

FINAL REPORT

OHMSETT DISPERSANT TEST PROTOCOL DEVELOPMENT

for

U.S. Department of the Interior

Minerals Management Service

Herndon, VA

by

SL Ross Environmental Research

Ottawa, ON

December 31, 2001

FINAL REPORT

OHMSETT DISPERSANT TEST PROTOCOL DEVELOPMENT

for

U.S. Department of the Interior

Minerals Management Service

Herndon, VA

by

SL Ross Environmental Research

Ottawa, ON

December 31, 2001

The project described in this report was funded by the U.S. Minerals Management Service (MMS) through Purchase Order 17092.

Executive Summary

The objective of this study was to develop and validate a technical protocol for testing dispersant effectiveness at the Ohmsett facility. Test results would be used to estimate field effectiveness of dispersants as a function of variables such as sea state, oil type and condition, slick thickness, dispersant type and dispersant dosage. The basic concept was to obtain benchmark data on the ability of dispersant tests at Ohmsett to reproduce effectiveness results obtained with similar tests at sea and in laboratory test methods.

The test variables were restricted to: oil viscosity; wave conditions and, dispersant dose rate. The test matrix involved two oil viscosities tested at two dispersant treatment rates and in two wave conditions: regular waves with different frequencies, one of which was high enough to cause some of the waves to begin to break, or crest. In the available time, five tests were conducted. In addition, a baseline “natural dispersion” test was conducted with the lowest viscosity oil.

The test results showed that realistic dispersant effectiveness testing at Ohmsett is feasible. The Ohmsett facility produced results during dispersant testing that were consistent with observations and measurements made at field trials. The test series also revealed that a suitable protocol can be devised that would enable a systematic investigation of test variables such as oil viscosity, dispersant treatment rate and sea conditions. The best way to measure dispersant effectiveness at Ohmsett appears to be collecting the surface oil following one hour of wave action. The experimental design employing booms to contain the treated slick that was used during this test series successfully minimised the ‘wall effects’ inherent in using any tank test, although larger booms are required.

The use of a 50/50 mix of diatomaceous earth and cellulose in the leaf filter allowed for effective removal of dispersed oil from the tank water in a period of one week. It was not possible to determine how quickly, or how efficiently, the activated carbon treatment system removed dissolved dispersant from the tank water. Further study of the removal of the dissolved dispersant by activated carbon is necessary, in order to ensure that the Ohmsett tank water can be returned to an acceptable quality for subsequent equipment testing. The analytical technique to detect dissolved dispersant in the tank water will also have to be improved.

Acknowledgements

The project described in this report was funded by the U.S. Minerals Management Service (MMS) through Purchase Order 17092. The authors of this report were Ian Buist and Alun Lewis. The authors would like to acknowledge the contributions of Mr. Jim Lane and Mr. Joe Mullin, with MMS, and the staff of MAR, Inc. who operate Ohmsett.

Disclaimer

This report has been reviewed by the U.S. Minerals Management Service staff for technical adequacy according to contractual specifications. The opinions, conclusions, and recommendations contained in this report are those of the authors and do not necessarily reflect the views and policies of the U.S. Minerals Management Service. The mention of a trade name or any commercial product in this report does not constitute an endorsement or recommendation for use by the U.S. Minerals Management Service. Finally, this report does not contain any commercially sensitive, classified or proprietary data release restrictions and may be freely copied and widely distributed.

Table of Contents

Executive Summary	i
Acknowledgements	ii
List of Tables	v
List of Figures	v
1. Introduction	1
1.1 Background	1
1.1.1 Advantages of Ohmsett	2
1.1.2 Previous Study on the Feasibility of Dispersant Testing at Ohmsett	3
1.1.3 Rationale for Protocol Development	4
1.2 Objective	5
1.3 Report Contents	5
2. The Dispersant Test Protocol	6
2.1 Test Concept	6
2.2 Test Variables and Test Matrix	7
2.3 Tank Preparations and Equipment Installation	8
2.3.1 Tank Filtration Systems	8
2.3.2 Test Oil Blending	10
2.3.3 Test Oil Slick Distribution System	13
2.3.4 Dispersant Spray System	18
2.3.5 Surface Slick Containment Boom	21
2.3.6 Dispersed Oil Sampling Systems	23
2.4 Data Acquisition	29

2.5 Procedures for a Typical Test	30
3. Protocol Test Results and Discussion	33
3.1 Test Results	33
3.1.1 Test 1 - Natural Dispersion with 2,000 cP Oil Blend	33
3.1.2 Test 2 - 2,000 cP Oil Blend Dosed at 1:25	36
3.1.3 Test 3 - Repeat 2,000 cP Oil blend dosed at 1:25	38
3.1.4 Test 4 - 2,000 cP Oil blend dosed at 1:25 in Non-breaking waves	40
3.1.5 Test 5 - 10,000 cP Oil blend dosed at 1:25	42
3.1.6 Test 6 - 10,000 cP Oil blend dosed at 1:10	43
3.2 Comparison with Field and Laboratory Data	45
3.2.1 Comparison with observations made at field trials	46
3.2.2 Comparison with results of laboratory studies	51
3.3 Tank Filtration	53
3.3.1 Dispersed Oil Removal	53
3.3.2 Dissolved Dispersant Removal	55
4. Conclusions and Recommendations	56
4.1 Conclusions	56
4.2 Recommendations	56
5. References	58

List of Tables

1	Detailed test summary	34 and 35
2	Dispersed oil removed by the leaf filter	54

List of Figures

1	Photo of activated carbon treatment system	9
2	Brookfield viscosity curve for oils, oil blends and Corexit 9500	11
3	Haake viscosity/temperature plots for oil blends	12
4	General layout	14
5	Oil pumping schematic	15
6	Oil spray bar detail	16
7	Photo of oil distribution manifold	17
8	Slick generated by oil distribution system	17
9	Dispersant pumping schematic	19
10	Photo of dispersant pump module	20
11	Photo of dispersant spray bar	20
12	Photo of boom rectangle	22
13	Photo of Turner AU-10 fluorometer	22
14	Submersible sampling pump schematic	24
15	Photo of fluorometers being calibrated	25
16	Fluorometer calibration curve for 2,000 cP oil blend	27
17	Fluorometer calibration curve for 10,000 cP oil blend	28

1. Introduction

1.1 Background

The major problem in developing a dispersant-use capability is deciding when to use dispersants and evaluating how effective they are or might be under a range of actual conditions. There are some situations where, historically, oil spill dispersants have been found to be effective at real oil spills, for example on freshly spilled crude oils in moderately rough seas in temperate climates (the *Sea Empress* is one case). At other incidents, such as spills of heavy fuel oil in cold, calm seas, dispersants have been found to not be effective. However, assessing the degree of effectiveness at real oil spill incidents is extremely difficult because there are normally too many unknown factors.

Translating the results of laboratory testing of dispersants into predictions of performance at sea have proved to be contentious. All laboratory test methods are poor simulations of the mixing processes that occur at sea and most were designed to give only a relative indication of dispersant performance under arbitrary mixing conditions. The agitation system used in different laboratory methods may simulate some aspects of performance under particular sea conditions. It has not proved possible, however, to unambiguously assign performance in a particular laboratory test method to performance at sea in all but the most generalized, indicative terms.

Despite their limitations, laboratory tests have proved useful in identifying the main parameters that govern dispersion, namely:

- oil properties, especially the apparent existence of a limiting oil or emulsion viscosity;
- sea-state; and,
- dispersant treatment rate.

The factors are inter-related. The effectiveness of a dispersant is therefore a function of the oil being dispersed and the prevailing sea-state as well as the dispersant being used and the rate at which it is applied. While one dispersant may be potentially more effective than another, it requires a combination of oil properties and sea-state for this to become apparent. An individual laboratory test

might reflect dispersant performance under a particular set of conditions at sea, but it is unlikely to provide information that is applicable to all sea conditions and all oils that might be dispersed.

Dispersant testing in ocean field trials has yielded good results, but these are only valid for the very narrow range of conditions that were experienced in the trials. In addition, there are fundamental problems with quantifying the effectiveness of dispersants at sea trials. It is not possible to determine dispersed oil concentrations in the sea underneath a treated oil slick at all locations and at all times during the dispersion process. Towed UVF (Ultra-Violet Fluorometry) provides a quantitative measure of the oil at discrete locations within the dispersing oil plume (or along transects), but simultaneous measurements cannot be made with enough resolution to calculate the total quantity of oil dispersed in the sea. Similarly, there is a problem with measuring the amount of oil on the sea surface. There is currently no method of visual observation or remote sensing that can accurately quantify the amount of oil on the sea surface at any stage of a dispersant sea trial. It is therefore impossible to construct an accurate mass balance of the quantities of oil on the sea surface or dispersed into the sea at any time during the experiment. The best that can be obtained is a semi-quantitative estimate by assessing all the data from various sources (including UVF and remote sensing).

1.1.1 Advantages of Ohmsett

The Ohmsett facility in New Jersey seems to be an ideal place for doing realistic dispersant testing. The two clear advantages over experiments at sea are (1) the ability to alter and control variables in a systematic way, and (2) the much lower costs of the testing, compared to testing at sea. These are the same advantages that have justified the activity at Ohmsett in the area of boom and skimmer testing. As with the testing of mechanical cleanup equipment, the main idea with dispersants is to do testing with a view toward predicting product performance over a range of actual spill conditions.

There are also two main advantages of Ohmsett over laboratory systems. The first is that Ohmsett does much better in simulating a range of sea state conditions than laboratory systems do. The second is that dispersant spray systems can be tested at full scale at Ohmsett. This does not mean that aircraft

need to be used to apply dispersant, but that the spray nozzles and pumps used in the full-scale systems can be used at the Ohmsett trials. This is a major advantage because the drop size distribution of the dispersant spray is likely an important parameter.

1.1.2 Previous Study on the Feasibility of Dispersant Testing at Ohmsett

Considering the above advantages and the current interest in dispersant-use, SL Ross and MAR, Inc., the operators of Ohmsett examined various ways that dispersant testing at Ohmsett might be accomplished and evaluated their feasibility and costs. The final report on the study was completed in March 2000 (SL Ross 2000). The following is a very brief description of the major tasks in the study and their results:

1. Interfacial tension tests were performed to determine the critical concentration of dispersant in the tank water that could affect subsequent tests involving boom and skimmer work. It was found that a few ppm of dispersant in the water are enough to lower the interfacial tension of floating oil. The conclusion was that the tank will have to be thoroughly cleaned of dispersant after a dispersant testing program.
2. Experiments were done in the laboratory to determine the effect of residual dispersant in the tank water on dispersant effectiveness tests. It was found that many dispersant experiments could be done sequentially without concern for dispersant in the water affecting the results.
3. Turbidity tests were conducted to determine the critical concentration of dispersed oil in the tank that would prevent underwater viewing of the dispersant tests. It was found that a few ppm of dispersed oil would be enough to cloud the tank water. This means that only the first of a day's dispersant tests would be visible underwater. This poor result was not considered crucial because it does not affect in-water sampling and quantitative measurements, the key elements of any program to evaluate dispersant effectiveness.
4. A preliminary design of a dispersant testing program was completed to determine, among other things, how many consecutive dispersant experiments could be done before the

concentration of residual oil dispersed in the tank water would make measurements of dispersant effectiveness in subsequent tests difficult or impossible. It was determined that two or three dispersant experiments could be done sequentially before critical concentrations of dispersed oil would be reached, at which point the tank water would need to be filtered to reduce oil concentrations. An appropriate location of the tests in the tank (i.e., near the “beach” end of the tank where the filter intake is located) should allow this filtering to be completed overnight.

5. Tests to assess the current filter system were performed to determine whether the current filtering material used at Ohmsett, namely, diatomaceous earth (DE), was able to remove mechanically dispersed oil, chemically dispersed oil and dispersant chemicals themselves. It was found that the DE was inadequate in all cases.
6. Research was undertaken to find better filter materials and to test them in the laboratory. A cellulose product was found to perform well at removing dispersed oil droplets. Full-scale testing at Ohmsett in October 1999 confirmed the laboratory work and the ability of the cellulose filter aid to remove dispersed oil from the tank water using the existing filtration system at a normal throughout.
7. Initial qualitative tests with activated carbon indicated that it would effectively remove dissolved dispersant from Ohmsett water, allowing the tank to be readied for conventional mechanical equipment tests after a dispersant test program.

Generally, the results of the feasibility study were promising, indicating that dispersant effectiveness testing at Ohmsett would be able to be done efficiently and relatively inexpensively.

1.1.3 Rationale for Protocol Development

If it is decided that dispersant effectiveness testing at Ohmsett is both feasible and desirable, the next logical step would be to develop a standard protocol for such testing. The concept is to have a test procedure in place – similar to the Ohmsett test protocol for booms and skimmers – that is accepted

by the oil spill response community as being the standard for realistic dispersant effectiveness testing in the U.S. Users of Ohmsett who pay for standard-testing services will expect that any test methodologies be proven and not experimental. Therefore, the protocol for dispersant effectiveness testing must be well designed and validated through a series of trial-and-error experiments at Ohmsett.

1.2 Objective

The objective of this study was to develop and validate a technical protocol for testing dispersant effectiveness at the Ohmsett facility. Test results would be used to estimate field effectiveness of dispersants as a function of variables such as sea state, oil type and condition, slick thickness, dispersant type and dispersant dosage.

Dispersant effectiveness in the Ohmsett facility will be defined as a combination of:

- (i) the rate at which the test oils are dispersed into the water, as measured by UVF (Ultra-Violet Fluorometry) at locations in the water, during the first hour after the application of dispersant;
- (ii) the proportion of oil dispersed into the water after an hour as assessed by recovery of the oil remaining on the surface; and,
- (iii) the amount of oil “permanently” dispersed in the water after the surface oil is recovered by mixing the water with harbor chop waves for one hour, then measuring the dispersed oil concentrations with UVF along transects through the oil cloud.

1.3 Report Contents

Section 2 of the report describes the test protocol equipment and procedures. Section 3 contains the results of six tests with Corexit 9500 on two types of fuel oils to determine the efficacy of the test protocol. The results are also compared to other test data sets. Section 4 lists the conclusions and recommendations arising from the study. The appendices contain raw and processed data.

2. The Dispersant Test Protocol

2.1 Test Concept

The basic concept of these tests was to obtain benchmark data on the ability of dispersant tests at Ohmsett to reproduce effectiveness results obtained with similar tests at sea and in laboratory test methods. Intermediate Fuel Oil (IFO) blends were selected because they have been used in field trials for which good data exists, are easy to obtain and prepare on-site, and do not weather (evaporate or emulsify) significantly during the one-hour test period. Laboratory dispersant effectiveness data with several standard test protocols (Labofina/WSL, IFP and Swirling Flask) also exist for these fuels.

The plan was to apply a chemical dispersant (Corexit 9500) to meso-scale (100 L), long (20 m), narrow (5 m), 1 mm-thick test slicks of two blends of Bunker C heavy fuel oil and Marine Diesel Oil (MDO). These oil blends were to be produced to simulate different grades of IFO, namely IFO 80 and IFO 180¹. The precise proportions of Bunker C and MDO were to be adjusted to produce fuels oils that have viscosities of 2,000 and 10,000 cP at the prevailing water temperature at the time of the tests. These oils were to be treated with dispersant in different wave conditions and the rate of oil dispersion during the first hour and the percent of the surface slick dispersed after one hour measured.

Two techniques were evaluated for determining dispersant effectiveness:

- In-water sampling using Turner Model AU-10 fluorometers, and solvent extraction/IR analysis, both during the test period and after the test section of the tank has been thoroughly mixed laterally.
- Skimming and measuring the amount of oil remaining on the water surface one hour following dispersant application.

In order to optimize underwater visibility to allow underwater video of each test, each successive test would be conducted in a “clean” section of the tank. This would also minimize downtime. The first

¹ The number in the IFO series of fuel oils denotes the target viscosity of the oil blend (cSt) at 50°C.

test was intended be run near the north end (i.e., the beach end) of the tank where the inlet to the filtration system is located. After the first test had run its course, the next test would start 10 m or so south of the end point of the first test, in a section of clean water. A slick length of 20 metres was chosen to allow three tests to be conducted in clear water in a 100-m length of the tank, approximately one-half of the total length. The reason for beginning near the north end of the tank was to allow for the water containing dispersed oil from the three tests to be treated overnight by the filter system. The next day, clean water from the south end of the tank would have been moved to the north end, and be ready for testing.

2.2 Test Variables and Test Matrix

The test variables were restricted to:

- Oil viscosity;
- Wave conditions and,
- Dispersant dose rate.

The following parameters were not varied during the tests:

- Slick dimensions (20 m x 5 m x 1 mm);
- Dispersant application time (the dispersant will be applied to fresh oil shortly after it has been released);
- Tank salinity (35 ppt); and,
- Tank water temperature.

The test matrix involved two oil viscosities tested at two dispersant treatment rates and in two wave conditions: regular waves with different frequencies, one of which was high enough to cause some of the waves to begin to break, or crest. In the available time, five tests were conducted. In addition, a baseline “natural dispersion” test was conducted with the lowest viscosity oil.

2.3 Tank Preparations and Equipment Installation

2.3.1 Tank Filtration Systems

Most present-day dispersants are designed to operate best in full-salinity sea water. In fact, many lose effectiveness if the salinity drops too low (Blondina et al. 1999). In order to bring the salinity of the Ohmsett water to the 33 to 35 ppt range, 118 tonnes (130 tons) of road salt was added to the tank. This addition of such large quantities of salt to the tank caused a reduction in water clarity. This was presumably caused by insoluble fines associated with the bulk salt. These settle out before they reach the filter intake, and must be removed by vacuuming the tank bottom, using standard procedures.

The filtration system was prepared for two-weeks operation with Pre-Co-Floc PB-100M cellulose filter aid with a pre-coat of 30 lbs/100 ft². The normal filter sluicing criteria of exceeding a 50-psi pressure drop across the membrane did not ensure that the filter was removing dispersed oil drops efficiently. Therefore, the oil content of the effluent from the filter system was sampled regularly during the tests to ensure that the filter was operating effectively, and to gain operating experience with the Pre-Co-Floc filter aid. Of particular interest was the time needed for the filtration process to return the tank water to regular, background oil concentrations (ca. 3 to 5 ppm).

A portable activated carbon adsorption system, with a capacity of 9,000 kg (20,000 lbs.) was also obtained to remove dissolved dispersant from the tank water after the test program was complete and the filtration system had removed most of the dispersed oil. The portable activated carbon treatment system was erected next to the filter system, on the east side of the tank (Figure 1).

Figure 1 - Photo of Portable Activated Carbon Treatment System



2.3.2 Test Oil Blending

Electrical resistance heating bands were used to warm the drums of No. 6 fuel oil for blending. The mixtures of various oils made up to the desired viscosity for the tests were blended in an open-topped 55-gallon drum using a portable mixer with propellor-type blades. The appropriate portions of the oils added to the blend were measured by weighing the drum using a hoist and mechanical scale. The appropriate proportions of the oil blend were estimated from viscosity/temperature plots using ASTM D341 – Appendix A.

Figure 2 shows a viscosity vs. temperature plot for the No. 6 fuel oil, Sundex 790 (a standard Ohmsett test oil), the resultant blends of the two oils, and the dispersant Corexit 9500. It is apparent from this plot that the No.6 fuel oil was less viscous than 2,000 cP at 11.7 °C (the tank water temperature). As such, it was necessary to abandon the plan to dilute the No. 6 with diesel fuel and use the No. 6 to dilute Sundex 790 to the appropriate target viscosities. The recipes for the two test oils were:

$$2,000 \text{ cP Oil blend} = 20 \text{ wt\% Sundex 790} + 80 \text{ wt\% No. 6}$$

$$10,000 \text{ cP Oil blend} = 90 \text{ wt\% Sundex 790} + 10 \text{ wt\% No. 6}$$

The data shown on Figure 2 was obtained with a Brookfield viscometer, a relatively simple, easy to use device. With this tool, the viscosities of the two blends at the tank water temperature were 2,000 cP and 6,500 cP. Figure 3 shows a viscosity vs. temperature curve for the two oil blends generated with a cone-and-plate viscometer (the Haake model VT550 fitted with an SV 1 sensor). This device is capable of more sophisticated rheological measurements than the Brookfield viscometer. The viscosity of the oil blends (measured at a constant shear rate of 100 s^{-1} for the 2,000 cP oil blend and 10 s^{-1} for the 10,000 cP oil blend) at the tank temperature were 3,725 and 19,640 cP. The difference in the measurements from the two viscometers is likely related to the fact that they measured the fluids' characteristics at different shear rates (the Brookfield tends to use low shear rates, on the order of 1 s^{-1} while the Haake was set at 10 or 100 s^{-1}). The different results are a reflection of the fact that the oil blends likely exhibited non-Newtonian rheology. Full data printouts on the oils may be found in Appendix B.

Figure 2 - Brookfield viscosity curves for oils, oil blends and Corexit 9500

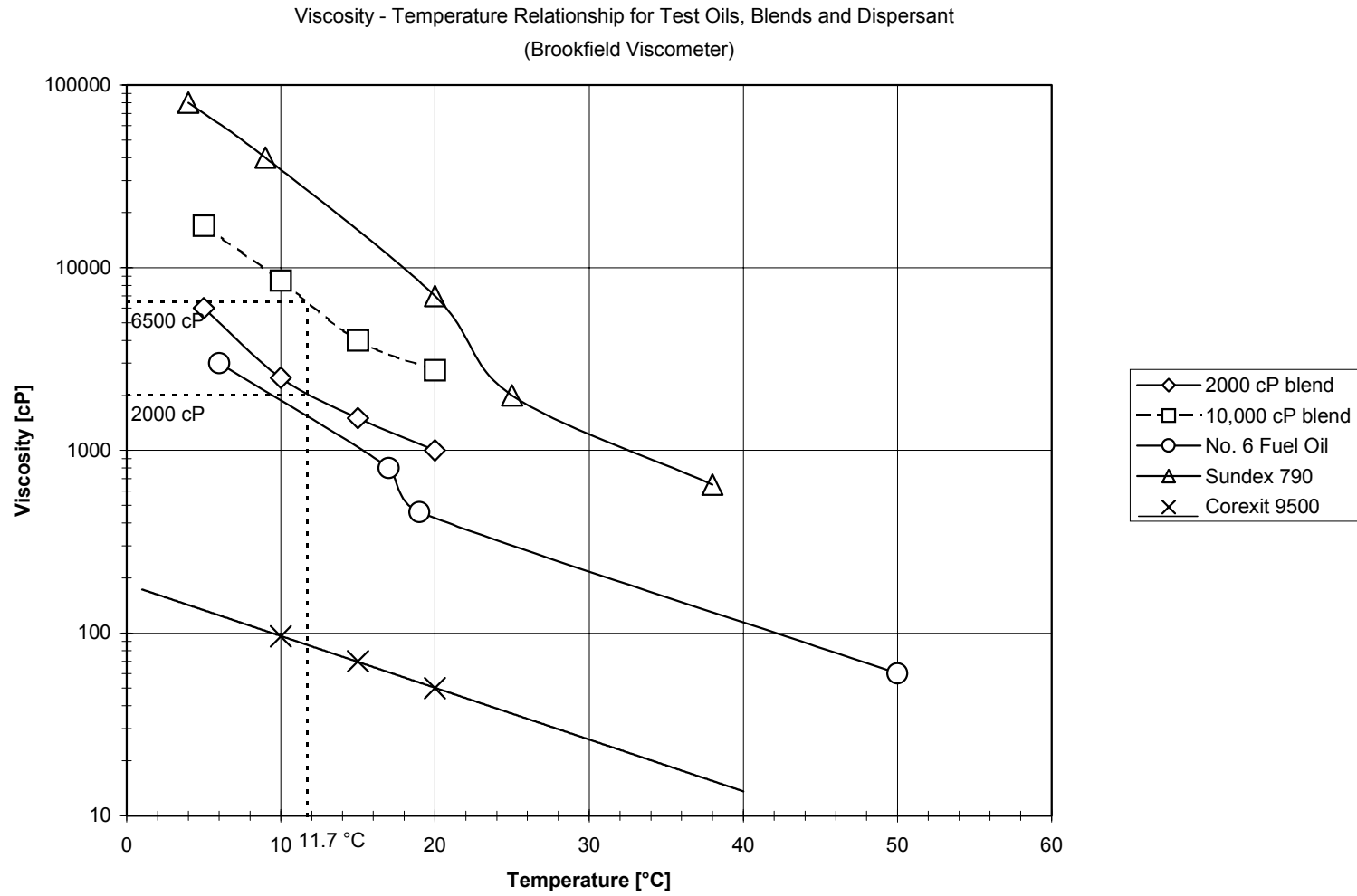
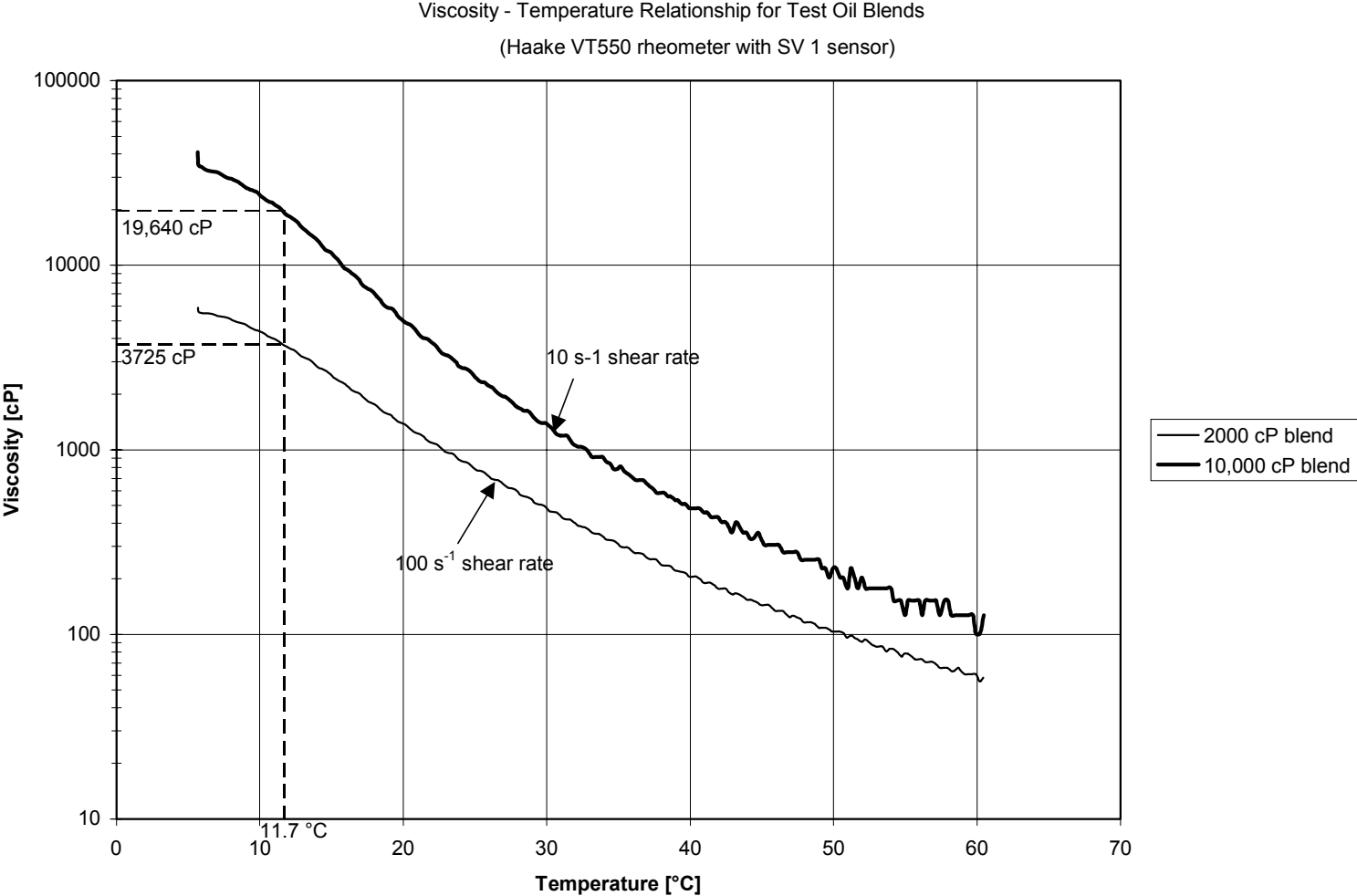


Figure 3 - Haake viscosity/temperature plots for oil blends



2.3.3 Test Oil Slick Distribution System

The layout of the various components of the dispersant test system is shown on Figure 4.

A metered oil release system that could accurately measure 100 L volumes was assembled on the Main Bridge. It was used to distribute oil from the north side of the Main Bridge onto the water along the centerline of the tank to produce a slick 5 m wide and 1 mm thick. The oil distribution schematic is shown in Figure 5. The oil feed tank was a 55-gallon drum filled with the appropriate blend of test oil. The suction hose from a portable gear pump (Viking LS 4124 - 110 gpm @ 350 rpm) was inserted into the drum to draw oil for a test. The pump was plumbed to continuously recycle oil through itself; flow control was achieved by adjusting a valve on the recycle pipe. The flow rate of oil was determined by measuring the depth of oil remaining in the drum as a function of time, both manually and by recording the output from a portable ultrasonic level sensor mounted above the drum.

The discharge from the pump was fed to the inlet of a specially-designed oil distribution manifold (Figure 6) designed to create slicks 5 m wide with the bridge moving at speeds on the order of 0.5 m/s (1 knot). The desired slick thickness was produced by matching a given bridge speed with a pump rate. The flow from the oil pump was started by operating pneumatic valve actuators that opened valves on the six nozzle assemblies mounted to the manifold. The oil then flowed into horizontal PVC pipes that had been slotted along most of their length to distribute the oil onto the water surface. For each test, the manifold was adjusted such that the slotted pipes were positioned just above the water surface (Figures 7 and 8). This meant that, when the waves were running, the oil distribution nozzles would be immersed in the peaks of the waves. For future dispersant tests, it would be advantageous to modify the oil distribution manifold to swing up out of the way after the test slick has been laid down.

For the tests with the higher viscosity oil it was necessary to heat the oil in the drum, using clamp-on electrical band heaters, to reduce its viscosity enough to allow pumping at high enough rates.

Figure 4 - General Layout

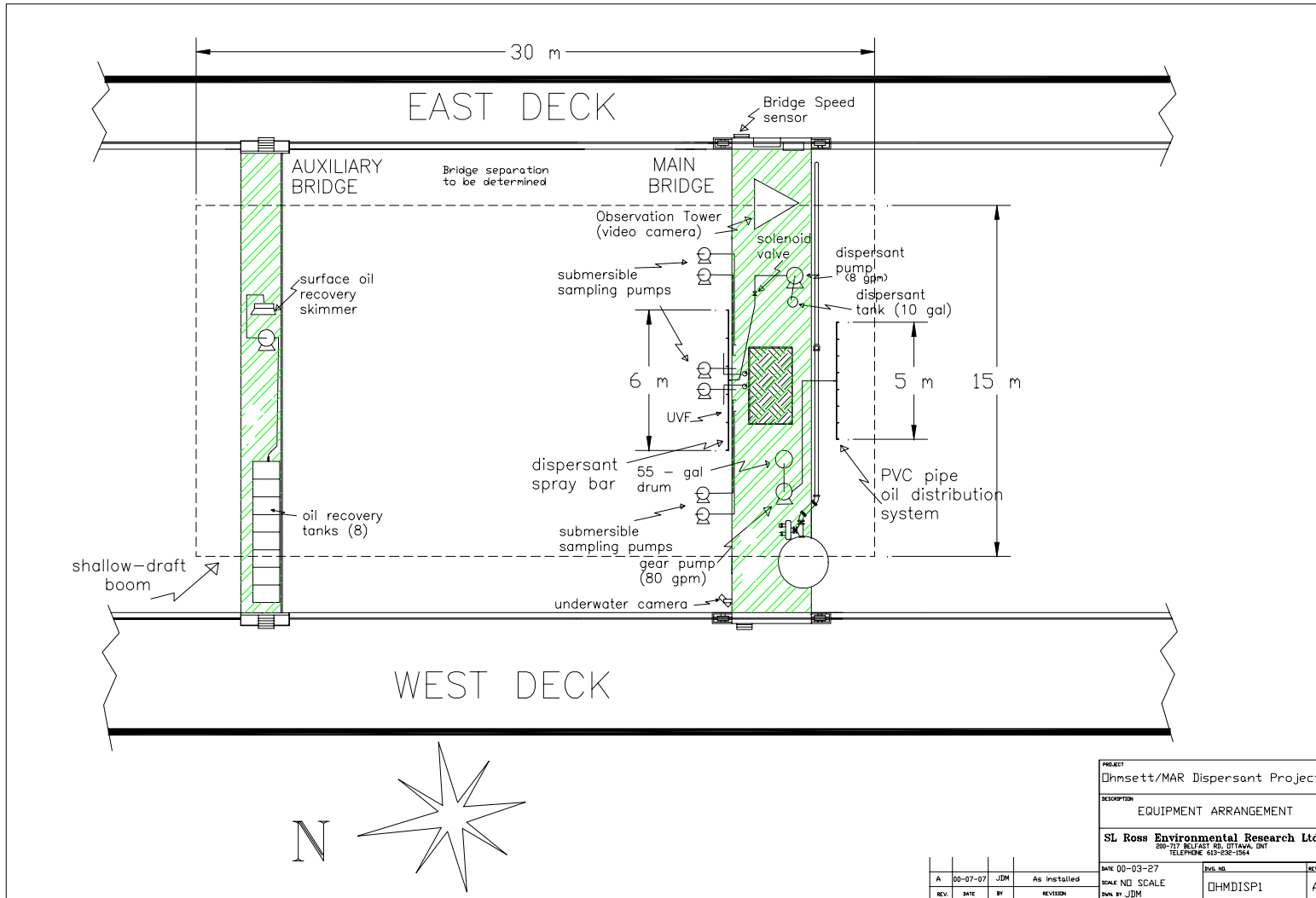


Figure 5 - Oil Pumping Schematic

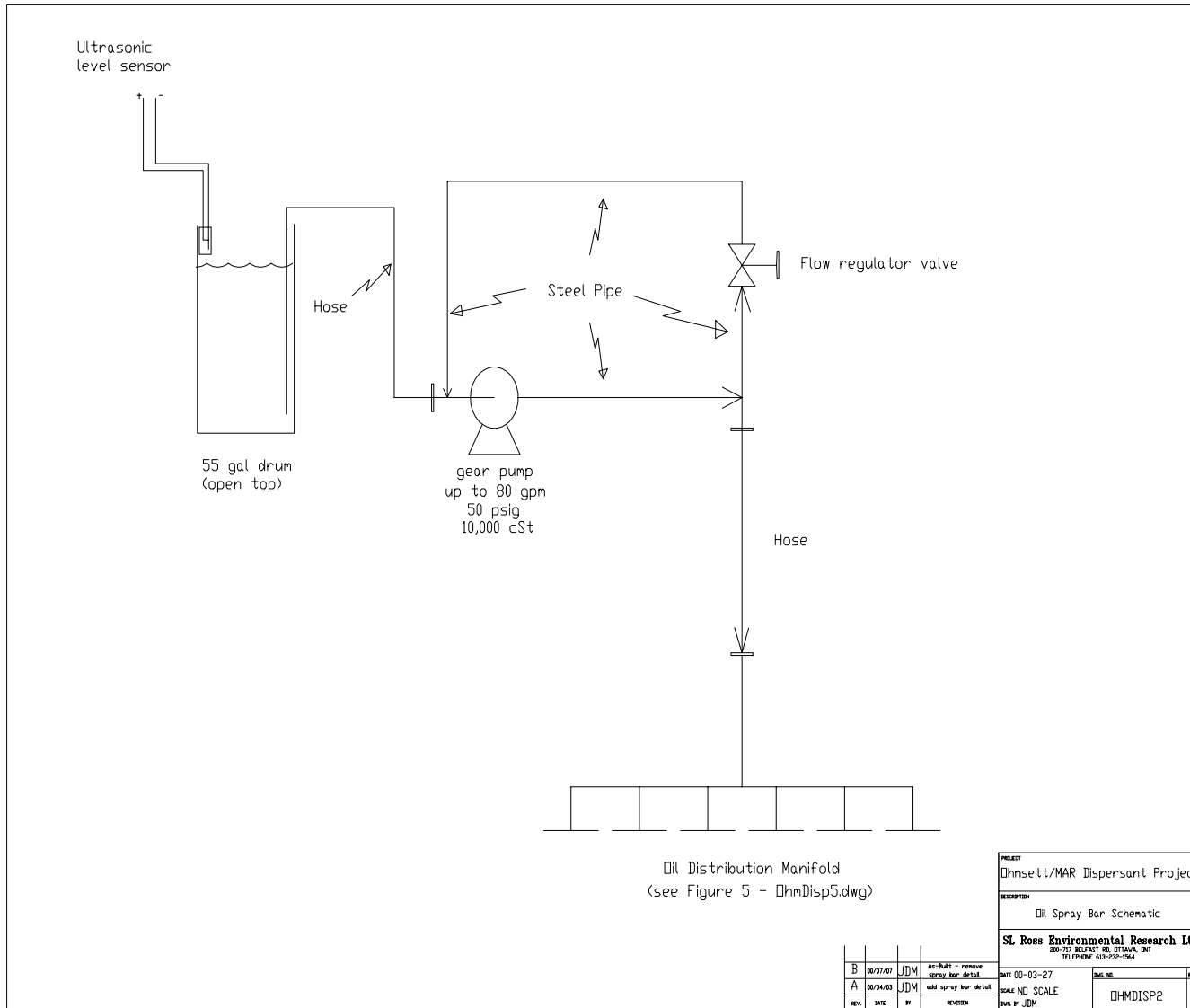


Figure 6 - Oil Spray Bar Detail

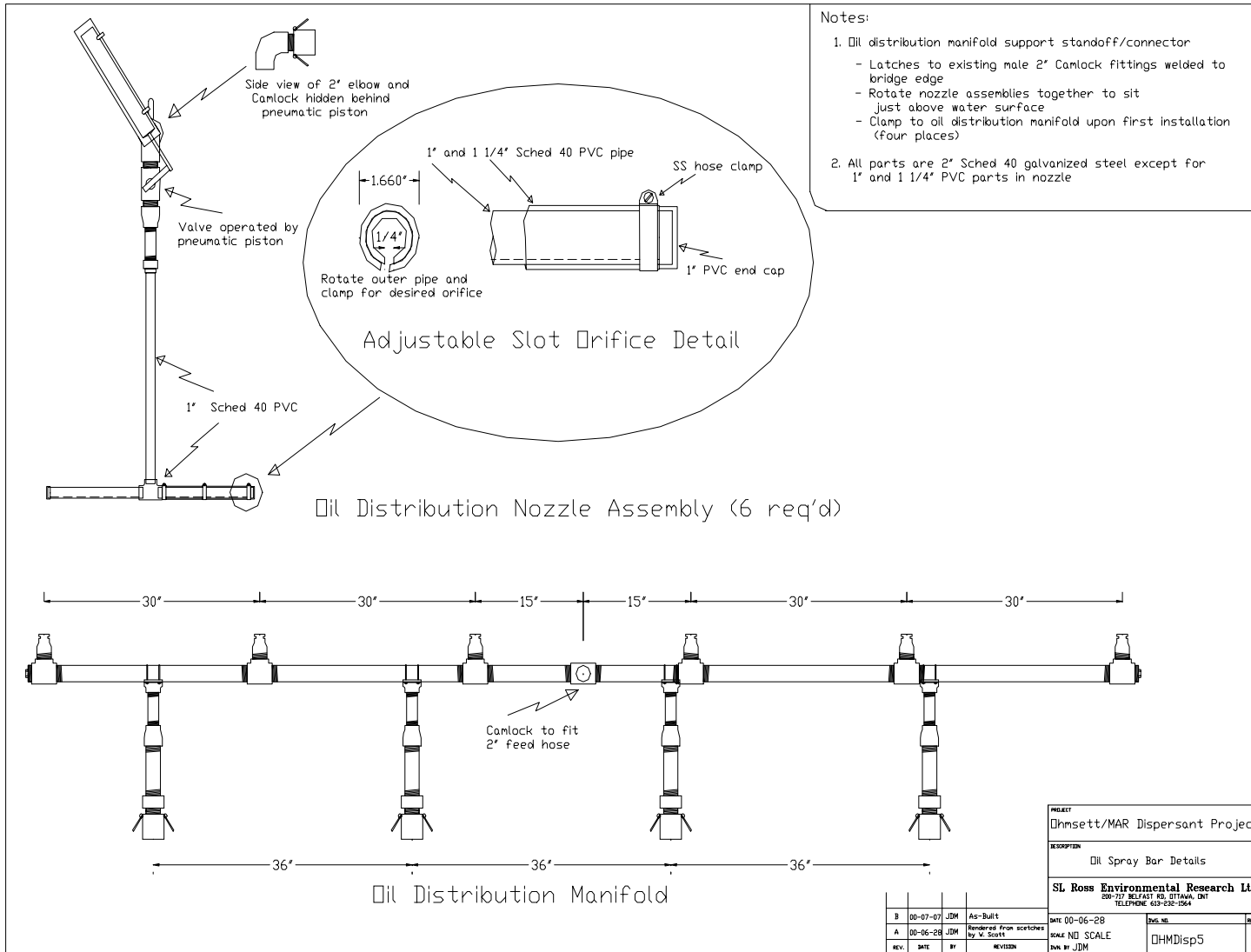


Figure 7 - Photo of Oil Distribution Manifold

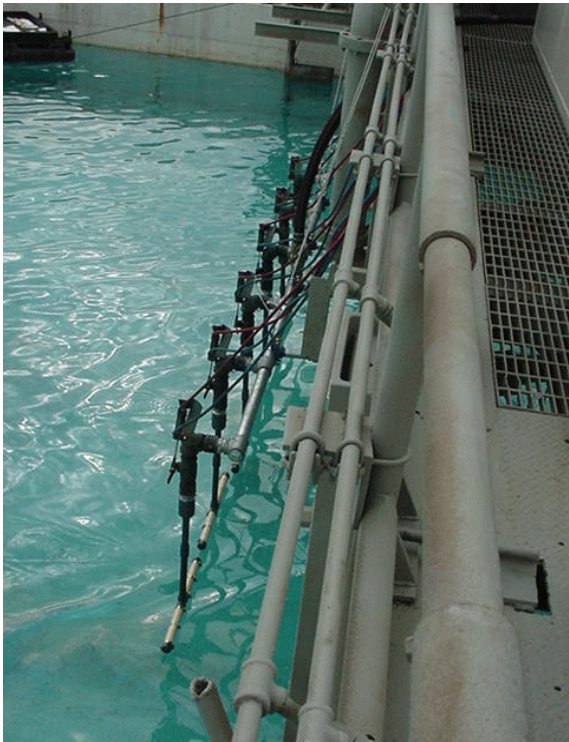
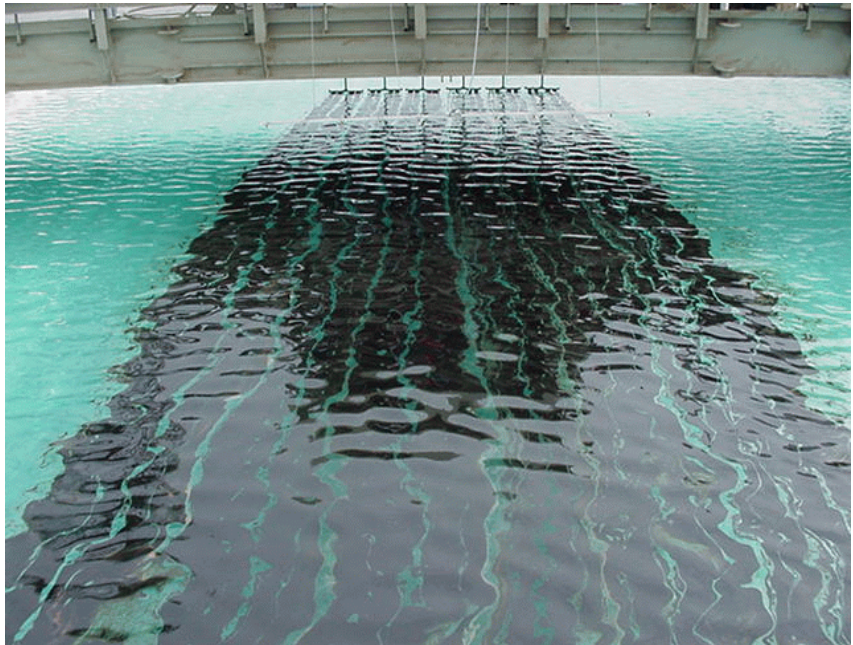


Figure 8 - Slick Generated by Oil Distribution System



2.3.4 Dispersant Spray System

A dispersant spray system (Figure 9) was assembled, calibrated and mounted on the south side of the Main Bridge (see Figure 4). The system consisted of a pump and pressure control module (Figure 10) connected to a spray bar (Figure 11). The spray bar itself comprised 11 Spraying Systems Quick UniJet 40° flat fan spray nozzles mounted on a piece of aluminum angle set about 2 metres above the water surface, centered on and spanning the width of the test slick. The height of the spray bar was adjustable and it was easily accessible in order to change nozzle tips to adjust dispersant dosage. The dispersant spray system was designed to deliver a uniform distribution of appropriate-sized dispersant droplets over a width of 6 m (slightly wider than the test slick) at design dose rates of 1:10, 1:25 and 1:50 dispersant:oil. Several different sets of interchangeable nozzle tips were obtained to cover this range of application rates. Based on the nozzle manufacturers data, 25° nozzles should have provided the correct spray angle, and when tested and calibrated with tap water (following ASTM F 1460 - 93), they did (see Appendix C). However, when the Corexit 9500 dispersant was cold, it was quite viscous (see Figure 2), which dramatically reduced the spray angle achieved by the nozzles. This problem was solved by substituting 40° nozzles for the 25° ones, raising the spray bar and angling it upwards (pointing north) from vertical. This, combined with heating the dispersant by recirculating it through the gear pump, allowed good spray patterns to be achieved.

The dispersant spray system was fed by a small gear pump capable of delivering up to 0.5 L/s (8 gpm) at a constant pressure of 40 psig to ensure the flow and spray pattern of the nozzles was correct. A relatively low-pressure delivery system was used to avoid excessive dispersant losses as fine spray. Plastic tubing was used to connect the pump module and nozzles. The pump module piping system was designed to allow constant operation of the pump by recycling the flow back to the dispersant supply tank/drum, with dispersant fed to the spray nozzles only when an electric solenoid valve was held open. This allowed positive on/off control of the dispersant spray. It also allowed the dispersant to be warmed by recycling it through the gear pump. Electric heat tracing was also added to the recycle line from the pump discharge back to the dispersant tank to assist with the heating. In order to ensure that the dispersant sprayed on the test slick was applied correctly, it was necessary before each test to waste the cold dispersant onto the tank water outside of the test area,

Figure 9 - Dispersant Pumping Schematic

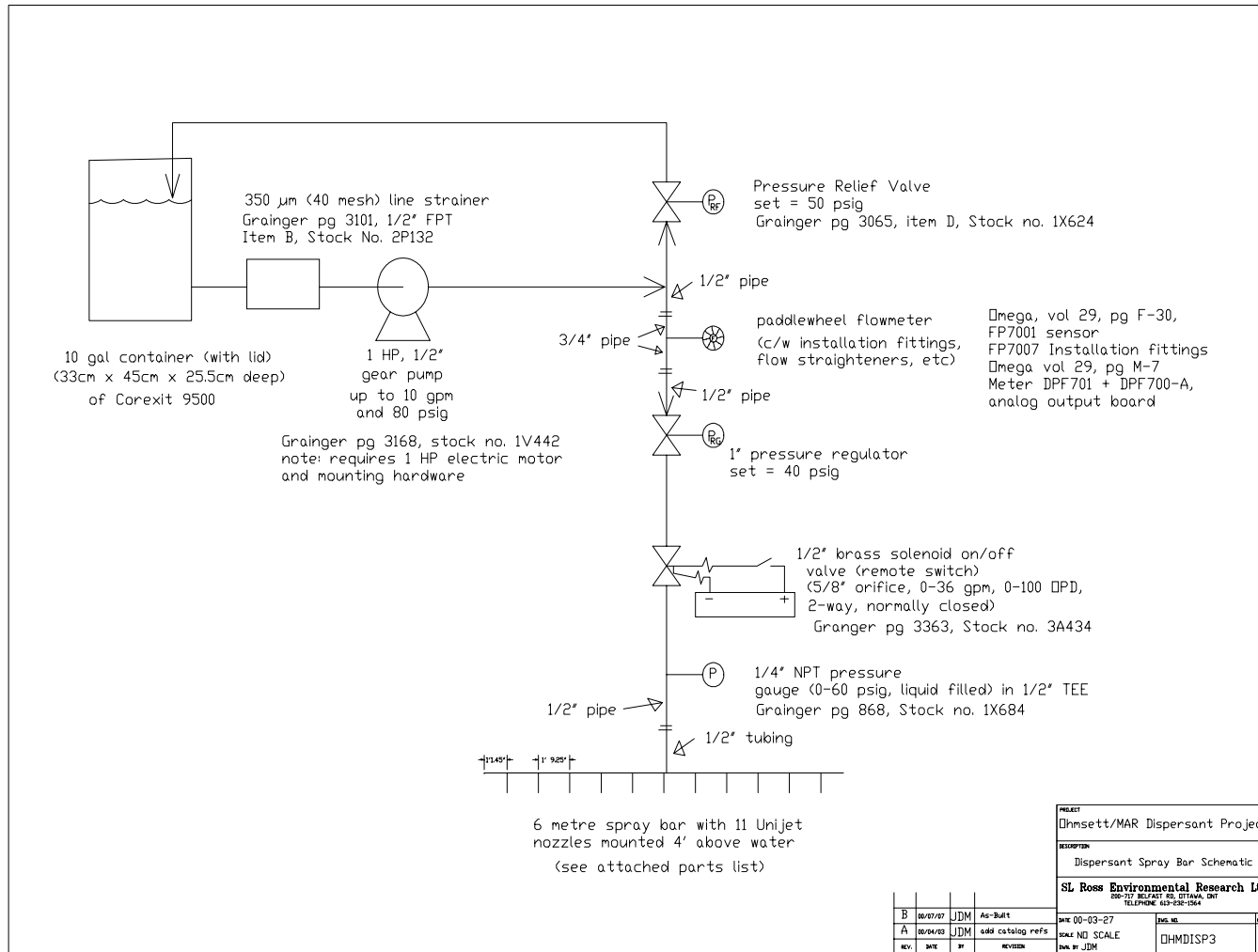


Figure 10 - Photo of Dispersant Pump Module

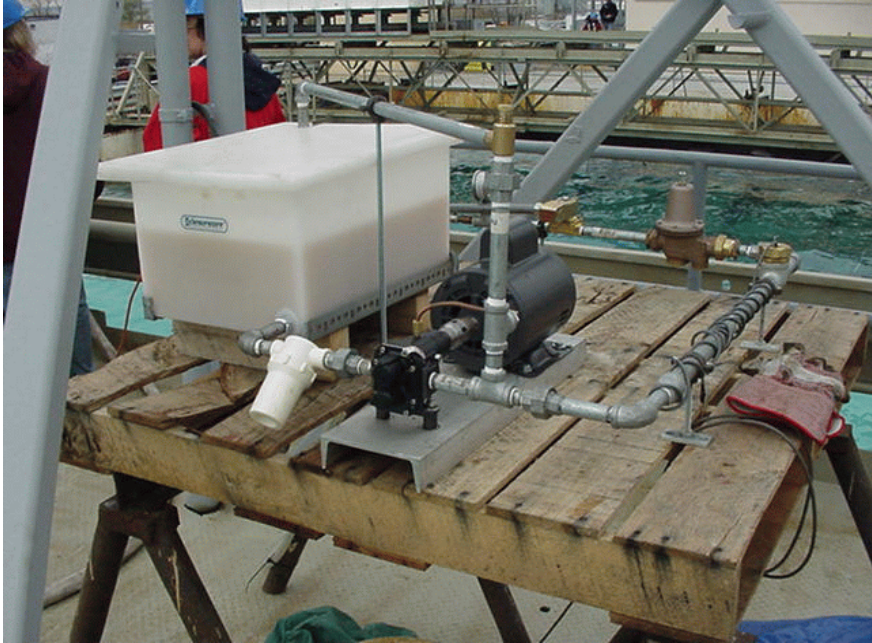


Figure 11 - Photo of Dispersant Spray Bar



until the dispersant spray pattern was acceptable (i.e., when warm dispersant reached the outboard-most nozzles on the spray bar). At this point a stopwatch and graduated cylinder were used to measure the flow rate of dispersant from one nozzle for calibration purposes (all the nozzles had been calibrated according to ASTM F 1460 - 93, to ensure they all produced the same flow, prior to mounting the spray bar on the Main Bridge).

In future, it would be advantageous to either heat trace the tubing connecting the pump module and the spray bar and the spray bar itself, or re-locate the solenoid to the spray bar, and allow the dispersant to recirculate from the spray bar back to the pump module.

2.3.5 Surface Slick Containment Boom

In order to ensure that wind did not blow the surface oil to the tank wall (where it could stick and greatly detract from efforts to estimate a mass balance for the oil) a rectangle of shallow-draft boom was deployed around the test area (Figure 12). This boom (see Figure 4) was to extend 5 m beyond each end of the 20-m long test slick and 5 m on either side (resulting in dimensions of 30 m x 15 m for the rectangular contained area - total boom length = 90 m or 300 feet). The boom was attached with ropes at the four corners of the rectangle to points far down the tank, to allow the bridges to move unfettered. It was recognized that the use of a boom to prevent undue wind-induced motion of the surface slick was a compromise; however, it was the lesser of two evils. If the surface oil reached the tank walls it would have been impossible to quantitatively recover it to determine its volume.

The boom system deployed was a combination of two different types: a very small calm-water boom formed the sides of the rectangle and a larger protected-water boom formed the ends. Unfortunately, in the wave conditions used, the calm water boom became submerged at the wave peaks and the protected water boom experienced occasional splash-over in the 35 cpm wave condition but not in the 30 cpm wave condition. The 35 cpm wave has historically been measured with a period of 1.76 seconds, an $H_{1/8}$ of 12 inches and an average wavelength of 15.86 feet.

Figure 12 - Photo of Boom Rectangle



Figure 13 - Photo of Turner AU-10 Fluorometers



These losses resulted in considerable error in determining the volume of the surface slick after a test. In future tests a larger protected-water boom should be used to form the rectangle. A curtain-type boom with a high buoyancy-to-weight ratio and a smooth profile (to minimize dispersion caused by the boom itself) would be ideal. The boom should have a freeboard of 12 to 18 inches and a draft of 24 inches.

Another problem was having the boom rectangle only slightly larger than the test slick length. This proved to be a considerable impediment to the dispersed oil cloud sampling. It was not possible to sample beyond the ends of the rectangle during the test, whereas the dispersed oil could, and did, move under the ends of the rectangle. For future dispersant testing, sufficient boom to create a rectangle almost the full length of the tank (from 30 m south of the wave paddle to 15 m north of the wave beach) would be ideal. Taking into account the 15-m width of the rectangle, this would require 350 m (1135 ft.) of boom.

2.3.6 Dispersed Oil Sampling Systems

A system for in-water sampling for dispersed oil concentration was installed on the Main Bridge (see Figure 4). This consisted of three sets of two small submersible pumps suspended at specified depths below the water surface (one in each set at 1 m and one at 2m) and two Turner Model AU-10 fluorometers (Figure 13). One set of submersible pumps was suspended below the intended centerline of the test slick, with the other two an equal distance on each side of the slick centerline. The depth and distance sideways from the test slick centerline of each set of submersible pumps was adjustable. The pumps ran constantly, feeding, through plastic tubing, a series of valves that directed the flow from one set either back into the tank, or to a fluorometer. Figure 14 shows a schematic of the submersible pump layout and piping. The flow characteristics of the submersible pumps used ensured that they could easily overcome the head required to pump water to the fluorometers. This has been noted as a problem with the submersible pumps supplied with the fluorometers.

Both Turner AU-10 fluorometers with the “short” filter set were calibrated, following the procedures

Figure 15 - Photo of Fluorometers being Calibrated



in the fluorometer manual, in the Ohmsett High Bay prior to their installation on the Main Bridge house. This calibration was accomplished by filling a drum with Ohmsett water containing a measured amount of 2,000 cP oil blend and dispersant (Figure 15). The initial concentration was approximately 500 ppm. The actual concentration of oil in the drum was determined by analyzing a sample using solvent extraction/IR to determine Total Petroleum Hydrocarbons (TPH) according to standard Ohmsett procedures. As a check on the calibration of the fluorometers, the water in the drum was then serially diluted in steps of one-half, until the nominal concentration was 12.5 ppm. Samples at each dilution were taken and analyzed for TPH to construct the calibration curve (Figure 16). After the tests with the 2,000 cP oil blend were completed the fluorometers were re-calibrated with the more viscous oil since each oil blend had a different concentration of aromatic compounds that fluoresce. The calibration curve for this oil blend is given in Figure 17. The raw calibration data may be found in Appendix D. Samples for calibration check purposes were also taken from the submersible pump discharge during the tests and analyzed for TPH using solvent extraction/IR spectrophotometry employing the standard Ohmsett techniques.

A second method for measuring dispersant efficiency was to turn off the waves (after one hour) and herd the remaining surface oil to a collection point inside the rectangle of boom. At the collection point, the oil was recovered with the Ohmsett P-trap skimmer. Depending on the location of the collection point the recovered oil was either pumped to one of the recovery tanks on the Auxiliary Bridge or to a 55-gallon, open-topped drum to settle. Standard Ohmsett procedures were used to determine the volume of oil collected. This included measuring the depth of oil/water mixture in the recovery tank/drum, decanting the free water and re-measuring the depth, then mixing the tank/drum contents thoroughly before obtaining a sample for water content analysis. The water content analysis was done using standard Ohmsett techniques in the Ohmsett lab. For the less-viscous oils, the solvent/centrifuge technique was employed; for the more viscous samples a Karl-Fischer titration was used.

A third method of measuring dispersant efficiency was to mix the contents of the tank in the test area thoroughly across the width of the tank and measure the average concentration of oil in the water with the fluorometers. By lowering the wave beach at the north end of the tank and setting the wave generator to produce harbor chop conditions, the tank contents were agitated sufficiently in a

Figure 16 - Fluorometer calibration curve for 2,000 cP oil blend

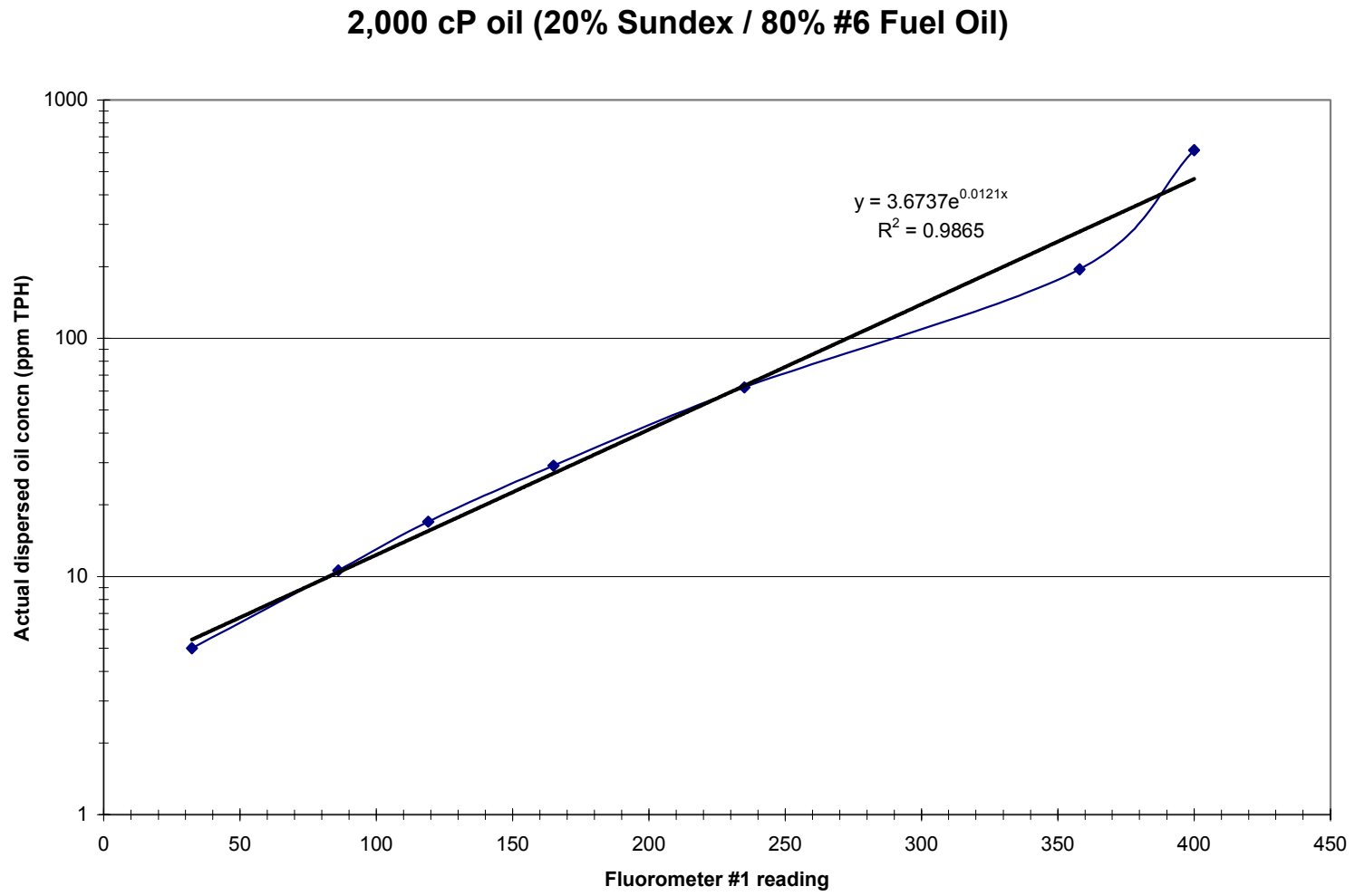
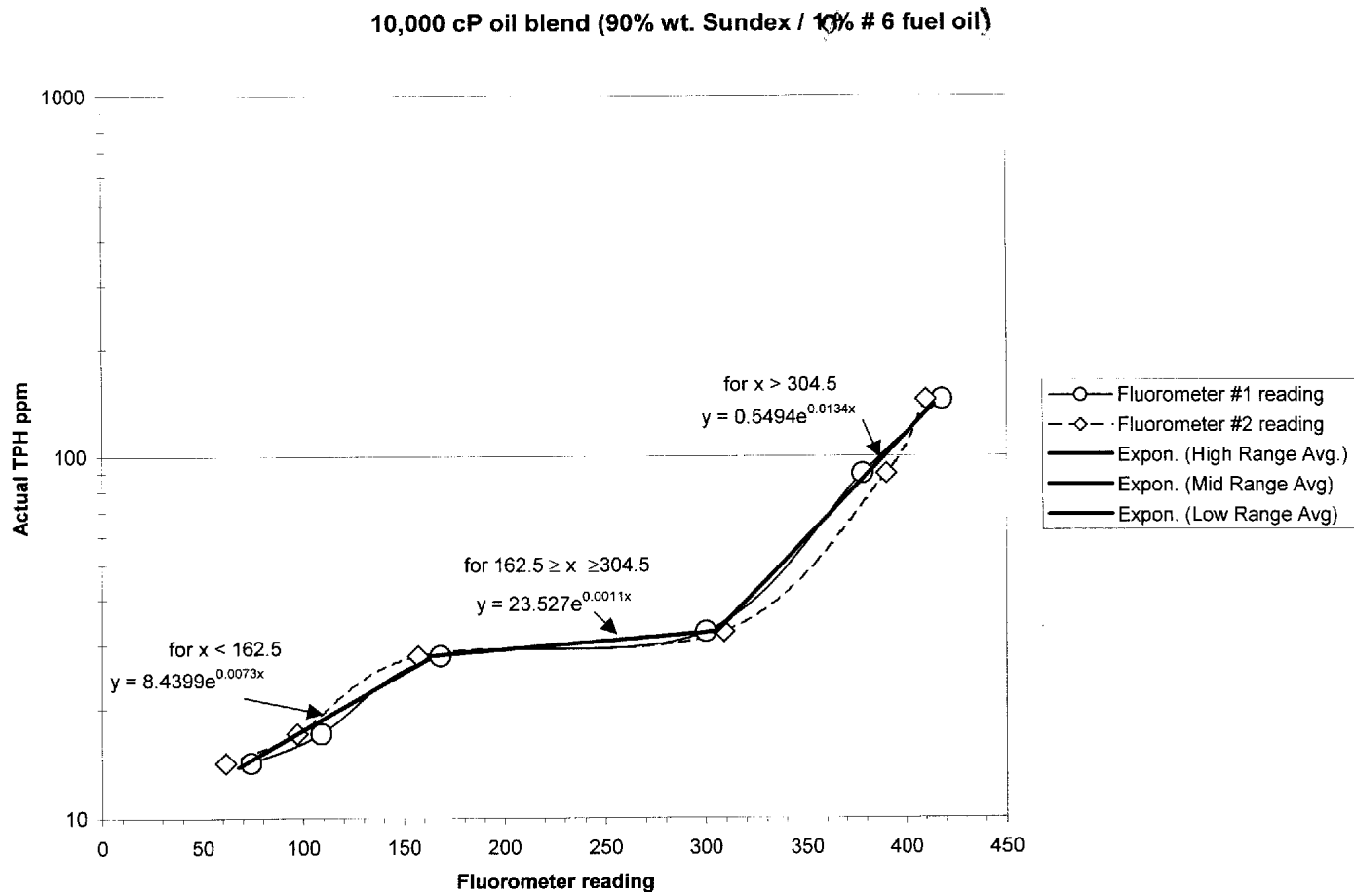


Figure 17 - Fluorometer calibration curve for 10,000 cP oil blend



reasonable time (one-half to one hour) to mix the dispersed oil fairly evenly across the width of the tank, without mixing it too far lengthwise along the tank. This was confirmed prior to the tests by adding a narrow strip of potassium permanganate dye to the center of the tank and observing its dispersion under the influence of the harbor chop waves. In approximately one hour the dye strip had diffused laterally to reach both walls of the tank, and had increased only slightly in length.

In order to estimate the volume of water containing the dispersed oil, the area of the tank containing the cloud was estimated by pacing the length of the tank affected and estimating the width visually.² Using this estimate and the average concentration of oil in the cloud determined with the fluorometers, it was hoped that it would be possible to estimate the volume of oil dispersed. Unfortunately, two factors prevented this technique from working in these tests: first, the action of the wind greatly influenced the motion of the water in the tank, causing it to carry the dispersed oil to either one side and/or end or the other of the tank; and second, the small size of the rectangle of boom prevented the Main Bridge from accessing much of the dispersed oil cloud by the end of the one-hour test period. The provision of a larger rectangle of boom should permit the post-test tank mixing technique for determining the volume of dispersed oil to work. Alternatively, it may be necessary to deploy weighted plastic sheeting or tarpaulins, that extend from the water surface to the bottom of the tank, across the width of the tank at either end of the rectangle of boom in order to isolate the water containing the dispersed oil from the rest of the tank.

2.4 Data Acquisition

The following parameters were logged electronically on the Ohmsett data acquisition system for each test:

- Elapsed time (s)
- Bridge Speed (knots)
- Wind speed (mph)
- Wind direction (° true)
- Air temperature (°F)

² It had originally been planned to use the Ohmsett data acquisition system to do this, by correlating fluorometer readings with the position of the bridge; however the Main Bridge distance sensor had been disconnected some time ago and was no longer available.

- Water temperature (°F)
- Oil discharge tank level (inches)
- Wave height sonic probe (inches)
- Wave generator frequency (cpm)
- Dispersant flow rate (gpm)
- Analog output from Fluorometer 1
- Analog output from Fluorometer 2

The setup of the data acquisition system and the offset, gain and calibration factors are documented in Appendix E. There were several difficulties encountered with this set up:

1. The wave height sonic probe signal contained a large amount of noise in the form of numerous spikes in the output. This rendered analysis of the wave patterns useless, even after Fast Fourier Transform massaging of the signals.
2. The flow meter used for the dispersant spray system had a minimum flow cut-off that was above most of the dispersant flow rates applied; thus no data were received for most runs.
3. The analog output from the Turner AU-10 fluorometers did not contain a signal that indicated with which scale the device was operating. Because the fluorometers operated with automatic scale ranging (as recommended by the manufacturer), it was not possible to directly determine concentration from the logged signal.

This latter problem was overcome by recording the digital output from each of the two fluorometers directly onto two laptop computers. The spreadsheet used to record the output contained the information required to determine concentration directly.

2.5 Procedures for a Typical Test

For a typical test, the following tasks were carried out:

1. Position rectangle of boom over clean water.

2. Load desired test oil into Main Bridge oil distribution system. Start recirculating. Measure oil temperature periodically. When oil warm enough, set position of oil pump recirculating valve by calibrating flow from discharge hose with bucket and stopwatch. Connect discharge hose to oil distribution system.
3. Start dispersant pump recirculating and turn on heat tracing.
4. Position Main Bridge at middle of intended test area.
5. Power up fluorometers. Start submersible pumps and take background readings for all six. Collect one sample for TPH analysis.
6. Reposition Main Bridge towards north end of rectangle of boom.
7. Measure dispersant temperature. If warm enough, spray dispersant over north boom until good spray pattern established. Shut solenoid valve.
8. Turn on videos, data acquisition.
9. Accelerate bridge to specified speed.
10. When Main Bridge oil distribution system is 5 m south of north end of rectangle of boom, begin laying down test slick by opening air-actuators. When oil appears from nozzles start stopwatch.
11. Lay oil for 20 m travel distance. Close air actuators when specified oil discharge time reached.
12. When dispersant spray bar is 1 m from beginning of test slick, activate solenoid valve to begin spray – hold open until spray bar is 1 m past end of test slick.
13. Turn on waves at desired setting³ and reposition Main Bridge to middle of slick (approx. 10 m from each end).
14. Begin in-water sampling. Take three samples, spanning the range of expected concentrations encountered, for TPH analysis. Occasionally transit to either end of slick to obtain off-center fluorometry, samples and video.
15. Turn off and secure oil and dispersant pumps.

16. Visually observe dispersion (both directly and underwater video).

³ Concern has been expressed about waiting until the slick has been laid down and sprayed before turning on the wave generator. Consideration could be given to either modifying the oil distribution system to allow it to follow waves (thus allowing the oil slick to be laid and sprayed with dispersant with the waves running), or turning on the wave generator at just the right time before the oil distribution is complete to allow the first wave to reach the end of the slick just as the dispersant spraying stops.

17. One hour after first wave hit slick, stop waves and allow surface to calm.
18. Herd remaining surface oil to downwind end of rectangle of boom for recovery and volumetric/water content measurements.
19. Lower beach and turn on harbor chop.
20. One hour later, after the tank contents are thoroughly mixed laterally, measure dispersed oil concentrations at several locations with fluorometers, including along length of test area.
21. Reposition test set up to middle of next test area and raise wave beaches.

3. Protocol Test Results and Discussion

Six tests of the proposed dispersant test protocol were carried out in April 2000. These involved spraying various doses of Corexit 9500 dispersant on two different blends of oils that had different viscosities. The test data may be found in Appendix F.

3.1 Test Results

The results for all six tests are summarized in Table 1. Each test is discussed individually below.

3.1.1 Test 1 - Natural Dispersion with 2,000 cP Oil Blend

This test involved measuring the background levels of dispersed oil generated by the 2,000 cP oil blend in the tank. The wind for these tests averaged 24 km/hr from the east. The air temperature was 10.2 °C and the water temperature was 12.2 °C.

The wave generator was set at a frequency of 35 cycles per minute with a stroke of 3 inches. The wave beaches were raised to absorb some of the incident wave energy at the north end of the tank. This combination produced a wave train in which the occasional wave was beginning to crest.

The test slick was created with 68.3 L of the 2,000 cP oil blend discharged over a 40 second period from the Main Bridge while moving south at 0.517 m/s. The steady-state oil discharge rate was 1.37 L/s. The average thickness of the slick was 0.59 mm, below the target of 1 mm. The temperature of the oil when discharged was 15.3 °C. Its viscosity at the water temperature was 3500 cP at a shear rate of 100 s⁻¹.

No dispersant was applied for this test.

Prior to discharging the oil the fluorometers measured concentrations of oil in the tank at levels

Table 1 - Detailed Test Summary

Ohmsett Dispersant Test Protocol Development - Test Data Summary

Test Number	1	2	3
Descriptor	2000 cP Baseline/Natur	2000 cP @ 1:25 DOR	Repeat of 2 (2000 cP @ 1:25 DOR)
Environmental Conditions			
Avg. wind speed (km/hr)	24	24.3	22.8
Avg. wind direction (from °T)	90	93	41
Avg. air T (°C)	10.2	9.4	8.7
Avg. water T (°C)	12.2	12.4	11.6
Wave generator frequency (cycles/min)	35	35	35
Wave generator stroke (inches)	3	3	3
Wave descriptor	isional com	occasional combing	occasional combing
Comments			
Oil Discharge			
Volume from height in drum (L)	68.3	68.3	74.5
Time for height decrease in drum (s)	40	40	40
Oil temperature in drum (°C)	15.3	12.2	12.2
Oil temperature on water at spray bar (°C)	NR	NR	11.1
Oil flowrate from sonic probe (L/s)	1.37	1.58	2.12
Avg. bridge speed (m/s)	0.517	0.516	0.519
Avg. oil thickness calculated (mm)	0.59	0.68	0.9
Measured oil viscosity at water T at 100 s ⁻¹ (mPa)	3500	3400	3950
Comments			
Dispersant Spraying			
Nozzle body number		40015	40015
Pressure at spray bar (psig)		40	40
Volume of dispersant applied (L)		NR	3.7
Thickness of dispersant applied (mm)		0.0343	0.0259
Calculated DOR		1:29	1:39
Comments	persant applied		dispersant came out of nozzles as solid streams did not treat much of slick; bridge also stopped too early and missed treating last metre of slick
Surface Slick			
Volume of slick recovered after test (L)	125 L	0	71.5
Water content of recovered slick (% vol)	18		21.8
Volume of oil recovered	102		56
Percentage of oil discharged	150%		75%
Comments	ained by bc probably recovered oil from previous tests	no surface slick observed	
Dispersed Oil			
Background concentration from fluorometers (pp) 4.0 to 4.7		4	5.2 ppm @ 1 m; 5.0 ppm @ 2 m
Concentrations after dispersant applied (ppm) 3.7 to 6.4	50 to 190 ppm @ 1 m just after dispersant applied 100 to > 300 ppm @ 2 m after dispersant applied		much lower than Test #2 - increased by 5 to 10 ppm @ 1 m and 5 to 10 ppm at 2 m
Comments	ld visible in	dark brown cloud in water column	very little dispersed oil cloud observed, except near where solid streams of dispersant hit slick

Table 1 - Detailed Test Summary cont'd

4	5	6
2000 cP at 1:25 DOR in Non-breaking Waves	10,000 cP at 1:25 DOR	10,000 cP at 1:10 DOR
15	7.4	9.9
41	98	138
8.9	9.2	10
11.6	11.6	11.8
30	35	35
3	3	3
no breaking waves after one hour, increase waves to 35 cycles/min	occasional combing	occasional combing
80.7	108.7	94.7
40	40	53
20	31.1	25.5
15	20	14.2
2.33	2.72	2.33
0.519	0.52	0.386
0.99	1.16	1.3
3725	19,640	18,750
40015	40015	4003
40	40	40
5.3	5.19	14.6
0.0276	0.0238	0.0702
1:36	1:42	1:14.2
dispersant heated by recirc. to 46 °C to improve spray pattern, sprayed well	dispersant heated by recirc. to 46 °C to improve spray pattern, sprayed well	dispersant heated by recirc. to 49 °C to improve spray pattern, sprayed well
16.3 (after 2nd hour)	78 + 23 + 91	0
18.5	? + 74.7 + 42.6	
13	? + 6 + 52	
16	?	
much of surface slick remained after first hour, before wave frequency increased	most oil escaped from boom rectangle; oil collected from beach end of tank	no surface slick observed
5.1 ppm @ 1 m; 4.6 ppm @ 2 m one spike of 100 ppm @ 1 m in non-breaking waves consistent readings of 50 ppm after breaking waves only spikes of 100 ppm @ 2 m after breaking waves some visible dispersed oil cloud initially, but didn't last visible dispersion increased with breaking waves	10.2 ppm @ 1 m; 9.2 ppm @ 2 m some spikes to 60 - 70 ppm @ 1 m immediately after dispersant applied, 30 ppm declining to 20 ppm after 30 minutes; no oil detected @ 2 m some initial dispersion, but visually, mostly large drops which appeared to resurface rapidly	10 ppm @ 1m; 9 ppm @ 2 m large initial spikes to 175 ppm @ 1 m, then settle to 30 ppm avg; 30 ppm avg @ 2 m dark brown cloud in water column after waves on

averaging 4.0 to 4.7 ppm. Oil concentrations in the water under the test slick ranged from 3.7 to 6.4 ppm with the average for the fluorometer at 1 m depth being 4.9 ppm and the average for the fluorometer at a depth of 2 m being 4.1 ppm. No cloud of dispersed oil droplets was observed from either the surface or with the underwater video camera.

One hour after the waves had been turned on, they were turned off and the surface slick was collected. In total 125 L of emulsified oil was collected, which had a water content of 18% by volume. This equates to 102 L of oil. More oil was recovered than had originally been discharged. The reason for this is likely that oil from previous tests already on the water in the tank was recovered in this first test. As noted in the previous section, the boom forming the rectangle could not fully contain the oil slick in the wave conditions used. Some of the test oil escaped from the boom, and some tramp oil from previous tests entered the rectangle.

There was no appreciable dispersion detected in this test, either by the fluorometers, visual observation, or recovery of the surface slick for mass balance determination.

3.1.2 Test 2 - 2,000 cP Oil Blend Dosed at 1:25

This was the first test that involved applying dispersant to an oil slick in the tank. This test was used as the baseline for the test matrix. The wind for these tests averaged 24.3 km/hr from the east. The air temperature was 9.4 °C and the water temperature was 12.4 °C.

The wave generator was set at a frequency of 35 cycles per minute with a stroke of 3 inches. The wave beaches were raised to absorb some of the incident wave energy at the north end of the tank. This combination produced a wave train in which the occasional wave was beginning to crest.

The test slick was created with 68.3 L of the 2,000 cP oil blend discharged over a 40 second period from the Main Bridge while moving south at 0.516 m/s. The steady-state oil discharge rate was 1.58 L/s. The average thickness of the slick was 0.68 mm, below the target of 1 mm. The temperature of the oil when discharged was 12.2 °C. Its viscosity at the water temperature was 3400 cP at a shear rate of 100 s⁻¹.

The dispersant was sprayed from the bar from 40015-type nozzle tips at a pressure of 40 psig, measured at the center of the bar. The volume of dispersant sprayed was accidentally not recorded. Using the measured flow calibration of the nozzle tips with the unheated dispersant and the speed of the Main Bridge, the thickness of dispersant applied to the slick was 0.034 mm, equivalent to a dispersant-to-oil dosage ratio (DOR) of 1:29.

Until the first cresting wave passed through the treated slick, no dispersion was noted visually. Once breaking waves passed through the treated slick, a dark brown cloud of dispersed oil droplets was observed from both the surface and with the underwater video camera. This cloud of droplets spread into the water column and across to the upwind side of the tank during the test. It also moved under the north end of the boom rectangle.

Prior to discharging the oil the fluorometers measured concentrations of oil in the tank at levels averaging 4 ppm. After the dispersant was applied oil concentrations in the water under the test slick ranged from 50 to 190 ppm at 1 m depth. At a depth of 2 m the fluorometer measured concentrations ranging from 100 to greater than 300 ppm.

One hour after the waves had been turned on, they were turned off and the surface slick was to be collected. There was no surface oil visible, thus the collection was cancelled, and the tank mixing began.

For one hour the wave generator was run at 35 cpm with a 3-inch stroke, except this time with the wave beaches lowered to permit full reflection of the waves and the development of a “Harbor Chop” condition. In this wave condition many of the waves broke energetically. During and after this mixing period, the fluorometers were run back and forth through the boomed area. The dispersed oil concentrations declined as the cloud of dispersed oil was diluted by the mixing. Unfortunately, by the end of the one-hour mixing period, much of the cloud of dispersed oil had moved north beneath the north end boom of the rectangle, and was inaccessible to the fluorometers.

It was clear from the fluorometer data, visual observation and the obvious lack of a surface slick that the application of the dispersant to this test slick in these conditions had resulted in complete

dispersion.

3.1.3 Test 3 - Repeat 2,000 cP Oil blend dosed at 1:25

This test was intended as a repeat of the previous one; however, the cold temperature of the dispersant (left outside in the spray system overnight) resulted in a very poor application which resulted in almost no dispersion. The wind for these tests averaged 22.8 km/hr from the north-east. The air temperature was 8.7 °C and the water temperature was 11.6 °C.

The wave generator was set at a frequency of 35 cycles per minute with a stroke of 3 inches. The wave beaches were raised to absorb some of the incident wave energy at the north end of the tank. This combination produced a wave train in which the occasional wave was beginning to crest.

The test slick was created with 74.5 L of the 2,000 cP oil blend discharged over a 40 second period from the Main Bridge while moving south at 0.519 m/s. The steady-state oil discharge rate was 2.12 L/s. The average thickness of the slick was 0.9 mm, near the target of 1 mm. The temperature of the oil when discharged was 12.2 °C. For this run, the temperature of the oil on the water surface just before it was sprayed with dispersant, was measured with a hand-held infra-red thermometer. The slick temperature at this point was 11.1 °C. Its viscosity at this temperature was 3950 cP at a shear rate of 100 s⁻¹.

The dispersant was sprayed from the bar from 40015-type nozzle tips at a pressure of 40 psig, measured at the center of the bar. The volume of dispersant sprayed was 3.7 L. Unfortunately, due to the cold temperatures overnight, the viscosity of the dispersant had increased to a point where the nozzle tips could no longer atomize it at the given pressures, and the dispersant exited the nozzles as a solid stream, rather than an angled spray of droplets. The solid streams impacted the slick leaving only narrow trails of dispersant on the surface. It is quite possible that the streams penetrated the oil slick and much of the dispersant was injected into the underlying water.

In addition to the problem with the spray, the Main Bridge was stopped too soon after the oil discharge, resulting in the last metre of the slick not being treated with dispersant. Using the

measured flow calibration of the nozzle tips with the unheated dispersant and the speed of the Main Bridge, the thickness of dispersant applied to the slick should have been 0.026 mm, equivalent to a DOR of 1:29 on the portions of the slick treated.

Until the first cresting wave passed through the treated slick, no dispersion was noted visually. Even when breaking waves passed through the treated slick, only small amounts of dispersed oil cloud formation were observed, and only in the vicinity of the strips of oil that had been sprayed by the solid streams of dispersant.

Prior to discharging the oil the fluorometers measured concentrations of oil in the tank at levels averaging 5.2 ppm at 1 m depth and 5.0 ppm at 2 m. After the dispersant was applied oil concentrations in the water under the test slick were much lower than in Test 2. They ranged from only 10 to 15 ppm at both depths.

One hour after the waves had been turned on, they were turned off and the surface slick was collected. In total 71.5 L of emulsified oil was collected, which had a water content of 21.8% by volume. This equates to 56 L of oil, or some 75% of the volume of oil originally discharged. As noted in the previous section, the boom forming the rectangle could not fully contain the oil slick in the wave conditions used.

For the next hour the wave generator was run at 35 cpm with a 3-inch stroke, except this time with the wave beaches lowered to permit full reflection of the waves and the development of a “Harbor Chop” condition. In this wave condition many of the waves break energetically. After this mixing period, the fluorometers were run back and forth through the boomed area. The dispersed oil concentrations were approximately 5 to 7 ppm at both depths, near background. It is possible that by the end of the one-hour mixing period much of the cloud of dispersed oil had moved north beneath the north end boom of the rectangle, and was inaccessible to the fluorometers.

There was very little dispersion detected in this test, either by the fluorometers, visual observation, or recovery of the surface slick for mass balance determination. This was due to the mis-application of dispersant.

3.1.4 Test 4 - 2,000 cP Oil blend dosed at 1:25 in Non-breaking waves

This test was intended to explore the importance of the cresting waves on dispersion in the tank by repeating test 2, except with no cresting waves. Anecdotal evidence from sea trials indicates that good dispersion only occurs in the presence of cresting waves, or whitecaps. The wind for these tests averaged 15 km/hr from the north-east. The air temperature was 8.9 °C and the water temperature was 11.6 °C.

The wave generator was set at a frequency of 30 cycles per minute with a stroke of 3 inches. The wave beaches were raised to absorb some of the incident wave energy at the north end of the tank. This combination produced a wave train in which the none of the waves was beginning to crest.

The test slick was created with 80.7 L of the 2,000 cP oil blend discharged over a 40 second period from the Main Bridge while moving south at 0.519 m/s. The steady-state oil discharge rate was 2.33 L/s. The average thickness of the slick was 0.99 mm, at the target of 1 mm. The temperature of the oil when discharged was 20 °C; it had been warmed to permit faster pump rates. For this run, the temperature of the oil on the water surface just before it was sprayed with dispersant, was measured with a hand-held infra-red thermometer. The slick temperature at this point was 15 °C. Its viscosity at this temperature was 2450 cP at a shear rate of 100 s⁻¹; at the temperature of the water the slick viscosity was 3725 cP at a shear rate of 100 s⁻¹.

In order to avoid the dispersant spraying problems experienced in the previous test, for this run the dispersant was heated to 46 °C and the cold dispersant was purged from the spray system prior to the test. The dispersant was sprayed from 40015-type nozzle tips at a pressure of 40 psig, measured at the center of the bar. The spray pattern was good and covered the entire width of the slick. The volume of dispersant sprayed was 5.3 L. If all the dispersant had been sprayed onto he slick, this would have amounted to a DOR of 1:15; however, by design, some of the dispersant was sprayed onto water before the spray bar reached the slick, after it passed the end of the slick, and to the sides of the slick. A better measure of the dosage of dispersant that the slick actually received was to calculate the thickness of dispersant that was applied by the spray bar and compare that to the thickness of the slick. Using the measured flow calibration of the nozzle tips with the heated

dispersant and the speed of the Main Bridge, the thickness of dispersant applied to the slick was 0.028 mm, equivalent to a DOR of 1:36.

Initially, when the waves reached the slick, it appeared that the slick was going to disperse. The waves created some black clouds of oil droplets in the water; however, the dispersed oil droplets were ostensibly too large to remain permanently dispersed as they soon rose back to the surface and re-coalesced into a coherent slick.

Prior to discharging the oil the fluorometers measured concentrations of oil in the tank at levels averaging 5.1 ppm at 1 m depth and 4.6 ppm at 2 m. One hour after the dispersant was applied the 1-m and 2-m fluorometers registered one spike of oil to a concentration to approximately 100 ppm while transecting through the boomed test area. The remainder of the readings were in the range of the background levels.

By the end of the first hour, it was visually apparent that most of the oil was still in the surface slick. (It should be noted that the boom rectangle did a better job of retaining the surface slick in this wave condition than in the cresting waves.) Since this answered the question intended for this test - the presence of cresting waves in the tank was necessary for good dispersion, as it is at sea - a decision was made to see if increasing the frequency of the wave maker at this point would cause the slick to disperse. For a second hour the wave maker frequency was increased to 35 cpm, which created the occasional cresting wave, as with the previous three tests.

The increase in wave frequency did increase the dispersion rate. During and after the second hour the fluorometers detected consistent 50 ppm levels of dispersed oil while transiting along the boomed area, with the occasional 100 ppm reading at 2 m.

Once the waves began cresting, it was visually apparent that the dispersion process was increasing.

One hour after the wave frequency had been increased to 35 cpm, the waves were turned off and the surface slick was collected. In total 16.3 L of emulsified oil was collected, which had a water content of 18.5% by volume. This equates to 13 L of oil, or some 16% of the volume of oil originally

discharged. As noted in the previous sections, the boom forming the rectangle could not fully contain the oil slick in the 35 cpm waves.

It was apparent that increasing the wave frequency at the end of the first hour did increase the dispersion rate, although it did not reach the level attained in Test 2.

3.1.5 Test 5 - 10,000 cP Oil blend dosed at 1:25

This was the first test that involved using the 10,000 cP oil blend. This test was used both as a variation of Test 2 and as the baseline for the last test. The wind for these tests averaged 7.4 km/hr from the east. The air temperature was 9.2 °C and the water temperature was 11.6 °C.

The wave generator was set at a frequency of 35 cycles per minute with a stroke of 3 inches. The wave beaches were raised to absorb some of the incident wave energy at the north end of the tank. This combination produced a wave train in which the occasional wave was beginning to crest.

The test slick was created with 108.7 L of the 10,000 cP oil blend discharged over a 40 second period from the Main Bridge while moving south at 0.52 m/s. The steady-state oil discharge rate was 2.72 L/s. The average thickness of the slick was 1.16 mm, slightly above the target of 1 mm. The temperature of the oil when discharged was 31.1 °C; it had been warmed to permit faster pump rates. For this run, the temperature of the oil on the water surface just before it was sprayed with dispersant, was measured with a hand-held infra-red thermometer. The slick temperature at this point was 20 °C. Its viscosity at this temperature was 5000 cP at a shear rate of 10 s⁻¹; at the temperature of the water the slick viscosity was 19,640 cP at a shear rate of 10 s⁻¹.

In order to avoid the dispersant spraying problems experienced in a previous test, for this run the dispersant was heated to 46 °C and the cold dispersant was purged from the spray system prior to the test. The dispersant was sprayed from the bar from 40015 nozzle tips at a pressure of 40 psig, measured at the center of the bar. The spray pattern was good and covered the entire width of the slick. The volume of dispersant sprayed was 5.2 L. Using the measured flow calibration of the nozzle tips with the heated dispersant and the speed of the Main Bridge, the thickness of dispersant applied

to the slick was 0.024 mm, equivalent to a DOR of 1:42.

Initially, when the cresting waves reached the slick, it appeared that the slick was going to disperse. The waves created some black clouds of oil droplets in the water; however, the dispersed oil droplets were clearly too large to remain permanently dispersed as they soon rose back to the surface and re-coalesced into a coherent slick.

For the next two runs the fluorometers were re-calibrated with the 10,000 cP oil blend.

Prior to discharging the oil the fluorometers measured concentrations of oil in the tank at levels averaging 10.2 ppm at 1 m depth and 9.2 ppm at 2 m. Shortly after the dispersant was applied the 1-m fluorometer registered one spike of oil to a concentration of approximately 60 to 70 ppm; after 30 minutes the concentration had declined to 20 ppm. No oil was detected by the 2-m fluorometer.

One hour after the waves had been turned on, they were turned off and the surface slick was collected. As noted in previous sections, the boom forming the rectangle could not fully contain the oil slick in the wave conditions used. For this test, the oil was collected from one corner of the tank beside the wave beach. In total 192 L of emulsified oil was collected in three separate drums. The sample for water content analysis from the first drum, containing 78 L of emulsion, was misplaced and no data is available. The second drum contained 23 L of emulsion which had a water content of 74.7% by volume, which equates to 6 L of oil. The third drum contained 91 L of emulsion which had a water content of 42.6% by volume which equates to 52 L of oil. With the data from two of the three drums, 53% of the oil discharged can be accounted for. Unfortunately, due to the lost oil sample, a full mass balance cannot be performed.

There was only minimal, and temporary, dispersion detected by the fluorometers, visual observation, and recovery of the surface slick for mass balance determination in this test.

3.1.6 Test 6 - 10,000 cP Oil blend dosed at 1:10

This was the last test that there was time to conduct. Its purpose was to determine if increasing the

DOR on the 10,000 cP oil blend would result in better dispersion. The wind for these tests averaged 9.9 km/hr from the southeast. The air temperature was 10 °C and the water temperature was 11.8 °C.

The wave generator was set at a frequency of 35 cycles per minute with a stroke of 3 inches. The wave beaches were raised to absorb some of the incident wave energy at the north end of the tank. This combination produced a wave train in which the occasional wave was beginning to crest.

The test slick was created with 94.7 L of the 10,000 cP oil blend discharged over a 53 second period from the Main Bridge while moving south at 0.386 m/s. The steady-state oil discharge rate was 2.33 L/s. The average thickness of the slick was 1.3 mm, somewhat above the target of 1 mm. The temperature of the oil when discharged was 25.5 °C; it had been warmed with electrical band heaters to permit faster pump rates. For this run, the temperature of the oil on the water surface just before it was sprayed with dispersant, was measured with a hand-held infra-red thermometer. The slick temperature at this point was 14.2 °C. Its viscosity at this temperature was 13,000 cP at a shear rate of 10 s⁻¹; at the temperature of the water the slick viscosity was 19,640 cP at a shear rate of 10 s⁻¹.

In order to avoid the dispersant spraying problems experienced in a previous test, for this run the dispersant was heated to 49 °C and the cold dispersant was purged from the spray system prior to the test. In order to increase the volume of dispersant applied, the nozzle tips were changed for this run. The dispersant was sprayed from the bar from 4003 nozzle tips at a pressure of 40 psig, measured at the center of the bar. The spray pattern was good and covered the entire width of the slick. The volume of dispersant sprayed was 14.6 L. Using the measured flow calibration of the new nozzle tips with the heated dispersant and the speed of the Main Bridge, the thickness of dispersant applied to the slick was 0.07 mm, equivalent to a DOR of 1:14.

Until the first cresting wave passed through the treated slick, no dispersion was noted visually. Once cresting waves passed through the treated slick, a dark brown cloud of dispersed oil droplets was observed from the surface. This cloud of droplets spread into the water column and across the tank during the test. It also moved under the north end of the boom rectangle towards the wave beach.

Prior to discharging the oil the fluorometers measured concentrations of oil in the tank at levels

averaging 10 ppm at the 1 depth and 9 ppm at the 2 m depth. In the first hour after the dispersant was applied there was an initial spike in the oil concentrations in the water under the test slick at 1 m to 175 ppm which settled to a steady average of 30 ppm. At a depth of 2 m the fluorometer measured steady concentrations in the range of 30 ppm.

One hour after the waves had been turned on, they were turned off and the surface slick was to be collected. There was no surface oil visible, thus the collection was cancelled.

Since it was late in the day at this point, and it was clear that all the oil had dispersed, the one-hour harbor chop mixing phase of this test was cancelled and the test stopped.

It was clear from the fluorometer data, visual observation and the obvious lack of a surface slick that the application of the dispersant to this test slick in these conditions had resulted in complete dispersion.

3.2 Comparison with Field and Laboratory Data

The conditions for this series of tests at Ohmsett were selected to demonstrate that any test protocol subsequently developed would have the capability to discriminate between the effect of a number of variables including oil viscosity, wave conditions, dispersant treatment rate and dispersant type. If the results of all the tests had been total rapid dispersion, or if every test had resulted in very little dispersion, there would be no way of knowing whether Ohmsett was a suitable facility for studying dispersant effectiveness. However, it would also be important that the discrimination should not be achieved in a totally arbitrary way; the effect of altering the variables should produce similar effects to those observed at sea at real oil spill incidents or at experimental oil spills. Additionally, it would be very useful if some comparison could be made between the results obtained at Ohmsett and the results from laboratory testing.

Although not comprehensive, the results from the six tests that were conducted show many features in common with the results obtained and observations made at field trials of dispersant use at sea.

3.2.1 Comparison with observations made at field trials

In broad terms, the results of these dispersant tests at Ohmsett showed that if the test oil was going to be dispersed to a significant extent, this would proceed to almost total dispersion within the one hour period of the test. Conversely, if only a low level of dispersion was initially obtained, then prolonged agitation would not cause a higher level of dispersion. The results suggest that, for the oils tested and conditions used, the dispersant effectiveness would either be close to 100% (total dispersion) or close to 0% (no significant dispersion). An intermediate value was obtained only when dispersant application problems prevented all of the oil from being adequately treated with dispersant.

This is broadly in line with observations made at the field trials conducted in the Norwegian (Brandvik et al., 1995. Brandvik et al., 1996) and UK (Lunel et al., 1997) sectors of the North Sea in recent years. At these field trials, it was found that if an oil is going to disperse, the initial dispersion process would be rapid after dispersant was applied and dispersion would proceed almost to completion within a few hours (Lunel, 1994). Any oil that remained on the sea surface long after dispersant treatment had probably not been sprayed with dispersant. Almost all of the oil and dispersant combinations tested in these sea trials resulted in almost total dispersion within a few hours. It is very important to note that this effect only seems to apply to oils of varying viscosity. High viscosity emulsions can be broken back to their constituent oil and water phases by the emulsion-breaking properties of the surfactants and solvents in some dispersants. The emulsion-breaking process may be relatively slow and even when it is followed by relatively rapid dispersion, the emulsion-breaking process is the rate-limiting step (Lewis et al., 1994). The oils tested at Ohmsett were not emulsified when they were sprayed with dispersant, so the influence of these emulsion-breaking effects was not observed.

Effect of cresting or breaking waves

One major feature of the Ohmsett test results is the great influence of breaking or cresting waves. Visual observations and the readings from the fluorometers showed that the wave crest passing through the dispersant-treated oil initiated very rapid oil droplet formation. The subsequent dispersion and dilution of the very small oil droplets was not dependent on breaking waves, but more on the water movement under any wave. The wave generation characteristics of the Ohmsett wave maker cause a marked difference in the wave form when the oscillation rate is increased from 30 to 35 cycles per minute with a constant 3 inch stroke. Both set-ups create a short wavelength, 'harbor chop' type of wave pattern. The rate of initial process of dispersion (the creation of small oil droplets) will depend on the frequency of cresting waves.

This is very similar to observations made at sea trials. Although the creation of oil droplets by the flexing motion of non-breaking waves cannot be ruled out (and has been observed in tank tests - Goodman et al., 1994), it seems to be a minor process compared to the effect of the cresting or breaking waves when such waves are present. Only a very small degree of wave breaking is needed to instigate rapid, but localised dispersion of oil. At sea, it is considered that there is a "step-change" in the rate of dispersion that occurs between Beaufort Force 2 (Wind speed 4 – 6 knots, small wavelets, crests have a glassy appearance and do not break) and Beaufort Force 3 (Wind speed 7-10 knots, large wavelets, crests begin to break, scattered whitecaps) (Delvigne and Sweeney, 1988). Although the wave conditions produced at Ohmsett cannot be directly related to waves at sea, there seems to be a similar "step change" in the rate of dispersion caused by the onset of breaking wave incidence.

The results of Test 4 are particularly interesting. A significant degree of dispersion did not occur with non-cresting waves passing through the dispersant-treated slick for one hour. However, significant dispersion was obtained when the oscillation was increased one hour after dispersant was applied. This indicates that most of the dispersant surfactants stayed within the oil and did not migrate into the water during the hour before the waves started breaking.

Effect of oil viscosity and dispersant treatment rate

There is a common assumption that a generally applicable ‘limiting viscosity’ exists for dispersant use. The nominal viscosities of the test oils in the Ohmsett tests, 2,000 cP and 10,000 cP, were selected to be on either side of the generally quoted viscosity limit.

The UK test oil for dispersant approval is a Medium Fuel Oil and has a viscosity of 2,000 cP (measured at 10 s^{-1}) at the test temperature of 10°C and so would reasonably be expected to be dispersible. This oil was used in the harbor trials that were carried out by WSL (Cormack, 1983) before the WSL rotating flask test method was introduced as the dispersant approval test method. Although the results from some laboratory tests and from some flume tests (Fiocco et al., 1999) suggest that even very high viscosity oils (20,000 cP or more) could be dispersible under some circumstances, the general consensus from experience at actual oil spills is that this is unlikely to occur in most cases (IMO/UNEP, 1995). The purpose of this work was not to prove or disprove any particular limit, so a nominal value of 10,000 cP was selected. As discussed in the previous sections, the viscosity of the oils when sprayed with dispersant was higher than these nominal viscosity values. The viscosity was in the range of 3500 – 4,000 cP (measured at 100s^{-1}) for the lower viscosity test oil and up to nearly 20,000 cP (measured at 10s^{-1}) for the higher viscosity test oil. The test oils were therefore broadly equivalent to a Medium Fuel Oil (Fuel Oil No. 5) and a Heavy Fuel Oil (Fuel oil No. 6), although these oils have very ill defined and variable properties

Nominal 2,000 cP (actual 3,500 – 4,000 cP) viscosity oil results

The lower viscosity test oil did not naturally disperse to any appreciable extent (Test 1) and this as would be expected from observations at real oils spills and at the AEAT 1997 field trial with IFO-180 fuel oil (Lewis et al., 1998). Medium Fuels Oils do not naturally disperse in moderate sea states.

This test oil was totally dispersed when sprayed with Corexit 9500 at a DOR of 1:29 and subjected to cresting waves (Test 2). However, it was not dispersed to any significant degree when sprayed with a DOR of 1:36 and subjected to non-cresting waves, but was substantially dispersed (around 84% of the oil was transferred into the water) when subsequently subjected to cresting waves one hour after

being sprayed with dispersant (Test 4). The very low degree of dispersion obtained in Test 3 was a result of a very low level of dispersant treatment due to problems with the spray gear.

The initial viscosity of this test oil was very similar to the IFO-180 fuel tested in the AEA'97 sea trial where the oil had a viscosity of approximately 3,000 cP (measured at 10s^{-1}). The slightly emulsified IFO-180 fuel oil at the field trial was partially dispersed when sprayed with a DOR of around 1:30 of Corexit 9500. The wind speed was 10 knots, gusting to 14 knots (Beaufort Force 4) and gently breaking waves were present. This field experiment is one of the very few conducted at sea where rapid and total dispersion of the oil being tested did not occur. This was not intentional and was caused by insufficient dispersant being applied due to technical difficulties and the inability to re-treat rapidly because the spraying aircraft was taken out of service. 'Spikes' of up to 70 ppm dispersed oil at 1 metre depth were measured and this is very similar to the 'spike' of 100 ppm briefly observed in the first hour with non-cresting waves in Test 4. This might be due to small areas of oil that had received locally higher treatment rates than the overall treatment rate. Because it is impossible to accurately quantify the amount of oil on the sea surface by visual observation, particularly from a boat when only a small fraction of the slick area is visible, or by remote sensing from aircraft, it is impossible to accurately know how much of the IFO-180 oil was dispersed at the sea trial. An estimate made visually suggested that at least half of the oil had been dispersed.

The wave conditions used at Ohmsett produced results that 'bracketed' those that occurred on the AEA'97 sea trial, in terms of their effect on dispersion of a very similar oil, treated with the same dispersant and at a similar treatment rate. The 30 cps / 3 inch stroke condition caused less dispersion, and the 35 cps / 3 inch stroke condition caused more dispersion, than was estimated at the sea trial. This appears to indicate that the lower energy mixing regime at Ohmsett is, in terms of the effect on dispersion, equivalent to less than a Beaufort Force 4 sea state and that the higher energy mixing regime is equivalent to higher than a Beaufort Force 4 sea state. This confirms that the agitation regime is realistic and can be altered over relevant range for assessing the effectiveness of dispersants at sea.

Nominal 10,000 cP (up to 20,000 cP) viscosity oil results

The precise viscosity of the higher viscosity test oil when it was sprayed with dispersant varied according to the temperature that it had attained as it cooled from the heating it had received to allow it to be applied. In Test 5 this varied from 5,000 to 20,000 cP and in Test 6 from 13,000 to almost 20,000 cP (measured at 100 s^{-1}). Although this was an artificial situation created by the difficulty in pumping this test oil, it is quite likely that large local variations in spilled oil temperature do occur at heavy fuel oil spills. The thick layers of spilled fuel oil absorb solar radiation very effectively. Both tests were conducted with the more energetic, 35 cpm/3 inch stoke condition. When sprayed with a DOR of 1:42 (Test 5) the oil did not disperse significantly, although it initially appeared as if it might, and when sprayed with a DOR of 1:14 (Test 6) it did disperse, leaving no significant surface slick after one hour.

No large-scale sea trials of dispersant effectiveness have been conducted with No. 6 fuel oil. It has generally been believed that Heavy Fuel Oils (HFOs) cannot be dispersed under most conditions. Reports as to the effectiveness of dispersant treatment of HFOs at actual oil spills are not consistent; some claim that HFO can be dispersed and others claim that it cannot. In part, this might be due to where the spill has occurred; a spill of HFO in tropical waters might be dispersible, while an HFO spill in Arctic waters would almost certainly not be dispersible. The situation is further complicated by the ill-defined and variable nature of HFOs; they are produced to very broad specifications and their viscosity at sea temperatures can vary over an enormous range due to very non-Newtonian flow behaviour. HFOs with a high wax content (produced from paraffinic crude oils to produce low-sulphur HFOs) can have pour points of up to $+30^{\circ}\text{C}$.

The results obtained in Tests 5 and 6 are therefore very intriguing; they appear to indicate that using a high dispersant treatment rate can cause an HFO to be dispersed under conditions which are equivalent to more than a Beaufort Force 4 sea state, but which are not excessively, or artificially rough. Without confirmation from a sea trial, it is not possible to provide independent proof of this conclusion.

3.2.2 Comparison with results of laboratory studies

The conditions used in laboratory methods to test dispersants have generally been devised to provide a high level of discrimination between the performance of different dispersants. Most methods were devised for approval purposes and the intent was to ensure that a dispersant produced higher effectiveness than a stated minimum. The UK adopted a 60% 'pass-mark' in the WSL test method on the basis of very small-scale harbor trials where dispersant performance on the MFO (Medium Fuel Oil) was assessed visually by a team of observers in a boat following the oil-laying and dispersant spraying boat (Cormack, 1983). The visual indication of adequate performance was judged to be the presence of a brown cloud of dispersed oil, while inadequate performance was the formation of 'tea leaf' like coarse oil droplets. The discrimination between these two conditions 'at sea' was assessed to equate to a WSL effectiveness (or 'efficacy', as it was termed) of 60% in the WSL test with the same oil. The WSL method uses end-over-end rotation at 30 rpm of the dispersant treated oil and seawater mixture, followed by a one minute standing period to let the largest oil droplets float out of the volume of water that is sampled (Martinelli, 1984).

Different countries adopted different test methods. Following the Protecmar series of sea trials (Desmarquest et al., 1983), France adopted the IFP method (Desmarquest et al., 1985). The IFP method uses a more gentle mixing regime with no breaking waves. A hoop that moves sharply up and down is situated below the water surface in the test vessel. The Swirling Flask Test has been adopted in the USA (Fingas et al., 1987). The 3 different test methods are known to differentiate between the performance of dispersants with oils in slightly different ways. It is probably, but only approximately, correct that different laboratory test methods might simulate some aspects of different sea-states. In terms of agitation energy, the order of the test methods is:

WSL or Labofina test > IFP Dilution test > Swirling Flask Test

While it may be tempting to assign relative sea-states to the methods (for example, Beaufort Force 2 for the Swirling Flask test, Beaufort 4 for the IFP test, and Beaufort 5 for the WSL test - or some other correlation) there is currently no evidence to suggest that this can be rigorously justified. The different methods of agitation, the effects of the container walls (and the hoop in the IFP test) and the settling period used in the WSL method all confound such a simplistic comparison. Comparisons

of dispersant performance in laboratory tests and at sea trials conducted by CEDRE (Desmarquest, 1985), AEA Technology (Lunel, 1995) and SINTEF (Lewis et al., 1995) have all shown that the results obtained in different laboratory test methods broadly agree with observations made at sea, but it has so far proved impossible to devise a rigorous correlation. This is, in part, due to the inherent difficulties in obtaining an accurate measure of the rate or extent (at any particular time) of the dispersion of oil at sea, even under carefully controlled conditions. Attempts to use continuous release or 'steady state' experiments at sea (Lunel et al., 1995) to overcome these problems have yet to yield a firm correlation between laboratory results and performance at sea.

Although not the only oil characteristic that defines dispersibility, the oil viscosity has a large influence on dispersant effectiveness. The relationship between the results obtained and heavy fuel oil viscosity has been reported for the WSL and IFP methods by Guyomarch et al., 1999 and Fiocco et al., 1999. The effectiveness of Corexit 9500 at a treatment rate of DOR = 1:25 with fuel oils that have a similar viscosity to those used in the Ohmsett tests would be expected to be:

	WSL Test method	IFP Test method	Swirling Flask Test method
Nominal 2000 cP test oil (Actual viscosity of 3,500 – 4,000 cP)	85 – 100**	60 - 65**	5*** (Bunker C Light Fuel Oil tested at 20°C)
Nominal 10,000 cP test oil (Actual viscosity of up to 20,000 cP)	61 – 67*	1 – 54* 55**	7*** (Bunker C Fuel Oil tested at 20°C)

References

- * Fiocco et al 1999
- ** Guyomarch et al., 1999.
- *** Fingas et al., 2000.

In Test 2 of Ohmsett test series the lower viscosity test oil (with a nominal 2,000 cP viscosity) dispersed when cresting waves were present and a DOR of 1:29 was used. The WSL and IFP tests reflect this condition by having high numerical efficiencies. The low Swirling Flask Test result may be more indicative of the lower energy wave conditions (no cresting waves) initially used in Test 4. The factor that made a large difference in Tests 5 and 6 with the higher viscosity test oil (nominal 10,000 cP viscosity) was the treatment rate; a DOR of 1:42 in Test 5 caused no significant dispersion, while a DOR of 1:14 in Test 6 caused total dispersion. The preferred treatment rate of a DOR of 1:25 for laboratory test methods was not tested in the Ohmsett series. It is therefore not possible to decide whether significant dispersion would have occurred at Ohmsett with a DOR of 1:25 or which of the three laboratory test methods is more indicative of the results obtained.

A systematic study of the effect of dispersant treatment rate (DOR) on heavy fuel oil dispersibility in different laboratory test methods has not yet been openly published. However, earlier work on the effect of dispersant treatment rate in laboratory tests with less viscous oils has indicated that there is normally little effect caused by treatment rates in this high treatment level region. Whether this is an artifact of the laboratory methods or a true reflection of dispersant performance remains to be seen

3.3 Tank Filtration

Part of the purpose of these tests was to evaluate the effectiveness of the cellulose filter aid (Pre-Co-Floc) in removing dispersed oil from the tank water and the efficacy of activated carbon in removing dissolved dispersant.

3.3.1 Dispersed Oil Removal

During, and for one week after, the dispersant test period, the Ohmsett leaf filter was loaded with the Pre-Co-Floc filter aid. Initially, pure Pre-Co-Floc was put on the filter leaves; however, the mechanical properties of the cake proved unacceptable (the cake was apparently washed through the leaf fabric at higher flows/pressure drops) and finally, a mixture of 50% diatomaceous earth (DE) and

50% Pre-Co-Floc was found to give acceptable filter cake properties. It was clear that this combination was removing dispersed oil droplets from the water as the oil could be seen in the filter cake when it was backwashed off the filter and de-watered in the Oberlin filter press. At the beginning of the filtration period, the flow rate through the filter was reduced to half the normal 1800 gpm to prevent the filter from requiring back washing too frequently. By the end of the filtration period the normal 1800 gpm flow rate was being used. Over a two-week period following the tests, the clarity and color of the water improved to pre-test conditions.

Initially, water samples were taken periodically from the influent and effluent sample ports of the leaf filter, and grab samples were taken from the middle of the tank. At the end of this period, only grab samples were obtained. The data is given in Table 2 and appears to show a steady decrease in oil

Table 2: Dispersed Oil Removal by the Leaf Filter

Date	Sample Location	TPH (ppm)
April 26, 2000 (the last dispersant test was conducted on 4/27/00)	Filter influent 15 min after start	7.1
	Filter effluent 15 min after start	6.9
	Filter influent 60 min after start	8.1
	Filter effluent 60 min after start	3.7
	Grab sample from south end	6.3
May 1, 2000	Filter influent	15.1
	Filter effluent	3.9
	Grab sample from center of tank	8.9
May 2, 2000	Filter influent	6.9
	Filter effluent	5.5
	Grab sample from center of tank	6.7
May 3, 2000	Filter influent	23.2
	Filter effluent	6.2
May 4, 2000	Grab sample from center of tank	5
May 5, 2000	Grab sample from center of tank	2.9*

* normal background oil concentrations in the Ohmsett tank are 3 to 5 ppm.

concentration as the filter processed the water. Unfortunately, it was subsequently learned that a component of the IR spectrophotometer was dirty and the equipment's computer software was not performing properly, preventing accurate zeroing of the device. Zero standard values ranging from 2.5 to 7.9 ppm were obtained over the time of the filtering operation tests, while the readings for the influent, effluent and grab samples ranged from 2.9 to 23.2 ppm); thus, despite the strong trend in the analytical data it is not possible to conclude unequivocally that the filter was efficient. The raw data are contained in Appendix G.

3.3.2 Dissolved Dispersant Removal

The activated carbon system was not put online to treat the water exiting the filter until it was clear that most of the dispersed oil droplets had been removed from the tank water. This was to prevent the dispersed oil from fouling the activated carbon. Unfortunately, it was not possible to determine how quickly and effectively the activated carbon removed the dissolved dispersant. The technique of using oil/air interfacial tension (otherwise known as the water's surface tension) measurements to determine dispersant concentrations in the water that had been used effectively in the laboratory proved unworkable with the tank water because the presence of even very low concentrations of oil in the water (i.e., even at the level of background oil concentrations in the tank of a few ppm) a sheen was generated on the sample that interfered with measuring the water's surface tension.

The activated carbon system used was very large, in order to obtain flow rates that would allow treatment of all the tank water in a reasonable period of time. The system's capacity was 9,000 kg (20,000 lb.) of activated carbon to get a flow rate of 800 gpm. Previous lab tests had indicated that only 450 kg (1,000 lb.) of activated carbon, or less, would theoretically be required to remove all the dispersant. Further study of this aspect of the protocol should be carried out, if more dispersant tests are planned. It may be that adding 450 kg, or less, of powdered activated carbon to the tank, mixing the tank thoroughly with waves, then filtering out the suspended carbon particles with the leaf filter would prove to be just as effective in removing dissolved dispersant as the large activated carbon treatment tanks. The analytical technique to detect dissolved dispersant in the tank water will also have to be changed.

4. Conclusions and Recommendations

4.1 Conclusions

Realistic dispersant effectiveness testing at Ohmsett is feasible.

- The Ohmsett facility produces results during dispersant testing that are consistent with observations and measurements made at field trials.
- The test series revealed that a suitable protocol can be devised that would enable a systematic investigation of test variables such as oil viscosity, dispersant treatment rate and sea conditions.
- The best way to measure dispersant effectiveness at Ohmsett appears to be collecting the surface oil following one hour of wave action. The experimental design employing booms that was used during this test series successfully minimised the ‘wall effects’ inherent in using any tank test, although larger booms are required.
- The use of a 50/50 mix of diatomaceous earth and cellulose in the leaf filter allows for effective removal of dispersed oil from the tank water in a period of one week. It was not possible to determine how quickly, or how efficiently, the activated carbon treatment system removed dissolved dispersant from the tank water.

4.2 Recommendations

1. For future dispersant tests, it would be advantageous to modify the oil distribution manifold to swing up out of the way after the test slick has been laid down.
2. In future, it would be advantageous to either heat trace the tubing connecting the pump module and the spray bar and the spray bar itself, or re-locate the solenoid to the spray bar, and allow the dispersant to recirculate from the spray bar back to the pump module.
3. In order to achieve more accurate measurements of dispersant effectiveness, improvements to the rectangle of boom in which the tests are conducted are needed. In future tests a larger protected-water boom should be used to form the rectangle. A curtain-type boom with a high

- buoyancy-to-weight ratio and a smooth profile would be ideal. The boom should have a freeboard of 12 to 18 inches and a draft of 24 inches.
4. Another problem was having the boom rectangle only slightly larger than the test slick length. This proved to be a considerable impediment to the dispersed oil cloud sampling. It was not possible to sample beyond the ends of the rectangle during the test, whereas the dispersed oil could, and did, move under the ends of the rectangle. For future dispersant testing, sufficient boom to create a rectangle almost the full length of the tank (from 30 m south of the wave paddle to 15 m north of the wave beach) would be ideal. Taking into account the 15-m width of the rectangle, this would require 350 m (1135 ft.) of boom. Alternatively, it may be necessary to deploy weighted plastic sheeting or tarpaulins at the beginning of each test, that extend from the water surface to the bottom of the tank, across the width of the tank at either end of the rectangle of boom. With the dispersed cloud retained between the plastic sheets it would be easier to obtain the volume of oil dispersed from concentration measurements.
 5. Concern has been expressed about waiting until the slick has been laid down and sprayed before turning on the wave generator. Consideration could be given to either modifying the oil distribution system to allow it to follow waves (thus allowing the oil slick to be laid and sprayed with dispersant with the waves running), or turning on the wave generator at just the right time before the oil distribution is complete to allow the first wave to reach the end of the slick just as the dispersant spraying stops.
 6. The wave height sonic probe signal contained a large amount of noise in the form of numerous spikes in the output. This rendered analysis of the wave patterns useless, even after Fast Fourier Transform massaging of the signals. This has been rectified subsequently.
 7. Re-introducing a distance sensor on the Main Bridge would permit easier, and more accurate, measurement of the dimensions of the cloud of dispersed oil droplets.
 8. Further study of the removal of the dissolved dispersant by activated carbon is warranted. It is likely that adding 450 kg (1000 lbs.), or less, of powdered activated carbon to the tank, mixing the tank thoroughly with waves, then filtering or vacuuming out the suspended or settled carbon particles would prove to be just as effective, and far less costly and time-consuming, in removing dissolved dispersant as directing the effluent through the large activated carbon treatment tanks. The analytical technique to detect dissolved dispersant in the tank water will also have to be changed.

5. References

- Brandvik, P. J., T. Lunel, P. S. Daling and A. Lewis. 1995. Measurements of the dispersed oil concentrations by in-situ UV fluorescence during the Norwegian experimental oil spill in 1994 with Sture Blend. Proceedings of the 18th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Environment Canada, Ottawa. PP 519-536.
- Brandvik, P. J., T. Strom Kristiansen, A. Lewis, P. S Daling, M. Reed, H. Rye and H. Jensen. 1996. The Norwegian Sea Trial 1995: Offshore testing of two dispersant application systems and simulation of an underwater pipeline leakage. Proceedings of the 19th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Environment Canada, Ottawa. PP 1395-1415.
- Blondina, G., M. Singer, I. Lee, M. Ouano, M. Hodgins, R. Tjeerdema and M. Sowby. 1999. Influence of salinity on petroleum accommodation by dispersants. Spill Science and Technology Bulletin 5(2): 127-134.
- Cormack, D. 1983. Chapter 4, Section 4.2 in "Response to Oil and Chemical Marine Pollution" Applied Science publishers, Barking, England 1983.
- Delvigne, G.A.I. and C. E. Sweeney. 1988. Natural Dispersion of Oil. Oil and Chemical Pollution 4, pp 281-310.
- Desmarquest, J. P., J. Croquette, F. Merlin, C. Bocard and C. Gatellier. 1983. A field test and assessment of oil dispersant efficiency. Proceedings of the 1983 International Oil Spill Conference. Pp 574-583.
- Desmarquest, J. P., J. Croquette, F. Merlin, C. Bocard, G. Castaing and C. Gatellier. 1985. Proceedings of the 1985 International Oil Spill Conference. Pp 445-452.
- Fiocco, R. J., P. S. Daling, G De Marco, R. J. Lessard and G. P Canevari. 1999. Chemical Dispersibility Study of Heavy Bunker Fuel Oil. Proceedings of the 22nd Arctic and Marine

Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, pp 173-186.

Fingas, M. F. K. A. Hughes and M. A. Schweitzer. 1987. Dispersant testing at the Environmental Emergencies Technology Division. Proceedings of the 10th Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, pp 343-356.

Fingas et al , M., B. Fieldhouse, Z Wang, L. Sigouin, M Landriault and J. V. Mullin.2000. Recent Results from Dispersant Testing. Proceedings of the 23rd Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, pp 681-695.

Lewis. A., P. S. Daling, T. Strom-Kristiansen, A. B. Nordvik and R. J. Foicco. 1995. Weathering and chemical dispersion of oil at sea. Proceedings of the 1995 International Oil Spill Conference. Pp 157-164.

Lewis,. A., P. S. Daling, T. Strom-Kristiansen, I. Singaas, R. J. Fiocco and A. B. Nordvik. 1994. Chemical dispersion of oil and water-in-oil emulsions: A comparison of bench scale methods and dispersant treatment in a meso-scale flume. Proceedings of the 17th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Environment Canada, Ottawa. Pp 979-1010.

Lewis, A. A. Crosbie, L. Davies and T. Lunel. 1998. Large Scale Field Experiments into Oil Weathering at Sea and aerial application of Dispersants. Proceedings of the 21st Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, pp 319-344.

Lunel, T., P. Wood and L. Davies. 1997. Dispersant effectiveness in field trials and operational response. Proceedings of the 1997 International Oil Spill Conference. Pp 923-927.

Lunel, T., G. Baldwin and F. Merlin. 1995. Comparison of meso-scale and laboratory dipsersant tests with dispersant effectiveness measured at sea. Proceedings of the 18th Arctic and Marine

Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, pp 629-651.

Lunel, T, 1994. Dispersion of a large experimental slick by aerial application of dispersant. Proceedings of the 17th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Environment Canada, Ottawa. Pp 951-978.

Lunel, T. Dispersant effectiveness at sea. Proceedings of the 1995 International Oil Spill Conference. Pp 147-155.

Martinelli, F. 1984. The status of Warren Spring Laboratory's rolling flask test. In "Oil Spill Chemical Dispersants, Research, Experience and Recommendations" (ASTM STP 840). Edited by T. E. Allen. American Society for Testing Materials, Philadelphia, Pennsylvania, USA. Pp 56-58.

S.L. Ross Environmental Research Ltd. 2000. Feasibility of using Ohmsett for dispersant testing and research. Report to MAR, Inc. Atlantic Highlands, NJ.