorescence was taken as the indicator of fluorescence for the test. The data for the 2-metre depth of the third fluorometry pass was used because these

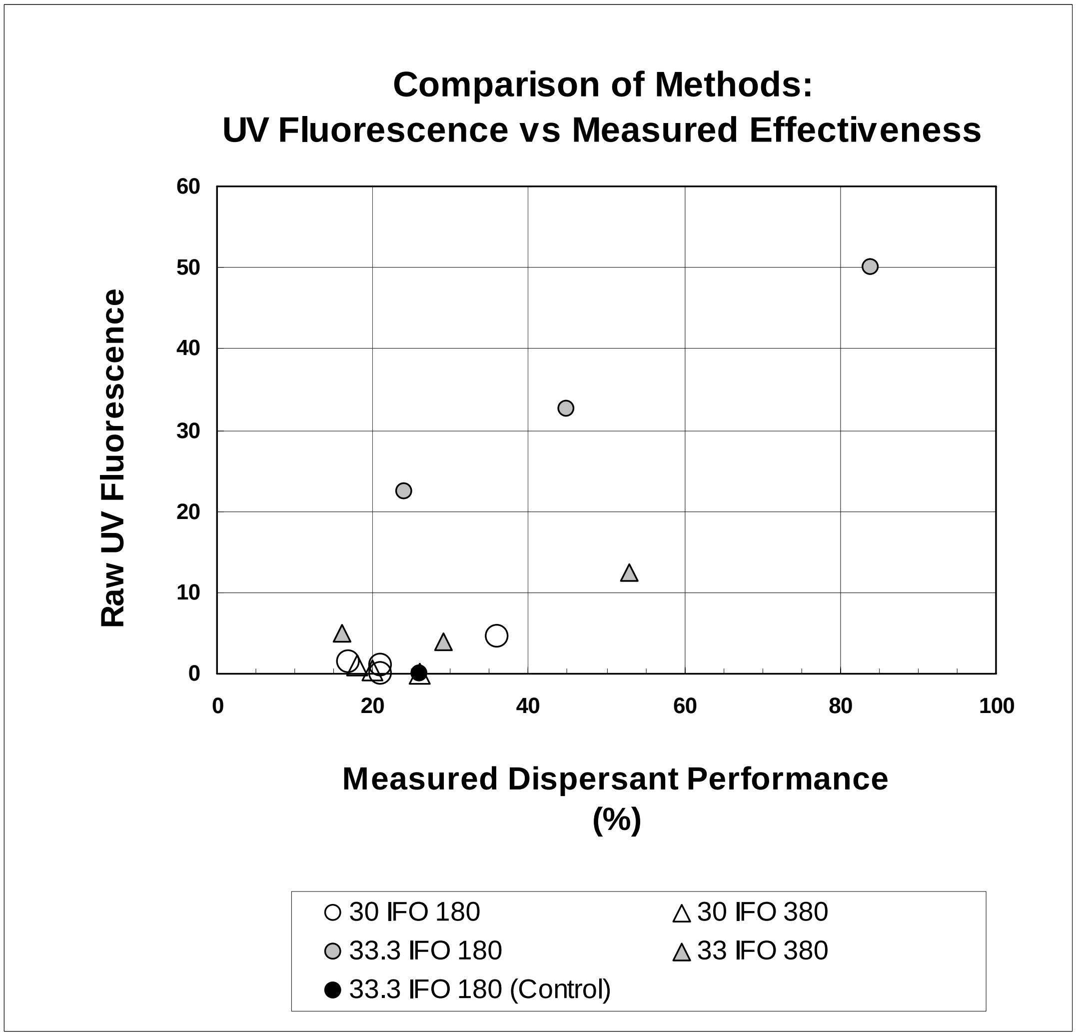

Figure 4-2: Comparison of UV Fluorescence with Measured Dispersant Effectiveness

data consistently showed the least fluctuation. These data are recorded in Table 3-5 and plotted in Figure 4-2.

The results in Figure 4-2 show that in the control test at 33.3 CPM and in all but one test at 30 CPM, there was no increase in the level of in-water fluorescence at any time in the test. This is consistent with the visual observations and results of direct measurements that suggest that dispersion rates were negligible. The single exception was the elevated in-situ fluorescence recording in run #19. This IFO 180 test involved a DOR level that was twice as high as in the other tests. The elevated level of in-situ fluorescence in this run was consistent with the much higher measured DE value reported for the run. Overall these results show that in-situ fluorescence yielded no false positives in the control and low-wave energy testing.

In-situ fluorescence levels increased in all dispersant runs completed at 33.3 CPM. Even though the number of tests was small, the following trends were observed. Levels of measured fluorescence increased substantially with increasing measured DE values in all test runs with IFO 180. Fluorometry readings were elevated for all IFO 380 runs too, but fluorescence values were markedly lower for IFO 380 than for IFO 180, even when tests with similar levels of measured dispersion are compared. The reason for this difference in fluorescence between oils is not immediately clear, but may be due to different oil drop size distributions. It is also interesting to note that two tests involving Agma dispersant showed elevated in-situ fluorescence levels, even though the low measured DE values suggest that little dispersion had taken place. In both of these tests, observers also reported visual evidence of “slow and partial dispersion”. The reasons for these apparent false positive indications of dispersion are not clear. The high fluorometry readings may be from the Agma dispersant itself. Visual observations made during the tests suggest that the Agma dispersant may have leached from the oil. If the Agma dispersant itself fluoresces it may have been the cause of the high UVF values. This was not investigated further during the test program.

4.4 Comparison of Ohmsett and At-Sea Results

The at-sea results in Table 4-3 show the differences in dispersibility between IFO180 and 380 and the influence of dispersant type, dispersant-to-oil ratio (DOR) and wind speed on dispersant performance. In at-sea tests, only Corexit 9500 produced high levels of dispersion performance, i.e., moderately rapid dispersion or better (visual = 3 or 4). Only in at-sea tests with Corexit 9500 at low mixing energy (wind speed = 7 to 10 knots) were limiting effects of oil viscosity clearly evident. Under those conditions, the less viscous IFO 180 was readily dispersible (visual = 3.0), while the more viscous IFO 380 clearly did not disperse (visual = 1.0 to 1.1). These results suggest that in winds of 7 to 10 knots the oil viscosity that limits dispersion falls between that of IFO 180 (approximately 2075 cP) and that of IFO 380 (7100 cP.) However, other tests showed that dispersant performance was clearly influenced by mixing energy, which was expressed as wind speed. Tests at slightly higher wind speeds, 11 to 14 knots, yielded higher effectiveness for both IFO 180 and 380. The limited data show that as winds increased from 7 to 10 knots to 11 to 14 knots, dispersion performance on IFO 180 increased from visual = 3 to visual = 4. However, the effect of mixing energy was greatest with IFO 380, in which effectiveness increased from undetectable levels (visual = 1.0) in 7 to 10 kt winds to moderate dispersion (visual = 3.0) in 11 to 14 kt winds. The latter trend, though based on a small number of observations, suggest that for these oils, the limiting oil viscosity for dispersion might not be absolute, but may vary with wind speed and sea state. The type of dispersant also appeared to influence effectiveness. Corexit 9500 produced high levels of dispersion (visual = 3) in winds of 7 to 10 knots, but both Superdispersant 25 and Agma 379 produced markedly lower levels of effectiveness (visual = 1 to 2). On the other hand, while effectiveness of Corexit 9500 in 7 to 10 knot winds was strongly influenced by oil type (visual = 3 with IFO 180 and visual = 1.0 with IFO 380), the performance of SD 25 was the same with both oils (visual = 2).

At Ohmsett, preliminary tests in the October 2003 series confirmed that mixing energy influenced dispersant performance as was shown at sea (see Section 4.1 above). In short, the 30-cpm-wave tests produced very little chemically augmented dispersion (visual = 1.0 to 1.5) and therefore were of little value in testing for effects of oil viscosity on dispersant performance. In the same way, the tests in 35 cpm waves produced maximum dispersion (visual = 4.0) with the most viscous oil, so further tests at 35 cpm would be of little value in detecting effects of oil viscosity on dispersant performance. Of the wave conditions tested, only tests at the intermediate wave frequency 33.3 cpm yielded a full range of dispersant performance (1.0 to 4.0) making it possible to distinguish the effects of experimental variables such as viscosity and oil type.

As was observed at sea, Ohmsett tests on IFO 180 at 33.3 cpm with Corexit produced a high level of dispersant effectiveness (visual = 4.0). This was consistent with dispersant performance at sea at both high and low wind speeds. Ohmsett tests with IFO 380 in 33.3

cpm waves produced a high level of effectiveness, which was inconsistent with at-sea results at low wind speeds, but was consistent with results at higher wind speeds. In general, the effects of variables like dispersant type on dispersion were qualitatively similar at Ohmsett and at sea, except that dispersion performance appeared to be generally somewhat higher at Ohmsett in 33.3 cpm waves than at sea at 11 to 14 knots.

In short, the limiting effect of oil viscosity on dispersion was detectible in the at-sea tests only in tests involving Corexit 9500 and then only in tests at lower wind speeds of 7 to 10 knots. Tests with slightly higher wind speeds, 11 to 14 knots, produced moderate to high levels of dispersant effectiveness with both IFO 180 and 380, thus eliminating the limiting effect of viscosity. Tests at Ohmsett with Corexit 9500 did not reproduce the results observed at sea at wind speeds of 7 to 10 knots, but rather produced results more similar to those of 11 to 14 knots or higher and therefore did not detect the limiting effect of oil viscosity. The limiting effect of oil viscosity has been observed in other recent Ohmsett tests. In 2005, viscous OCS crude oils with viscosities ranging from 1500 to 30,000 cP were treated with Corexit 9500 at DOR's of 1:10 to 1:25 and tested in 33.3 cpm waves. In these tests all of the less viscous oils were readily dispersible, while oils with viscosities over 19,000 cP were not dispersible, showing that the limiting oil viscosity in 33.3 cpm waves at Ohmsett is clearly 19,000 cP or less (SL Ross et al. 2005a). While the at-sea tests suggest that an oil with a viscosity of 7000 cP may limit the dispersibility under some conditions, both at-sea and at Ohmsett tests suggest that this limitation may be overcome by increasing the mixing energy. Indeed the Ohmsett results suggest that in the 33.3 cpm waves the limiting viscosity may lie between 7,100 and 19,000 cP. Operationally, this means that despite the evidence for oil viscosity limiting dispersion of IFO 380 at sea in winds of 7 to 10 knots, oils of 7000 cP or greater may indeed be dispersible if the level of mixing energy is high enough. Clearly more research is required to delineate the relationship roles of mixing energy, dispersant type and DOR in determining the limiting viscosity of oil for dispersion.

Table 4-2: Summary of At-Sea and Ohmsett Tests

Test Oil	Dispersant	DOR	UK At-Sea Trials		Ohmsett Tests		
			Winds 7 to 10 kts	Winds 11 to 14 kts	30 cpm	33.3 cpm	35 cpm
IFO 180	Control	0	1.0			1.0, 1.0, 1.0	-
IFO 180	Corexit 9500	1:25	3.0, 3.0	4.0	1.0, 1.5	4.0, 4.0	-
IFO 180	Corexit 9500	1:50	1.7	2.3	1.2	-	-
IFO 180	Corexit 9500	1:100+	-	1.8	1.0	4.0	-
IFO 180	SD 25	1:25	1.7, 2.0, 1.7, 2.0	-	-	-	-
IFO 180	SD 25	1:50	1.0	-	-	-	-
IFO 180	SD 25	1:100+	-	-	1.0	3.5	-
IFO 180	Agma	1:25	1.5, 2.2	-	-	-	-
IFO 180	Agma	1:50	-	-	-	-	-
IFO 180	Agma	1:100+	-	-	1.0	2.0	-
IFO 380	Control	na	1.0	-	-	-	1.0
IFO 380	Corexit 9500	1:25	1.0, 1.1	3	-	3.5	-
IFO 380	Corexit 9500	1:50	1.7	-	1.0	-	-
IFO 380	Corexit 9500	1:100+	-	-	1.0	3.0	4.0
IFO 380	SD 25	1:25	2.0, 2.0	2.5, 2.7	-	-	-
IFO 380	SD 25	1:50	1.4	-	1.0	-	-
IFO 380	SD 25	1:100+	-	-	1.0	3.5, 2.75	-
IFO 380	Agma	1:25	1.6	1.7	-	-	-
IFO 380	Agma	1:50	-	-	-	-	-
IFO 380	Agma	1:100+	-	-	-	2.0	-

4.5 Combined Results of Laboratory and Wave Tank Tests

The Ohmsett study was one of five in which oils, dispersants and DORs tested at sea in the UK in 2003 were retested in standard laboratory effectiveness tests and wave tank tests. The objective was to compare dispersant effectiveness results from a range of dispersant testing methods with dispersant performance at sea and to consider the ability of each method to predict dispersibility-limiting conditions at sea. Apparatus used and results are summarized in Table 4-4. Study details are reported elsewhere (Belore et al. 2005, Clark et al. 2005; Colcomb et al. 2005, Lewis 2004).

Limitations of laboratory tests in predicting dispersant performance are known from earlier work (e.g., Daling and Lichtenthaler 1986). It has been assumed that a potential advantage of wave tank tests over lab-scale tests is that they can reproduce many of the at-sea operational and dispersion processes that cannot be reproduced in smaller-scale lab tests. One of the objectives of this work was to attempt to verify this assumption. The following is a very brief overview of the results.

Most laboratory and wave tank tests produced high levels of effectiveness in tests with combinations of oil, dispersant and DOR (O/D/DOR) that yielded high levels of effectiveness at sea. The exception was the Swirling Flask Test (SFT), which produced very low estimates of effectiveness under conditions that produced the highest levels of dispersant performance at sea. There are possible explanations for this, but none were tested in this study. The SFT was not considered further here. All other test methods produced moderate to high levels of effectiveness for IFO 180 and IFO 380. None of the tests predicted the oil viscosity limitation on dispersion observed in the at-sea tests at low wind speeds. That is, none predicted both a high level of dispersibility for the IFO 180 and the almost complete resistance to dispersion observed in the IFO 380 at low wind speeds at sea. All tests showed some dispersibility for IFO 380. On the other hand, all methods showed IFO 180 to be more dispersible than the IFO 380. Hence, all methods produced results more consistent with the at-sea tests with Corexit in winds of 11 to 14 knots. Both wave tanks and most laboratory methods ranked the performance of the dispersant products in the same order as at sea, but some did not.

All laboratory test methods, except the SFT, produced high levels of dispersant performance for some O/D/DOR conditions that produced little or no effectiveness at sea. This suggests that the processes that limit dispersant performance at sea may be prevented from occurring in laboratory tests. These limiting processes may include dispersant failing to mix with the oil and simply running off into the water because the oil is too viscous to permit mixing. This problem appears to be overcome, in part, in tests in both the SL Ross wave tank and at Ohmsett wave tank. In these tests some O/D/DOR conditions that produced little or no effectiveness at sea produced no effectiveness in tests in the tanks.

Based on the data sets developed in these projects, some or most methods may be calibrated to identify O/D/DOR conditions that will produce high levels of dispersion at sea and to distinguish them from others that produce low levels of effectiveness at sea. Lewis (2004) used the empirical relationship between WSL data and at-sea data to demonstrate that moderate and high levels of dispersion performance at sea were achieved under O/D/DOR combinations that produced over 60% and 80% effectiveness, respectively, in tests in the WSL apparatus.

Table 4-3: Comparison of Laboratory, Wave Tank and At-Sea Tests

		Laboratory Tests								Wave Tank Tests								At Sea (c)	
Test name	DOR	SFT (a.b)		Exdet (a,b)		BFT (a,b)		WSL (a,c)		SLR (a,d)		Ohmsett (e)							
Oil Type		180	380	180	380	180	380	180	380	180	380	180			380			180	380
Mixing Energy												30 cpm	33 cpm	35 cpm	30 cpm	33 cpm	35 cpm		
Control		0.06	0.05			3	4			0 (1)	0 (1)		26 (1.0)				30 (1.0)	1	1
C9500	1:25	7	5	44	32	77	65	95	51	97 (4)	53 (3)	36(1.0)	84 (4), 96 (4)		13(1.3)	84 (3)		3,3,4	1,1.1,3
	1:50			31	21	72	41	86	48	50 (3)	32 (3)	21 (1.2)	84 (4)		26 (1.2)		58 (4)	3.2	1.7
	1:100							66	45	39 (3)								2.3	
	1:150																		
SD 25	1:25			14	6	79	57	-	63	82 (3)	15(1)				20 (1.1)	53 (3.5)		1.7,2.0	2,2,2.5,2.7
	1:50			4	4				52		1(1)	21 (1)	45 (3.8)		18 (1.8)	29 (2.5)		1	1.4
	1:100								50		1(1)							-	
	1:150																		
Agma	1:25			18	6				26	23 (2)	1 (1)	24 (1)	17 (2.2)			16(2)		1.5,2.0	1.6, 1.7
	1:50			5	4				12									-	1
	1:100								9									-	
	1:150																		

a. Test names are SFT = swirling flask test, BFT = Baffled flask test, WSL = Warren Spring test, SLR = SL Ross wave tank
b. From Clark et al. 2005
c. From Lewis 2005
d. From Belore et al. 2005
e. Values in parentheses are visual observations on four-point scale

5 Summary

A series of dispersant effectiveness tests were completed at Ohmsett in order to compare results with tests conducted at sea in the UK in 2003 with identical oils, dispersants and dispersant to oil ratios (DOR). The UK at-sea tests estimated the oil viscosity that limits chemical dispersion by testing a number of IFO oils that spanned a range of viscosities, up to approximately 7000 cP. The work at Ohmsett determined whether tests at Ohmsett could predict the effectiveness limitations observed at sea.

The at-sea tests showed that for these oils, the oil viscosity that limits dispersion may be influenced by mixing energy (i.e., wind speed, wave energy). In the at-sea tests Corexit 9500 produced the highest levels of effectiveness and in tests at lower wind speeds (7 to 10 knots), the limiting oil viscosity clearly lay between the viscosities of IFO 180 (viscosity = 2075 cP at 15º C) and IFO 380 (viscosity = 7100 cP at 15º C). In slightly higher wind speeds (11 to 14 knots) Corexit produced high levels of effectiveness with both oils, suggesting that at the higher wind speed the limiting oil viscosity had been shifted above the 7100-cP viscosity of IFO 380. Superdispersant 25 (SD 25) and Agma 379 (Agma) produced some dispersant effectiveness at sea, but neither produced the moderate or high levels of effectiveness shown by Corexit. The SD 25 was markedly less effective on the IFO 180 at low wind speeds, but its effectiveness appeared to be less affected by oil viscosity and wind speed than Corexit.

Ohmsett tests also showed that for these oils wave energy exerted a strong influence on dispersion performance. Preliminary tests conducted at 35 wave cycles per minute (cpm) in the Ohmsett wave tank produced levels of dispersant performance that were far higher than at sea and were discontinued. Tests in 33.3 cpm waves produced levels of effectiveness that appeared to be similar to at sea, though effectiveness later proved to be slightly higher than at sea. Tests in 30 cpm waves produced no evidence of chemically augmented dispersion with any combination of oil, dispersant and DOR. Tests with Corexit in 33.3 cpm waves produced high levels of effectiveness with both IFO 180 and IFO 380 showing that at 33.3 cpm oil viscosity did not limit chemical dispersion at Ohmsett as it had at sea at the lower wind speeds of 7 to 10 knots. The 33.3 cpm results were more consistent with at sea results in winds of 11 to 14 knots where the limiting oil viscosity limiting dispersion was clearly greater than that of IFO 380, 7100 cP. In general, effectiveness results in 33.3 cpm waves appeared to produce higher levels of effectiveness than at sea for most combinations of dispersants and oils.

A comparison of visual effectiveness assessments (four-point scale) versus direct measurements of amounts of oil left in the oil slick at the end of each test showed the following.

a) Controls (no dispersant) always yielded no visible evidence of dispersion (visual = 1.0), but some losses of oil were observed in all tests amounting to 4 to 30% of the amount of oil spilled.
b) In tests in which dispersant were used but which produced no visible evidence of dispersion (visual = 1.0 to 1.4) oil losses during the test were similar to the “no dispersant” controls. In two cases where losses were greater than in controls, the differences could be attributed to clearly visible losses through dispersion caused during collection at the end of the test.
c) In dispersant tests that produced evidence of slow and partial dispersion (visual = 1.5 to 2.4) oil losses during the test were also similar to the “no dispersant” controls.
d) In dispersant tests that produced moderately rapid but incomplete dispersion (visual = 2.5 to 3.4) oil losses during the test were higher than in controls in the 30 to 40% range.
e) In dispersant tests that produced very rapid and total dispersion (visual = 3.5 to 4.0) oil losses during the test were much greater than in the controls in the 45 to 96% range. It did not appear to be possible to distinguish visually between the highly effective tests and the less effective tests in this group.

The usefulness of in-water UV fluorescence measurements for monitoring dispersant effectiveness was assessed by comparing UV fluorescence data with direct measurements of dispersant effectiveness. In control tests there was no increase in the level of in-water fluorescence at any time in the test. On the other hand, levels of measured fluorescence increased substantially with increasing DE values in all test runs with IFO 180. Readings were elevated for all IFO 380 runs as well, but fluorescence values were markedly lower for IFO 380 than for IFO 180, even when tests of similar DE values were compared.

The Ohmsett study was one of five in which the oils, dispersants and DORs tested at sea in the UK in 2003 were retested in laboratory effectiveness tests and wave tank tests. The objectives were to compare dispersant effectiveness results from a range of dispersant testing methods with effectiveness at sea and to consider the ability of each method to predict dispersibility-limiting conditions at sea. It had been assumed that wave tank testing could reproduce many of the at-sea operational and dispersion processes that cannot be reproduced in small-scale lab tests, and as a result, wave tank tests would better predict dispersant performance at sea. One of the objectives of this work was to attempt to verify this assumption. Tests were completed in bench-scale laboratory apparatus, including: Swirling Flask Test (SFT) (EPA standard, Environment Canada standard), Baffled Flask Test (BFT) (developed by EPA to replace the SFT), Exxon Dispersant Effectiveness Test (EXDET), and Warren Spring Laboratory Test (WSL Test) (UK standard), as well as in the SL Ross intermediate scale wave tank and the large scale Ohmsett wave tank.

Most laboratory and wave tank tests produced high levels of effectiveness in tests with combinations of oil, dispersant and DOR (O/D/DOR) that yielded high levels of effectiveness at sea. The exception was the Swirling Flask Test (SFT), which produced very low estimates of effectiveness under conditions that produced the highest levels of dispersant performance at sea under conditions of very low mixing energy. This result calls into question the potential usefulness of the SFT for assessing the potential dispersibility of oils at sea. There are possible explanations for this, but none were tested in this study. No further testing was conducted on the SFT.

All other test methods produced moderate to high levels of effectiveness for IFO 180 and IFO 380. None of the tests predicted the oil viscosity limitation on dispersion observed in the at-sea tests at low wind speeds. That is, none predicted both a high level of dispersibility for the IFO 180 and the almost complete resistance to dispersion observed in the IFO 380 at low wind speeds at sea. All tests showed some dispersibility for IFO 380. On the other hand, all methods showed IFO 180 to be more dispersible than the IFO 380. Hence, all methods produced results more consistent with the at-sea tests with Corexit in winds of 11 to 14 knots. Both wave tanks and most laboratory methods ranked the performance of the dispersant products in the same order as at sea, but some lab methods did not.

6 Recommendations

The key recommendations from this study are the following.

a) Studies should be completed to characterize wave environments so that wave conditions at Ohmsett (and the dispersant results produced under these conditions) can be related to wave conditions at sea in ways that are useful for dispersant research and testing.

b) Testing at Ohmsett should be used to establish the limits of dispersant performance on crude oils (e.g., viscous Outer Continental Shelf oils) and other viscous oils of interest, as well as to elucidate the process(es) by which oil viscosity, wave energy, dispersant type and DOR interact to limit the chemical dispersibility of viscous oils.

c) The capability of the Ohmsett wave tank should be used to assess the limits of dispersibility of oils in non-breaking waves.

d) The wave energy setting to be used in standard dispersant effectiveness testing at Ohmsett should be re-assessed in light of the present work.

e) The visual dispersant effectiveness assessment scale developed in the UK field trials and used in this study is an effective and valuable tool for quantifying dispersant performance in actual spills and for research purposes. The system should be updated based on the experience gained at Ohmsett in this and other studies and should also be standardized and more fully documented to improve its usefulness by other practitioners.

f) In future Ohmsett studies, replicate control runs should be completed with all oils tested in order to more gain a better understanding of the oil losses that occur during the tests by natural and method-related means.

g) In future test programs the following analyses should be done within 24 hours of a test completion to confirm that the primary test parameters are being achieved and to provide early feedback on the basic test outcome, specifically:

    a. Quantification of the dispersant-to-oil ratio; and
    b. Quantification of the parameters needed to estimate the amount of oil recovered at the end of each test including: the volume of emulsion collected, the amount of free water, replicate measurements of the water content of the remaining oil, evaporative losses from the oil during the test.

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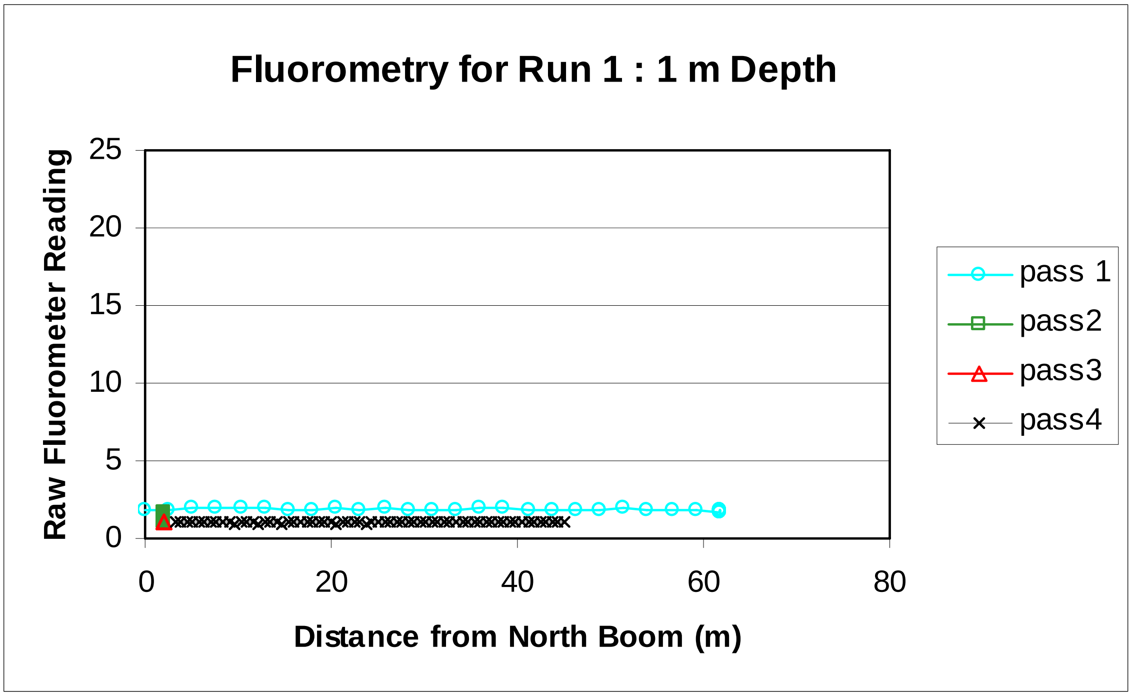
Appendix 1: Analysis of IFO 180 and IFO 380 Oils in this Study

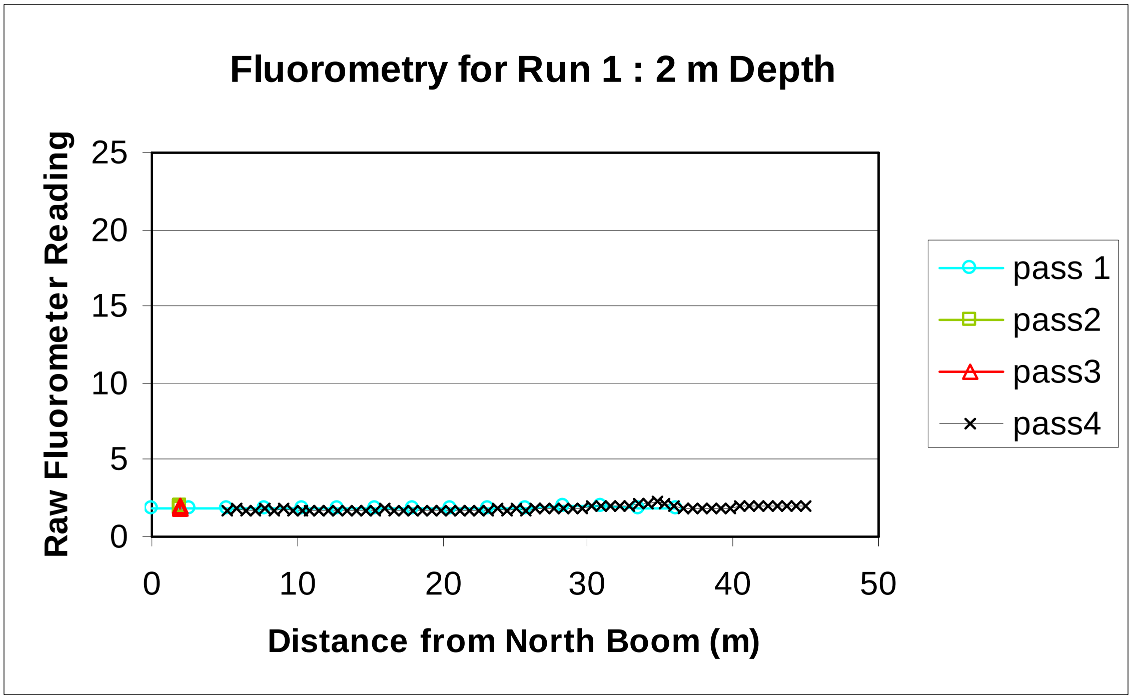
Physical properties and chemical composition of oils used in this study as well as analytical methods used are provided Table A1.

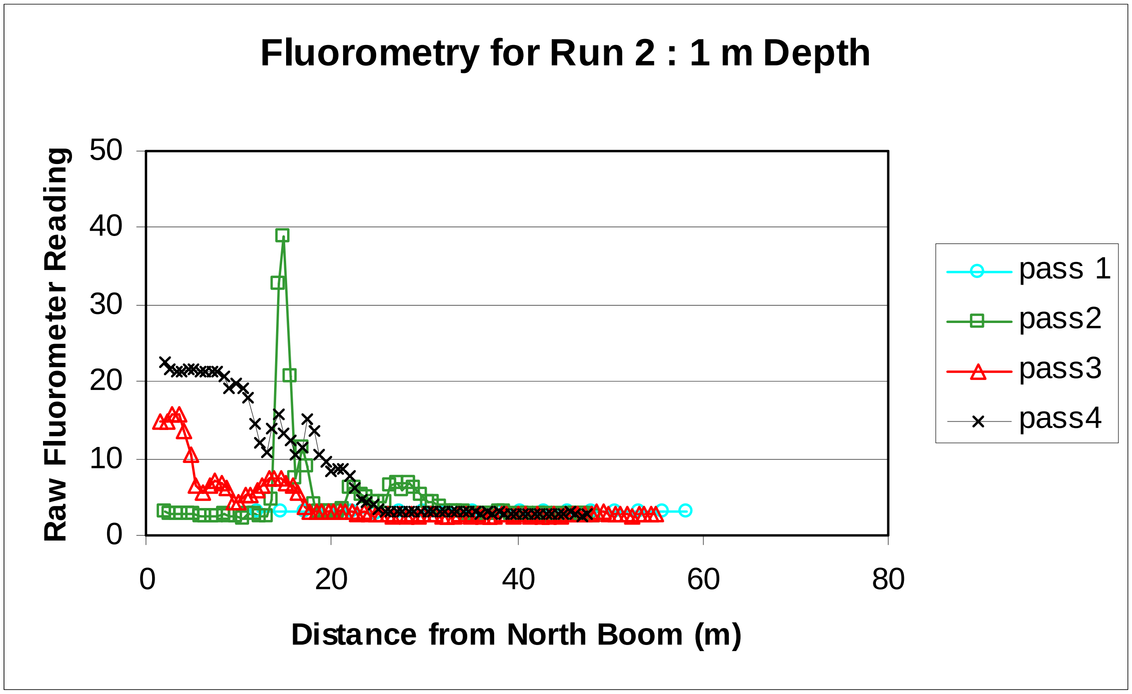
Table A1 Results of Chemical Analysis of Original IFO 180 and 380 Oils

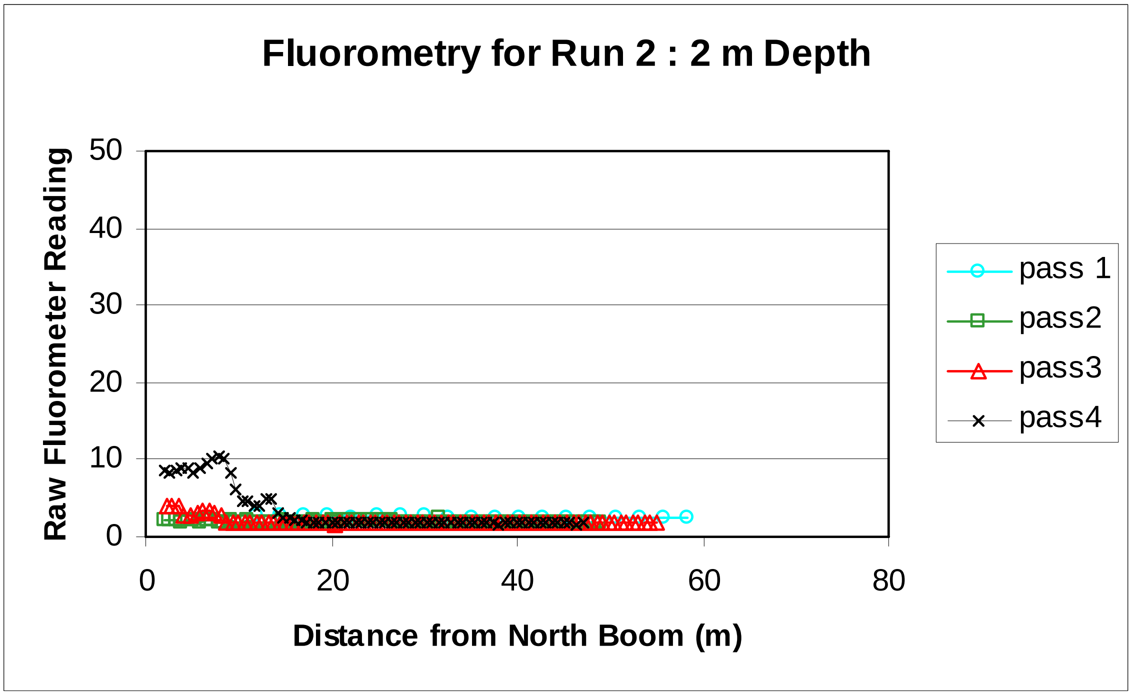
Oil	Weathering days	Alkanes $\mu g \cdot g^{-1}$	Aromatics $\mu g \cdot g^{-1}$	Resins $\mu g \cdot g^{-1}$	Asphaltenes $\mu g \cdot g^{-1}$
IF 180 Fresh	0	216399	15343	234310	218492
IF 180 2 Days	2	230378	14666	175195	209324
IF 180 2 Weeks	14	237210	14939	229942	259159
IF 360 Fresh	0	224017	15702	145691	208198
IF 380 2 Days	2	215315	14949	237751	207007
IF 380 2 Weeks	14	214657	14878	177916	271892

Appendix 2: Fluorometer Results






Fluorometry for Run 2 : 1 m Depth
Raw Fluorometer Reading
0
10
20
30
40
50
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4


Fluorometry for Run 2 : 2 m Depth
Raw Fluorometer Reading
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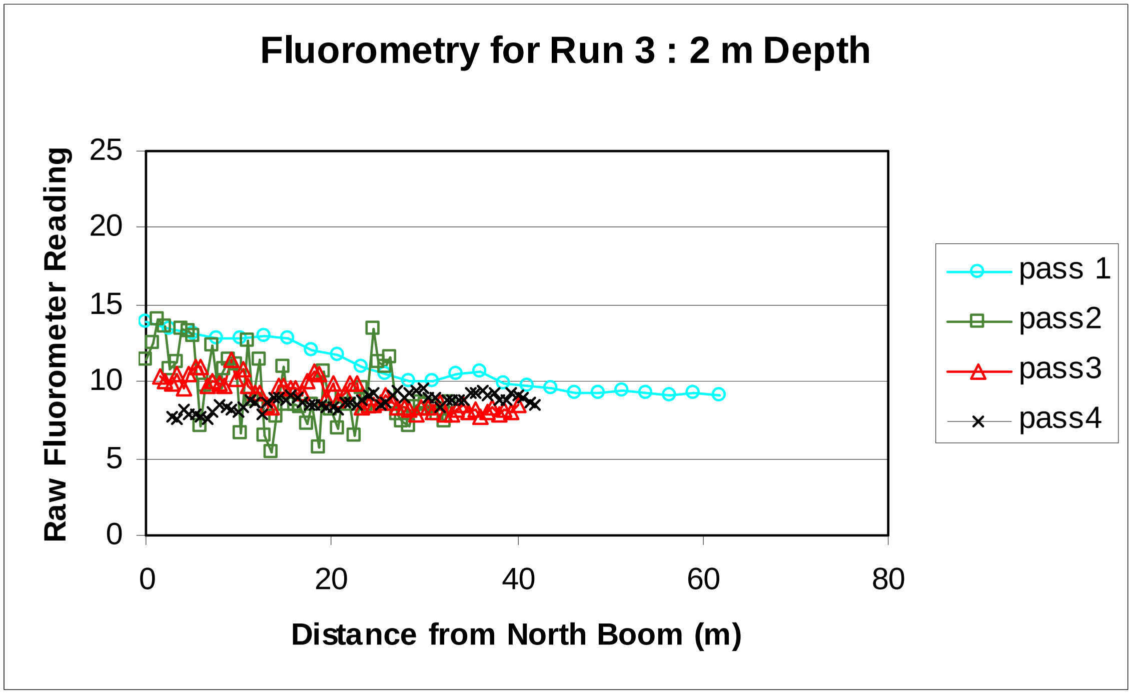
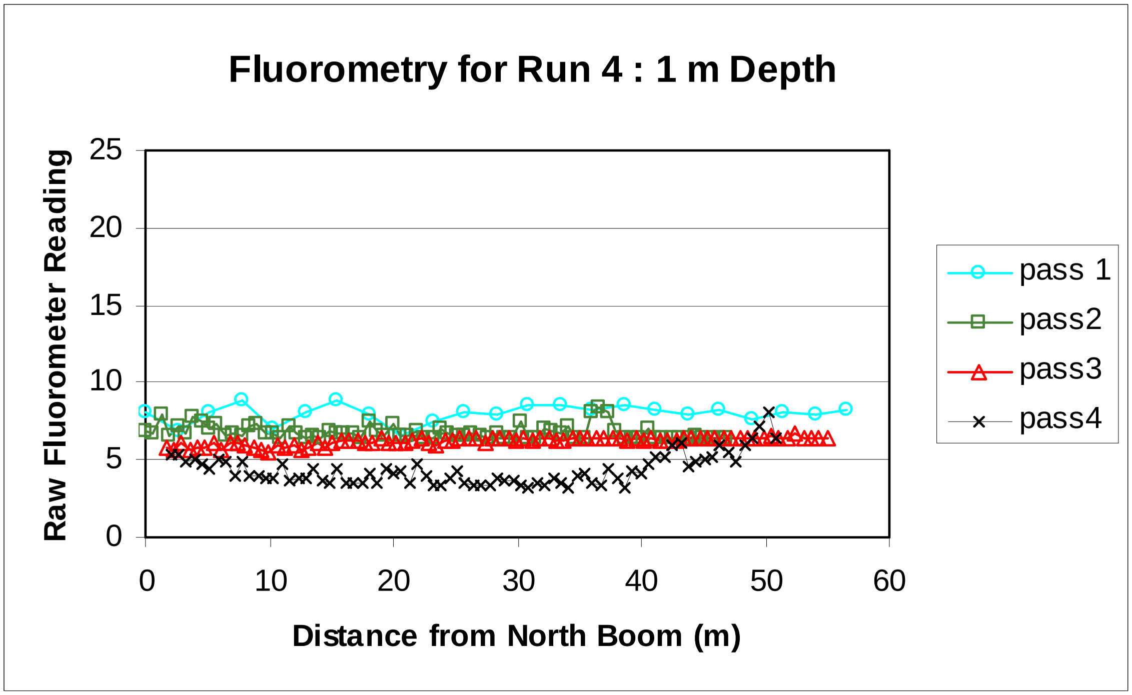
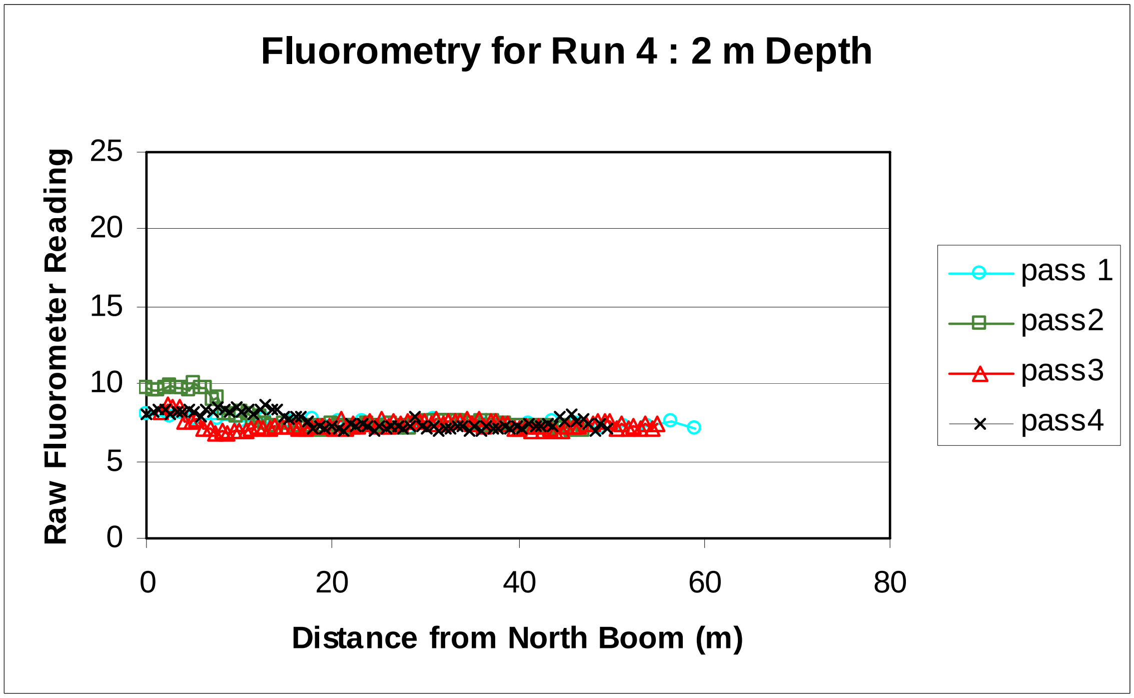
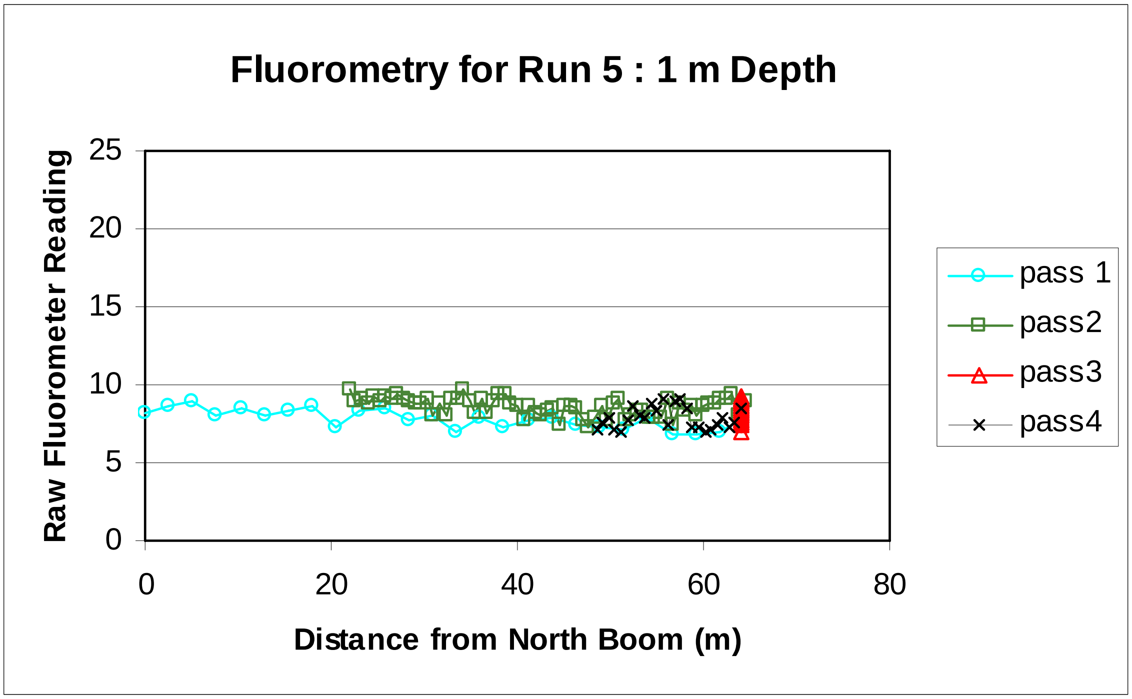
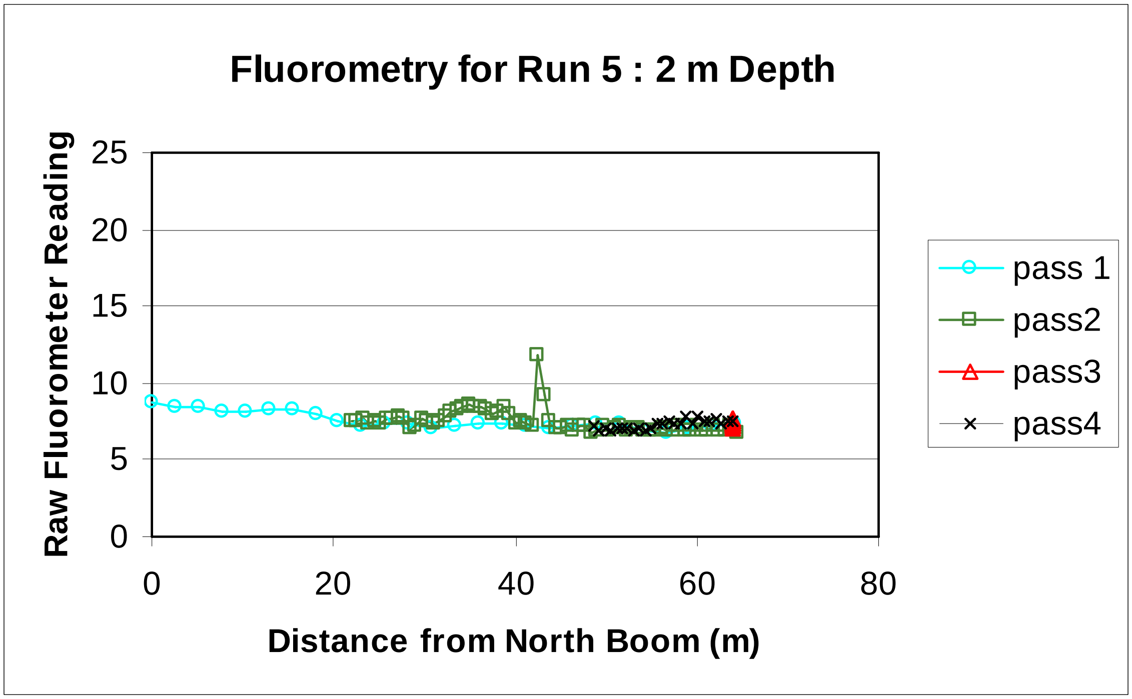
10
20
30
40
50
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

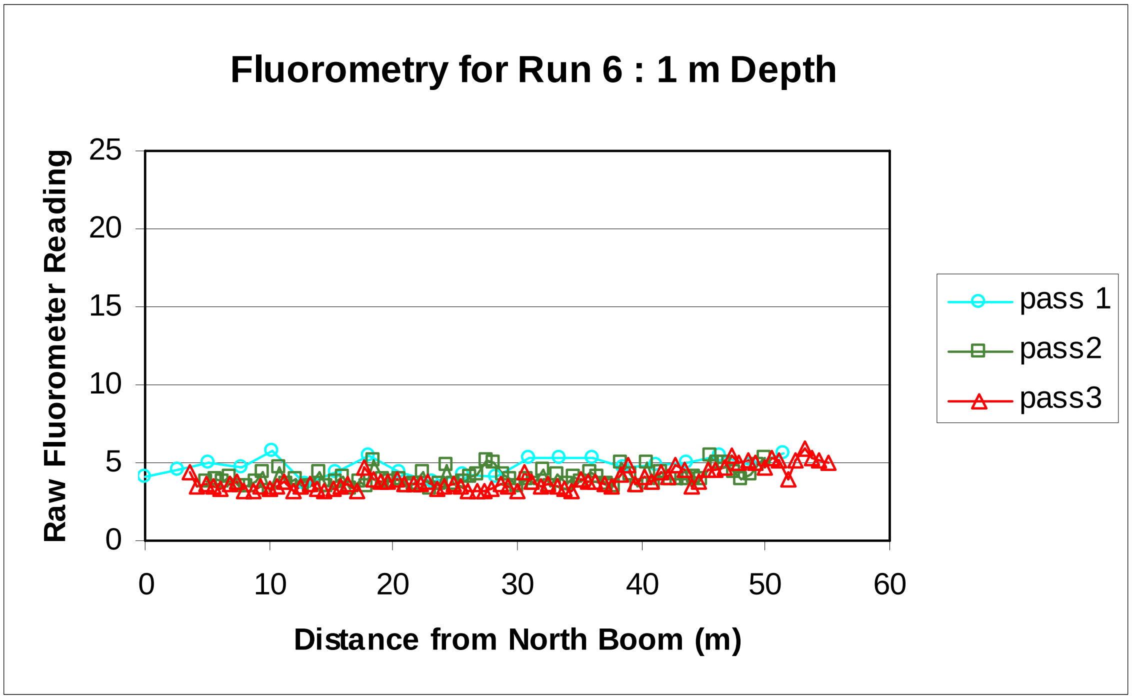

Fluorometry for Run 3 : 2 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

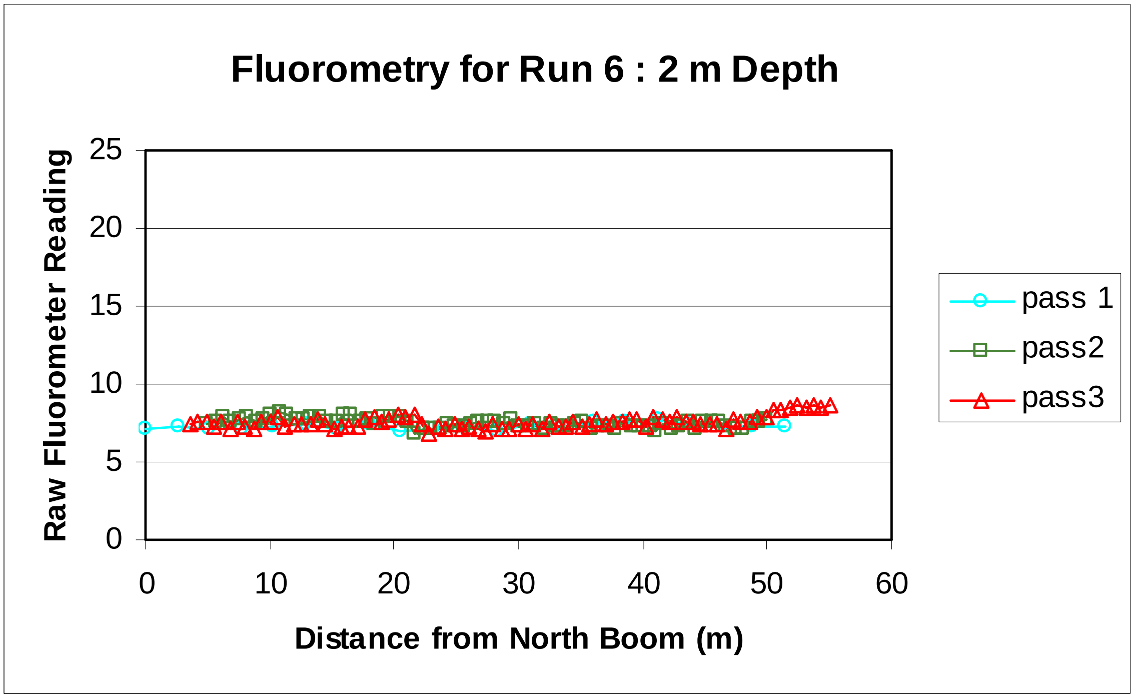

Fluorometry for Run 4 : 1 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

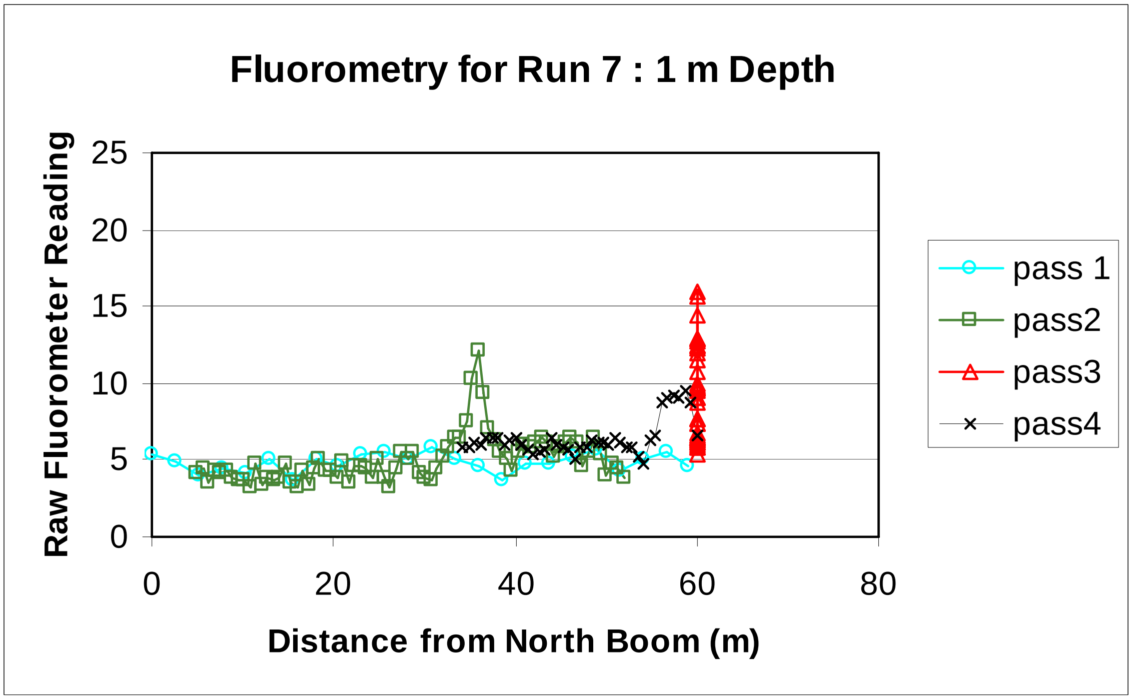

Fluorometry for Run 4 : 2 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

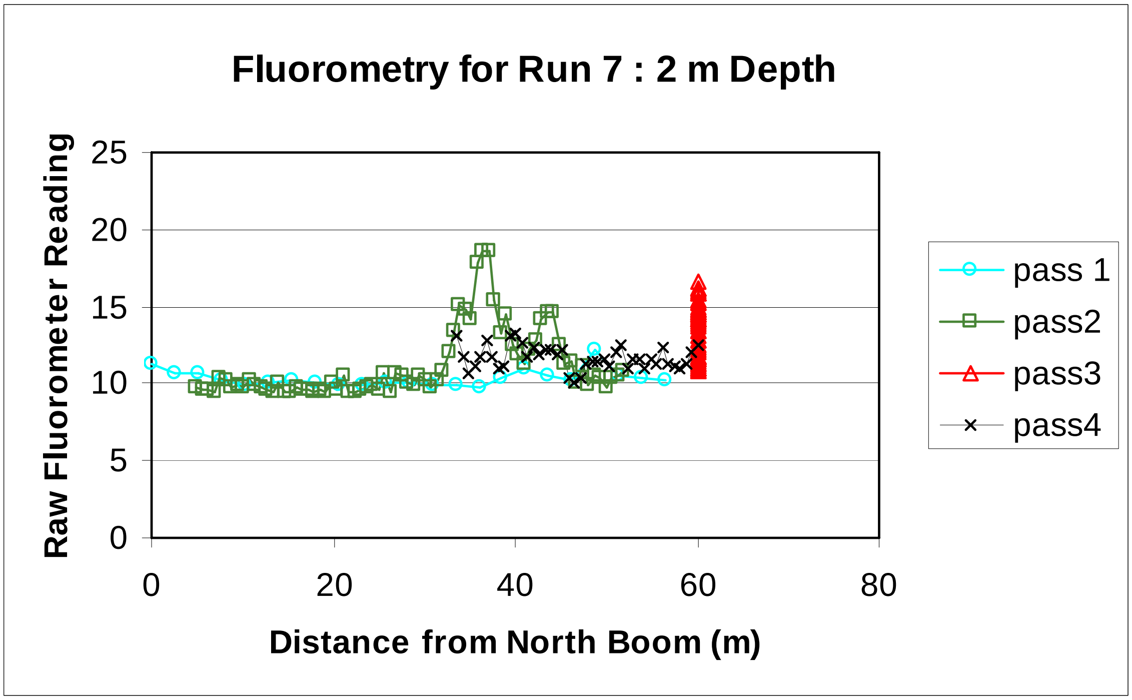

Fluorometry for Run 5 : 1 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

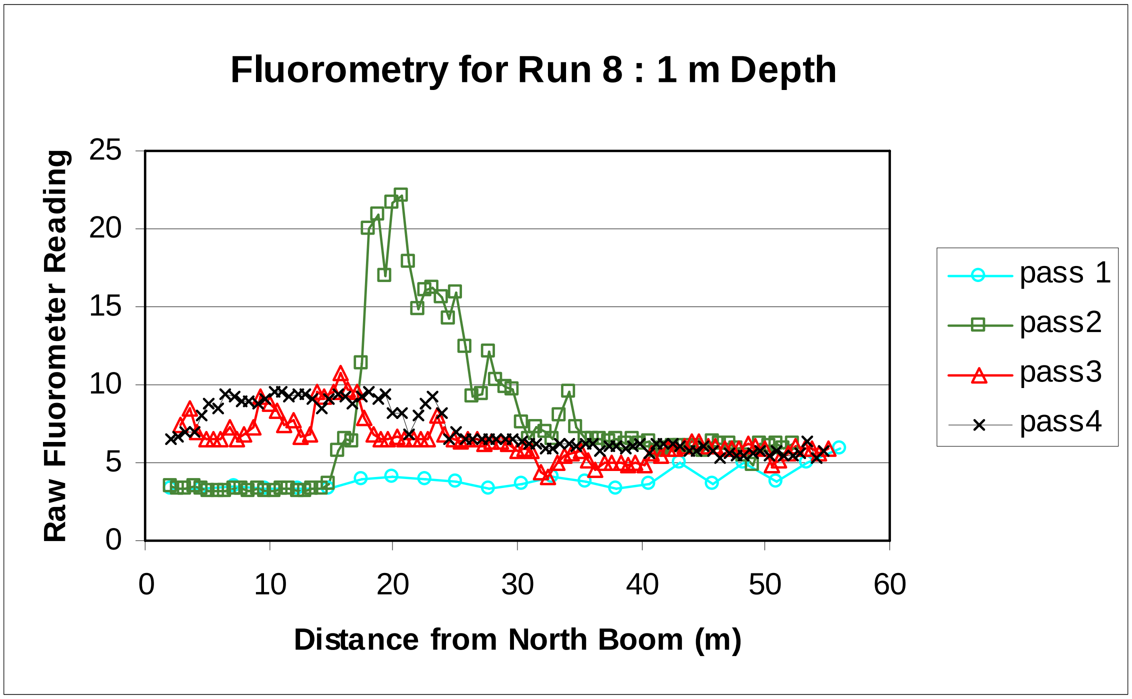

Fluorometry for Run 5 : 2 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

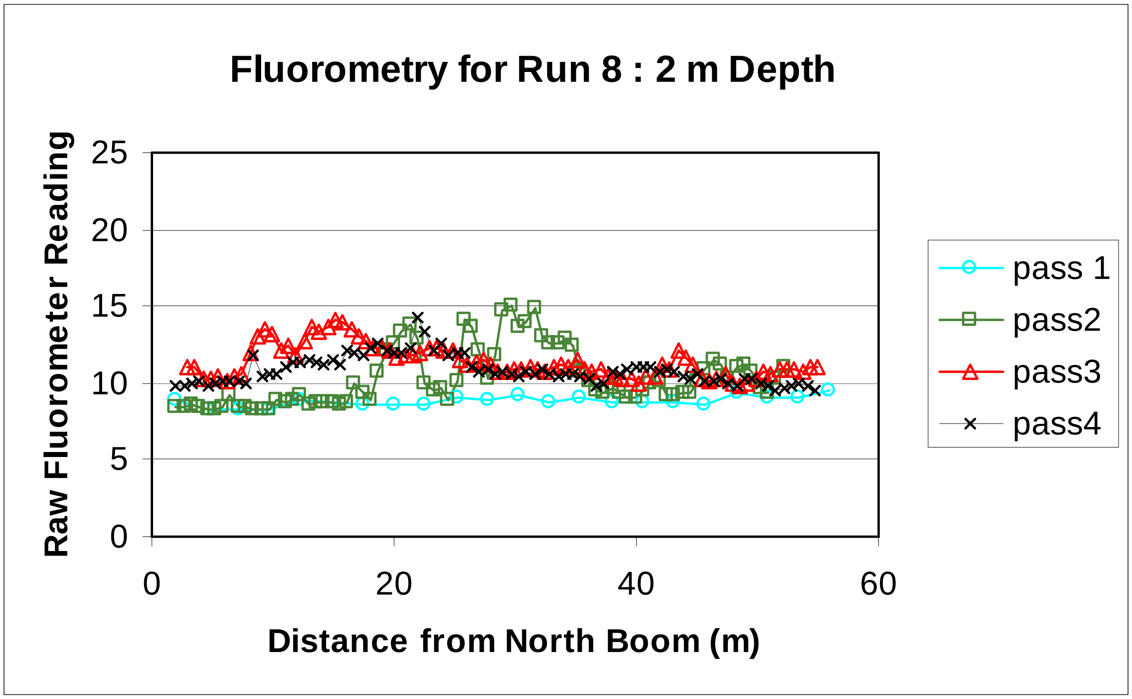

Fluorometry for Run 6 : 1 m Depth
Raw Fluorometer Reading
0
5
10
15
20
25
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3

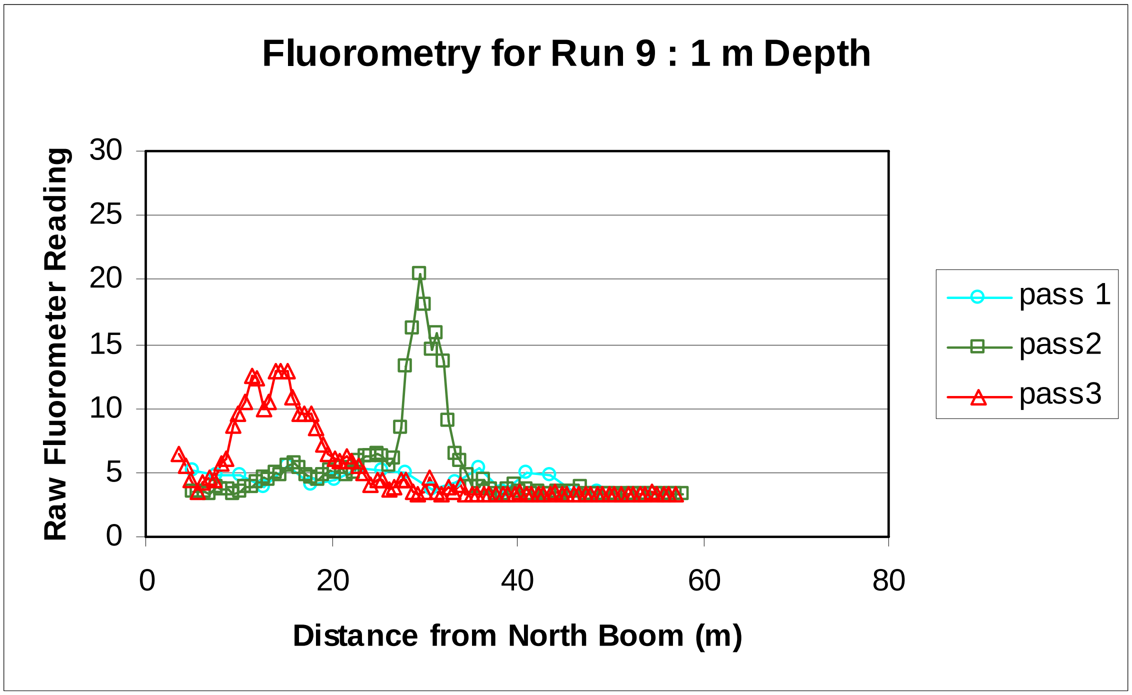

Fluorometry for Run 6 : 2 m Depth
Raw Fluorometer Reading
0
5
10
15
20
25
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3


Fluorometry for Run 7 : 1 m Depth
Raw Fluorometer Reading
0
5
10
15
20
25
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

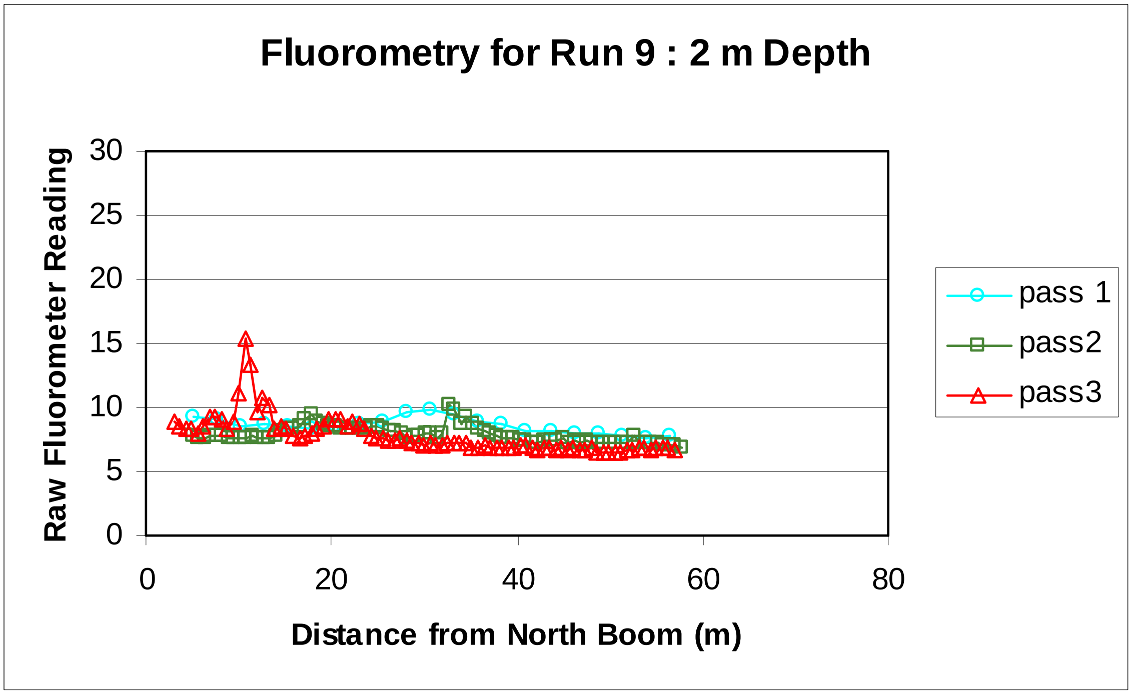

Fluorometry for Run 7 : 2 m Depth
Raw Fluorometer Reading
0
5
10
15
20
25
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4


Fluorometry for Run 8 : 1 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

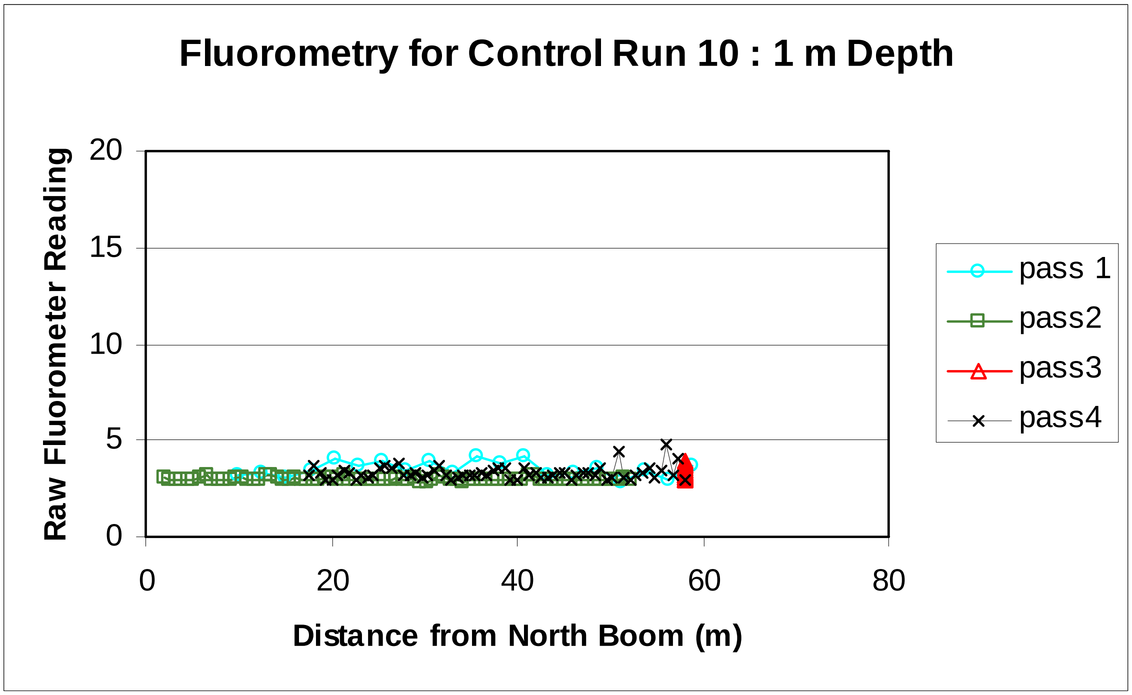

Fluorometry for Run 8 : 2 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

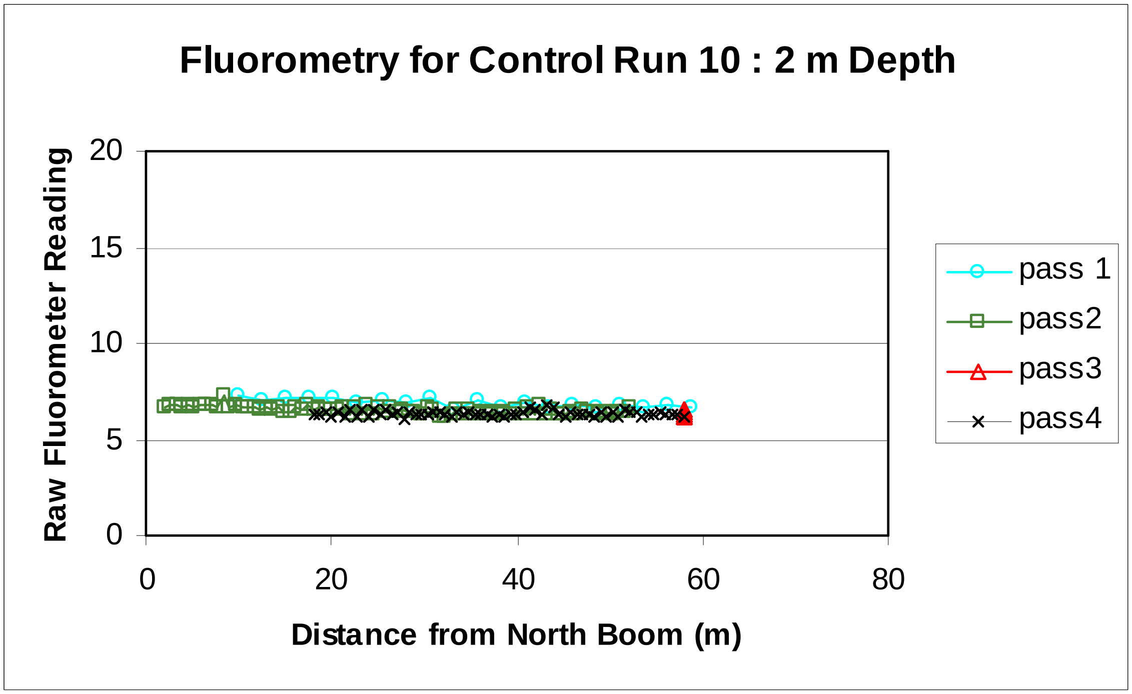


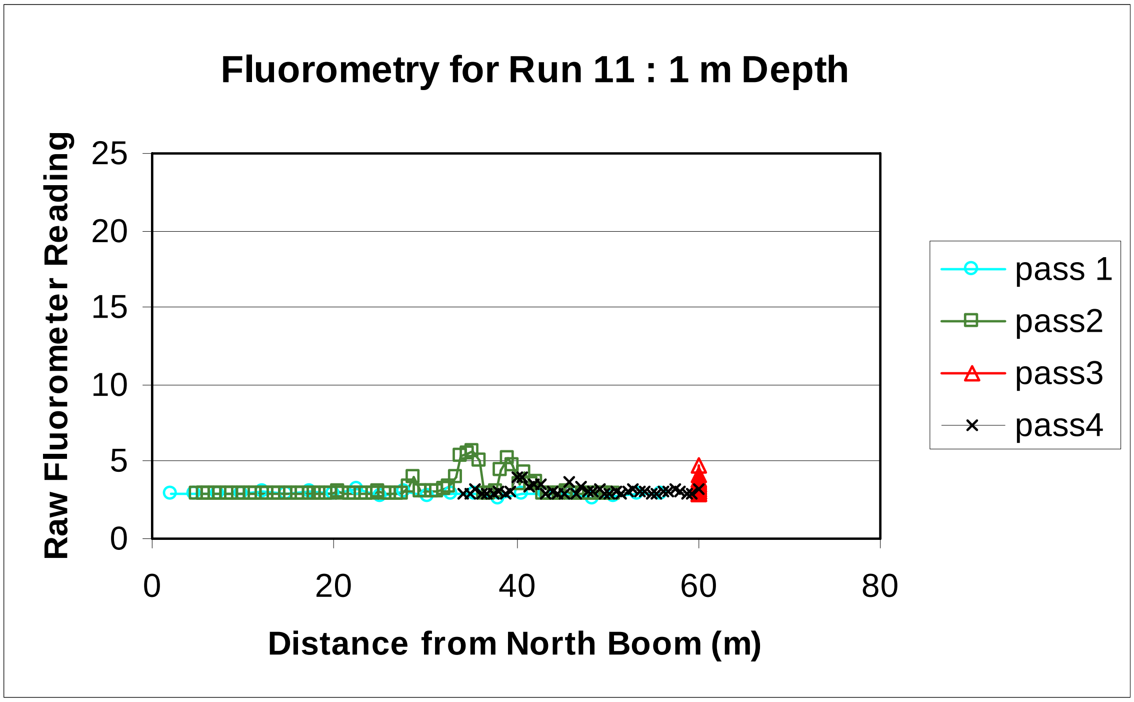
Fluorometry for Run 9 : 1 m Depth

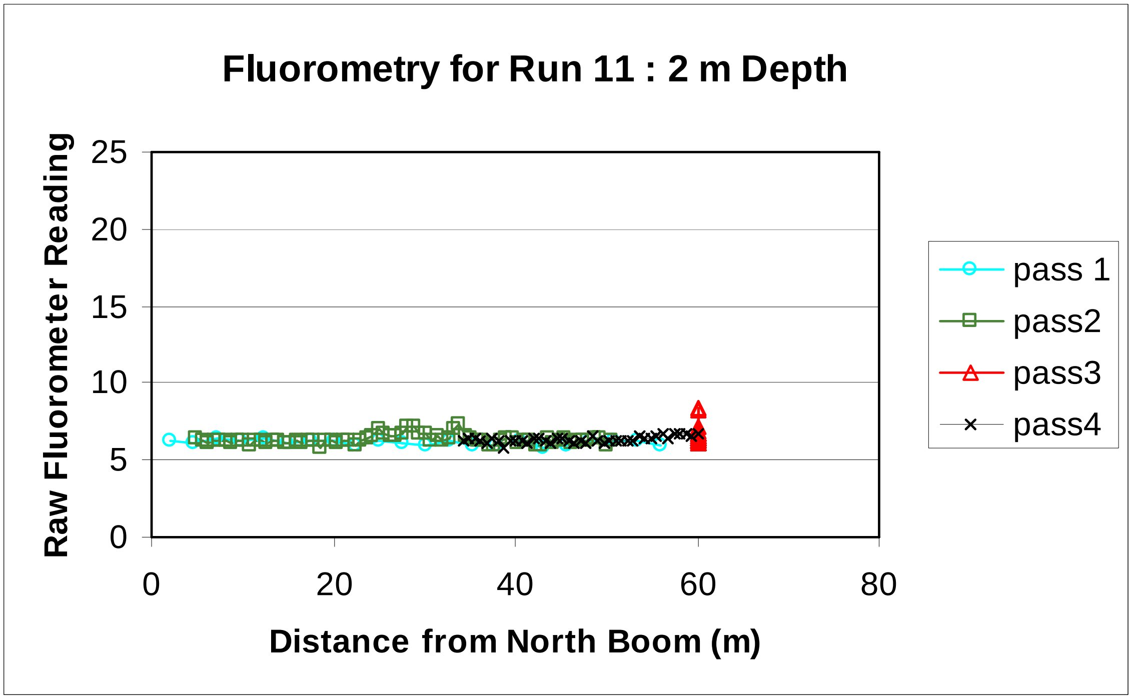


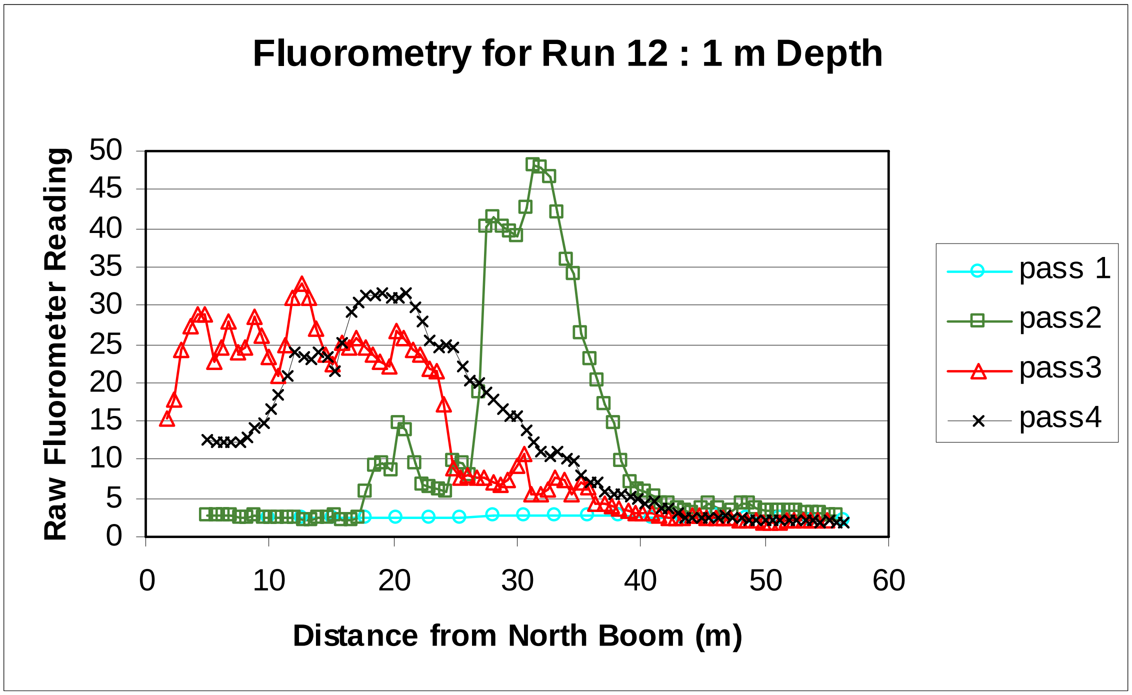
Fluorometry for Run 9 : 2 m Depth

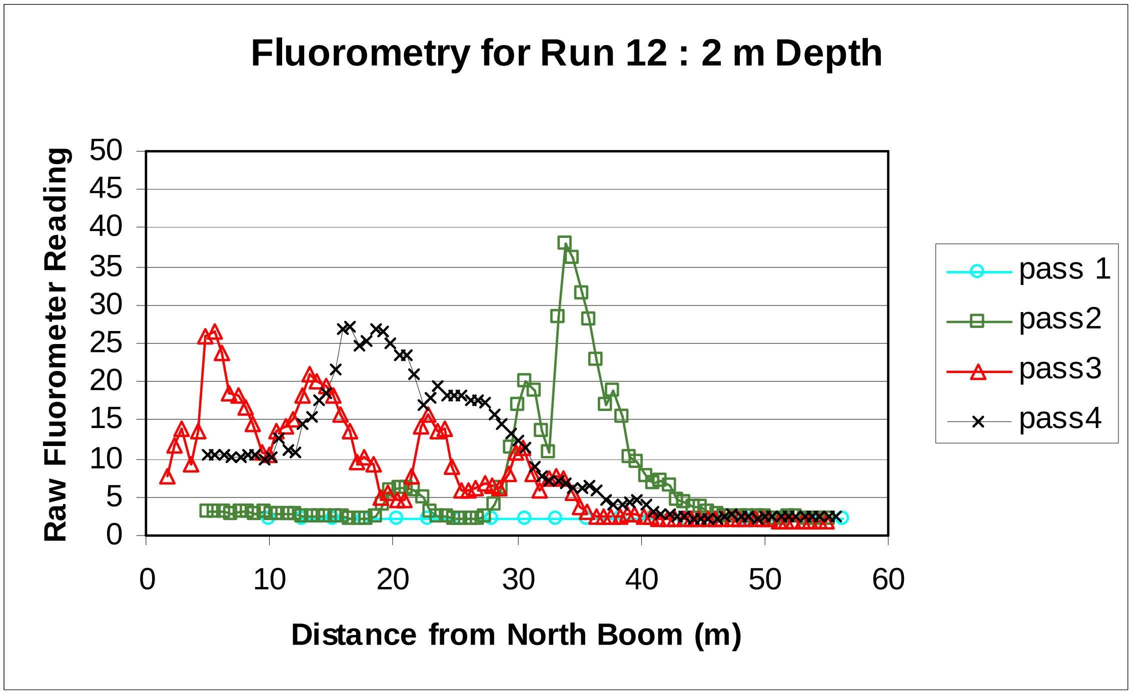

Fluorometry for Control Run 10 : 1 m Depth
Raw Fluorometer Reading
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

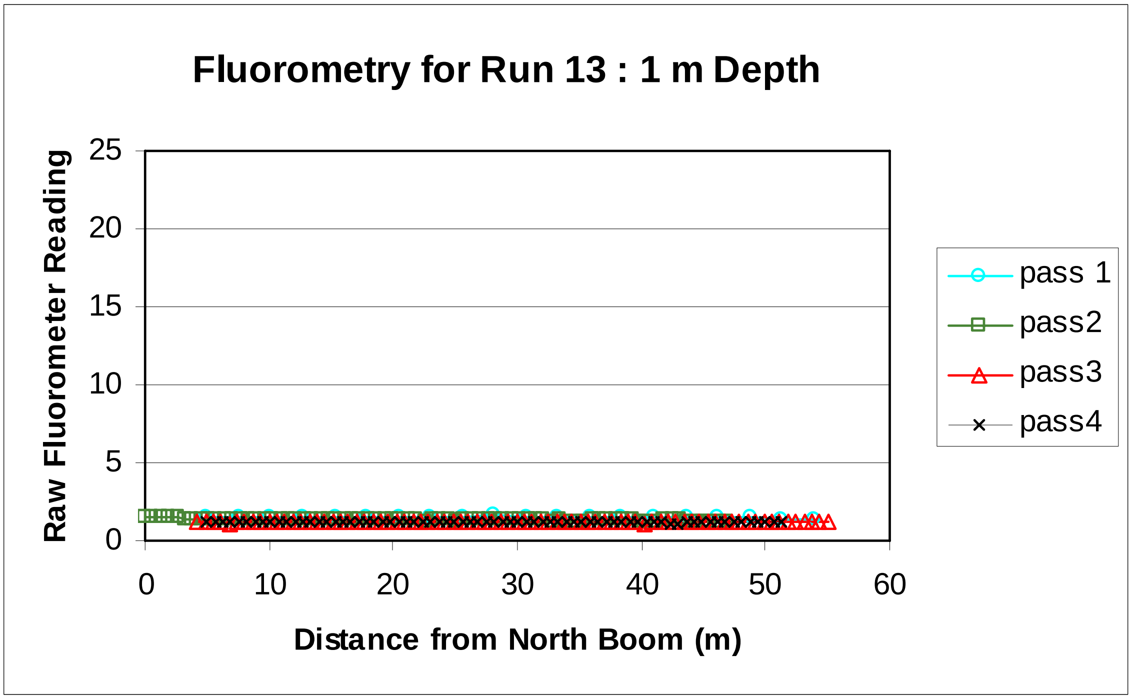

Fluorometry for Control Run 10 : 2 m Depth
Raw Fluorometer Reading
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

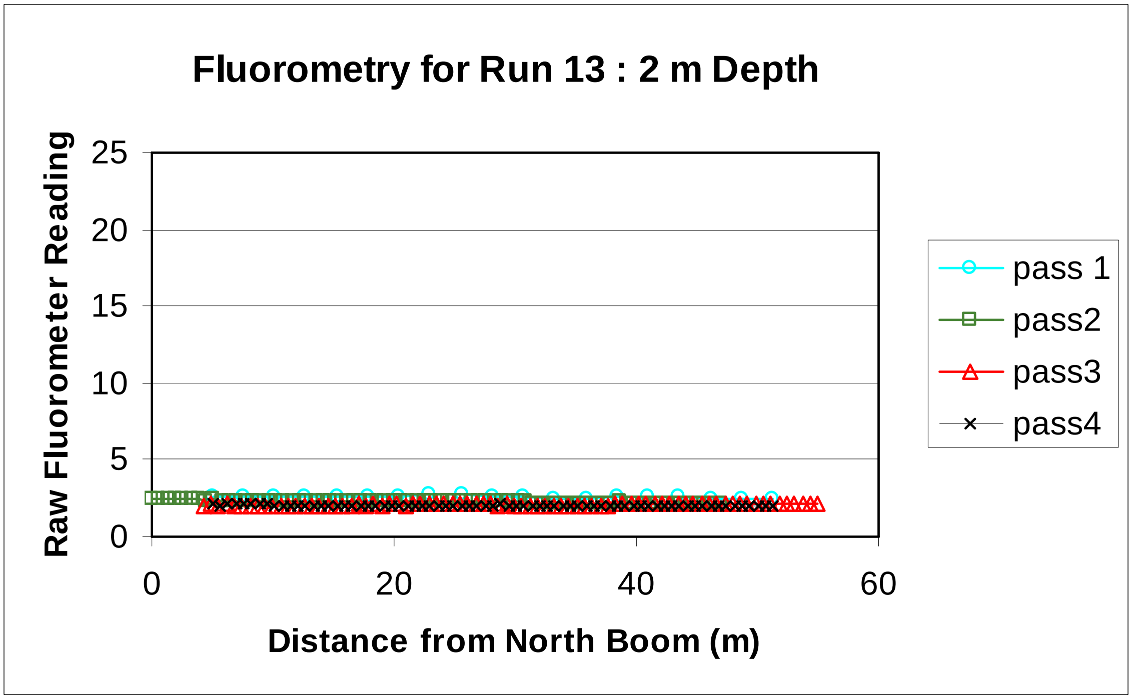

Fluorometry for Run 11 : 1 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

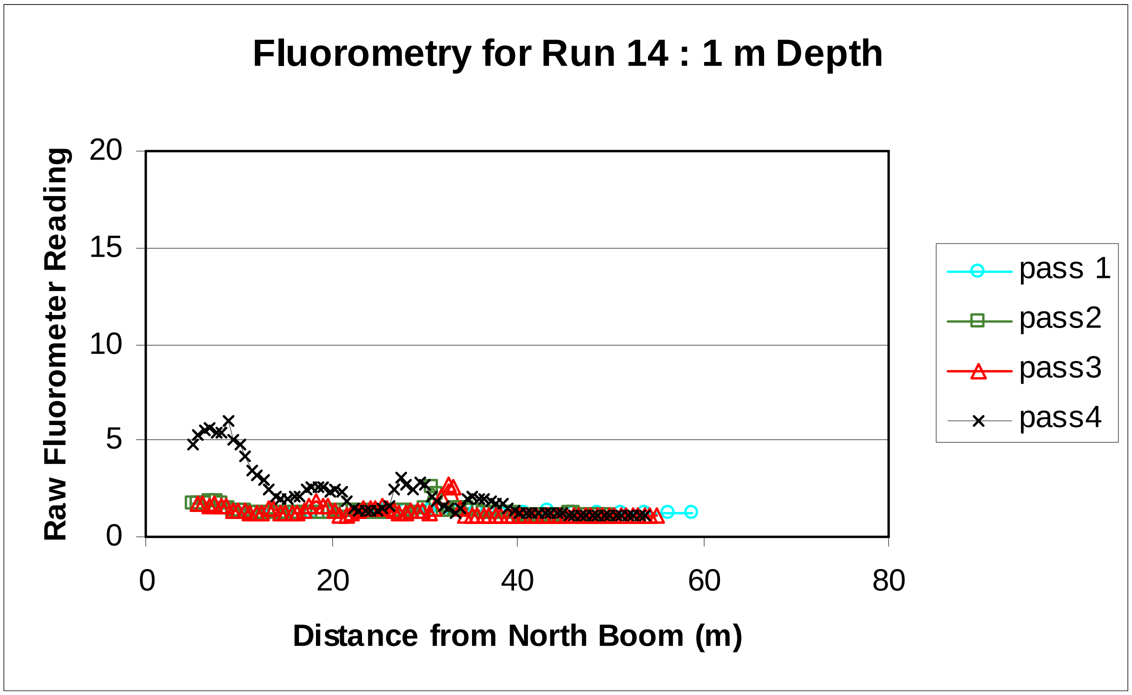

Fluorometry for Run 11 : 2 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

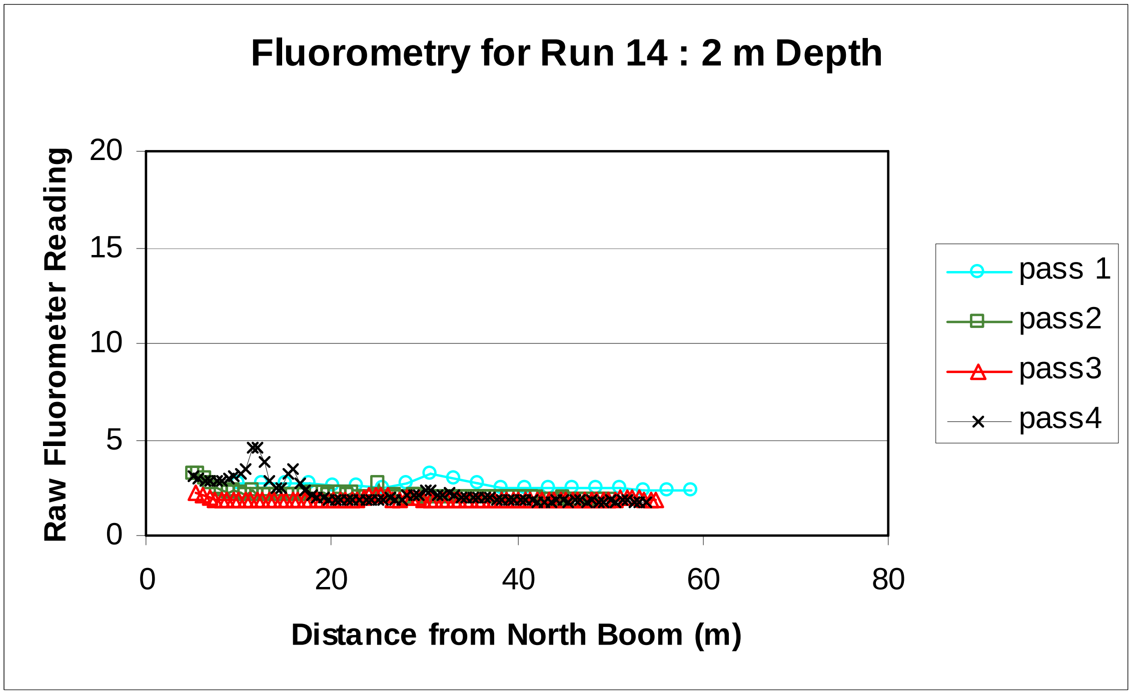

Fluorometry for Run 12 : 1 m Depth
Raw Fluorometer Reading
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

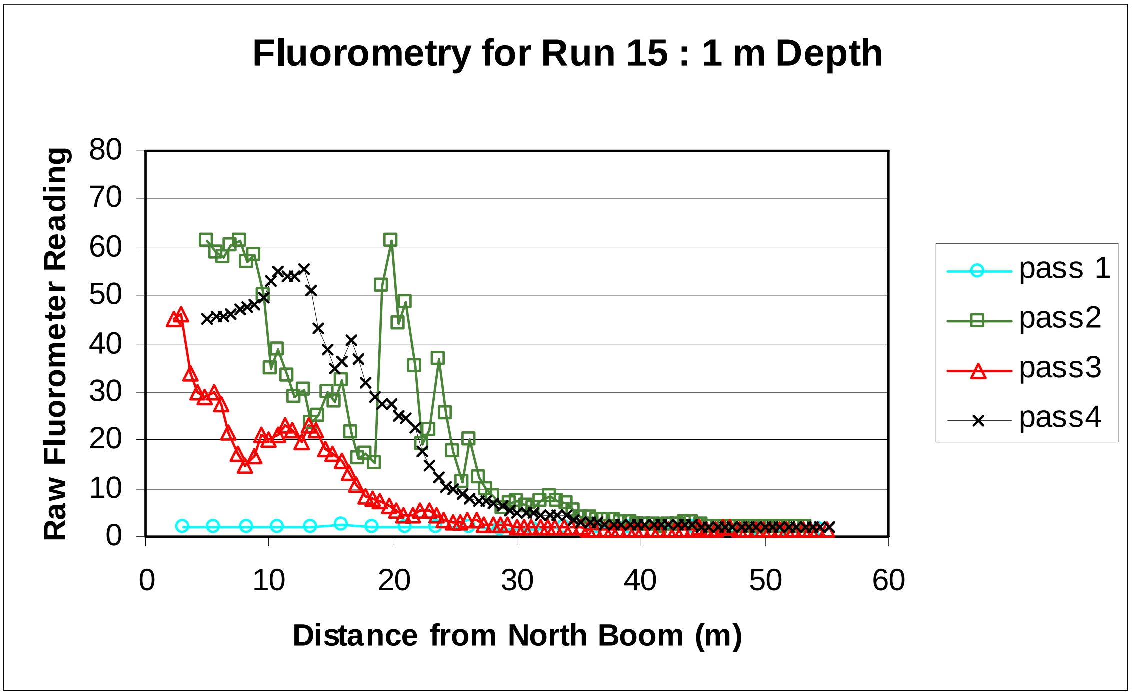

Fluorometry for Run 12 : 2 m Depth
Raw Fluorometer Reading
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

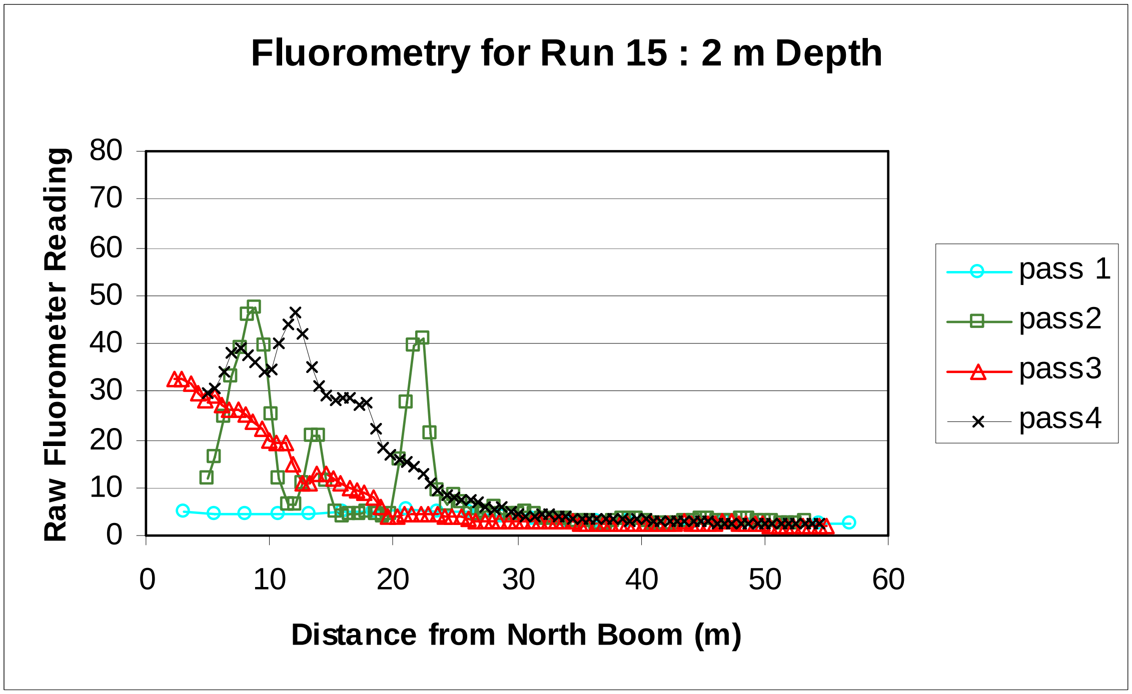

Fluorometry for Run 13 : 1 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

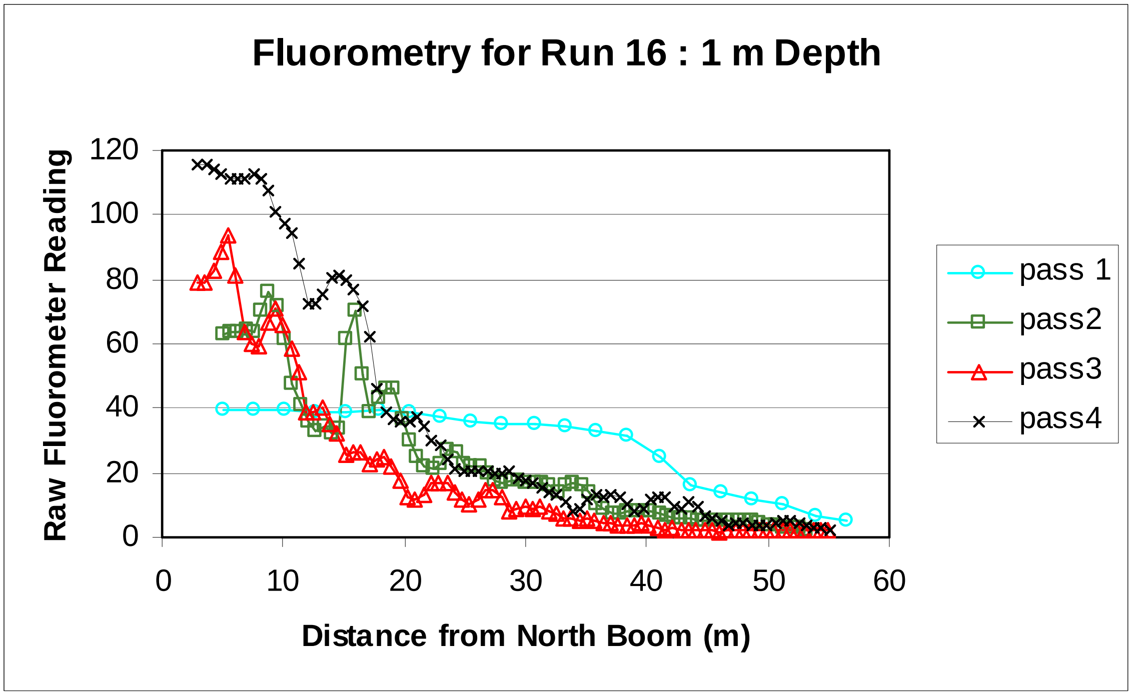

Fluorometry for Run 13 : 2 m Depth
Raw Fluorometer Reading
25
20
15
10
5
0
0
20
40
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

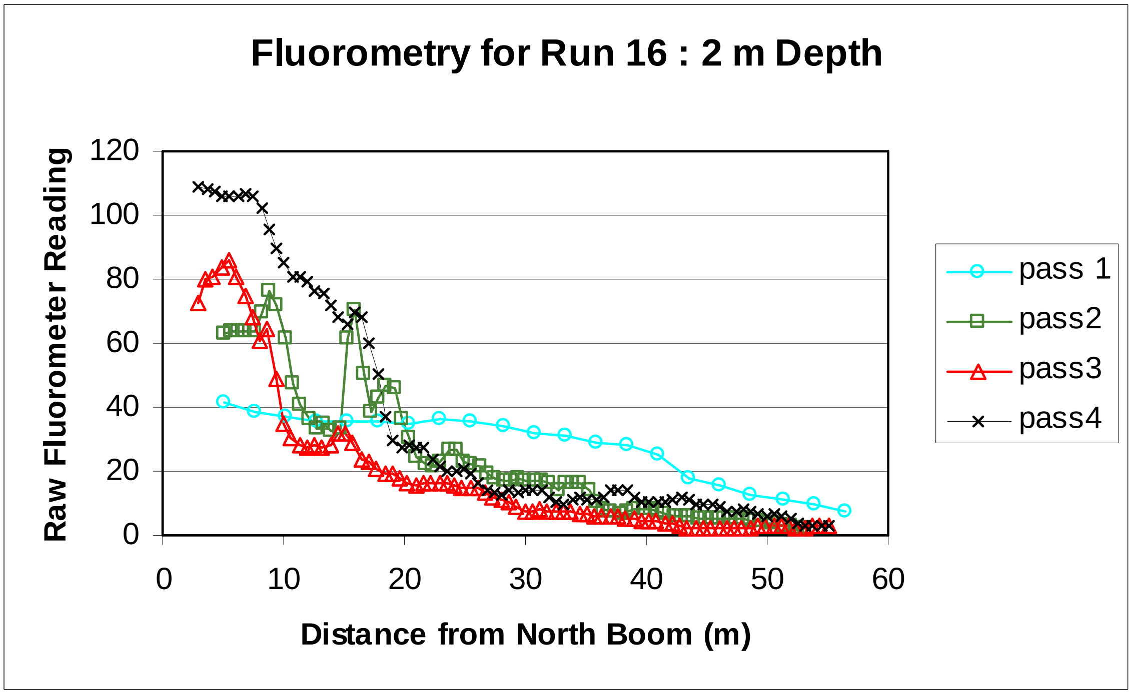

Fluorometry for Run 14 : 1 m Depth
Raw Fluorometer Reading
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

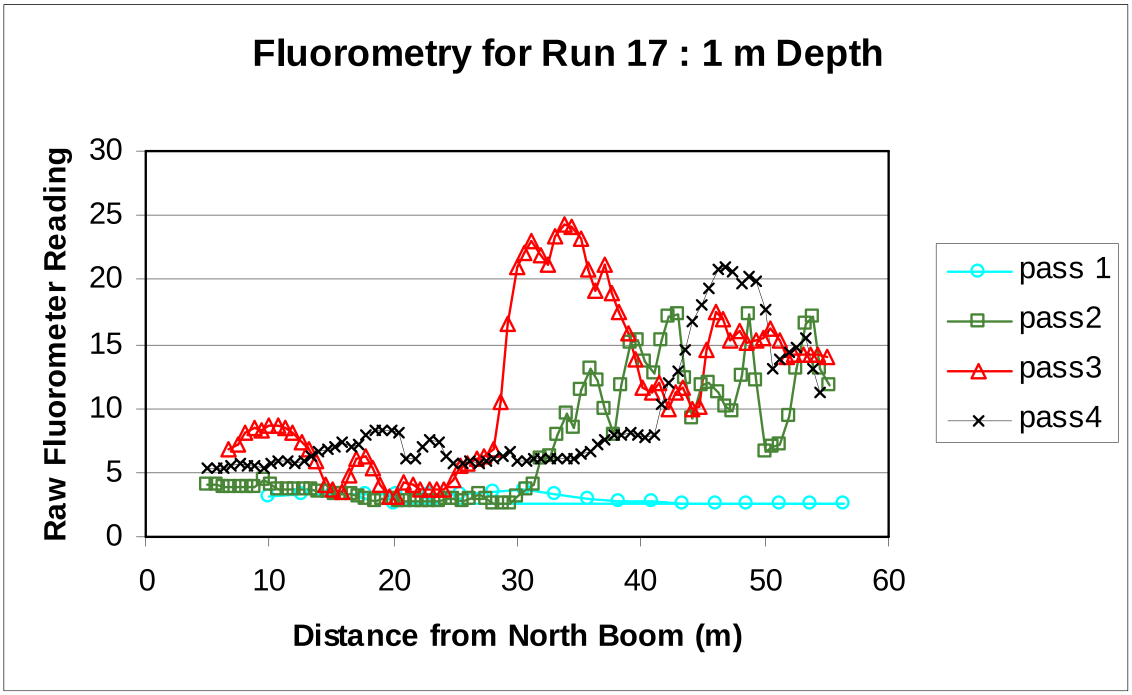

Fluorometry for Run 14 : 2 m Depth
Raw Fluorometer Reading
20
15
10
5
0
0
20
40
60
80
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

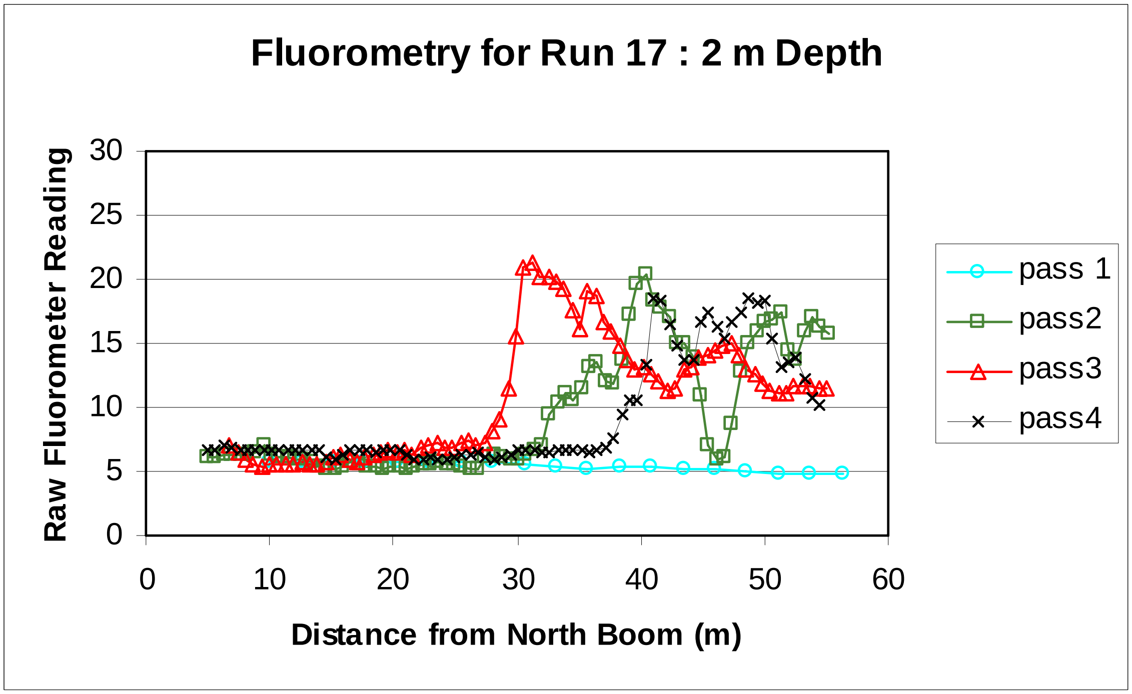

Fluorometry for Run 15 : 1 m Depth
Raw Fluorometer Reading
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

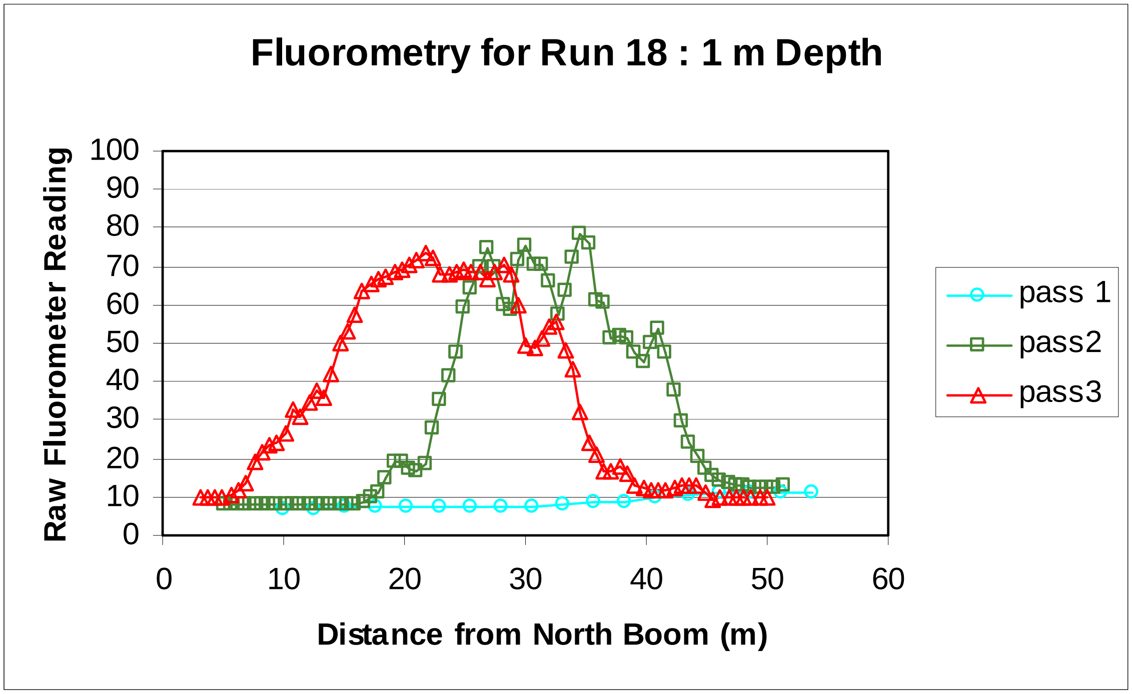

Fluorometry for Run 15 : 2 m Depth
Raw Fluorometer Reading
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

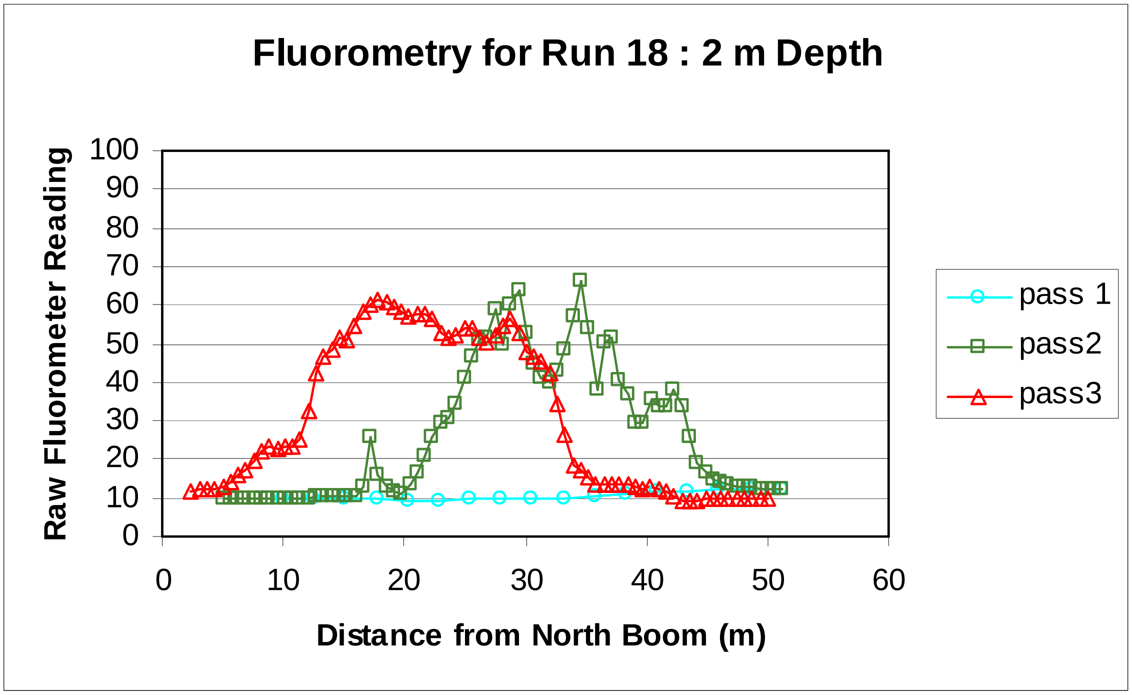

Fluorometry for Run 16 : 1 m Depth
Raw Fluorometer Reading
0
20
40
60
80
100
120
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

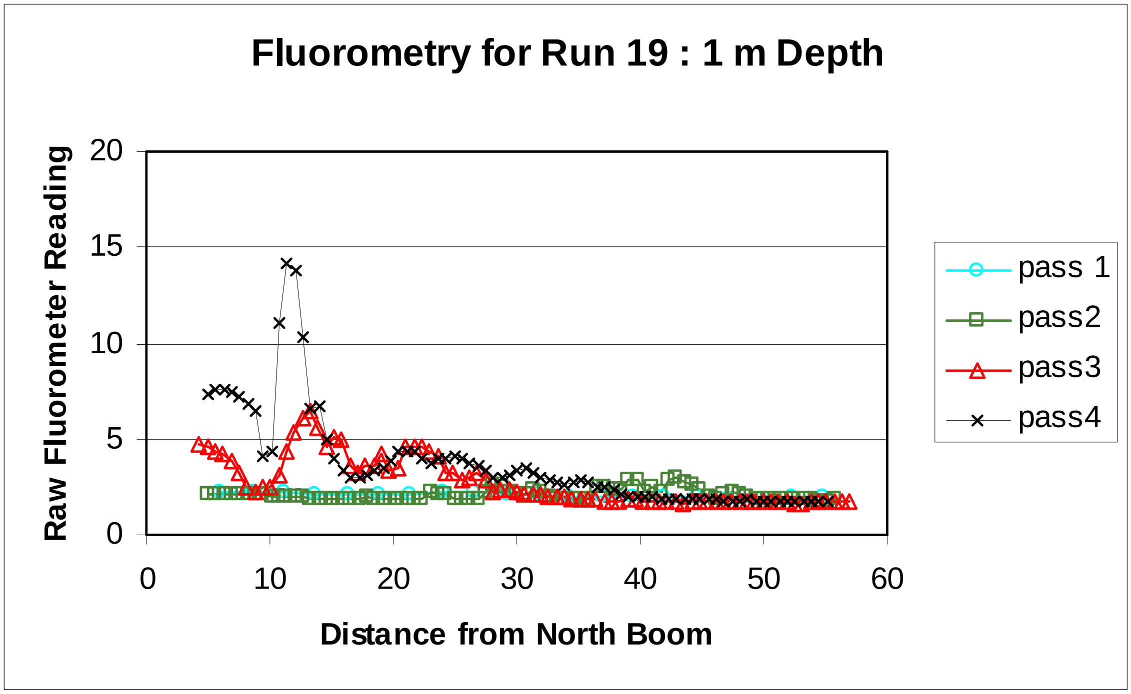

Fluorometry for Run 16 : 2 m Depth
Raw Fluorometer Reading
0
20
40
60
80
100
120
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4


Fluorometry for Run 17 : 1 m Depth
Raw Fluorometer Reading
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4

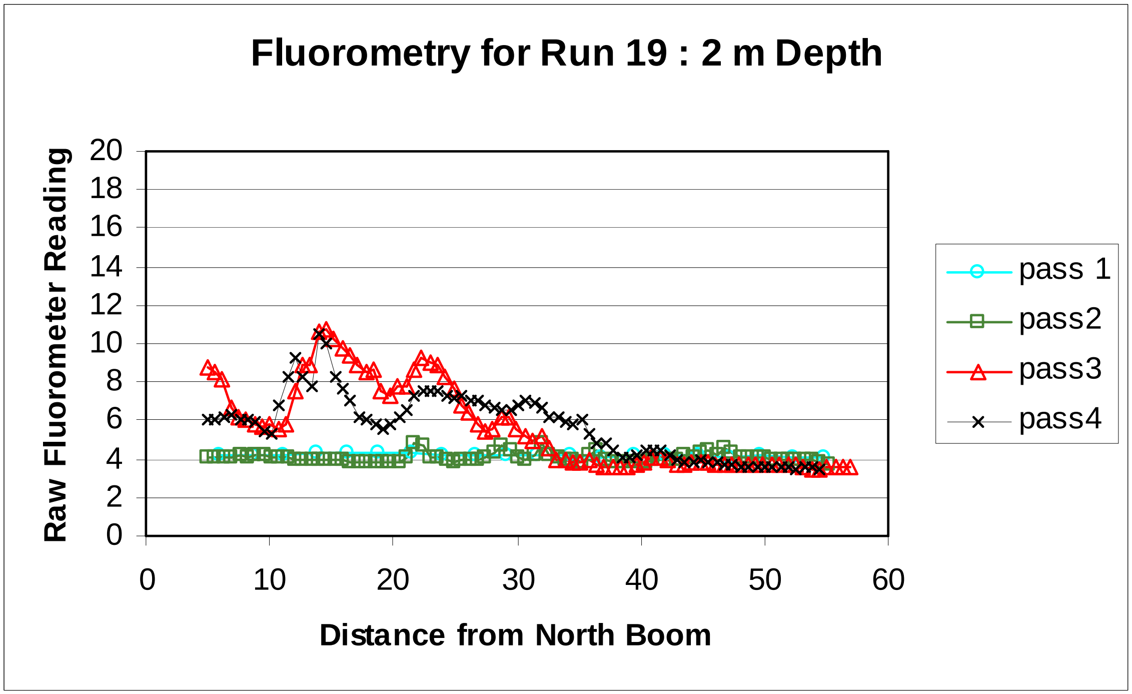

Fluorometry for Run 17 : 2 m Depth
Raw Fluorometer Reading
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4


Fluorometry for Run 18 : 1 m Depth
Raw Fluorometer Reading
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3

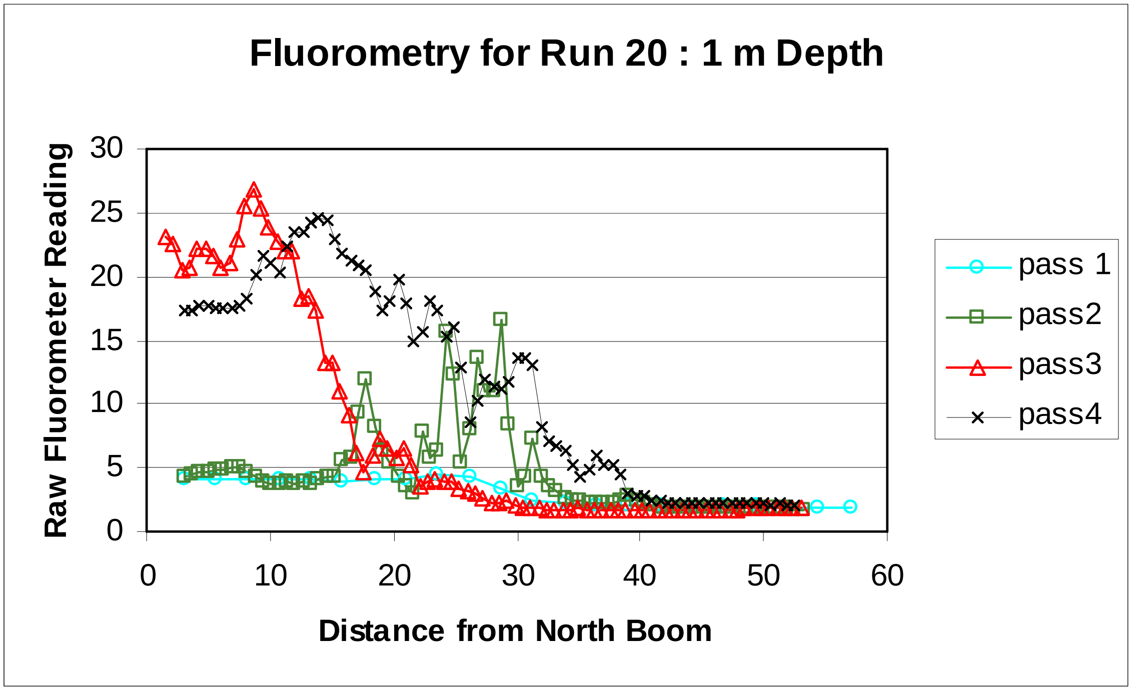

Fluorometry for Run 18 : 2 m Depth
Raw Fluorometer Reading
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3

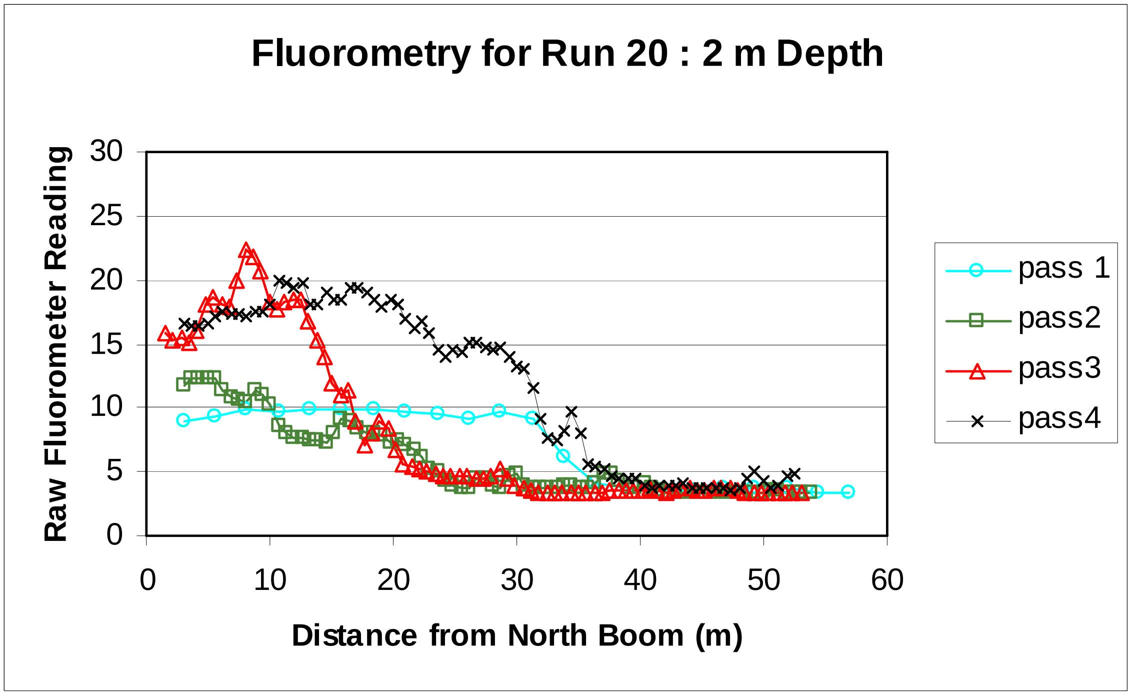


Fluorometry for Run 19 : 1 m Depth
Raw Fluorometer Reading
20
15
10
5
0
0
10
20
30
40
50
60
Distance from North Boom
pass 1
pass2
pass3
pass4



Fluorometry for Run 19 : 2 m Depth
Raw Fluorometer Reading
20
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
Distance from North Boom
pass 1
pass2
pass3
pass4


Fluorometry for Run 20 : 1 m Depth
Raw Fluorometer Reading
0
5
10
15
20
25
30
0
10
20
30
40
50
60
Distance from North Boom
pass 1
pass2
pass3
pass4


Fluorometry for Run 20 : 2 m Depth
Raw Fluorometer Reading
0
5
10
15
20
25
30
0
10
20
30
40
50
60
Distance from North Boom (m)
pass 1
pass2
pass3
pass4