Revising the Ohmsett Dispersant Test Protocol. Final Report

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EXECUTIVE SUMMARY

Ohmsett is the largest facility of its kind in the world and offers significant advantages for testing response technologies in controlled conditions at full and near-full scale – something not achievable at smaller facilities. There is an ongoing need for dispersant testing at Ohmsett, to study the basic science into the mechanisms controlling dispersion, predicting effectiveness for applications to real world spills, and for choosing appropriate products to stockpile for use during spill response.

Limitations with the original Dispersant Effectiveness Test Protocol were identified over time at the Ohmsett facility up through 2020. Improvements to the Ohmsett infrastructure along with innovations by other researchers has sparked the current project to revise and update the test protocol. The main objective was to develop a new protocol that was more repeatable, while still being representative of dispersant applications at sea.

The scenario simulated by the revised test protocol remains unchanged, being an uncontained surface slick in the open ocean with dispersant applied by spraying. Revisions to the test protocol included:

- Reducing the volume of oil used per test.
- Constraining the test slick to a section of the tank with water spray jet barriers.
- Applying the dispersant with a hand-held sprayer.
- Subjecting the test slicks to a series of seven identical, discrete breaking waves at 5-minute intervals.
- Recovering residual oil from within the test area.

In control tests completed with weathered HOOPS crude oil, the recovery averaged 90% of the oil initially deployed after exposure to the wave regime. This compares to recoveries of around 40% with the original protocol using the same crude oil. This improvement is a result of increased accuracy of the oil distribution method, reduced losses from the test area due to the containment system, and enhanced recovery techniques. In tests with Corexit 9500, dispersant effectiveness averaged 96%, which is within the expected result range for this crude oil.

Plume monitoring with electronic sensors (the LISST and SilCam) were able to detect significant differences in oil-in-water concentrations and oil droplet size distributions between control and treatment runs. Control tests typically required 2 to 2.5 hours to complete, while treatment runs could be completed faster if dispersant effectiveness was high. Residual oil recovery was the longest step, typically taking approximately 75 minutes for a control run.

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1 INTRODUCTION

Testing of oil spill response technologies in wave tanks provides a useful intermediate scale between laboratory and field tests, and (with well-designed experiments) can connect the two extremes (Belore et al., 2005; Trudel et al., 2011). While dispersant testing using laboratory tests (e.g., Baffled Flask, Swirling Flask, Warren Springs Lab, ExDET) can provide comparative data between oil and dispersant combinations, it is generally acknowledged that they are poor simulations of the mixing environment at sea, and it has not been possible to directly translate performance in the lab to a particular set of conditions (Ghurye et al., 2014). Testing dispersants in wave tanks provides more realistic turbulent energy and allows for monitoring of the characteristics of the dispersed oil plume (e.g., oil-in-water concentration, droplet size distribution) which are key components of assessing effectiveness. The dispersant application systems used in wave tank experiments can also be more realistic, and provide the same droplet sizes, spray patterns and impact velocities as are used in the field. Wave tank experiments provide an opportunity to use a variety of instruments to measure surface oil and the sub-surface plume that is not practical with other smaller-scale experiments.

Ohmsett is the largest facility of its kind in the world and offers significant advantages for testing response technologies in controlled conditions at greatly reduced cost compared to field trials. There will be a continued need for dispersant testing at Ohmsett, to study the basic science into the mechanisms controlling dispersion, predicting effectiveness for applications to real world spills, and for choosing appropriate products to stockpile.

One of the issues with conducting dispersant testing in wave tanks is the finite size, and the accumulation of dispersed oil. Resurfacing of oil is affected by oil droplet coalescence, and in a closed system coalescence will increase as additional experiments are conducted. However, Ohmsett is a very large tank and the amount of oil used with each test is comparatively tiny. The frequency of collisions between oil droplets resulting in coalescence will be low. As well, the presence of dispersant at the surface of the dispersed oil droplets will further limit coalescence (Frankiewicz and Walsh, 2017).

One of the tasks conducted during the development of the original protocol was a feasibility study that answered the question of whether dispersant effectiveness testing could be conducted at Ohmsett (Ross et al., 2000). The study looked at issues of dispersant and oil accumulation in the tank following tests. Fortunately, the large size of Ohmsett helps, and it was determined that:

- Residual dispersant in water is not a concern for subsequent dispersant testing, as persistent concentrations around 400 ppm were needed before effects were noted.
- Residual oil concentration is somewhat of a concern, but it was possible to conduct two to four experiments involving approximately 26 to 53 gallons (100 to 200 L) of oil each without background concentrations becoming excessive. Visibility in the tank water is adversely impacted, but sampling and analysis is not.
- Residual dispersant in water is a potential concern for use of Ohmsett with subsequent projects (e.g., equipment testing); the existing filter system with an alternative filter aid was found to effectively remove dispersed oil but not dispersant.

- Activated carbon will remove dispersant. Custom-built portable tanks were designed to clean the tank.

Subsequent experience with the tank filters since 2000 has demonstrated that the existing filter system does remove dispersant from the water, and that activated carbon is not required.

Dispersant Effectiveness is defined as the fraction of treated oil that becomes stably entrained as small droplets in the water column (NRC 2005). The existing dispersant effectiveness test protocol was developed by SL Ross between 2000 and 2003 (SL Ross Environmental Research, 2001 and 2003) using the available Ohmsett infrastructure and was used most recently in 2015 (Steffek et al., 2017). In those tests, unrecovered oil from for the control runs with HOOPS crude oil was high (average > 60%), making it difficult to identify statistically significant differences from the tests with dispersant. Reducing the quantity of unrecovered oil and unaccounted losses during the tests, particularly the controls, would improve the ability to detect statistical differences between treatment and control runs.

Test protocols are often created using theoretical or practical knowledge that may incorporate some compromises with respect to specific target conditions or operational concerns, and can in some ways be considered works-in-progress. Knowledge and experience gained from using the original dispersant test protocol naturally led to identifying items for improvement, and several changes were made for subsequent projects.

Ohmsett itself has undergone improvements and modernizations to several systems. For example, the wave maker and controller were significantly updated in recent years, and Ohmsett now has a digital system that offers greater capabilities for producing waves than the legacy analog system. The equipment for measuring and recording the wave field in the tank has also been updated. Ohmsett currently has several methods for measuring and tracking waves, including acoustic altimeters, pressure transducers, and capacitive wave gauges. There have been other additions to the Ohmsett technology suite, including cameras and software for measuring the surface area of oil slicks, that would be useful in various aspects of dispersant testing.

The objective of the current project was to leverage improvements at Ohmsett, and lessons learned from the previous protocol and other researchers, to develop an improved protocol that could generate results that were more accurate and repeatable.

1.1 Target Scenario

The real-world scenario that is to be simulated by the test protocol remains unchanged from the original protocol, and is summarized as follows:

- An uncontained surface slick in the open ocean
- Dispersant applied by spraying, such as from an aircraft or vessel

Operational issues, such as the slick being in potentially discontinuous patches of oil of varying thickness or the ability to accurately deliver dispersant to the oil, while important to successful dispersant use, should not be the focus of the Ohmsett dispersant test protocol. As much as possible, the protocol attempts to deliver dispersant at the target dose rate to a slick of known volume and dimensions. Therefore, the results achieved in the wave tank experiments will reflect the best possible outcome for the conditions.

Oil weathering processes such as evaporation, dissolution, the formation of water-in-oil emulsions, and photo-oxidation, can have a significant effect on dispersant performance. Given that Ohmsett is an outdoor tank, the degree of exposure will depend on the prevailing weather. Therefore, oil weathering in-situ was not included as a component of the revised test procedure. Weathered oil or emulsions could be evaluated with the protocol, but the preparation of the weathered samples would be a separate process not covered here (e.g., Stone and Guarino, 2017).

1.2 DEVELOPMENT AND TESTING OF THE REVISED PROTOCOL

The dispersant effectiveness test consists of several discrete components, describing the steps for tank preparation, oil containment and distribution, dispersant application, measurements and observations of the dispersed oil plume, and residual oil recovery and cleanup. Each of these components was reviewed for potential areas of improvement.

A literature review of dispersant testing in large tanks was completed to investigate methods and practices used in other research (see Section 2). Evaluations of the revisions to the dispersant test protocol were then completed in three phases, as follows:

- October 5 to 9, 2020. Developed a containment system to hold oil slicks in a small area of the tank. Generated waves that broke within the test area. Test summaries are provided in Appendix A.
- December 7 to 18, 2020. Characterized breaking waves. Developed method to apply dispersant to slicks within the test area. Tested methods to characterize dispersed oil plume. Developed techniques to recover residual oil and evaluated mass balance issues. Drafted revised test protocol. Test summaries are provided in Appendix B.
- April 26 to 30, 2021. Evaluated new draft test protocol. Test summaries are provided in Appendix C.

The results of the development testing are provided in Sections 3 through 9. The revised protocol is presented in Section 10, and considerations for using the protocol in other large tanks are provided in Section 11.

2 REVIEW OF DISPERSANT TESTING IN OTHER WAVE TANKS

In preparing a revised test protocol, it was important to review previous research and testing to ensure that effort was not spent on reproducing work that had already been done. While there are many wave tanks around the world, relatively few have been used for testing with oil (Fingas, 2005). This section summarizes the significant research on dispersant testing with oil that has been done in other large wave tanks.

2.1 ESSO RESOURCES WAVE BASIN

Some of the earliest dispersant testing in large tanks was done at the Esso Resources Wave Basin in Calgary, AB, Canada (see Table 2-1). The tank was used for experiments from about 1984 through 1996, with most trying to improve the understanding of dispersant effectiveness in cold water and in ice. It was recognized that tank testing was a useful intermediate between lab-scale testing and field trials. This tank was decommissioned in 1998.

Table 2-1: Esso Resources Wave Basin

Location	Outdoors, Calgary, Alberta, Canada		
Operator	Esso Resources Canada Ltd.		
Dimensions		m	ft
	Length	54.5	178.8
	Width	30.8	101
	Depth	1.85 to 3.3	6 to 10.8
Wave Maker	Four hydraulically driven, computer-controlled wave boards.		
Beach	Inclined pebble beach at the shallow end of tank		
Water	Municipal water amended with salt or in some cases a mixture of ions including Na^+, Mg^{2+}, Ca^{2+} and Cl^- to 28 ppt. Most tests were with cold water (-2 to 8°C).		

The important conclusions from dispersant effectiveness tests at this facility include:

- In-water dispersed oil concentrations are highly variable spatially and over time
- Dispersant effectiveness calculated from residual oil amounts were significantly higher than when calculated from in-water concentrations
- Dispersant effectiveness decreased with increased oil viscosity and weathering
- Dispersant effectiveness is a function of time, and dispersants were most effective in the first 15 to 30 minutes after being applied

The following papers on tests conducted at this facility were reviewed:

MacNeill et al. (1985). The experiments in this paper were conducted in May and June of 1983.

Objective	Investigate the effectiveness of Corexit 9527 on Issungnak crude oil in non-breaking waves
Containment	Oil slicks were contained in a 4.6-m diameter ring made from twelve foam cylinders covered with a layer of plastic that extended 1.85 m below the water surface.

Test Conditions	Fresh slicks of Issungnak oil were exposed to regular (i.e., non-breaking) waves between 10 and 28 cm in height for four hours. The test program included four control tests with untreated slicks, and four tests where dispersant was applied at a nominal 20:1 ratio. Water temperature varied between 10 and 18°C over the course of the tests.
Dispersant Application	Dispersant was sprayed onto the slick from nozzles on a straight section of pipe that was suspended from wires above the tank and pulled by hand over the slick containment area.
Sampling and Plume Characterization	Subsurface samples were taken several times during the tests from six ports below the slick containment area. Oil concentrations were quantified by both radioisotope tracing and fluorometry. Droplet size measurements were done using a HiAc Model PA-720 particle analyzer capable of measuring droplets between 1 and 45 µm.
Dispersant Effectiveness	Residual oil remaining in the containment area after the tests was collected, but not quantified.
Results	Treatment with Corexit 9527 significantly increased in-water oil concentrations even in non-breaking waves.

Brown, Goodman and Canevari (1985). These tests were conducted in November 1984.

Objective	Determine the effectiveness of Corexit 9527 and CRX-8 dispersants on crude oil in cold water.
Containment	The containment area was increased to a 10-m diameter ring, while the skirt depth was shortened to 1.5 m.
Test Conditions	Fresh and weathered slicks of Alberta Sweet Mixed Blend crude oil were exposed to regular waves between 10 and 20 cm in height for four hours. The test program included both control and treated slicks. Water temperature varied between 0 and -3°C, and ice had formed on the tank in some tests.
Dispersant Application	Dispersant was applied using the same system as in 1983.
Sampling and Plume Characterization	Oil concentrations in the water were measured using four flow-through fluorometers that sampled intermittently from seven ports around the tank. Samples were also analyzed for particle size distribution as with the 1983 tests.
Dispersant Effectiveness	Dispersant effectiveness between 10 and 33% was reported based on in-water concentrations measured 24 hours after the test start and 20 hours after waves were stopped.
Results	Both dispersants showed limited effectiveness (< 33%) under the test conditions.

Brown, To and Goodman (1986). These tests were conducted in April 1985.

Objective	These were conducted after the 1984 results demonstrated the difficulty in completing an accurate mass balance of the oil from the existing in-water concentration measurements.
Containment	A 10-m diameter ring with no skirt was used to contain the oil slicks.
Test Conditions	Fresh and weathered slicks of Norman Wells crude oil were exposed to regular waves. Water temperature varied between 1 and 12°C.

Dispersant Application	Dispersant was sprayed onto the slick with either the previously used spray arm or a hand-sprayer.
Sampling and Plume Characterization	Five fluorometers were used to measure in-water concentrations of dispersed oil, as follows: three were connected to sampling ports beneath the containment area that were used in the previous experiments, the fourth sampled in the middle of the basin, and the fifth sampled intermittently from four other locations outside of the containment area around the basin.
Dispersant Effectiveness	Undispersed oil was recovered from the containment area using a disc skimmer. Recovered fluids were transferred to a carboy and allowed to settle for 24 hours before free water was decanted.
Results	Significantly higher measures of dispersant effectiveness were calculated when residual oil was used as the basis for determining the amount of oil dispersed (i.e., oil dispersed = oil initial - oil residual) instead of in-water concentrations.

To, Brown and Goodman (1987). Data from the 1984 and 1985 tests were used in the development and calibration of a numerical dispersion/advection model for the simulation of dispersed oil plumes. Migration of subsurface oil away from the slick was modeled with reasonably good agreement with measured concentrations over time.

Brown and Goodman (1987). A review of dispersant effectiveness results from the above wave basin data and reported field trials in the U.S., Canada and Europe was presented. Wave tank results showed that dispersed oil plumes may be highly variable spatially, and extensive sampling was required for an accurate measurement of the amount of oil dispersed. When the dispersed oil concentrations were compared with the residual oil remaining in the containment area after the experiments, it was clear that much of the oil lost from the boom was unaccounted for. Dispersants have been shown to be effective in some field trials, but only when sufficient sampling of the water column was done and when it was verified that the dispersant had been applied to thick portions of the parent slick.

Brown and Goodman (1988). The dispersant application system was redesigned as a 5-m spray arm that rotated around the center of the 10-m diameter containment area. The objective was to simulate how dispersants are applied in the field (i.e., constant rate per unit area), which may result in under dosing of the slick if it is herded by wind and waves. The dispersant application ratio was determined using oil slick area as measured from overhead images.

Brown, Weiss and Goodman (1990).

Objective	These tests investigated the effect of dispersants on the formation and properties of emulsions in residual or undispersed oil.
Containment	Three 10-m diameter booms were placed across the mid-point of the tank.
Test Conditions	The booms were filled with 75 L of crude oil (Drift River and Alaska North Slope crude oils) and weathered for 16 hours.
Dispersant Application	Dispersant (Corexit 9550 or 9527) was applied using a hand-sprayer to two of the test slicks, while the third was left untreated as a control. Regular waves (20 cm high, 1.6 s period) were generated for 8 hours per day for four days.
Sampling and Plume Characterization	Samples of the surface slick were taken several times over the course of the experiment and analyzed for emulsified water content and emulsion stability

Dispersant Effectiveness	Dispersant effectiveness was not measured, as it was not the focus of the study.
Results	Higher water content was measured in emulsions that formed from residual Drift River crude oil after treatment with dispersants. The opposite effect was measured with Alaska North Slope crude oil.

Mackay (1995). These tests were completed in the fall of 1991 and spring of 1992.

Objective	Predict the effectiveness had dispersants been applied to the Exxon Valdez oil spill
Containment	A 5-m diameter containment boom with a 40-cm skirt was located near the middle of the tank.
Test Conditions	Tests were done with weathered Alaska North Slope crude oil and emulsions. Breaking waves were generated by installing a steel reef below the containment boom, about 20 cm below the water surface. Waves had a frequency of 0.4 s^{-1} and height of 15 cm, and were run for 2 hours.
Dispersant Application	Corexit 9527 was applied by hand using a pressurized sprayer. The dispersant was allowed to mix with the oil under gentle wave conditions for 1 to 30 hours.
Sampling and Plume Characterization	Visual observations.
Dispersant Effectiveness	Residual undispersed oil was collected using a small disc skimmer and allowed to settle overnight to separate out free water. Water content of the residual oil was measured and accounted for in the mass balance.
Results	Most dispersion occurred in the first 15 minutes, but some continued for the full two hours.

Brown and Goodman (1996).

Objective	Determine the effectiveness of dispersants on oil in broken ice.
Containment	Containment booms were frozen in place in the wave tank. Testing was also done in leads cut in the ice.
Test Conditions	Slicks of Federated crude oil (39° API) were treated with Corexit 9527 or 9500 and then subjected to low-amplitude (15 cm height) waves for two hours. Ice concentrations were measured by digitally analyzing overhead photos of the tank.
Dispersant Application	Dispersant was applied to the slicks using a hand sprayer.
Sampling and Plume Characterization	Oil in water concentrations were measured by fluorometers (Turner Designs Model 10) from three locations in the tank. Photographs and video recordings were made.
Dispersant Effectiveness	Oil and oiled ice remaining in the containment areas were collected and quantified.
Results	Dispersant effectiveness of 90% or more were measured, despite the presence of ice.

2.2 Delft Hydraulics Laboratory

Research on natural and chemical dispersion of oil due to breaking waves was conducted at the Delft Hydraulics Laboratory in the Netherlands. Two wave tanks have been used in research at this facility, the Oil Flume (see Table 2-2) and the larger Delta Flume (Table 2-3).

Table 2-2: Delft Hydraulics Oil Flume

Location	Indoors, Delft, Netherlands		
Operator	Delft Hydraulics Laboratory		
Dimensions		m	ft
	Length	20	65
	Width	0.5	1.6
	Depth	up to 0.6	2.0
Wave source	Computer-controlled wave board. Trains of waves were generated that created a breaking wave at a specific point in the tank.		
Beach	A wave damper is located at the opposite end of the flume from the wave board.		
Water	Tests were done with fresh, brackish (10 ppt) and saline (30 ppt) water at temperatures between 9 and 16°C.		

It is understood that the Delft Hydraulics Oil Flume tank has been decommissioned.

Table 2-3: Delft Hydraulics Delta Flume

Location	Outdoors, Delft, Netherlands		
Operator	Delft Hydraulics Laboratory		
Dimensions		m	ft
	Length	200	650
	Width	5	16
	Depth	4.3	14
Wave source	Computer-controlled wave board. Trains of waves were generated that created a breaking wave at a specific point in the tank.		
Beach	Details of the wave absorber were not provided.		
Water	Tests were done with fresh water.		

Important conclusions from dispersant effectiveness tests at this facility include:

- This research was some of the first to attempt to reproduce mixing from plunging breaking waves, and to quantify turbulence produced from different wave configurations. It was also among the first to characterize the oil droplet size distribution in the dispersed oil plume with laser measuring devices

The following papers on tests conducted at this facility were reviewed:

Delvigne, G.A.L. (1985). These experiments were conducted between 1982 and 1984.

Objective Field experiments in the North Sea in 1983 produced low dispersant effectiveness result, which was attributed to poor contact and mixing of the dispersant into the

	oil; dispersant effectiveness was much better when dispersant was premixed with the oil. This study attempted to determine the reasons for the poor field results.
Containment	Slicks of oil between 0.1 and 2.5 mm thick were released on the surface of the water between two barriers that spanned the width of the tank. The barriers were removed before the waves transited the slick area.
Test Conditions	Tests varied oil evaporation, photo-oxidation, emulsification and slick thickness. Turbulence from breaking waves was measured with a laser doppler anemometer.
Dispersant Application	Dispersant was sprayed from an overhead nozzle that could be moved across the slick area.
Sampling and Plume Characterization	The walls of the flume were made primarily of glass, which allowed for visual observation of dispersed oil created by breaking waves, and for the use of laser particle size analyzers from outside the tank.
Dispersant Effectiveness	Determined using in-water concentrations measured from grab samples or absorption from a laser beam across the width of the tank.
Results	Rapid herding of the oil layer was observed when dispersant spraying was initiated. Droplets of dispersant were observed to penetrate through the oil layer into the underlying water.

Delvigne, van der Stel and Sweeney (1987).

Objective	The Oil Flume and Delta Flume were used in a research program on the natural dispersion of oil for the U.S. Minerals Management Service.
Containment	Uncontained slicks were deployed in the flumes.
Test Conditions	Mid-scale experiments in the oil flume exposed slicks of Ekofisk and Prudhoe Bay crude oils between 0.6 and 1.2 mm thick to varying heights of breaking waves and characterized the resulting natural dispersion. Turbulent energy expended by the breaking waves was calculated by a combination of wave height data and video records of breaking length. Similar experiments were done in the Delta Flume to measure the effects of scale on natural dispersion.
Dispersant Application	Dispersants were not used in this project.
Sampling and Plume Characterization	Laser particle size analysers at two depths were used to measure oil droplet diameter in the subsurface (20 to 1900 µm). Grab samples were obtained using a novel subsurface sampler (Delvigne, 1989) as it was pulled across the dispersed oil plume, and oil droplet sizes were measured through a microscope.
Results	Relationships between turbulent energy dissipation rate (ε in W/kg) from breaking waves and entrainment from natural dispersion were developed, with droplet size distribution related to oil viscosity. These relationships are still used in oil spill fate and behaviour models.

The relationship between oil entrainment due to breaking waves was extended to other forms of turbulence (Delvigne, 1993) including flow over a dam, a cataract with a hydraulic jump, flow around an obstacle, and a ship transiting an oil slick.

2.3 SL Ross Environmental Research

Extensive research on dispersant effectiveness has been completed at the SL Ross Laboratory in Ottawa, Canada, in two tanks. The original wind/wave tank was primarily made of wood with glass viewing ports, and had a flap-type wave maker at one end driven by a DC motor with an analog controller (Belore, 1986). An angled, perforated board at the opposite end of the tank absorbed some of the wave energy. The tank was replaced in 2013 with one of similar dimensions (see Table 2-4) made of marine-grade aluminum, with a computer-controlled wave board and wave absorbing perforated panels (SL Ross, 2014a). Testing with dispersants has also been done in a recirculating flume (Table 2-5).

Some projects have involved testing in both SL Ross facilities and at Ohmsett. These projects are described in Section 2.4, below.

Table 2-4: SL Ross Wind Wave Tank

Location	Indoors, Ottawa, Ontario, Canada		
Operator	SL Ross Environmental Research		
Dimensions		m	ft
	Length	10	30
	Width	1.3	4.3
	Depth	1.2	3.9
Wave source	Computer-controlled wave board. Trains of waves were generated that created a breaking wave at a specific point in the tank.		
Beach	Wave absorbing panels are located at both ends of the tank.		
Water	Tests have been done with municipal water with added salt.		

Table 2-5: SL Ross Recirculating Flume

Location	Indoors, Ottawa, Ontario, Canada		
Operator	SL Ross Environmental Research		
Dimensions		m	ft
	Circumference (Outer)	16.6	54.5
	Width	0.5	1.6
	Depth	1	3.2
Wave source	Plunging wave maker driven by an eccentric flywheel and variable speed motor.		
Beach	The flume does not have a beach		
Water	Tests have been done with municipal water with added salt.		

The important conclusions from dispersant effectiveness tests at this facility include:

- Adjusting the dispersant effectiveness results based on the proportion of dispersed oil droplets expected to remain permanently dispersed has merit.
- The LISST Type 100-C is a useful tool for characterizing a dispersed oil plume, but the droplet diameter range is limited to 2.5 to 500 µm. There are often oil droplets that exceed this size, although they will likely rapidly resurface and quickly form part of a surface slick. It may be worth investigating if alternative measurement devices are available.

- Having the LISST in place beneath the dispersing slick may be more valuable than periodic transects through the test area.

The following papers on tests conducted at this facility were reviewed:

Belore (1987a). This paper summarized a project completed for the Environmental Studies Research Fund (Canada).

Objective	Develop a protocol for meso-scale laboratory dispersant effectiveness testing.
Containment	Test were done on uncontained oil slicks that had been allowed to spread for 15 minutes after distribution.
Test Conditions	The tank was filled with municipal water at 15°C with 32 ppt salt added. Fresh and weathered slicks of Alberta Sweet Mixed Blend crude oil were exposed to 15 and 20 cm regular waves for 60 minutes after dispersant was applied. The average energy dissipation rate was 6.8 x 10^{-4} J/kg.
Dispersant Application	Corexit 9527 and Enersperse 700 dispersants were applied by a spray nozzle mounted to a cart on rails that was pulled along the top of the tank.
Sampling and Plume Characterization	Water samples for oil concentration were obtained from three sampling ports at the center of the tank between 15 and 60 minutes after dispersant application. Droplet size distribution was measured by photographing tank water pumped through glass cells.
Dispersant Effectiveness	Background oil concentrations were taken prior to tests and compared with post-test concentrations. Dispersant effectiveness was calculated based on the increase in oil-in-water concentrations.
Results	Tests were run for one hour, but it was suggested that 15 minutes would have been sufficient as most dispersant activity was seen during that time frame. It was recommended that future tests sample the water phase at more locations to improve characterization and quantification of the dispersed oil plume.

Later tests in the wind/wave tank investigated applying dispersant through followed by mixing with high-pressure water jets (Belore 1987b).

Belore and Ross (2000), SL Ross (2000b). These tests were completed in 2000.

Objective	Compare the effectiveness of dispersants applied neat or diluted
Containment	Oil slicks were contained in a 0.75 m^2 portion of the tank with a subsurface bubble barrier
Test Conditions	Tests were done with 0.75- and 3-mm thick slicks of fresh Alaska North Slope crude oil. The tank was filled with municipal water at 17°C with salt added at 32 ppt. Tests were done at two wave settings: low energy was 12 cm height and 1.8 s period, and high energy was 22 cm height and 1.5 s period. Waves were generated for thirty minutes.
Dispersant Application	Corexit 9527 and 9500 dispersants were applied to the slicks neat and diluted with water from an overhead spray arm. Dispersant dose rate (mass per area) was measured with a collection tray positioned near the test slick.
Sampling and Plume Characterization	Water samples for oil concentration were obtained from four ports at different locations in the side of the tank.

Dispersant Effectiveness	Dispersant effectiveness was determined by completing a mass balance between the oil that was applied to the tank initially, and the oil remaining in the containment area after the test.
Results	The results showed reduced effectiveness for Corexit 9500 when diluted 1:10 with salt water (32 ppt), such as might occur when being applied by ship-based fire monitor, as opposed to by aerial spraying.

A similar test procedure was used to investigate the effectiveness of Corexit 9500 on Hibernia crude oil in cold water (Belore, 2002).

Belore, Trudel and Lee (2005). The results of dispersant effectiveness tests on two marine fuel oils, IFO 180 and IFO 380, in the wind/wave tank were compared to results from 2003 UK field trials. The wave tank tests used similar procedures as described above, with Corexit 9500, Superdispersant 25 and Agma DR 379 dispersants at dose rates between 1:150 and 1:20. In general, lower effectiveness was measured in the tank tests compared to the field observations, although the differences were small and attributed to the lower mixing energy in the tank compared to the offshore environment during some of the trials.

Belore et al. (2011). Bench-scale and wave tank dispersant effectiveness tests with fresh Mississippi Canyon 252 crude oil were completed to determine if there were better alternatives to Corexit 9500 dispersant for that oil. Corexit 9500, Corexit 9527, Finasol OSR 52, Dispersit SPC 1000, JD-2000, Nokomis 3-AA, Nokomis 3-F4, Saf-Ron Gold and Sea Brat dispersants were tested. Corexit 9500 and 9527, and Finasol OSR 52 showed the highest effectiveness.

SL Ross (2014a), Belore (2015).

Objective	The new wind/wave tank was used to test dispersant effectiveness on four Alaskan crude oils in cold water with varying salinity.
Containment	Slicks of fresh, weathered, and emulsified Endicott, Kuparuk, Northstar and Alaska North Slope crude oils were contained near the center of the tank with a subsurface bubble barrier.
Test Conditions	The tank was filled with municipal water, which was maintained at 10°C. Salt was added to bring salinity to 5, 10, 20 and 30 ppt. The wave paddle was programmed to generate a 20 cm breaking wave at the slick location every 30 seconds for 15 minutes.
Dispersant Application	Dispersant was applied with a pressurized hand-sprayer that was charged with enough dispersant to produce a 1:20 dispersant-to-oil ratio.
Sampling and Plume Characterization	A LISST Type 100 C was used to characterize oil droplet size distribution (5 to 500 µm) in the plume below the containment area.
Dispersant Effectiveness	Dispersant effectiveness was calculated by collecting and weighing residual oil remaining in the collection area after the test, and subtracting that from the initial mass of oil or emulsion deployed. Residual oil was treated with an emulsion breaker (Alcopol) and heated, and any free water was decanted before weighing. In a novel approach, adjusted dispersant effectiveness values were calculated by multiplying the proportions of droplets less than 70 and 125 um, which were

	identified by researchers as limits above-which droplets may quickly resurface and not remain dispersed (Lunel, 1995; Neff, 1990).
Results	The maximum droplet size of the LISST (i.e., 500 um) was identified as a limitation, and a device capable of measuring droplet sizes in the range of about 10 to 3000 µm would be useful to better characterize the dispersed oil plume.

2.4 OHMSETT

Ohmsett, the National Oil Spill Response Research and Renewable Energy Test Facility is located on the grounds of Naval Weapons Station Earle in Leonardo, New Jersey. The tank was opened in 1974.

Location	Outdoors, Leonardo, New Jersey, United States		
Operator	Bureau of Safety and Environmental Enforcement, U.S. Department of the Interior		
Dimensions		m	ft
	Length	203	667
	Width	20	66
	Depth	2.4	8
Wave source	Two computer-controlled flap-type wavemakers driven by hydraulic pistons are located at the south end of the tank.		
Beach	Adjustable wave-absorbing ramp at the north end of the tank.		
Water	The tank is filled with seawater from the adjacent Sandy Hook Bay.		

The following papers on tests conducted at this facility were reviewed:

SL Ross (2000a), Ross (2000). This study investigated the feasibility of using Ohmsett for large-scale dispersant testing. Since 1974, only one project had used dispersants in the tank. There was concern that dispersant surfactants may be difficult or expensive to remove from the water, and that residual concentrations could interfere with subsequent projects. The project identified the critical dispersant concentration that would affect subsequent tests, and methods to remove dispersed oil and residual dispersant from the tank at reasonable cost and time frame. It was determined that many dispersant tests of reasonable scale (i.e., a few hundred litres) could be performed without accumulating dispersant in the tank and affecting subsequent results.

SL Ross 2001, Ross et al. (2001). The Ohmsett testing portion of this project was conducted in April 2000.

Objective	This project was to develop and validate a protocol for dispersant effectiveness tests at Ohmsett.
Containment	Tests were done with uncontained oil slicks deposited on the tank by spraying from the moving main bridge. Initial slick dimensions were nominally 20 m long, 5 m wide and 1 mm thick. A containment boom was deployed around the test area (30 m long by 15 m wide) to prevent surface oil from contacting the walls of the tank.
Test Conditions	Tests were done with two blends of Sundex 790 lubricating oil and No. 6 fuel oil in two wave conditions, a non-breaking wave and a more energetic setting with

	occasional breaking waves. Waves were run for one hour after dispersant was applied to the slick.
Dispersant Application	Dispersant was applied through a spray bar with 11 flat fan spray nozzles (40° spray angle). The resulting spray spanned a 6-m width. Dispersant had to be warmed in order to produce the desired spray pattern.
Sampling and Plume Characterization	Two fluorometers (Turner AU-10) measured oil-in water concentrations at two depths at three locations (i.e., six total sampling points) in the test area.
Dispersant Effectiveness	Three measures of the amount of oil dispersed were used to calculate dispersant effectiveness: 1. Integrate oil-in-water concentrations measured by fluorometry over the course of the test. 2. Residual surface oil remaining after the test was herded to a corner of the containment boom and collected. Free water was decanted before measuring the volume of oil recovered; the water content of the recovered oil was measured. Dispersed oil was calculated by mass balance. 3. The amount of oil dispersed in the water after the residual was recovered was determined by mixing the tank with harbor chop waves for one hour, then measuring the dispersed oil concentrations with UVF along transects through the dispersed oil plume.
Results	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.

A number of recommendations were made to improve the test protocol including modifications to the oil and dispersant distribution systems, the test area containment boom, and the timing of the initiation of waves after dispersant is applied.

Belore (2003). The Ohmsett testing for this project took place between February and March, 2002.

Objective	Determine the effectiveness of dispersants on Hibernia and Alaska North Slope crude oils in very cold (-0.5 to 2.4°C) water.
Containment	Tests were done with uncontained fresh and weathered oil slicks deposited on the tank by spraying from the moving main bridge. Initial slick dimensions were nominally 20 m long, 5 m wide and 1 mm thick. A containment boom was deployed around the test area to prevent surface oil from contacting the walls of the tank.
Test Conditions	Waves were initiated immediately after dispersant spraying, and continued for one hour. The wave maker used a paddle stroke of 7.6 cm and frequency of 35 cpm. The measured wave conditions, which accounts for reflected waves, were average height between 16.5 and 22.5 cm, and average period between 1.7 and 1.9 s.
Dispersant Application	Corexit 9500 and 9527 dispersants were sprayed onto the slick from a spray-bar on the opposite side of the main bridge from the oil distribution system. Dispersant spray was initiated when the spray bar was about 1 m from the start of the test slick.
Sampling and Plume Characterization	Visual observations, photos and video recordings.

Dispersant Effectiveness	Residual oil was herded to a corner of the containment boom and then collected by hand or with a small skimmer, depending on amount, and quantified after each test.
Results	Both dispersants were effective at dispersing the crude oils in cold water.

A refrigeration unit was used to keep the water temperature in the tank at near-freezing temperatures. A number of recommendations were made to improve the test protocol, as follows:

- The containment boom around the test area should be as large as possible. The movement of the waves tended to push the test slick north over the course of the test, and the interaction between the north end of the containment area and the slick was undesired.
- Test duration should be shortened to 20 or 30 minutes; most dispersion occurred within the first 10 minutes of the onset of breaking waves.
- Residual surface oil in the tank outside of the containment area should be removed between tests.
- Dispersed oil concentrations could be measured in the tank but should not be used to determine dispersant effectiveness.
- Droplet size distribution of the dispersed oil could be measured.
- A photograph of the test slick immediately prior to dispersant application would be helpful in determining applied dispersant-to-oil ratio.

A follow-up study on removing dissolved dispersant from the tank water with powdered activated carbon (SL Ross, 2003a) designed and tested a system that effectively reduced the concentration below the limits of detection (1 ppm). A key component of this system was measuring the interfacial tension of the tank water against a highly refined mineral oil. Cleaning the entire tank with the leaf filter and activated carbon required about approximately one week.

SL Ross (2003b). Preliminary dispersant effectiveness testing for this project was done at the SL Ross wind/wave tank (see Section 2.3), with subsequent larger-scale testing at Ohmsett.

Objective	Determine the effectiveness of Corexit 9500 and Corexit 9527 at dispersing selected Alaskan crude oil in cold water.
Containment	Uncontained oil slicks were deposited on the tank by spraying from the moving main bridge. Initial slick dimensions were nominally 20 m long, 5 m wide and 1 mm thick. A containment boom was deployed around the test area to prevent surface oil from contacting the walls of the tank. The containment boom had two cross sections at the north end, to capture oil that splashed over in the breaking waves.
Test Conditions	Test oils were fresh and weathered Alaska North Slope, Northsar, Endicott, Point McIntyre and Middle Ground Shoals crude oils. Tests at SL Ross determined that Corexit 9500 and 9527 both performed well, so only Corexit 9527 was used at Ohmsett. Water temperature varied from -0.4 to -1.1°C.
Dispersant Application	Corexit 9527 was sprayed onto the containment rings using the same system used in previous experiments at Ohmsett. Cold temperatures created problems with some of the valves in the system.

Sampling and Plume Characterization	In-water concentrations were measured with two flow-through fluorometers. Grab samples were collected and analyzed by IR spectrophotometery. Droplet size distribution in the dispersed oil plume was measured with a LISST Type 100 C.
Dispersant Effectiveness	Residual surface oil remaining after each test was recovered and quantified.
Results	Residual oil recovered after control tests varied from 58 to 97% of initial volume spilled.

Recommendations arising from the tests included the following:

- The use of continuous flow through fluorometry to monitor in-water oil concentrations and in situ laser particle size measurement provided valuable insight into the dispersion process.

Owens and Belore (2004).

Objective	Determine the effectiveness of dispersants for oil spills in brash ice.
Containment	3-m diameter rings of containment boom were placed in the tank and filled with varying concentrations of ice pieces. Oil was transferred to the containment area by hand.
Test Conditions	Nominal ice concentrations were 8/10, 4/10 and ice-free. Tests were conducted with fresh and weathered Chayvo, Hibernia and Alaska North Slope crude oils. Two regular wave settings were used: 33 cm height and 4 s period, and 17 cm height and 5.5 s period. Waves were started immediately after dispersant was applied.
Dispersant Application	Corexit 9527 was sprayed onto the containment rings using the same system used in previous experiments at Ohmsett.
Sampling and Plume Characterization	Visual observation of the dispersed oil plume.
Dispersant Effectiveness	Visual observation of oil remaining in the containment rings.
Results	The presence of ice improved dispersant effectiveness, with higher energy levels required to disperse oil in the rings with 4/10 coverage compared to the rings with 8/10 coverage.

SL Ross et al. (2005). Parallel dispersant effectiveness tests were conducted using laboratory protocols (Swirling Flask, Baffled Flask, Exdet), the SL Ross wind/wave tank, and Ohmsett, and compared to results from UK field trials.

Objective	Results from dispersant effectiveness tests at Ohmsett were compared to at-sea trials conducted in 2003 in the United Kingdom.
Containment	Uncontained oil slicks were deposited on the tank by spraying from the moving main bridge. Initial slick dimensions were nominally 20 m long, 5 m wide and 1 mm thick. A containment boom was deployed around the test area to prevent surface oil from contacting the walls of the tank.
Test Conditions	Test oils were Intermediate Fuel Oil (IFO) blends 180 and 380. Wave settings were varied from 33.3 to 35 cpm with a 3-inch paddle stroke length, producing wave

	heights between 12.7 and 17.6 cm. Waves were started and allowed to fully develop before oil was discharged. Waves were run for 35 to 40 minutes after dispersant was discharged. Water temperature ranged between 15 and 18°C.
Dispersant Application	Corexit 9500, Superdispersant 25 and Agma 379 dispersants were sprayed on the oil slicks immediately after they were deployed.
Sampling and Plume Characterization	Fluorometers were used to measure in-water oil concentrations during the tests. Visual observations using a four-point scale were made.
Dispersant Effectiveness	Residual surface oil remaining after each test was recovered and quantified. Control tests were done to estimate losses to natural dispersion, adherence to test apparatus, and evaporation.
Results	Wave energy had a strong effect on dispersant performance at Ohmsett.

Recommendations arising from the tests included the following:

- Studies should be completed to characterize wave environments so that wave conditions at Ohmsett (and the dispersant results produced under these conditions) can be related to wave conditions at sea in ways that are useful for dispersant research and testing.
- The capability of the Ohmsett wave tank should be used to assess the limits of dispersibility of oils in non-breaking waves.
- The wave energy setting to be used in standard dispersant effectiveness testing at Ohmsett should be re-assessed in light of the present work.
- In future Ohmsett studies, replicate control runs should be completed with all oils tested to get a better understanding of the oil losses that occur during the tests by natural and method-related means.
- In future test programs the following analyses should be done within 24 hours of a test completion to confirm that the primary test parameters are being achieved and to provide early feedback on the basic test outcome, specifically:
    - Quantification of the dispersant-to-oil ratio; and
    - Quantification of the parameters needed to estimate the amount of oil recovered at the end of each test including: the volume of emulsion collected, the amount of free water, replicate measurements of the water content of the remaining oil, evaporative losses from the oil during the test.

Supplemental tests were completed in April 2005 to provide additional results for some test conditions (Trudel and Belore, 2005).

SL Ross and MAR Inc. (2006a). Prior to this project, several improvements to the dispersant test protocol apparatus had been made, including:

- Upgrading the capability of the oil distribution system to pump viscous oil
- A longer and wider test area through removal of the containment booms along the side of the tank
- An acoustic doppler velocimeter (ADV) to measure turbulence from waves
- Dispersed oil concentration and droplet size distribution using a LISST 100-X Type C

This project took place between February and March 2006.

Objective	Determine the effectiveness of Corexit 9527 at dispersing four Alaskan crude oils.
Containment	Containment booms were positioned across the tank, with one at the south end and two at the north end. Uncontained oil slicks were deposited in this area while waves were developing by spraying from the moving main bridge. Initial slick dimensions were nominally 20 m long, 5 m wide and 1 mm thick.
Test Conditions	The test oils were fresh and weathered Alaska North Slope, Endicott, Pt. McIntyre and Northstar crude oils. Waves were allowed to develop until just prior to the formation of breaking waves, and were run for 30 minutes after dispersant was applied.
Dispersant Application	Dispersant was sprayed onto the slick just after it was deposited.
Sampling and Plume Characterization	In-water oil concentrations and drop size distributions were measured using the LISST 100 particle size analyzer. In-water oil concentrations were also measured with three flow-through fluorometers.
Dispersant Effectiveness	Residual surface oil remaining after each test was recovered and quantified. Control tests with no dispersant were completed to estimate losses to natural dispersion, evaporation, and adherence to test apparatus.
Results	Dispersant effectiveness ranged from 85 to 100%.

Additional testing was conducted on these oils using Corexit 9500 dispersant (SL Ross and MAR Inc., 2007).

This version of the Ohmsett Dispersant Effectiveness Test Protocol was used in several subsequent projects, as follows:

- SL Ross et al. (2006b) investigated the dispersibility of selected crude oils in non-breaking waves. No significant dispersion in non-breaking waves was measured.
- SL Ross et al. (2006c) investigated the dispersibility of crude oil emulsions. Testing with emulsions complicated the mass balance calculations as high water contents needed to be accounted for at multiple stages of the test.
- SL Ross and MAR Inc. (2006b) investigated the dispersibility of several viscous crude oils from the U.S. Outer Continental Shelf.
- SL Ross and MAR Inc. (2009) investigated the effects of repeated low doses of dispersants.
- SL Ross and MAR Inc. (2011) compared the results of dispersant effectiveness tests at Ohmsett with three laboratory-scale tests (WSL, Exdet and Swirling Flask).
- SL Ross (2013) compared the results of dispersant effectiveness tests of four dispersants at Ohmsett with small-scale test protocols.

SL Ross et al. (2006d). This project involved laboratory and wave-tank studies at the SL Ross laboratory in Ottawa, Canada, and wave-tank studies at Ohmsett.

Objective	Determine how long dispersants will remain effective if applied when there is insufficient turbulence to cause dispersion.
Containment	5-m diameter circular containment rings.

Test Conditions	Test oils were Alaska North Slope and Ewing Bank Block 873 crude oils, and Intermediate Fuel Oil 30. Oils were deployed in the test rings and allowed to weather for up to six days. Waves were 3.5 in stroke at 33 to 34 cpm for 30 minutes.
Dispersant Application	Corexit 9500 dispersant was pre-mixed with the test oils at a 1:20 dispersant-to-oil ratio.
Sampling and Plume Characterization	Slicks were observed visually, with dispersant activity being reported using a 4-point scale. A LISST Type 100 C was towed beneath the containment rings to characterize the dispersed oil plumes.
Dispersant Effectiveness	Residual surface oil remaining after each test was recovered and quantified.
Results	The tests oils rapidly and completely dispersed when exposed to breaking waves, even after being exposed to the environment for between 3 and 6 days.

Similar testing in 2007 and 2008 found that a differential water current beneath the test slicks reduced the amount of time the dispersant remained effective (SL Ross et al., 2007; SL Ross et al., 2008). The latter report recognized the value in the droplet size information provided by the LISST and recommended that continuous data throughout the test would be valuable, as opposed to only periodic transects of the test area.

SL Ross (2012). This project combined on-tank weathering in realistic conditions with laboratory-scale dispersant effectiveness tests to determine windows of opportunity for dispersant use.

Objective	Compare dispersant effectiveness on weathered oils with modeled predictions.
Containment	Oil was contained at the north end of the tank using five submerged 'ice-eater' pumps placed across the tank to create a surface current barrier. A containment boom with ice-eaters placed inside the boom side-wall attachments points was used to contain the oil at the south end of the tank.
Test Conditions	Test oils were weathered on the tank in breaking waves.
Dispersant Application	N/A
Sampling and Plume Characterization	Samples of the test oils were taken periodically to measure oil property changes and for dispersant effectiveness testing.
Dispersant Effectiveness	The Exdet dispersant effectiveness test was used to measure dispersibility of the test oil samples.
Results	The wave density in a 30 m section of the test tank was determined using video footage to count breaking wave events over a nine-minute time frame. The breaking wave density from this determination was 0.496×10^{-3} events/m²/s.

SL Ross (2014b).

Objective	Determine the effectiveness of dispersant when applied at 5 gal/acre to relatively thick oil slicks.
Containment	2.4-m diameter ring of 5-cm ABS pipe held test oil prior to dispersant application. Ring was removed immediately before dispersant was applied.

Test Conditions	Three test oils were BHP Neptune, Dorado and Anadarko crude oils. Slick thickness was 1 and 4 mm. Water temperature was 25 to 26°C.
Dispersant Application	Dispersant dose rate ranged from 5.4 to 7.6 gal/acre. Corresponding dispersant-to-oil ratios were between 1:170 and 1:550. Dispersant was applied by spray arm.
Sampling and Plume Characterization	LISST particle size and Turner C3 fluorometry readings were taken during the test to further quantify the dispersion.
Dispersant Effectiveness	Oil remaining on the surface at the end of the test was collected to determine overall effectiveness.
Results	Dispersant effectiveness correlated with dose rate. Low effectiveness was measured with light to medium oils that are dispersible. The 5 gallon/acre application limit sometimes imposed on aircraft dispersant operations may underdose thick slicks.

Steffek, Bittler and Guarino (2017).

Objective	Compare effectiveness of five dispersants (Corexit 9500A, Finasol OSR 52, Accell Clean DWD, Marine D-Blue Clean, and ZI 400).
Containment	Tests were done on uncontained slicks of HOOPS crude oil.
Test Conditions	Average air temperature was 15.8°C, and average water temperature was 14°C. Three replicates of each test were conducted, and three replicates of the control test were done.
Dispersant Application	Dispersants were applied through a spray bar at a 1:20 target application rate.
Sampling and Plume Characterization	Droplet size distribution in the dispersed oil plume was measured with two LISTT 100-X Type C.
Dispersant Effectiveness	Dispersant effectiveness was measured by mass balance.
Results	Statistical analysis showed the difference between controls and treatments were not significant. This was due to high losses from the control slick. Statistically significant reductions in average droplet size were measured with the treated slicks compared to the controls.

2.5 SERF

The Shoreline Environmental Research Facility (SERF), which was originally named the Coastal Oil Spill Simulator (COSS), was constructed between 1993 and 1997, and consists of nine parallel wave tanks (Kitchen et al., 1997).

Table 2-6: COSS wave tanks

Location	Outdoors, Corpus Christi, Texas, United States		
Operator	Texas A&M University		
Dimensions		m	ft
	Length	33.5	110
	Width	2.4	7.9
	Depth	2.1	6.9

Wave source	Waves are generated by stainless steel flaps driven by hydraulic pistons. Wave makers are computer-controlled and can be programmed to create a variety of wave patterns.
Beach	The tanks can be loaded with a variety of shoreline materials (e.g., sand, gravel, clay).
Water	The tank is filled with seawater from the adjacent Corpus Christi Bay. The tanks can be operated in flow-through mode, where additional seawater is continuously pumped through the tanks. Tidal ranges can be varied up to 0.7 m with a maximum water depth of 2 m.

The following paper on tests conducted at this facility was reviewed:

Page et al. (2002).

Objective	Study dispersant effectiveness in shallow marine environments.
Containment	Air booms at either end of the tank stabilized the oil slick for 30 minutes prior to dispersant application.
Test Conditions	Waves were started immediately following dispersant application and were continued for 24 hours. Wave height was 0.12 m with 1.25 s period. Tests were done with weathered Arabian crude oil.
Dispersant Application	Corexit 9500 dispersant was applied at a 1:10 dispersant-to-oil ratio from four nozzles on a motorized bridge.
Sampling and Plume Characterization	Samples of the water column, water surface and tank walls were collected periodically during the experiments. A fluorometer and LISST-100 particle size analyzer were mounted on a movable sled 0.6 m below the water surface.
Dispersant Effectiveness	A specialized skimmer was used to recover undispersed oil from the water surface. Dispersant effectiveness was calculated by mass balance, accounting for oil lost to the tank walls.
Results	After 24 hours of waves, 69 to 87% of the oil was dispersed.

2.6 SINTEF Ocean AS

SINTEF Ocean AS (SINTEF) have completed several studies with dispersants in a recirculating flume (see Table 2-7).

Table 2-7: SINTEF recirculating flume

Location	Indoors, Trondheim, Norway		
Operator	SINTEF Ocean AS		
Dimensions		m	ft
	Circumference (Outer)	16.6	54.5
	Width	0.5	1.6
	Depth	1	3.2
Wave source	Plunging wave maker driven by an eccentric flywheel and variable speed motor.		
Beach	The flume does not have a beach		
Water	The flume is filled with seawater.		

The design of the SINTEF flume was used as the basis for the one built by SL Ross in Ottawa (see Section 2.3). The following papers on tests conducted at this facility were reviewed:

Faksness et al. (2017), Brandvik et al. (2010).

Objective	SL Ross and SINTEF Ocean AS jointly investigated the use of dispersants in cold water and broken ice as part of the Arctic Oil Spill Response Technology Joint Industry Program. Testing was done in identical recirculating flumes in Ottawa, Canada, and Trondheim, Norway.
Containment	Removable barriers were placed across the long side of the flume to isolate a 2 m by 0.5 m area.
Test Conditions	The flume was filled with municipal water with salt added to bring the salinity to 35 ppt. The water temperature was maintained between 0 and at -2°C. The containment area was filled with broken ice pieces to 50 or 80% coverage. Fresh crude oil (Alaska North Slope, Troll Blend, Oseberg Blend and Grane) was added to the containment area and weathered in place for 16 hours with the wave maker set to produce gentle swells. After the weathering period, ice was placed in the remainder of the tank area to achieve the same coverage as was originally in the containment area, and then dispersant was applied using a hand-held paint sprayer. The containment barriers were removed and the wave maker motor was set to produce more energetic waves. In some experiments, an electric trolling motor was used to simulate prop wash from a vessel and provide additional mixing energy.
Dispersant Application	Dispersant was applied using a hand-held paint sprayer (Wagner).
Sampling and Plume Characterization	Grab samples were obtained from the water phase several times over the course of the experiments and analyzed for oil concentration. A LISST Type 100-C was used to characterize the droplet size distribution.
Dispersant Effectiveness	Dispersant effectiveness was calculated from the grab samples and the total volume of water in the tank.
Results	Shorter weathering times corresponded to increase dispersant effectiveness. Ice coverage did not significantly affect dispersant effectiveness.

Similar procedures were used to investigate dispersibility of oil in frazil ice conditions (SL Ross, 2019).

2.7 CEDRE

Cedre has used a recirculating flume for testing with dispersants (see Table 2-8). The original was built in 1997, and replaced with a new model in 2011. A flume based on this design was commissioned by Environment and Climate Change Canada, Emergencies Science and Technology Section in 2019.

Table 2-8: Cedre Polludrome recirculating flume

Location	Indoors, Brest, France		
Operator	SINTEF Ocean AS		
Dimensions		m	ft
	Circumference (Outer)	30	100
	Width	0.6	2

	Depth	1.2	3.9
Wave source	Flap-type wave maker driven by an eccentric flywheel and variable speed motor.		
Beach	The flume does not have a beach		
Water	The flume is filled with seawater.		

Cedre participated in the Arctic Oil Spill Response Technology Joint Industry Programme with SINTEF Ocean AS and SL Ross Environmental Research. The following paper on tests conducted at this facility was reviewed:

Faksness, Belore and Merlin (2013).

Objective	Dispersant effectiveness tests using identical crude oils, temperatures and dispersants were conducted in the Cedre Polludrome, and SINTEF and SL Ross recirculating flumes to measure differences in dispersant effectiveness results between the three facilities.
Containment	An oil containment ring was used on the wavemaker side of the flume to hold the slick in place. The ring was removed 1 minute after dispersant application.
Test Conditions	Tests were done with natural seawater (Cedre and SINTEF) or municipal water with salt added (SL Ross). Water temperature was maintained at 13°C. Three wave energy levels were used.
Dispersant Application	Dispersant was applied by hand using a Wagner 450 paint sprayer. Application rate was estimated by calibrating the sprayer delivery rate. Actual application rates were measured by weighing the sprayer before and after use.
Sampling and Plume Characterization	Droplet size distribution in the dispersed oil plume was measured by SINTEF and SL Ross using a LISST-100X, Type C (2.5 to 500 µm). Cedre used a Malvern particle size analyzer. Grab samples were obtained at three intervals (20, 40 and 60 minutes) over the course of a test from one location in the tank.
Dispersant Effectiveness	Dispersant effectiveness was calculated from measured dispersed oil concentration determined from the grab samples.
Results	The results showed good correlation between the dispersant efficiency in the flumes at SINTEF and SL Ross at all three energy levels. Although the Cedre flume is different than the flumes at SINTEF/SL Ross, the correlation in dispersant efficiency was good, particularly at low and high energy conditions.

2.8 BEDFORD INSTITUTE OF OCEANOGRAPHY

A wave tank was constructed at the Bedford Institute of Oceanography (see Table 2-9) for dispersant effectiveness testing with controlled breaking waves (Venosa et al., 2005). The length of the tank was extended to 32 m from its initial 16 m (Wickley-Olsen et al., 2008). The tank can be operated in batch mode, or in flow-through mode (Lee et al., 2009).

Table 2-9: Bedford Institute of Oceanography Wave Tank

Location	Outdoors, Dartmouth, Nova Scotia, Canada		
Operator	Bedford Institute of Oceanography, Fisheries and Oceans Canada		
Dimensions		m	ft
	Length	(16) 32	(52.5) 105
	Width	0.6	2

	Depth	2.0	6.6
Wave source	A computer-controlled flap-type wavemaker driven by an eccentric fly wheel is located at one end of the tank. A train of high frequency waves was generated, followed by a train of low-frequency waves which intersected at a specific point in the tank. The water surface profile was measured with a wave gauge and an Acoustic Doppler Velocimeter.		
Beach	Porous screens were located at the opposite end of the tank from the wave paddle.		
Water	The tank is filled with seawater from the adjacent Bedford Basin.		

The energy dissipation rate from two different breaking wave heights was measured with an Acoustic Doppler Velocimeter and compared to the Swirling Flask and Baffled Flask laboratory dispersant effectiveness tests. The near-surface energy dissipation rate for a 0.17 m breaking wave was 5.0×10^{-2} W/kg (Wickley-Olsen et al., 2007). A theoretical model for oil droplet formation from the breakup of a slick due to turbulent energy was developed by Boufadel et al. (2008) based, in part, on energy dissipation rates measured in the tank.

The following papers on tests conducted at this facility were reviewed:

Li et al. (2008).

Objective	Dispersant effectiveness tests were conducted in the tank with fresh Alaska North Slope and weathered Medium South American crude oils, and with Corexit 9500 and SPC1000 dispersants.
Containment	For each test, 300 mL of crude oil was transferred into a 40-cm diameter PVC ring located 10 m from the wave paddle. The ring was removed following dispersant application and immediately prior to contact with the first wave.
Test Conditions	Three wave conditions were maintained for two hours after dispersant was applied: regular (non-breaking) waves, a spilling breaker, and a plunging breaker.
Dispersant Application	Dispersant was applied at a 1:25 dispersant-to-oil ratio from a pressurized nozzle.
Sampling and Plume Characterization	Droplet size distribution in the dispersed oil plume was measured using a LISST-100X, Type C (2.5 to 500 µm). Grab samples were obtained at three intervals over the course of a test from twelve ports distributed along the side of the tank and analyzed for dispersed oil concentration.
Dispersant Effectiveness	Dispersant effectiveness was calculated from measured dispersed oil concentration.
Results	Dispersant effectiveness varied from 30 to 70%. Higher dispersant effectiveness was measured with higher energy dissipation rate (Venosa et al. 2008)

2.9 AKER ARCTIC TECHNOLOGY BASIN

Aker Arctic Technology Oy manages a test basin that has been used primarily for ice modeling (see Table 2-10).

Table 2-10: Aker Arctic Technology Basin

Location	Indoors, Helsinki, Finland		
Operator	Aker Arctic Technology Oy		
Dimensions		m	ft
	Length	77.3	254
	Width	6.5	21
	Depth	2.3	7.5
Wave source	The basin does not have wave generating capabilities.		
Beach	The basin does not have a beach or wave absorbers.		
Water	The tank is filled with seawater.		

The following papers on tests conducted at this facility were reviewed:

Nedwed et al. (2007) and Spring, Nedwed and Belore (2006). Initial testing of the concept of using ship propellers to supply mixing energy for dispersant use was done in the SL Ross wind/wave tank (Table 2-4). Subsequent testing was done in Finland with a scale-model ice breaker.

Objective	Investigate the potential for azimuthal-stern-drive propulsion systems to provide mixing energy for dispersants applied in ice conditions.
Containment	Sakhalin Island Chayvo crude oil was spilled into ice leads or on ice floes.
Test Conditions	Tests varied ice floe size, air temperature, and oil on ice.
Dispersant Application	Corexit 9527 was sprayed onto the slicks at a 1:20 or 1:110 dispersant-to-oil ratio using a pressurized hand sprayer.
Sampling and Plume Characterization	A LISST-100 was mounted to the model ice-breaker 0.5 m below the water surface.
Dispersant Effectiveness	Residual oil remaining on the surface of the tank was recovered with absorbents and measured.
Results	Vessel-based mixing was effective at dispersing slicks of weathered Chayvo crude oil.

3 TANK CONDITIONS

Ohmsett tank conditions that may affect dispersant effectiveness testing include water level, water salinity and the concentration of other dissolved ions, background concentrations of oil and surfactants, and ambient conditions.

3.1 TANK WATER LEVEL

The water level in the tank can affect the characteristics of waves generated by the wave maker, although it is unclear how significant the differences are. The water depth is typically between about 7.5 and 8.2 ft (2.3 and 2.5 m), and changes as water is lost from the tank through evaporation and leakage, or gained through precipitation. Changes due to weather can be difficult to predict, although high water levels are more common than low. Due to the size of the tank, adjusting the water level by adding or removing water takes time and there are restrictions to discharging tank water that complicate this process. Options for discharging water from the tank are as follows:

- **Municipal sewer.** Ohmsett has an agreement with the Township of Middletown Sewerage Authority which permits water to be discharged to the municipal sewer. The discharge must comply with effluent limits and is typically only done during work hours.
- **Sandy Hook Bay.** Ohmsett has a permit to discharge water to the nearby bay. Effluent must comply with the New Jersey Discharge Pollution Elimination System, and authorization is needed from BSEE, the US Navy and the New Jersey Department of Environmental Protection. There is considerable setup with this option, as hoses must be run out to the pier.

Municipal water may be added to the tank, but the flow rate is limited. Water may be added from Sandy Hook Bay, but this is logistically challenging and has historically only been done when the tank is filled from empty after having been drained for maintenance.

To try to ensure that the wave characteristics are as consistent as possible between test events, it would be ideal if the tank level could be specified and maintained by adding or removing water as necessary; however, given the limitations noted above, some differences between test events is expected. It is recommended that the water level in the tank be monitored during the period leading up to a dispersant test, and best efforts made to adjust the level to keep it within the normal range of 7.5 to 8.2 ft.

3.2 SALINITY AND OTHER DISSOLVED IONS

Commercially available dispersants are formulated for use in marine conditions and work best near ocean salinity. The Ohmsett tank is filled with water from Sandy Hook Bay, which is typically around 15 to 20 ppt (parts-per-thousand). Brine or salt is added after filling to raise the salinity.

Recent research (Boufadel, 2016) indicated that water hardness may also affect dispersant effectiveness results. Hardness of the tank water was sometimes measured below typical ocean concentrations (i.e., <6500 mg/L as $CaCO_3$). This may bias dispersant effectiveness results high by increasing the solubility of surfactant molecules, although the magnitude of the change is unclear.

It is recommended that the tank salinity, and perhaps hardness, be measured in advance of the dispersant test and best efforts made to adjust the concentration to keep it within the typical range for marine conditions (32-35 ppt). The hardness of the tank water is of secondary concern compared to the salinity.

3.3 BACKGROUND CONTAMINATION

The presence of free-phase oil on the surface and dispersed in the water column, and of surfactants, could potentially impact dispersant testing results. For example, free-phase oil on the tank surface could introduce errors in mass balance calculations. Dispersed oil in the water column will accumulate in the tank as successful dispersant tests are completed. The large volume of the tank means that many dispersant tests can be completed before concentrations become problematic. While visibility will be impaired at low concentrations, previous research has indicated that concentrations up to several thousand ppm will not significantly affect dispersant effectiveness test results.

The leaf filtration system in the tank using cellulose and diatomaceous earth will reduce the concentration of dispersed oil, albeit slowly. Some dispersed oil will also rise and coalesce on the surface of the tank overnight. This oil should be removed in the mornings before tests are started.

Surfactants from previous experiments may be present, and dispersant will accumulate in the tank throughout the tests. However, the large volume of the tank and the relatively small quantities of surfactants used means that these should have little effect on dispersant effectiveness tests. Research completed during development of the original dispersant test protocol indicated that concentrations up to 400 ppm would not adversely affect tests. The concentration of surfactants in the tank can be inferred by measuring the interfacial tension of the water against a highly refined mineral oil (USP or Technical Grade). This method gives good discrimination at the sub-10 ppm dispersant concentration range with reliable measurements down to 2 ppm (SL Ross 2003a).

The tank surface should be kept as clear of surface oil as practical by skimming regularly before and between tests. Barriers (physical and subsurface propellers) should be deployed in strategic locations to prevent fugitive oil from entering the test area. Plume monitoring and characterization activities should account for initial conditions by starting measurements before the oil is dispersed and measuring the relative changes in concentration and droplet size distribution.

3.4 AMBIENT CONDITIONS

Wind speed and direction, air temperature, water temperature, and cloud cover will affect oil properties and movement during the test, and wave characteristics.

As Ohmsett is an outdoor tank, some effects from weather fluctuations between tests are inevitable. Conducting several repeats of each test condition will help to mitigate changing conditions and isolate differences due to treatments. If specific temperature ranges are required, for example to test dispersants under cold conditions, then the tests should be scheduled for an appropriate season.

4 SLICK CONTAINMENT

The capability of the new wave generator raised the possibility of containing a slick at the point where the breaking waves occur, thereby having greater control over the wave energy impacting the slicks. Several options for the containment or positioning of the test slick were considered, as follows:

- **Unconfined Slick.** This is the most realistic slick presentation, but there are several drawbacks to this approach. Wind and waves will move the slick around the tank, which may introduce time pressure to conduct an experiment before the slick moves too far. It is important that the slick does not contact the walls of the tank, as this would complicate the mass balance and introduce factors that would be difficult to replicate between tests.
- **Boom Enclosure.** Use of rigid containment affects turbulence in the vicinity, which is undesirable (Fingas and Kaiaihue 2004). This would also complicate mass balances, by having to account for oil adhered to the enclosures.
- **Bubble Barrier.** Bubble barriers can contain oil while allowing waves to pass through relatively unchanged. However, air bubbles may entrain oil droplets and promote coalescence and resurfacing of dispersed oil. A system would require a compressor and subsurface air distribution system, adding cost and complexity.
- **Water Jets.** Water jets oriented near to horizontal with the water surface can entrain air and create sufficient force to herd or contain oil. Meikle et al. (1985) and Laperriere et al. (1987) successfully tested a system that contained oil slick in current up to 1.5 kts, wind up to 20 kts and waves 0.15 m high.
- **Subsurface Propeller or Jet.** Submerged propellers used to generate a current have been used in previous experiments at Ohmsett to contain oil.

Water jets were felt to be the most promising technique for surface slick control at Ohmsett and were the focus of testing.

4.1 HIGH-PRESSURE, LOW-VOLUME WATER JETS

High-pressure water jets using flat-fan spray nozzles fed from water pumped from the tank had been used previously at Ohmsett and there were existing installations on the north side of the vacuum bridge and the south side of the auxiliary bridge. These consisted of four nozzles (BETE #NF 40080, 1-in. 80° Flat Fan Pattern) on two manifolds that were fed from the centrifugal fire monitor pumps at the north and south ends of the tank, respectively. The pumps were operating at between 50 to 60 psig, at a flow rate of 45 to 50 gpm. The nozzles were about two feet above the water surface and were canted downward at about 10 to 15° angle below horizontal. The manifolds were each fed by 2-inch hose run on the decks on the side of the tank. Valves at the pumps were used to adjust the flow of water to each manifold. Schematic diagrams and photographs of the north and south spray barriers are provided in Figure 1 and Figure 2.

For the side barriers, four prototype hand-held spray jets were fabricated from 1-inch schedule 40 steel pipe with flat-fan spray nozzles to test the concept with movable and adjustable jets before committing to a fixed design. A manifold was fed from the fire pump on the main bridge and directed water to the jets. Valves and pressure gauges on the manifold allowed the flow to each jet to be controlled. Tests conducted in October 2020 demonstrated the ability of spray jets to contain oil in winds up to 32 km/h.

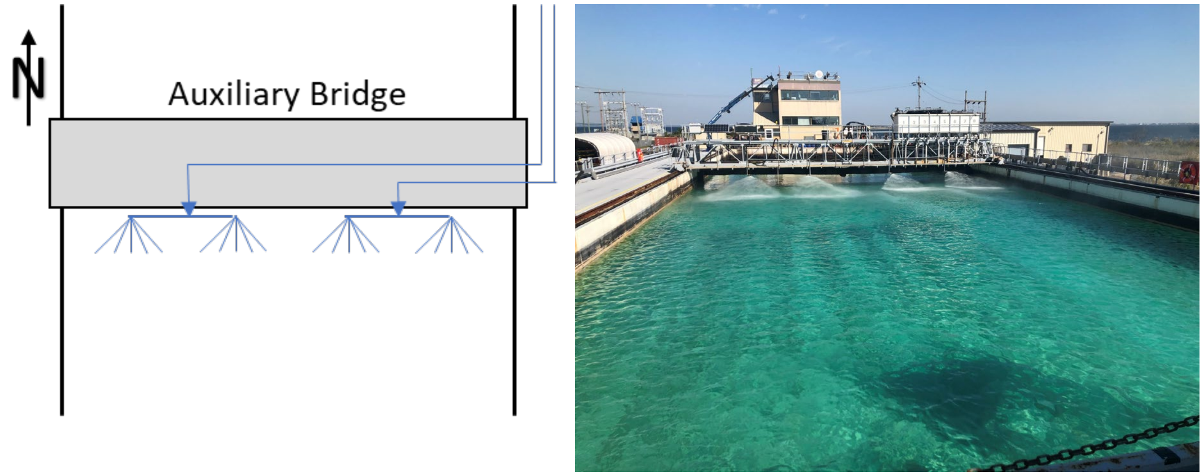

Figure 1: North spray barriers.

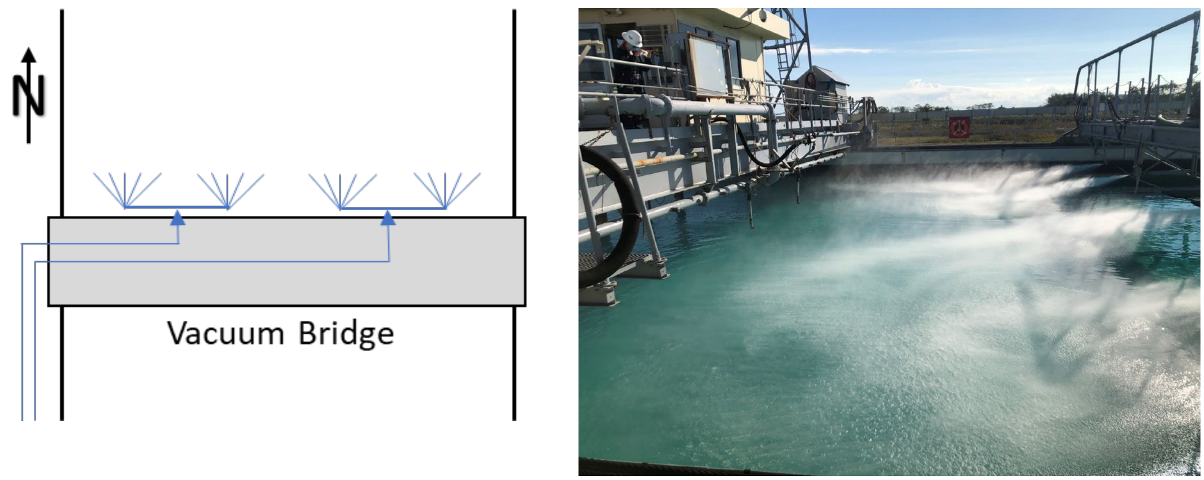

Figure 2: South spray barriers.

The hand-held jets were fixed temporarily to the east wall of the tank, and the containment system was tested with a small slick of Hydrocal 300 (~ 8 L) in waves (see Figure 3). It was observed that the oil slick was pushed north by the breaking wave, but not past the spray jets. The slick consistently reformed in the test area after the wave passed.

Following the successful test, more permanent sprayers for the east and west sides of the tank were designed, assembled and tested in December 2020 (see Figure 4). The sprayers consisted of nozzles (BETE #1/2 NF 10110, ½-in 110° Flat Fan Pattern) in PVC housings angled at approximately 15 to 25° below horizontal. Four sprayers were deployed on each side of the tank through the scuppers beneath the bridge rails. Each side of the tank used a four-way manifold fed by a centrifugal pump producing 30 to 40 psig at each nozzle. This arrangement allowed the main bridge to move within the test area.

Figure 3: Prototype side sprayers tested with waves.

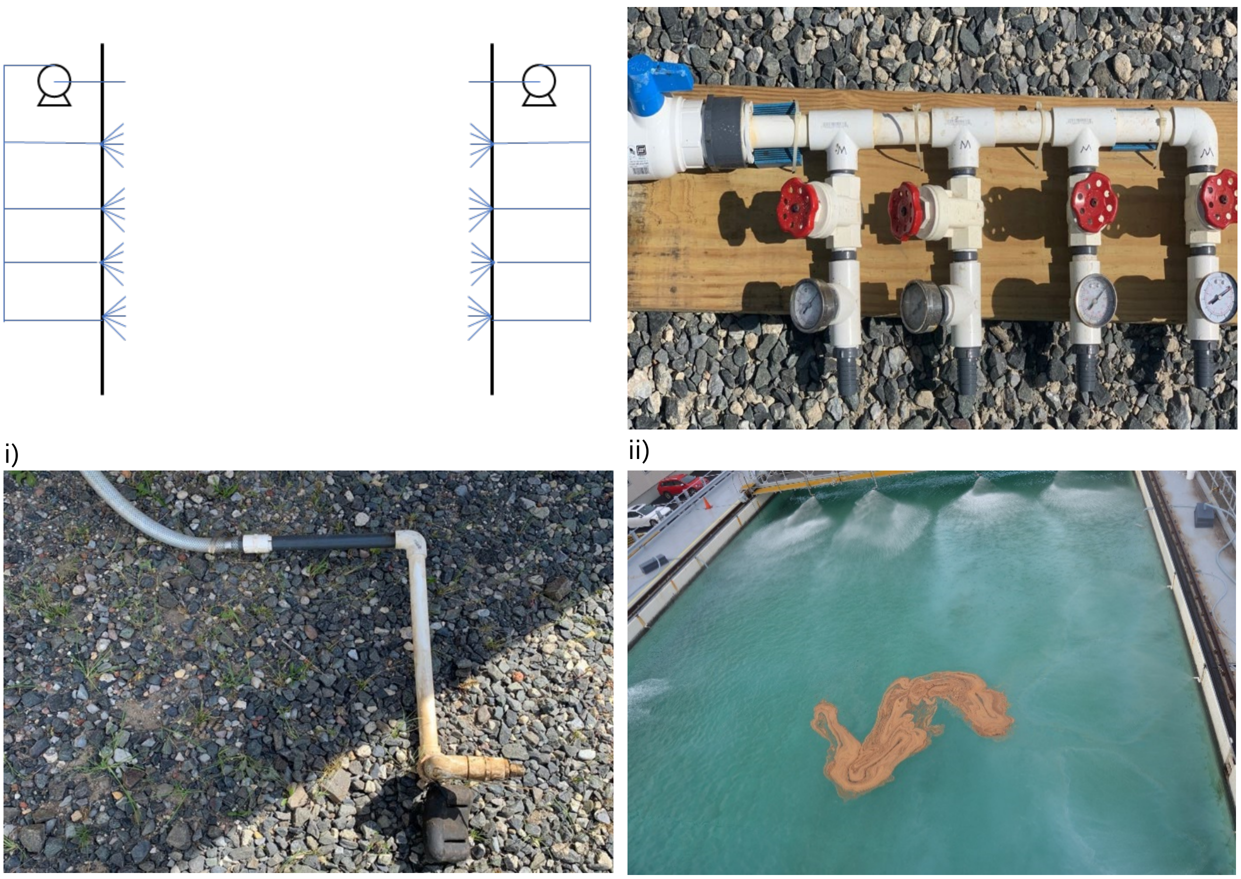

Figure 4: Redesigned side spray barriers, showing i) schematic layout, ii) manifold, iii) individual spray nozzle, and iv) containing a small slick of oil.

The new side spray barriers worked well during two weeks of testing in December, 2020, and one week in April, 2021. Cold temperatures in December required that the sprayers and manifolds be flushed and filled with anti-freeze every night to prevent damage from freezing, but normal operation was unaffected.

Wind speeds and directions encountered during testing in April, 2021, are summarized in Table 4-1. On the final day of testing on April 30, 2021, the winds were forecast to be 35 km/hr from the west northwest (a wind warning was in effect for the area). During the afternoon test, it was noted that some oil was pushed into the east wall between the second and third spray barrier. Measurements at the tank recorded an average wind speed of 40 km/h during the test. Test one, which was completed earlier in the week, with an average wind speed of 31 km/h in the same direction did not have containment issues. Therefore, the limit of performance with regards to wind speed appears to be somewhere between 31 and 40 km/h, which is quite high. It is likely that wind direction will also be a factor in determining limits of performance.

Table 4-1: Ambient conditions during April 2021 tests.

Test Number	*Slick Area (m^2)*	*Average Thickness (mm)*	*Wind Speed (km/h)*	*Wind Direction*	*Air Temperature (°C)*
1	7.0	4.1	31	WNW	16.8
2	13.9	2.1	14	SE	17.9
3	20.1	1.5	14	SE	21.5
4	16.6	1.8	15	SE	17
5	14.9	2.0	7	E	22.9
6	10.5	2.8	4	NW	20.6
7	9.9	2.9	8	SSW	22
8	8.1	3.6	9	SSW	26.1
9	9.0	3.3	40	WNW	20.9

After the April 2021 tests, several recommendations were made for improving the spray jets based on experience to date:

- Improve the mounting of the south manifolds on the Vacuum Bridge to make it more secure and permanent.
- Design a more convenient method to flush the side-sprayers and fill with anti-freeze during cold temperatures.
- Equip all sprayers with flow meters to quantify flow rates and record operational settings.

4.2 SUBSURFACE PROPELLERS

Tests were done in October of 2020 to evaluate the ability of subsurface propellers to contain oil in the test area without adverse interactions with the surface slick. Ohmsett already had several "Ice Eaters" (Powerhouse Inc. P 500) that have been used for previous projects to prevent surface oil from migrating to certain areas of the tank, such as behind the wave paddles. The Ice Eaters had been modified with legs so that they could sit on the bottom of the tank and direct a current upwards; the current radiates outward at the surface and several propellers in a line create a barrier to oil flow.

Ohmsett had a limited number of ice eaters so they were tested in combination with side sprayers. Four ice eaters were deployed along the west wall, and another four were deployed across the tank at the south end of the test area, providing half of the test area containment. Spray jets were used for containment on the north end of the test area and along the east wall of the tank (see Section 4.1). Several test slicks of increasing size (between about 14 to 40 L) of Hydrocal 300 and then a less viscous Hydrocal 38 were subjected to several breaking waves about five minutes apart.

The subsurface propellers were successful at containing the oil within the test area. The waves were observed to have slightly different characteristics than previous tests with just the spray jets, but this was attributed to significantly higher winds during the tests with ice eaters and not the water movement imparted by the propellers.

4.3 Air Bubble Curtains

Air bubble curtains were not investigated during this series of testing because the initial two methods were able to successfully contain the oil slick during breaking wave events. It is expected that air bubble curtains would perform similarly to the subsurface propellers and be effective at containing an oil slick; however, they would require additional equipment (i.e., air compressors) and the bubbles could affect the subsurface water flow patterns and the dispersed oil plume characteristics.

4.4 Final Test Area Layout

Both the Ice Eaters and surface water jets were able to contain slicks of medium and light oil in waves and high winds without visible loss of oil; however, the water jets have the advantage of only affecting the water near the surface of the tank, which would have less impact on the movement of the dispersed oil plume. Therefore, water jets were chosen as the primary test slick containment method.

Ice eaters were used in several areas of the tank to control the movement of fugitive oil present on the tank from previous tests. Four ice eaters were deployed across the tank south of the auxiliary bridge to prevent oil from migrating towards the wave paddles. Two additional ice eaters were added to the test layout in December, 2020, just to the north of the Auxiliary Bridge in the east and west corners. It was noted during early tests in December that a small amount of oil in the north portion of the tank from previous tests was migrating past the fence boom under the Auxiliary Bridge at the connector. The ice eaters were effective at preventing further oil from entering the test area. The final test area layout is shown in Figure 5.

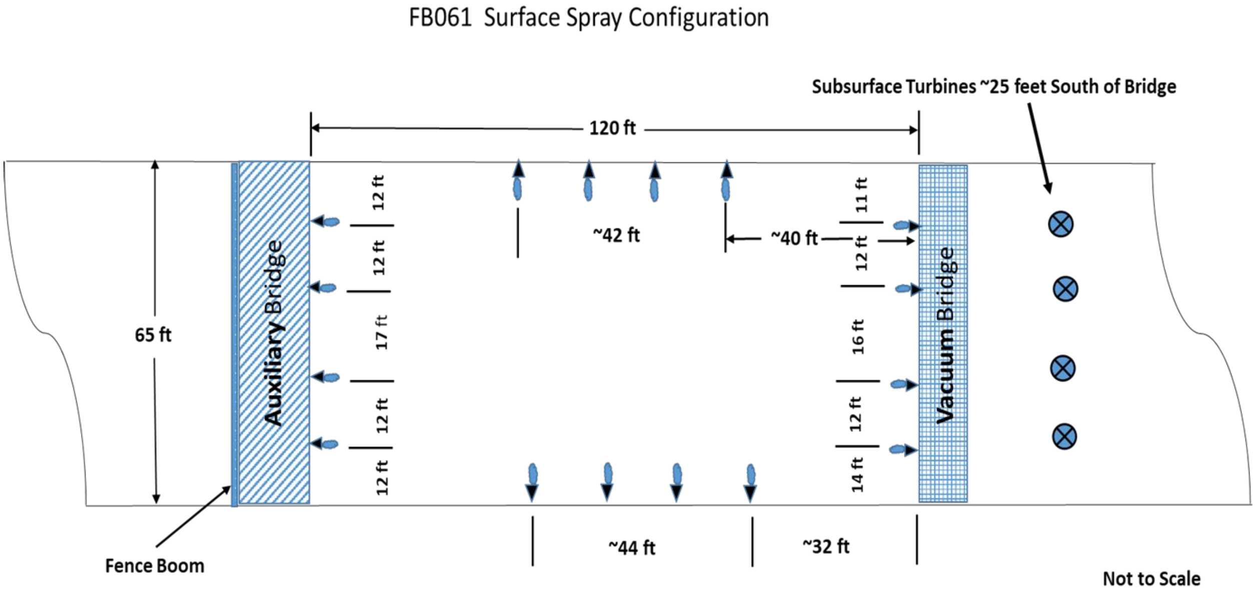

Figure 5: Test area layout.

5 Oil Distribution

The method of distributing oil on the tank should quickly introduce the desired quantity of oil into the test area and minimize potential conflicts with mass balance calculations. Two options were considered:

- **Pre-measured in Containers.** Measure (by weight or volume) the quantity of oil and transfer to the test area.
- **Oil Pump and Distribution Manifold.** Apply oil using a metered pump and manifold that directs it into the test area. This is the method used by the original test protocol.

The first option was the simplest and was the focus of testing.

The original test protocol used 100 L of oil per test, which was distributed in a slick measuring approximately 5 m (16 ft) wide by 20 m (66 ft) long. The smaller test area developed for the revised test protocol meant that less oil could be used for each test, which had several advantages. Each test had less impact on the visibility in the tank, and overall there would be less oil to procure and dispose of for the same number of tests.

Initial testing suggested that 30 L of oil was a reasonable volume to create an appropriately sized slick in the test area. Oil was applied manually to the surface of the tank using two pre-weighed 20-L (5-gal) buckets with a measured volume of oil. The buckets were weighed after distributing the oil to determine the total mass of oil used for each test.

For the first several tests, the oil was deployed from a man-lift that could reach to the middle of the tank. However, when the design of the side sprayers was finalised, which allowed the main bridge to move within the test area, it was decided to use the bridge platform to deploy oil. The buckets of oil were lowered to the water surface with ropes and then tipped up to release the oil in the desired location (see Figure 6).

After distribution, oil slicks were observed to coalesce and move to an equilibrium position within the test area. The position was affected by the prevailing wind speed and direction. The slicks were contiguous (i.e., all the oil was present in one patch), but the shape shifted under the influence of the wind and spray jets. The typical appearance of a slick is shown in Figure 7.

Overhead images were taken of slicks of weathered HOOPS crude oil during nine tests completed in April, 2021. The area of the slicks was calculated for each test by scaling the area in the image to that of a plastic square of known dimensions. Slick area varied from 7 to 20 m^2, with an average of 12 m^2. Average slick thickness (calculated by dividing the volume of oil by the slick area) varied from 1.5 to 4.1 mm, with an average of 2.7 mm.

Figure 6: Oil distribution by plastic bucket.

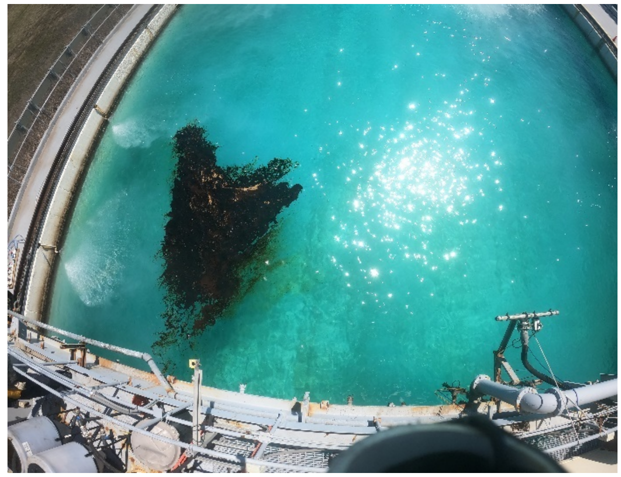

Figure 7: Typical appearance of 30-L slick.

6 DISPERSANT APPLICATION

Two broad methods of applying dispersant were originally considered:

- **Hand Spray.** Use a pressurized sprayer (e.g., for spraying herbicides or pesticides). Potentially offers more flexibility and accuracy in treating test slick than bridge spray system. However, requires that operator be able to reach test slick.
- **Bridge Spray System.** The existing spray system on the bridge has the advantage of most closely mimicking a vessel spray system that transits a slick at a steady speed and removes operator from potential variables. Test slick may shift around test area and be difficult to target with a fixed spray system.

It was decided that hand spraying was the favored alternative, since accurately targeting the slick with dispersant would improve repeatability of the protocol. It was important that the sprayer chosen produce droplets that were neither too fine, where wind could blow dispersant away, or too coarse, where falling dispersant would penetrate through the slick.

Several different sprayers were evaluated during testing in December 2020. For the first two tests with dispersant, it was applied manually using a pressurized paint sprayer from a man lift on the west deck of the tank. The paint sprayer produced droplets that were too fine and were easily carried away by the wind. Three hand-held sprayers, such as for misting plants or applying lawn chemicals, were subsequently tested; however, none of the devices were deemed satisfactory. Generally, the spray patterns were too coarse.

For the last two tests, a cylindrical dispersant wand based upon a dispersant application device employed by SL Ross for large scale dispersant testing was built out of 1.5-in PVC pipe, with a Spraying Systems Co. 80° flat-fan spray nozzle at the bottom, and valves and fittings for an air compressor to charge the system at the top (see Figure 8). Air pressure was supplied by the Ohmsett Main Bridge compressor through an equalization pressure vessel equipped with regulator, valves, and pressure gauges. Application pressures between 15 and 50 psig were tested safely. The final chosen application pressure range was 35 to 40 psig.

The wand had sufficient internal capacity to hold enough dispersant to treat a 30-L slick (1.5 L for a 1:20 application ratio) and was long enough to reach slicks from the main bridge. To account for internal hold-up, the wand was pre-charged with a small quantity of dispersant and then sprayed to empty before being refilled for an actual dispersant effectiveness test. Application rate was measured to be 3.5 L/min at 35 psig with Corexit 9500 at room temperature.

In practice, the spray wand worked well to apply dispersant. Breakthrough was occasionally seen on thinner portions of a test slick, but most of the time the dispersant remained on the surface of the slick after spraying. It was sometimes difficult to reach all parts of the slick when it was spread out or if obstructions on the main bridge (e.g., oil distribution mechanism, tow points) were in the way. Typically, the slicks were sprayed in sections and the bridge was moved as needed.

The valve on the bottom of the sprayer was difficult to reach to turn off the spray; it is recommended that a way to activate the spray from the top of the wand be implemented (e.g., solenoid activated valve or mechanical system to operate the valve from the bridge deck).

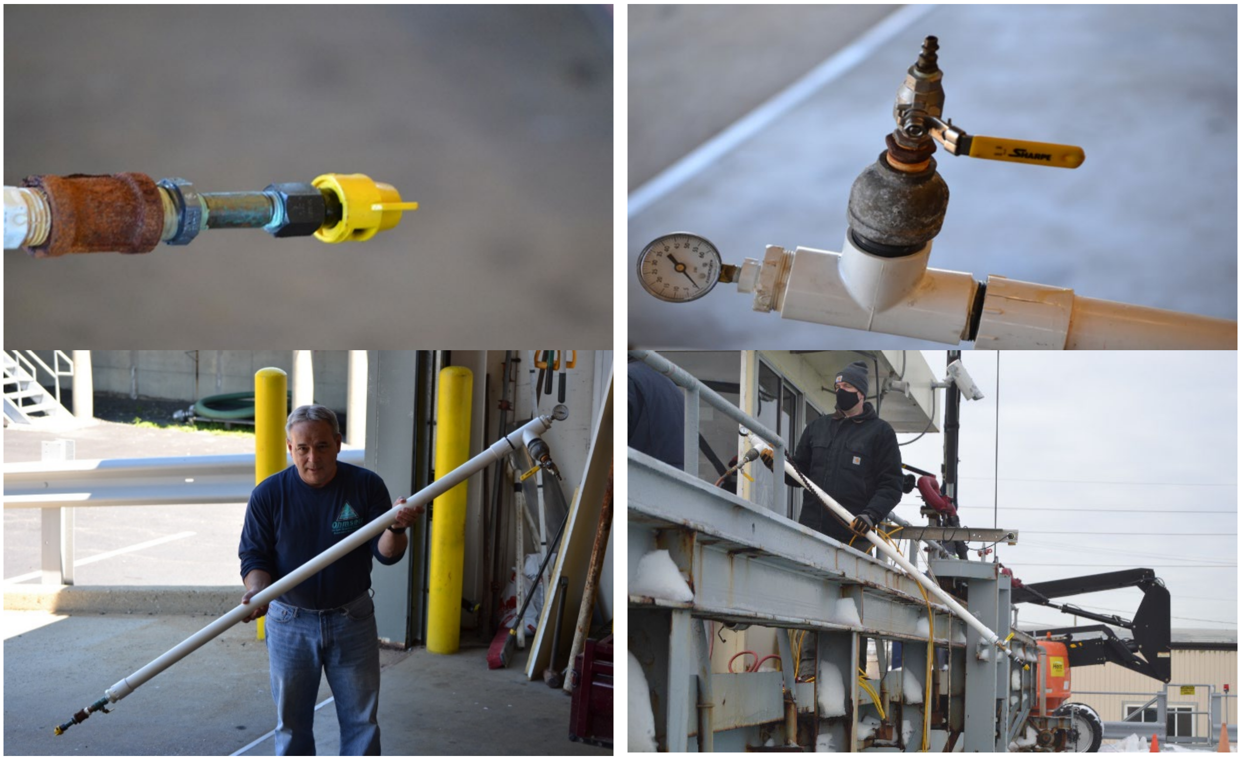

Figure 8: Dispersant spray wand.

7 WAVES

The energy imparted to the slick by waves is a critical factor in natural dispersion and is one of the most important factors in dispersant effectiveness (NRC, 2005). The characteristics of the wave to use at Ohmsett was an important component of the revised dispersant test protocol. Two different philosophical approaches to simulating sea states have been employed by researchers (Funke and Mansard 1979):

- **Probabalistic.** Develop a random sea state and test over a sufficiently long period that the conditions of interest are assumed to occur often enough.
- **Deterministic.** Select and simulate only the specific short-duration feature of interest (e.g., breaking wave events).

The probabilistic approach was taken with the original Ohmsett Dispersant Effectiveness Test Protocol (SL Ross Environmental Research, 2001 and 2003), because at the time that was the only way the wave maker could create breaking waves in the tank. Upgrades to the wave maker in the past decade allowed the use of a deterministic approach for this project, which resulted in more repeatable conditions.

Desirable characteristics of a breaking wave for use in dispersant effectiveness testing are as follows:

- Single breaker that spans the width of the tank
- Consistent breaking characteristics each time the wave is repeated
- Sufficient turbulent energy to instigate dispersion

7.1 BACKGROUND - WAVES

Waves at sea are formed primarily by the movement of air over water. The basic parameters to describe a wave are the length (L), the height (H) and the water depth (h) in which the wave is moving (Dean and Dalrymple, 1991). The speed at which a wave propagates (the celerity) is given by:

$$C = \frac{L}{T} \qquad (1)$$

Where: T is the period (s^{-1}).

The wave period is related to the angular frequency (σ) by:

$$\sigma = \frac{2\pi}{T} \qquad (2)$$

Dispersant use is typically restricted to ocean depths greater than about 10 m, so deep water conditions will apply. For waves in deep water (i.e., for h/L > 0.5) it can be shown that:

$$C = \frac{g}{2\pi}T \qquad (3)$$

Where: g is acceleration due to gravity (9.81 m/s^2)

This relationship indicates that the celerity of a wave is proportional to its period: short-period waves travel slower than long-period waves.

Wave steepness is defined as the height of the wave divided by the length. Waves begin to break when the steepness exceeds about 0.17 (Dean and Dalrymple, 2004). Waves break over a range of scales and intensities, starting with gently spilling breakers and extending to violent plunging breakers (Rapp and Melville, 1990). Important parameters of a breaking wave (Delvigne and Sweeney, 1988) relating to oil entrainment and oil droplet breakup include the length within the slick over which breaking occurs, the energy dissipation rate per unit volume in the breaking wave area, and the wave height.

Longuet-Higgins (1974) identified that the relationship between wave celerity and period could be used to generate breaking waves in a tank. If a discrete train of waves with angular frequency σ_1 is generated at time t_1, followed by a second train of waves with σ_2 at t_2, for $\sigma_2 > \sigma_1$ the trains will converge at a distance *x* from the wave maker according to:

$$\frac{\sigma_1 - \sigma_2}{t_2 - t_1} = \frac{g}{2x} \tag{4}$$

Depending on the selection of wave heights, a breaking wave can result at the convergence point if the maximum steepness threshold is exceeded. By changing the delay between the generation of each wave, the distance down the tank where the waves converge can be adjusted. This general approach may be further extended and refined by generating a series of many waves of decreasing frequency in sequence that all converge at the same point. This provides more control over the characteristics of the breaking wave but is more complicated to design and program.

The characteristics of the wave tank and wave maker play important roles in the generation of breaking waves. The depth of the tank will limit the height of waves that can be produced, and the length of the tank will limit the area in which waves are able to converge. The nature of the beach or wave absorbers will affect how much wave energy is reflected into the tank. Various wave maker configurations have been used (e.g., flap, piston, wedge), and relationships between stroke length, frequency, water depth and resulting wave forms have been developed (Dean and Dalrymple, 1991). The capabilities of the wave maker will also be affected by the type of drive (e.g., eccentric flywheel, hydraulic piston) and controller (e.g., analog or digital).

The wavelength (L) is given by (Dean and Dalrymple, 1991):

$$L = \frac{g}{2\pi} T^2 \tanh\left(\frac{2\pi h}{L}\right) \tag{5}$$

Where: g is acceleration due to gravity, h is the water depth

From equation (6), it is seen that the wavelength is proportional to the wave period but is also affected by the water depth. In "deep water" (i.e., when h > L/2), equation X simplifies to:

$$L = \frac{g}{2\pi} T^2 \tag{6}$$

The water depth at Ohmsett is typically around 2.4 m (7.9 ft), which means that equation 6 is valid for high-frequency waves (> 30 cpm) but becomes less accurate as the frequency decreases (period increases). At a certain point, long waves start to "feel" the bottom of the tank and the assumption of deep water is not valid.

Waves at Ohmsett are generated by two flap-type wave paddles located at the south end of the tank. Each paddle is driven by a separate hydraulic piston, with adjustable stroke length and frequency. Controls for the wave paddles are located on the Main Bridge. It is possible to operate each wave paddle individually, but typically the paddles are operated synchronously and were done so for this project.

Wave height is a function of the paddle stroke length, as given by (Dean and Dalrymple, 2004):

$$\frac{H}{S} = 4\left[\frac{\sinh kh}{kh}\right]\left[\frac{kh \sinh kh - \cosh kh + 1}{\sinh 2kh + 2kh}\right] \tag{7}$$

Where: k is the wave number ($2\pi/L$)

It is desirable that wave energies in test tanks be related to actual sea states (Fingas and Banta, 2009). Energy dissipation rates at sea are typically between 1 to 10 J/m^3.s (10^{-3} to 10^{-2} W/kg; Delvigne and Sweeney, 1988). Energy dissipation rates measured at Ohmsett during breaking waves were found to be on the order of 10 J/m^3.s (Wang and Wijesekera, 2018), which matches the upper end of expected at-sea conditions.

There are several approaches to quantify the energy dissipation rate due to turbulence (Kresta, 1991; Wang et al. 2020). The autocorrelation method has been used previously to calculate energy dissipation rate from breaking waves in a wave tank (Wickley-Olsen et al., 2008) under the assumption that the turbulence is isotropic (i.e., the same magnitude in all directions). This method requires knowledge of the 3-dimesional velocity field in the water over time. Acoustic Doppler Velocimeters (ADVs) have been used by several researchers to measure instantaneous velocity fluctuations (e.g., Voulgaris and Trowbridge, 1996; Thomson et al., 2016) for the purpose of characterizing turbulence.

The fluctuating velocity in a fluid (u_i') can be described as follows:

$$u_i' = u_i - \overline{U_\iota} \tag{8}$$

Where: u_i is the instantaneous velocity in direction i

$\overline{U_\iota}$ is the time-averaged velocity in direction i

The energy dissipation rate (ε) using the autocorrelation function is given by:

$$\varepsilon = A\frac{(u_{rms}')^2}{\tau} \tag{9}$$

Where: u_{rms}' is the root mean square of the fluctuating velocity

A is a constant, equal to one

τ is the integral time scale

The integral time scale is calculated by:

$$\tau = \int_0^\infty R_E dt \tag{10}$$

Where :

$$R_E = \frac{\overline{u_i'(t')u_i'(t'+t)}}{\overline{(u_i')^2}} \quad (11)$$

7.2 Component Wave Trains

The Ohmsett wave paddle control system has several modes of operation, including regular, spectrum and frequency sweep. For this project, the wave control system was operated in frequency sweep mode, in which several commands can be input and executed in sequence. The commands consist of the following parameters:

- Number of Cycles
- Cycles per Minute (cpm)
- Amplitude (Stroke Length, in)
- Delay before next command (s)

The number of cycles is the number of times the wave paddle operates at the specified frequency and amplitude. Cycles per Minute is the frequency of the wave paddle and resulting wave, and is related to the wave period, T (s^{-1}), according to:

$$T = \frac{60}{F} \quad (8)$$

The stroke length and frequency of the wave paddle are adjustable, but there are limits. The wave maker also has power limitations; longer strokes move more water, which requires more power. There are hard limits programmed into the controller which cannot be exceeded to minimize the risk of equipment damage. A summary of some of the permitted settings and theoretical wave characteristics for several stroke lengths is presented in Table 7-2.

Table 7-1: Wave heights and theoretical characteristics of waves for several controller settings.

CPM	*Period*	*Wavelength*	*Celerity*		*Wave Height (in)*							
	T (s)	*L (ft)*	*C (ft/s)*	*Stroke (in)*	*3*	*5*	*6*	*7.5*	*9*	*12*	*15*	*18*
45	1.3	9.1	6.8		4.9							
40	1.5	11.5	7.7		4.6	7.6	9.2					
35	1.7	15.1	8.8		4.2	6.9	8.3	10.4				
30	2.0	20.5	10.2		3.5	5.8	7.0	8.8	10.5	14.0		
25	2.4	29.5	12.3		2.6	4.3	5.2	6.5	7.8	10.4	13.0	
20	3.0	46.1	15.4		1.6	2.7	3.3	4.1	4.9	6.6	8.2	9.9

In October 2020, several wave settings were tested and trains of between 3 and 5 waves were created and observed. The following observations were made:

- The first one or two waves in a train were smaller than the rest.
- Reflections from the higher CPM (i.e., shorter wavelength) waves dissipated faster than the lower CPM waves.

- It took about 5 minutes for reflections from the lower CPM waves to dissipate almost completely.

Characteristics of the wave trains are provided below. Wave height was measured with two ultrasonic altimeters (Banner Engineering, model QT50ULB), which measure the distance from the sensor to the water surface. The altimeters are mounted on the north and south side of the Main Bridge, 18.5 ft apart.

7.2.1 Component Train 1

The wave maker settings for Train 1 were as follows:

# Waves	*CPM*	*Amplitude (in)*
5	40	5

These settings produced a train with five discrete waves. The third and fourth waves were larger than the rest, with heights between 10 and 11 inches. The measured heights for each wave, averaged between the north and south altimeters and over the three trains, were as follows:

Wave	*Average Height (in)*
1	4.5
2	7.1
3	11.1
4	10.0
5	4.6

The typical appearance of the wave train at the north altimeter is shown in Figure 9.

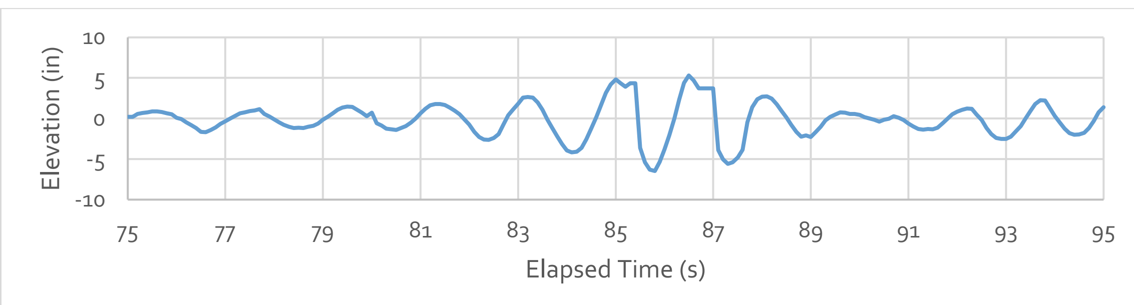

Figure 9: Profile of Component Train 1 at North altimeter.

7.2.2 Component Train 2

The wave maker settings for Train 2 were as follows:

# Waves	*CPM*	*Amplitude (in)*
4	40	5

These settings produced a train with four discrete waves. The first and last waves were smaller than the middle two, which had heights of 9.4 in. The heights for each wave, averaged between the north and south altimeters and over the three trains, were as follows:

Wave	*Average Height (in)*
1	6.6
2	9.4
3	9.4
4	5.7

The typical appearance of the wave train at the north altimeter is shown in Figure 10.

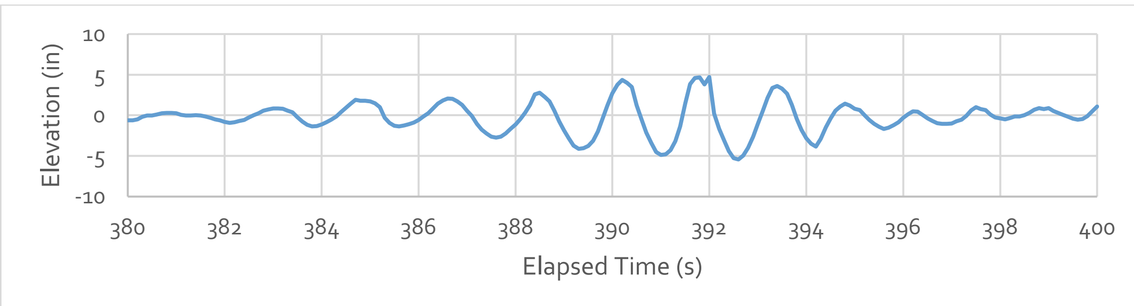

Figure 10: Profile of Component Train 2 at north altimeter.

7.2.3 Component Train 3

The wave maker settings for Train 3 were as follows:

# Waves	*CPM*	*Amplitude (in)*
5	30	12

These settings produced a train with five discrete waves. The first three waves were larger than the last two. The middle wave had a height of 19.1 in. The heights for each wave, averaged between the north and south altimeters and over the three trains, were as follows:

Wave	*Average Height (in)*
1	13.3
2	19.1
3	13.4
4	8.9
5	9.7

The typical appearance of the wave train at the north altimeter is shown in Figure 11.

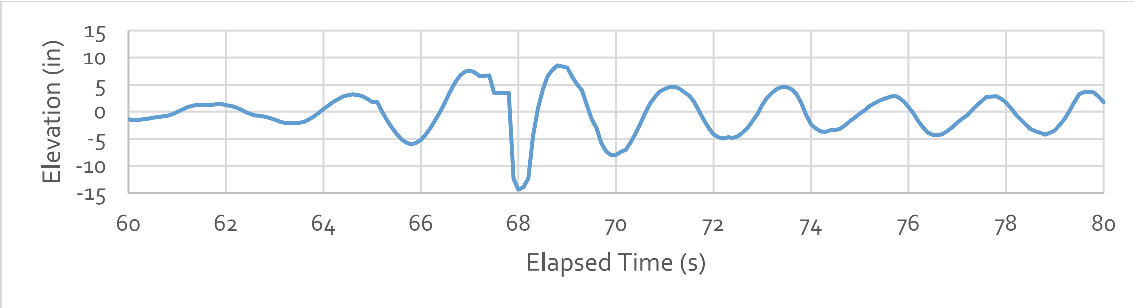

Figure 11: Profile of Component Train 3 at North altimeter.

7.2.4 Component Train 4

The wave maker settings for Train 4 were as follows:

# Waves	*CPM*	*Amplitude (in)*
4	20	18

These settings produced a train with four discrete waves. The first and last waves were smaller than the middle two, which had heights of 22 and 19.6 in. The heights for each wave, averaged between the north and south altimeters and over the three trains, were as follows:

Wave	*Average Height (in)*
1	13.8
2	22.0
3	19.6
4	12.7

The typical appearance of the wave train at the north altimeter is shown in Figure 12.

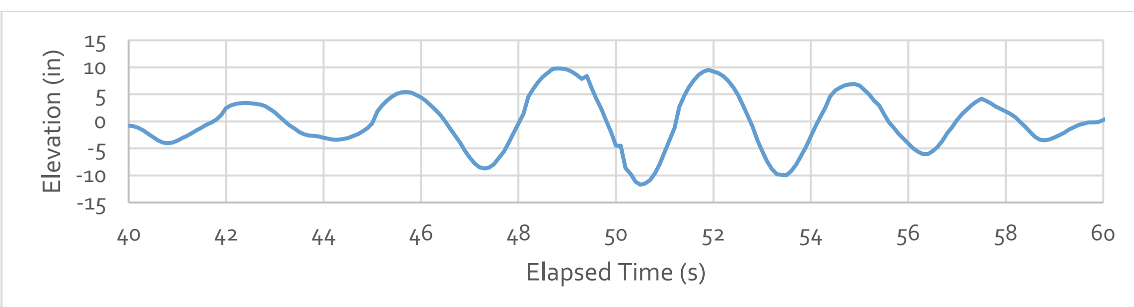

Figure 12: Profile of Component Train 4 at North altimeter.

7.3 Breaking Waves

The component wave trains were combined with appropriate delays between them to have the trains overlap in the test area. Several combinations of the wave trains were tested to try to develop breaking waves. Candidate waves with promising characteristics were developed and characterized in December 2020.

The Ohmsett beach has been estimated to absorb only 30 to 60% of the incident energy depending on the wave period (Boufadel, 2016), while the remainder is reflected down the tank. The north end of the tank is not square, and incident waves are reflected at an angle. This limits the number of breaking waves that can be generated over time without interference from reflections. Testing determined that approximately five minutes was required between wave events for the tank to return to calm.

In addition to the acoustic altimeters, two ADVs (Nortek Vector) were mounted to the eastern tow point on the north side of the main bridge at 2 ft and 4 ft below the static water surface, respectively. The ADVs monitor a cylindrical volume of water with diameter 14 mm and height 14.9 mm, located 157 mm from the center point of the probe. The ADVs were set to sample at a rate of 8 Hz. The ADVs were mounted facing east, across the tank, with the marked arm of the probe at the top; therefore, the directions of the measured velocities corresponded to the following tank axes:

ADV Axis	*Tank Dimension*
X	Vertical (up-down)
Y	Along (north-south)
Z	Across (east-west)

Inspection of the ADV data showed small oscillations in velocities continued between wave events, as is expected (i.e., the water in the tank is never perfectly still). A 1.25 s centred moving average of the velocity data ($\overline{U_i}$) was found to follow the trend of the small oscillations reasonably well. The 10th and 90th percentile velocity values were determined over the first 50 s of each data set from the December 2020 tests, which covered the relatively calm period before a wave event. The oscillatory components of the velocity measurements were then determined as the minimum of the moving average or the 90th or 10th percentile velocities. In this way the oscillatory components were capped at a value dependent on the characteristics of the calm tank to not mask the effects of the waves passing by the sensors.

The integral time scale was calculated from equation (10) for each wave event for both ADVs in each of the three component directions. The integral was calculated until the first crossing of the y-axis, rather than to infinity, as per the procedure in Wickley-Olsen et al. (2008). Integral time scales were typically in the 0.4 to 1.0 s range.

It was noted that the X- and Z- velocity measurements from the ADVs correlated well with each other, whereas the Y-velocity measurements were consistently significantly higher. Given the assumption of isotropic turbulence, the more similar X- and Z-velocity components were used to calculate the turbulent energy dissipation rate. Turbulent energy dissipation rate was calculated at each time step and averaged over 10 s following the beginning of each wave event.

7.3.1 Breaking Wave 1

The wave maker settings for breaking wave 1 were as follows:

# Waves	*CPM*	*Amplitude (in)*	*Delay (s)*
4	40	5	12.6
5	30	12	

These settings produced a breaking wave with a height of 11 in. (averaged over the north and south altimeters and three repeats). The average energy dissipation rate over the top and bottom ADVs was 0.044 W/kg, with a peak around 0.2 W/kg. Visually this wave presented as three relatively small breakers in series over a distance of about 10 ft. The typical appearance of the wave at the north altimeter is shown in Figure 13.

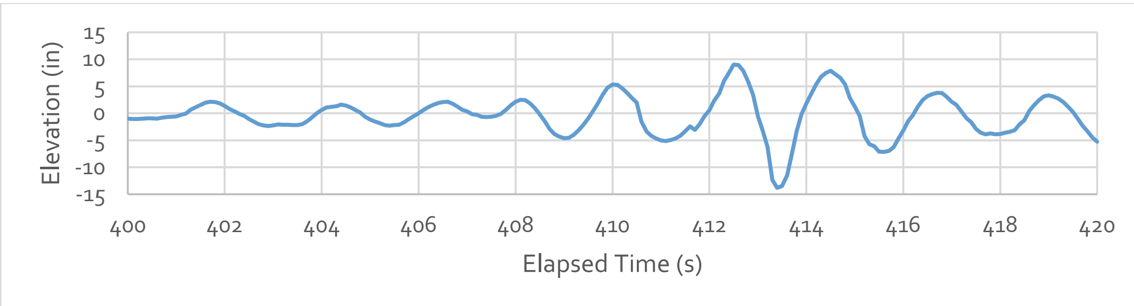

Figure 13: Profile of Breaking Wave 1 at North Altimeter.

7.3.2 Breaking Wave 2

The wave maker settings for breaking wave 2 were as follows:

# Waves	*CPM*	*Amplitude (in)*	*Delay (s)*
5	30	12	6.2
4	20	18	

These settings produced a breaking wave with a height of 24 in. (averaged over the north and south altimeters and three repeats). The average energy dissipation rate over the top and bottom ADVs was 0.060 W/kg, with a peak around 0.3 W/kg. Visually this wave presented as a single breaker that extended over about 10 ft. Sometimes a smaller breaker near the vacuum bridge preceded the main wave. The typical appearance of the wave at the north altimeter is shown in Figure 14.

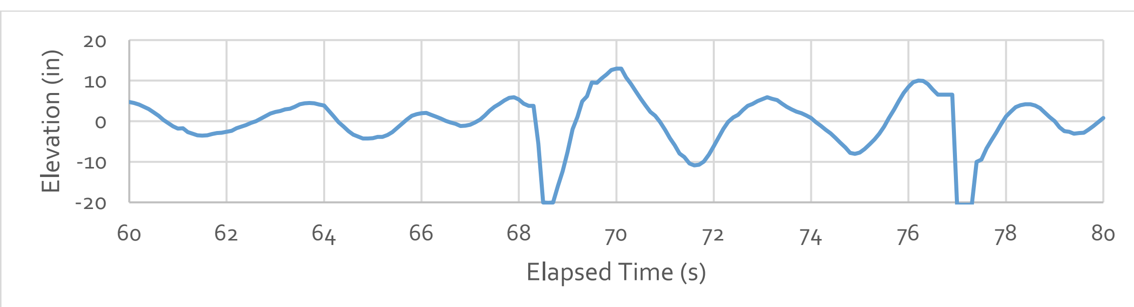

Figure 14: Profile of Breaking Wave 2 at North Altimeter.

Figure 15 shows images of Breaking Wave 2 impacting a treated surface slick of weathered ANS crude oil.

Figure 15: Breaking Wave 2 impacting treated test slick.

7.3.3 Breaking Wave 3

Breaking Wave 3 was created with three component wave trains. The wave maker settings were as follows:

# Waves	*CPM*	*Amplitude (in)*	*Delay (s)*
4	40	5	12.6
5	30	12	6.2
4	20	18	

These settings produced a breaking wave with a height of 34 in. (averaged over the north and south altimeters and three repeats). The average energy dissipation rate over the top and bottom ADVs was 0.057 W/kg, with a peak around 0.4 W/kg. Visually this wave presented as a single, large plunging breaker. The typical appearance of the wave at the north altimeter is shown in Figure 15.

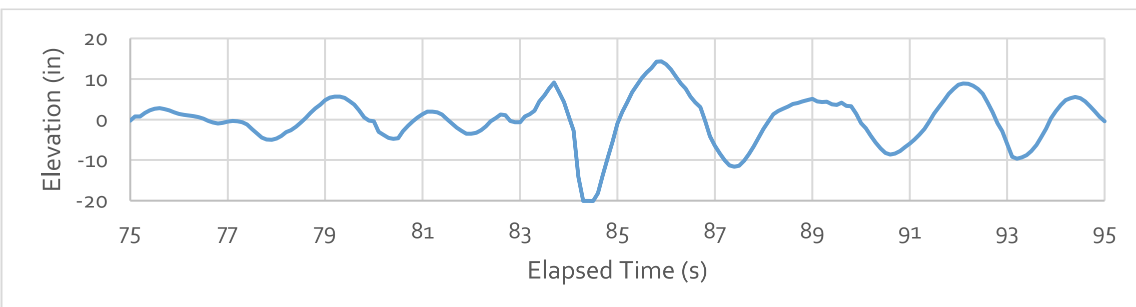

Figure 16: Profile of Breaking Wave 3 at North Altimeter.

7.4 Conclusions

The three breaking waves were tested with the draft revised dispersant test protocol in April 2021. Breaking Wave 2 was able to disperse treated slicks of weathered HOOPs crude oil with the expected high effectiveness (90% average over three tests) for a light crude oil. Breaking Wave 3 was also able to disperse treated slicks. Breaking Wave 1 did not instigate dispersion with a treated slick.

The following conclusions regarding the waves were made:

- Average turbulent energy dissipation rates were within the desired range (~10^{-2} W/kg).

- Breaking Wave 2 produced the most consistent break at different locations in the tank (i.e., as the delay between component trains was changed).
- Breaking Wave 3 produced a strong breaker, but because it comprised three wave trains it was more difficult to adjust the location of breaking in the tank.
- Breaking Wave 1 was too gentle to disperse treated slicks.
- None of the waves were observed to push significant amounts of oil outside of the containment area.
- Dispersant effectiveness and control tests were done with a series of seven consecutive wave events at 5-minute intervals. This was observed to be a sufficient amount of wave energy to instigate dispersion with the oil/dispersant combinations used in the test protocol evaluation.

8 MONITORING DISPERSED OIL PLUME

Accurately characterizing the properties of the dispersed oil plume is important to understanding and analysing dispersant effectiveness results, and predicting the likelihood that the oil will remain dispersed. However, the oil distribution in the plume is highly heterogeneous, and no study has been able to completely measure or describe the system. Parameters that were considered for measurement included the following:

- **Droplet Size Distribution.** The amount of oil (mass or volume) that is present in droplets of various sizes.
- **In-water Oil Concentration.**

The droplet-size distribution of dispersed oil is a particularly important factor for dispersant effectiveness because it will determine whether the entrained oil will remain in the water column or float back to the surface under low energy conditions (NRC 2005). The fraction of oil present as small droplets (< 70 µm) is a strong indicator of performance (Lunel 1995).

Measurement of oil concentration in the water column are important in field application of dispersants, for both monitoring and risk analysis. Oil concentrations can theoretically be related to dispersant effectiveness; however, researchers have had limited success with accurately calculating dispersant effectiveness in this way (e.g., Brown, Goodman and Canevari 1985).

LISSTs (Sequoia Instruments) have proven effective for in-water measurements of droplet size and concentration in the range of interest to dispersant use (< 500 µm) and two were available at Ohmsett. The LISSTs were deployed off the north side of the Main Bridge and measurements were taken as it was moved from one side of the test area and back after each wave event, which took about two minutes. Figure 17 shows the LISST measurements for a control run after the first wave, while Figure 18 shows the corresponding measurements for a dispersant run. The shift to smaller droplet sizes is evident.

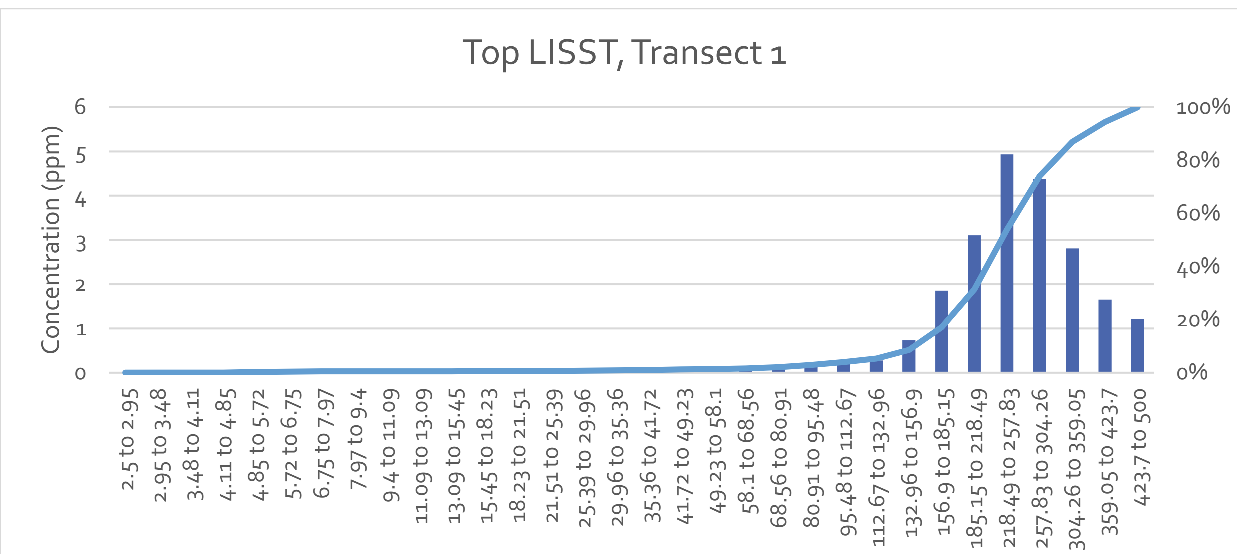

Figure 17: Oil droplet size distribution for control run (Test 1).

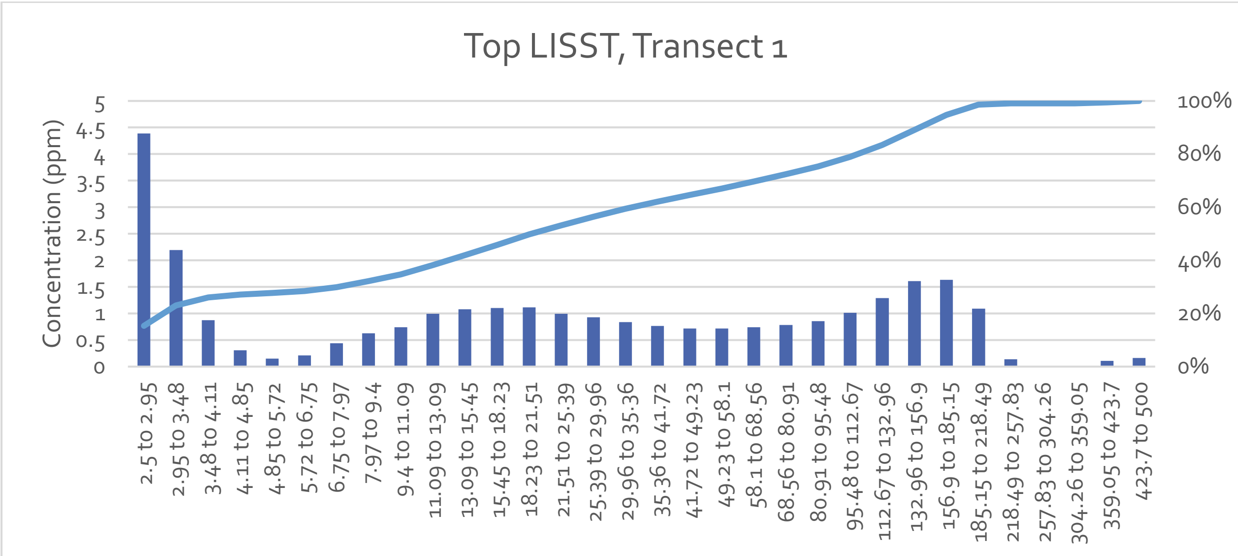

Figure 18: Oil droplet size distribution for dispersant run (Test 3)

SINTEF Ocean AS developed an optical in-situ particle imaging system (SilCam) and delivered a prototype to Ohmsett (Exponent and SINTEF 2018). The device as configured can detect droplets and measure concentrations in water in the diameter range of 100 to 12,000 µm. Figure 19 shows the droplet size distribution for a control run completed in December 2020, and Y shows the same for a dispersant run.

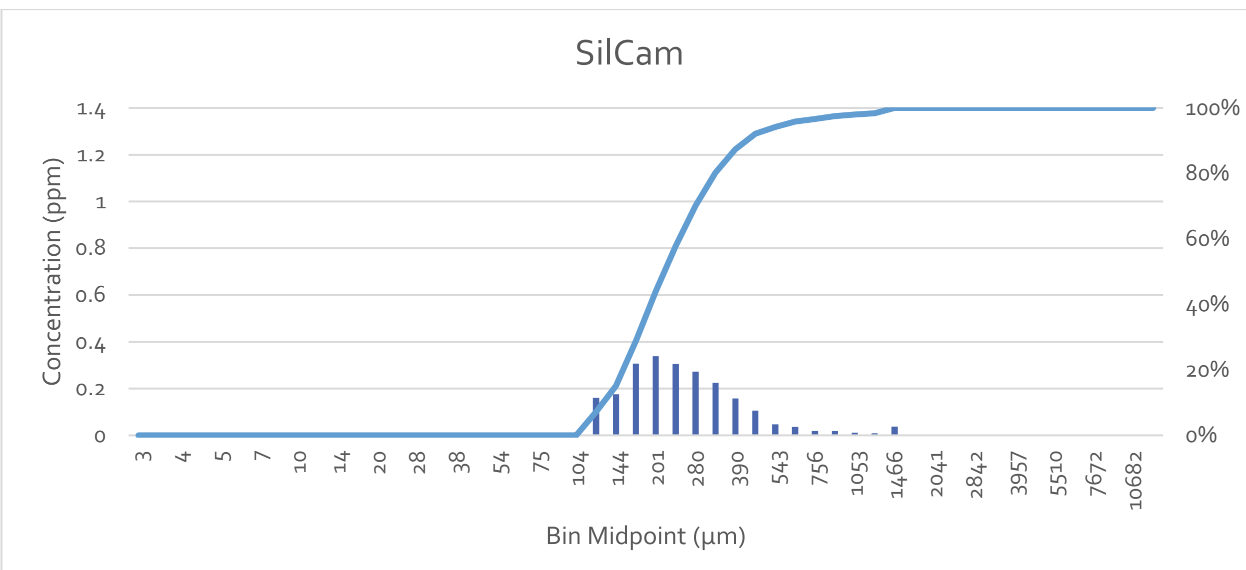

Figure 19: Oil droplet size distribution for control run (Test 9).

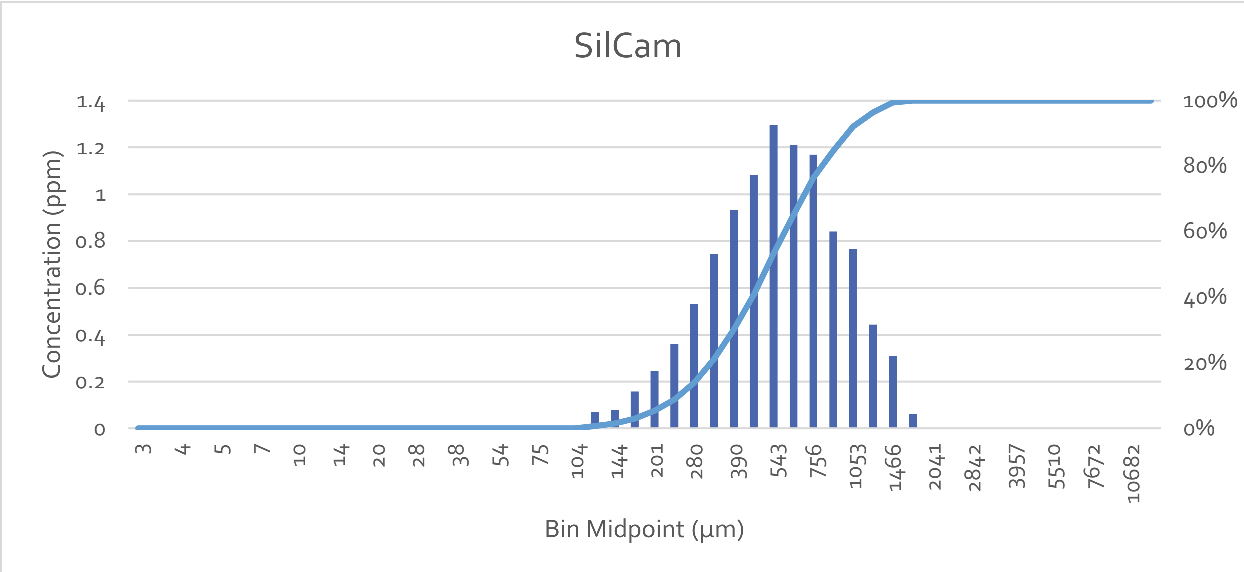

Figure 20: Oil droplet size distribution for dispersant run (Test 10).

The SilCam was comparable to the LISSTs in its ability to measure oil droplet size distributions and in-water concentrations, and to differentiate between control and treatment runs. The SilCam required significantly more time and labour to process the data than the LISST.

9 Residual Oil Recovery

Recovering oil remaining on the water surface after the control and dispersant test runs is critical for the mass balance to determine dispersant effectiveness, and losses from the containment area due to natural dispersion and other processes. Experience with the original test protocol was that losses from the control runs were often high enough to impact the significance of the results. Containing the oil slick within a smaller portion of the tank made this step significantly easier.

Oil was recovered into two 200-L conical bottom tanks located on the Main Bridge. The tanks were decanted of free water as necessary back into the test area after settling. The final volume of the recovered oil was measured, and samples were collected for density and water content measurements.

Tests investigated manual collection, and mechanical recovery with 1-inch and 2-inch double diaphragm pumps. The final system employed a J-tube attached to a long suction hose that was manually moved around the slick. A Hand-held T-shaped pole and a leaf-blower were used to help move oil towards the collection point.

Tests during December of 2020 investigated using herder (SilTech OP40) to assist with the residual oil recovery. While some benefit to the recovery operation was noted, it was felt that the improvement was significantly outweighed by potential complications from introducing another surfactant to the test.

During testing in April 2021, the recovery operations were started shortly after the final wave had passed the test slick and plume monitoring operations were finished. For control tests, recovery took between 60 and 75 minutes. Recovery efficiency for three control runs with weathered HOOPS crude oil averaged 90% (std. dev. 6%). This is a significant improvement compared to the original dispersant test protocol, and it is likely that this would improve further as personnel gain experience with the new methodology.

The recovery technique can cause emulsification of the recovered oil. Water contents of the recovered fluid from the control runs with weathered HOOPS crude oil were typically 50 to 75% water. While the water content is accounted for in the mass balance calculation, it does mean that more fluid must be handled. It is recommended that improvements to the recovery operation be investigated further. In particular, there may be commercially available skimming devices or selective skimmer heads that would allow for faster and less labour intensive recovery operations than the method used in this project.

10 Revised Ohmsett Dispersant Test Protocol

1. **Scope**
   1.1. This protocol measures the effectiveness of a dispersant at removing oil from the water surface in the Ohmsett wave tank, compared to a no-treatment scenario.
2. Terminology
   2.1. *Dispersant Effectiveness* is the percentage of oil that is dispersed. The amount of oil dispersed is equal to the initial mass of oil deployed less the mass of oil recovered from the surface of the test area after the test is complete. Dispersant Effectiveness is calculated as follows:

$$DE = \frac{Oil_{Dispersed}}{Oil_{Initial}} = \left(1 - \frac{Oil_{Recovered}}{Oil_{Initial}}\right) \times 100$$

   2.2. *Recovery* is the percentage of oil that is recovered from the surface of the test area after the control test, compared to the initial mass of oil deployed. Recovery is calculated as follows:

$$Recovery = \left(\frac{Oil_{Recovered}}{Oil_{Initial}}\right) \times 100$$

   2.3. *Loss* is the percentage of oil that is not recovered during the control tests from the surface of the test area after the test is complete. Loss is analogous to Dispersant Effectiveness, and is calculated as follows:

$$Loss = \left(1 - \frac{Oil_{Recovered}}{Oil_{Initial}}\right) \times 100$$

   2.4. *CPM* is cycles per minute
   2.5. *Oil Droplet Size Distribution* is the concentration of oil in the water column present in droplets of varying diameter, typically between 2.5 and 500 µm.

3. **Summary**
   3.1. This protocol describes the methods and equipment for conducting dispersant effectiveness tests in the Ohmsett test basin.
   3.2. The conceptual spill scenario that the test protocol is modeled after is an uncontained surface slick subject to breaking waves, with dispersant applied by spraying from a vessel or aircraft.
   3.3. Oil is deployed on the tank in an area constrained by water jet barriers, and subject to seven discrete breaking waves over a 30-minute period. The amount of oil removed from the water surface during runs with dispersant is compared to no-treatment control runs to determine Dispersant Effectiveness.
   3.4. Ideally, the controls and dispersant runs will be repeated 3 times so that treatment and control can be compared statistically. A balance will have to be struck between the advantages of maintaining visibility in the water column by conducting control runs early in the test program, and randomizing the program schedule to avoid biasing results due to uncontrolled variables (e.g., weather).

4. Test Facility

4.1. The tests are conducted in the Ohmsett test basin. A section of the tank measuring approximately 120 ft long is isolated using spray barriers along each of the four sides.

4.1.1. The north and south sides of the test area are bounded by the Auxiliary Bridge and Vacuum Bridge, respectively. The fence-boom barrier on the Auxiliary Bridge is lowered, except to sweep residual oil to the north portion of the tank to clear the test area between runs.

4.1.1.1. Spray barriers consisting of four flat-fan nozzles (BETE #NF 40080, 1-in., 80°) on two manifolds are mounted to each bridge at 10 to 15° below horizontal.

4.1.1.2. Tank water is pumped to the manifolds through 2-inch hose at 50 to 60 psig at a total flowrate of 45 to 50 gpm from centrifugal fire monitors located at each end of the tank.

4.1.2. The east and west sides of the test area are bounded by the tank walls.

4.1.2.1. Spray barriers consisting of four flat-fan nozzles (BETE #1/2NF 10110, ½-in., 110°) on a single manifold are mounted to the tank wall through the drainage scuppers at 15 to 22° below horizontal.

4.1.2.2. Tank water is pumped to the manifolds from 2-in centrifugal pumps (McMaster-Carr #99435K71) on each side of the tank. The nozzles are operated at 30 to 35 psig.

4.2. The Main Bridge is free to move north and south within the test area and serves as the working platform to deploy oil and dispersant, collect residual oil, and direct the tests and record data.

4.3. Ice eaters are deployed across the tank, south of the test area, to prevent oil from accumulating behind the wave paddles at the south end of the tank. Additional ice eaters may be deployed in the corners north of the Auxiliary Bridge to prevent oil from previous tests from migrating past the boom.

4.4. Dispersant is applied from the main bridge using a hand-held applicator with an 80° flat-fan nozzle (Spraying Systems Co. Unijet #8008) pressurized to 30 to 35 psig.

4.5. Breaking waves are generated with the wave-maker in the frequency sweep mode using the following settings to create two wave trains:

	# Waves	CPM	Amplitude (in)
Train 1	5	30	12
Train 2	4	20	18

4.5.1. The delay between wave trains should be adjusted so that the wave breaks in approximately the middle of the test area.

5. Test Instrumentation

5.1. Video and still cameras are deployed to record the tests.

5.1.1. The cameras should be positioned to get clear views of the tests, accounting for weather conditions, such as glare from the sun or wind-driven spray from the water jets.

5.1.2. At least one still camera should collect an overhead shot of the test oil slick.

5.2. Two LISST 100X Type C are deployed from the main bridge at 0.6 and 1.2 m (2 ft and 4 ft) below the water surface.
5.3. A weather station records the following information:
   5.3.1. Wind speed and direction
   5.3.2. Air temperature
5.4. Daily measurements are taken of the following tank parameters:
   5.4.1. Water level
   5.4.2. Water temperature
   5.4.3. Water salinity
5.5. Optionally, wave characteristics can be measured using ultrasonic altimeters (Banner Engineering, U-Gage Analog QT45U) and acoustic doppler velocimeters (Nortek Vector).

6. Test Fluids

6.1. The protocol can be used with any oil, including crude oils, refined products, and unconventional oils (e.g., dilbits, synbits).
   6.1.1. If testing with crude oil, the oil should be weathered to some degree to avoid changes to oil properties during testing. The amount of weathering will depend on the concentration of light ends in the crude oil.
   6.1.2. The following properties of the oil should be measured at two temperatures bounding the expected ambient conditions:
      6.1.2.1. Density
      6.1.2.2. Viscosity
      6.1.2.3. Interfacial Tension
6.2. The protocol can be used with any dispersant that is designed to be applied by spraying.

7. Test Variables

7.1. Control Tests are conducted without dispersant to measure the amount of oil lost from the test area (i.e., to loss of containment, natural dispersion, evaporation, dissolution, and other processes) over the course of a test run.
7.2. Dispersant Tests are conducted with dispersant to measure the amount of oil removed from the water surface.

8. Procedures

8.1. 30 L (7.9 gal) of oil is applied to the water surface by lowering containers of oil from the main bridge.
   8.1.1. The containers are weighed before and after deploying the oil to calculate the mass of oil applied.
8.2. The oil slick is allowed to spread and move to a steady-state position in the test area, approximately 5 to 10 minutes.
8.3. An overhead shot of the test slick is taken to determine approximate slick area.
8.4. Dispersant is applied at the desired application rate, for runs with dispersant.

8.4.1. The operator should try to apply dispersant as evenly as possible across the test slick.

8.5. Breaking waves are generated at a rate of one every five minutes for 30 minutes, for a total of seven breaking waves.

8.5.1. In between each wave event, the main bridge is moved across the test area and back to the starting point so that the plume monitoring instruments can sample or measure the dispersed oil concentration and droplet size distribution.

8.5.2. Transit speed of the main bridge should be approximately 0.5 to 0.8 ft/s.

8.6. After the seventh breaking wave and test area transects are finished, residual oil remaining on the water surface in the test area is recovered mechanically to temporary storage tanks on the main bridge.

8.6.1. Free water recovered during collection is decanted regularly back into the test area.

8.6.2. Recovery is stopped when the test director judges that the amount of oil remaining in the test area appears to be insignificant.

8.6.3. After final decanting, the volume of recovered fluid is measured, and it is mixed thoroughly and sampled for water content.

8.6.4. The mass of oil recovered is calculated from the volume of recovered fluid, corrected for emulsification that may occur during testing and recovery according to:

$$Oil_{Recovered} = Fluid_{Recovered} \times Water\ Content \times \rho_{Oil}$$

9. Report

9.1. The test report should include a description of the test apparatus, methods, and significant observations such as the possible effects of ambient conditions on the test outcomes.

9.2. Report the Dispersant Effectiveness of the treatment runs and Recovery of the control runs.

9.2.1. If repeats were done, report the average of the three dispersant and control runs. Calculate and report a t-test on the average Dispersant Effectiveness and control Losses.

9.3. Report the oil-in-water concentration, mean droplet size, and percentage of oil present in droplets < 75 µm for at least the first three transects.

11 CONSIDERATIONS FOR OTHER LARGE TANKS

The draft Ohmsett dispersant test protocol provided in Section 10 may be applicable for use in other large tanks, subject to the following considerations:

- The ability to create a breaking wave in another tank will depend on the nature of the wave paddle and controller. All the still-operating facilities previously used for dispersant research (see Section 2) would be able to create repeatable breaking waves at a specific location.
- The size of the breaking wave should be scaled according to the size of the tank. It is recommended that the height and turbulent energy dissipation rate of the wave used be measured.
- The containment techniques used at Ohmsett are transferrable to another tank. The test area and containment spray systems would have to be scaled according to the tank dimensions, but a wide variety of pumps and spray nozzles are commercially available to permit this.
- The size of test slick would have to be scaled to the tank dimensions.
- Recovering residual oil becomes easier with a smaller tank.

12 CONCLUSIONS AND RECOMMENDATIONS

The conclusions made during the development and evaluation of the revised Ohmsett dispersant test protocol were as follows:

- Using 30 L of oil per test showed good results from several perspectives:
  - The oil formed a large enough slick to target with a breaking wave
  - The slick was free to move within the test area
  - The slick produced a sufficiently large plume for characterizing with the LISSTs and SilCam
  - This amount was readily recoverable within an hour using the final recovery system
  - This was significantly less than the previous test protocol (100 L), which meant that less oil would be needed for a test program
- The oil containment system was able to hold test slicks in the test area with all breaking waves tested, even in winds up to 30 km/h. Breakthrough of the side sprayers was experienced during one test with average wind speed of 40 km/h.
- Deploying oil and dispersant from the main bridge was preferable than from the man-lift. The entirety of the test area was accessible to technicians from the main bridge and no extra equipment was needed.
- Breaking Wave 2 provided sufficient energy to disperse both test oils and was able to consistently make good contact with the test slicks in the test area. Average turbulent energy dissipation rate was in the desired range (~10^{-2} W/kg).
- Recovering oil with the larger 2-inch double-diaphragm pump apparatus worked well. The throughput of the smaller 1-inch pump was too low.
- Conducting these tests in winter, where overnight temperatures drop below freezing are possible, requires that the side sprayers be winterized each night (i.e., drained and filled with anti-freeze), which slightly reduces the time available for testing.

Recommendations for modifications or areas requiring further study were as follows:

- Recovering residual oil was the longest step in the revised protocol for control runs and required significant physical effort. Alternative methods of recovering oil from the water surface, such as a small mechanical skimmer or selective skimmer head, should be investigated.
- The design of the dispersant application wand could be refined further; in particular, a way to remotely operate the valve at the bottom of the wand would improve the ability to accurately target test slicks.
- The SilCam at Ohmsett is a version designed for studying underwater blowouts, and the lens is scaled for larger oil droplets than are encountered with successful dispersant tests. It may be possible to change the lens to improve the SilCam for use with dispersant testing.
- Improve the mounting of the south manifolds on the Vacuum Bridge to make it more secure and permanent.
- Design a more convenient method to flush the side-sprayers and fill with anti-freeze during cold temperatures.
- Equip all sprayers with flow meters to quantify flow rates and record operational settings.

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Appendix A

October 2020 Test Summary

Appendix A: Week One Test Summary

Test Number	Description	Wave Settings: Waves	CPM	Amp. (in)	Delay (s)	Observations	Date	Time	Weather Conditions: Temp. (°C)	Wind Speed (mph)	Direction (°)
1	Wave from 2016 report to BSEE on Ohmsett wave capabilities.	4 5	40 30	5 12	18.5	Three consecutive breakers near middle of the tank.	2020-10-05	11:30 AM	20	9.8	354
2	Wave from U. of Washington APL project	5 5	30 20	12 18	9.3	Produced one strong breaker (319.1 ft) and second smaller one (273.6 ft). May be time to run two consecutive waves before reflections return through test area.	2020-10-05	3:30 PM	24	6.9	90
3	Video of wave	5 5	30 20	12 18	9.3	Bridge position at 304.9 ft. First breaker before bridge and second below bridge.	2020-10-06	10:40 AM	19	10.2	199
4, 5, 6	Three waves separated by 5 minutes	5 5	30 20	12 18	9.3	~1 minute from wave start until first wave breaks.	2020-10-06	11:00 AM	19.5	4.8	265
7, 8, 9	Three waves separated by 5 minutes	5 5	30 20	12 18	9.3	Bridge position at 313.2 ft to be over first wave break. About 24 ft between first and second breaker. Tank is mostly calm after five minutes.	2020-10-06	11:30 AM	19.9	4.3	242
10, 11, 12	Reduced waves in second train to 4	5 4	30 20	12 18	9.3	First breaker was slightly further north than with 5 waves in second train. Second breaker was much more muted.	2020-10-06	1:20 PM	22.2	8.3	292
13, 14, 15	Component train	5	30	12		Collected head-on and across videos of the wave train.	2020-10-06	1:55 PM	22.5	5	274
16, 17, 18	Component train	4	20	18		Collected head-on and across videos of the wave train.	2020-10-06	2:15 PM	23	10	280
19	Adjusted delay between trains	4	40	5	18.5	Broke too far down tank.	2020-10-06	2:40 PM	23.4	9.4	260
		5	30	12	13	Broke too early; appeared less vigorous.					
					15.5	Broke close to 330 ft, with two succeeding breakers.					
					15	Broke near 330 ft, but seemed less vigorous.					
					16	"					
					18.5	Three small breakers in succession.					
20	Inverted number of waves in trains	5 4	40 30	5 12	18.5	Wave appearance not significantly different.	2020-10-06	3:15 PM	23.8	6.5	274
	North and east spray jets, ~2 L of oil in high winds.	5	30	12	16	Wave curled but didn't break vigorously in test area.		3:00 PM	23.5	6.5	277
		5	20	18	15	One nice breaker in test area, and second curl at north water jets.					
21	North and east spray jets, ~8 L of Hydrocal + 6 L residual oil in high winds.	5 5	30 20	12 18	15.5	Ran two consecutive trains with 10 s delay between them. Second breaker was not clean due to interference from reflected waves. Switched to one set of trains and ran several sets about 5 min apart.	2020-10-07	3:30 PM	28.1	12.1	226
22	Tested several wave settings.	5 5	35 30	7.5 12	15.5 16 15 14	No breakers.	2020-10-07	4:00 PM to 5:00 PM	28.6	8.8	251
		5 5	30 25	12 15	5 4	No breakers.					
		4 5	30 25	12 15	3	3 to 4 breakers at mid-point in tank.					

Appendix A: Week One Test Summary

Test Number	Description	Wave Settings: Waves	CPM	Amp. (in)	Delay (s)	Observations	Date	Time	Weather Conditions: Temp. (°C)	Wind Speed (mph)	Direction (°)
		3	30	12	3	3 breakers at mid-point in tank.					
		4	25	15	3.5	No breakers.					
23	Ice eaters along west wall of tank.	5	30	12	15.5	Break seemed to happen further south, and intensity of break appeared lower than on October 7.	2020-10-08	10:15 AM	17.7	12.3	290
		4	20	18							
24	Varied delay between wave trains. Increased waves to 5 in second train.	5	30	12	15.5	Very little break compared to October 7.	2020-10-08	12:00 PM	19.2	18.3	287
		4	20	18	15.8	Slick a little too far south. Recommend smaller test area.					
		5	30	12	16	No breaker.					
		5	20	18	15.6	First break before main bridge. Second break at slick.					
					15.7	Primary break at main bridge. No second break.					
					15.8	No breaker.					
					15.9	Good breaker just under main bridge and a secondary.					
					16	No breaker.					
					16.1	No breaker.					
					15.5	Breaker in middle of slick.					
					15.4	Good breaker in middle of slick.					
25	Added another 10 L of Hydrocal 300 to test area.	5	30	12	15.4	Oil held position in middle of test area. Hit with several waves with no visible loss from containment. Slick reformed soon after wave passed.	2020-10-08	12:30 PM	19.5	17.3	293
		5	20	18							
26	20 L of Hydrocal 38 to test with light oil. 2 waves 5 min apart.	5	30	12	15.4		2020-10-08	2:15 PM	21.1	8	322
		5	20	18		Oil held in SW corner of test area. Waves hit middle of test slick, although east side broke more intensely. No visible losses.					
27	Third wave.	5	30	12	15.5	Good breaker, on target. Slick holding in south middle of containment area. No visible losses from waves or wind.	2020-10-08	2:20 PM	21.1	8	322
		5	20	18							
28	Additional 20 L of Hydrocal 38 added to test area.	5	30	12	15.5	Containment performed well with 40 L of light oil in high wind and waves.	2020-10-08	2:30 PM	21.4	14.1	333
		5	20	18							
	Testing various wave settings.	5	40	6	5	No breakers.	2020-10-08	3:30 PM			
		5	30	9	5.4	No breakers.					
					4.5	3-4 small breakers at about 200' from wave paddles.					
					6	3 small breakers at about 250'.					
					7	Trains converged too far down tank.					
					6.5	3 good breakers and 1 small between about 275 to 300'.					
					6.6	3 good breakers at about 300'.					
					7.5	3 good breakers at about 330'.					
		5	40	5	18.5	1 breaker at 270' from wave paddles.	2020-10-08	4:00 PM			
		4	30	12	16	2 breakers at 280'					
					12	2 breakers at 330'					
29, 40	Testing several wave trains	5	30	12	5.5	Two consecutive trains. Video from across tank and main bridge. Elevation sensor data is Test 40.	2020-10-09	2:00 PM	21.3	3.9	19
		4	20	18	10						
		5	30	12	5.5						
		4	20	18							

Appendix A: Week One Test Summary

Test Number	Description	Waves	CPM	Amp. (in)	Delay (s)	Observations	Date	Time	Temp. (°C)	Wind Speed (mph)	Direction (°)
		Wave Settings							*Weather Conditions*		
30, 41	Testing several wave trains	5	40	5	11.3	Two consecutive trains. Video from across tank and main bridge. Elevation sensor data is Test 41.	2020-10-09	2:00 PM	21.3	3.9	19
		4	30	12	10						
		5	40	5	11.3						
		4	30	12							
31, 42	Testing several wave trains	5	30	12	1.3	Elevation sensor data is Test 42. Could shift this wave further north to get more breakers in target area. Second set of waves broke further north than first. 5 breakers in a row that shift progressively north.	2020-10-09	2:05 PM	21.3	3.9	19
		4	25	15	10						
		5	30	12	1.3						
		4	25	15							
32, 43	Testing several wave trains	5	35	7.5	4.5	Elevation sensor data is Test 43. Second train a bit weaker and a bit further north than first.	2020-10-09	2:12 PM	21.7	6.7	124
		4	30	12	10						
		5	35	7.5	4.5						
		4	30	12							
33, 45	Testing three-train wave	5	40	6	10	Elevation sensor data is Test 45.	2020-10-09	2:15 PM	21.7	6.7	124
		4	30	12	4.8						
		4	20	18							
34	Component wave trains	5	40	6		Series of rolling breakers to 100'	2020-10-09	2:25 PM	22.1	8.3	74
35	with video across tank	5	40	5		Six rolling breakers between about 75 and 150'	2020-10-09	2:29 PM	22.1	8.3	74
36	and from main bridge.	5	35	7.5		5 rolling breakers between about 75 and 150'	2020-10-09	2:36 PM	22.1	8.3	74
37	Wave height data.	5	30	12		4 breakers between 150 and 200'	2020-10-09	2:40 PM	22.6	7.5	112
38	Bridge at 340.2'	5	25	15		Smooth waves	2020-10-09	2:45 PM	22.6	7.5	112
39		5	20	18		Smooth waves	2020-10-09	2:46 PM	22.6	7.5	112

Appendix B

December 2020 Test Summary

Appendix B: Test Summary December 2020

Test Number	Description	Waves	Wave Settings CPM	Amp. (in)	Delay (s)	Observations	Date	Time	Weather Conditions Temp. (°C)	Wind Speed (mph)	Direction (°)
1	Control, 30 L weathered HOOPS,	5 4	30 20	12 18	6.2	Manual recovery of residual oil not feasible.	2020-12-10	2:45 PM	11.9	7.6	306
2	Measured wave trains	5	40	5			2020-12-11	9:51 AM	6.7	2.2	235
3	and breaking waves	4	40	5			2020-12-11	10:09 AM	6.9	3.6	232
4	(Tests 2 through 8)	5	30	12		~3 min for reflections to return	2020-12-11	10:26 AM	7.4	5.2	207
5		4	20	18		~2 min for reflections to return	2020-12-11	10:42 AM	7.7	11.1	214
6		4 5	40 30	5 12	12.6		2020-12-11	11:00 AM	8.0	4.9	216
7		5 4	30 20	12 18	6.2		2020-12-11	11:16 AM	8.4	7.0	183
8		4 5 4	40 30 20	5 12 18	12.6 6.2	Smaller breaker @340' and big one at 320'	2020-12-11	11:37 AM	8.7	4.4	191
9	Control, 30 L weathered HOOPS	5 4	30 20	12 18	6.2	Wave maker malfunctioned. Test aborted.	2020-12-14	3:15 PM	9.0	7.9	4
10	Control, 30 L weathered HOOPS, waves every 5 min for 30 min	5 4	30 20	12 18	6.2	1-inch pump too slow to recover residual oil.	2020-12-15	10:00 AM	4.1	12.5	294
11	30 L weathered HOOPS, waves every 5 min for 30 min, 1.5 L Corexit 9500 applied from paint sprayer	5 4	30 20	12 18	6.2	Paint sprayer producing mist of droplets that are too small. Mist was carried away from the test slick. Unable to reach slick with man lift due to wind.	2020-12-15	3:40 PM	6.4	13.2	304
12	30 L weathered HOOPS, waves every 5 min for 30 min, 1.5 L Corexit 9500 applied from hand-held sprayer	5 4	30 20	12 18	6.2		2020-12-16	11:00 AM	3.7	18.9	66
13	Control, 30 L weathered ANS	5 4	30 20	12 18	6.2		2020-12-17	1:45 PM	4.2	18.5	352
14	30 L weathered ANS, 1.5 L Corexit 9500 applied from spray wand	5 4	30 20	12 18	6.2	Applied 40 mL of OP40 herder around perimeter of residual oil	2020-12-18	11:00 AM	2.3	9.6	313
15	30 L weathered ANS, 1.5 L Corexit 9500 applied from spray wand	5 4	30 20	12 18	6.2	Applied 25 mL of OP40 herder around perimeter of residual oil	2020-12-18	2:00 PM	4.3	7.5	341

Appendix C

April 2021 Test Summary

Appendix C: Test Summary April 2021

Test Number	Description	Wave Settings: Waves	CPM	Amp. (in)	Delay (s)	Observations	Date	Time	Weather Conditions: Temp. (°C)	Wind Speed (m/s)	Direction (°)
1	Control, 30 L Weathered HOOPS, Breaking Wave 2	5	30	12	5.5	Good contact with waves.	2021-04-26	14:05	16.8	9	294
		4	20	18	-						
2	Control, 30 L Weathered HOOPS, Breaking Wave 2	5	30	12	5.5	Good contact with waves. Middle south sprayer is aimed a bit high.	2021-04-27	10:40	17.9	4.0	129
		4	20	18	-						
3	30 L Weathered Hoops, 1.5 L Corexit 9500, Breaking Wave 2	5	30	12	5.8	Adjusted delay due to wind. Slick spread more than previous tests.	2021-04-27	14:30	21.5	3.8	145
		4	20	18	-						
4	30 L Weathered Hoops, 1.5 L Corexit 9500, Breaking Wave 2	5	30	12	5.8	Good contact with waves.	2021-04-28	10:00	17.0	4.2	139
		4	20	18	-						
5	Control, 30 L Weathered HOOPS, Breaking Wave 2	5	30	12	5.8	Did transects of plume between waves.	2021-04-28	12:50	22.9	2.0	92
		4	20	18	-						
6	30 L Weathered Hoops, 1.5 L Corexit 9500, Breaking Wave 2	5	30	12	5.8	Good coverage with dispersant.	2021-04-29	9:00	20.6	1.1	322
		4	20	18	-						
7	30 L Weathered Hoops, 1.5 L Corexit 9500, Breaking Wave 1	5	40	5	11.3	Waves too weak to disperse oil. Oil dispersed during recovery.	2021-04-29	11:15	22.0	2.2	207
		4	30	12	-						
8	30 L Weathered Hoops, 1.5 L Corexit 9500, Breaking Wave 3	5	40	5	11.3	Good contact with waves. Good coverage with dispersant.	2021-04-29	14:30	26.1	2.6	204
		5	30	12	5.8						
		4	20	18	-						
9	Control, 30 L Weathered HOOPS, Breaking Wave 3	5	40	5	11.3	Poor contact with waves. High winds shifted slick north. Breakthrough observed on west side.	2021-04-30	9:00	20.9	11.0	295
		5	30	12	5.8						
		4	20	18	-						

Test Number	1
Date	26-Apr-21
Time	14:05
Test Type	Control
Test Oil	HOOPS

Weather Conditions

Temp. (°C)	Wind Spd. (m/s)	Wind Dir. (°)	Sky
16.8	8.6	294	Sunny

Oil Distributed Start 14:10

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
25.9	28.8	7.0	4.1

Dispersant Applied Start 9:15

1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave Two (BW2)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	30	12	5.8
Train 2	4	20	18	-
Train 3	-	-	-	-

Waves

		Top LISST			Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	14:20	21.8	221.0	2%	1.9	132.6	11%
2	14:25	0.2	367.4	1%	2.9	362.0	3%
3	14:30	0.0	332.2	6%	2.3	382.9	2%
4	14:35	0.2	297.9	5%	5.9	398.9	1%
5	14:40	8.5	298.7	1%	3.2	379.2	2%
6	14:45	3.4	328.1	0%	4.5	380.2	2%
7	14:50	4.6	337.1	1%	6.1	392.4	1%

Oil Recovered Start 9:55
End 10:09

Mass (kg)	Volume (L)	Recovery (%)
24.0	25.6	93%

Test Number	2							
Date	27-Apr-21			**Weather Conditions**				
Time	10:40			Temp.	Wind Spd.	Wind Dir.	Sky	
Test Type	Control			(°C)	(m/s)	(°)		
Test Oil	HOOPS			17.9	4.0	129	Sunny	

Oil Distributed Start 14:10

Mass	Volume	Area	Thickness
(kg)	(L)	(m^2)	(mm)
26.4	29.4	13.9	2.1

Wave Settings Breaking Wave Two (BW2)

	Cycles	CPM	Amp.	Delay
	(#)		(in)	(s)
Train 1	5	30	12	5.8
Train 2	4	20	18	-
Train 3	-	-	-	-

Waves		Top LISST			Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	11:01	17.5	171.3	2%	29.6	196.0	3%
2	11:06	66.5	192.0	1%	2.5	136.0	10%
3	11:11	106.4	202.7	2%	46.3	184.2	4%
4	11:16	102.6	220.5	1%	52.5	180.4	4%
5	11:21	89.4	216.2	1%	28.8	173.3	5%
6	11:26	0.4	32.8	49%	3.5	132.1	26%
7	11:32	0.5	36.6	50%	0.7	24.6	76%

Oil Recovered Start 9:55
End 10:09

Mass	Volume	Efficiency
(kg)	(L)	(%)
25.1	28.6	95%

Test Number 3
Date 27-Apr-21
Time 14:20
Test Type Dispersant
Test Oil HOOPS

Weather Conditions

Temp. (°C)	Wind Spd. (m/s)	Wind Dir. (°)	Sky
21.5	3.8	145	Sunny

Oil Distributed Start 14:30

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.3	29.3	20.1	1.5

Dispersant Applied Start 14:50
1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave Two (BW2)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	30	12	5.8
Train 2	4	20	18	-
Train 3	-	-	-	-

Waves

	Top LISST				Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	14:56	28.6	20.1	72%	28.4	15.9	84%
2	15:01	61.9	58.4	43%	38.8	29.4	74%
3	15:07	54.4	103.4	20%	8.7	21.6	92%
4	15:12	70.3	117.4	14%	18.5	72.1	38%
5	15:17	146.0	166.7	7%	30.3	112.5	26%
6	15:22	63.6	139.8	11%	11.6	55.3	51%
7	15:27	119.1	186.9	6%	8.9	47.3	57%

Oil Recovered Start 9:55
End 10:09

Mass (kg)	Volume (L)	Effectiveness (%)
1.2	1.6	95%

Test Number	4
Date	28-Apr-21
Time	10:00
Test Type	Dispersant
Test Oil	HOOPS

Weather Conditions

Temp. (°C)	Wind Spd. (m/s)	Wind Dir. (°)	Sky
17.0	4.2	139	Sunny

Oil Distributed Start 10:06

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.3	29.3	16.6	1.8

Dispersant Applied Start 10:18

1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave Two (BW2)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	30	12	5.8
Train 2	4	20	18	-
Train 3	-	-	-	-

Waves

		Top LISST			Bottom LISST		
	Time	Concentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	10:22	0.2	3.3	100%	0.4	50.3	40%
2	10:27	12.0	13.1	96%	3.6	15.8	94%
3	10:32	44.3	27.3	65%	22.4	8.6	98%
4	10:37	10.0	44.5	51%	7.1	10.6	100%
5	10:42	4.2	9.0	100%	6.8	9.9	99%
6	10:47	7.3	14.2	94%	8.3	10.5	97%
7	10:52	26.0	56.3	38%	15.6	44.8	60%

Oil Recovered Start 9:55
End 10:09

Mass (kg)	Volume (L)	Effectiveness (%)
1.6	2.4	94%

Test Number	5						
Date	28-Apr-21			**Weather Conditions**			
Time	12:50			Temp.	Wind Spd.	Wind Dir.	Sky
Test Type	Control			(°C)	(m/s)	(°)	
Test Oil	HOOPS			22.9	2.0	92	Sunny

Oil Distributed Start 12:52

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.1	29.1	14.9	2.0

Wave Settings Breaking Wave Two (BW2)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	30	12	5.8
Train 2	4	20	18	-
Train 3	-	-	-	-

Waves		Top LISST			Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	Concentratio	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	0.5	0.3	37.2	55%	3.8	127.2	17%
2	0.5	3.7	124.8	33%	16.3	171.2	16%
3	0.5	3.1	151.6	15%	5.2	124.5	27%
4	13:14	2.0	123.5	22%	2.1	104.4	40%
5	13:19	15.4	111.3	26%	3.1	118.2	30%
6	13:24	47.2	127.6	22%	8.3	158.7	21%
7	13:29	224.3	103.8	21%	9.0	114.2	28%

Oil Recovered Start 1:35:00 PM
End 2:19:00 PM

Mass (kg)	Volume (L)	Recovery (%)
21.8	24.2	83%

Test Number	6							
Date	29-Apr-21			**Weather Conditions**				
Time	9:00			Temp. (°C)	Wind Spd. (m/s)	Wind Dir. (°)	Sky	
Test Type	Dispersant			20.6	1.1	322	Sunny	
Test Oil	HOOPS							

Oil Distributed Start 9:05

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.2	29.2	10.5	2.8

Dispersant Applied Start 9:15

1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave Two (BW2)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	30	12	5.8
Train 2	4	20	18	-
Train 3	-	-	-	-

Waves		Top LISST			Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	9:18	12.9	84.0	29%	12.3	64.0	40%
2	9:23	21.7	10.4	91%	19.0	9.7	93%
3	9:28	11.3	17.8	77%	11.3	18.6	75%
4	9:33	28.9	65.7	36%	13.6	54.2	47%
5	9:38	8.1	17.2	81%	11.5	26.9	64%
6	9:43	9.2	19.2	80%	11.8	28.2	67%
7	9:48	7.2	16.0	88%	11.0	30.5	66%

Oil Recovered Start 9:55
End 10:09

Mass (kg)	Volume (L)	Effectiveness (%)
0.5	2.1	98%

Test Number	7
Date	29-Apr-21
Time	11:15
Test Type	Dispersant
Test Oil	HOOPS

Weather Conditions

Temp. (°C)	Wind Spd. (m/s)	Wind Dir. (°)	Sky
22.0	2.2	207	Sunny

Oil Distributed Start 9:05

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.2	29.2	9.9	2.9

Dispersant Applied Start 9:15

1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave One (BW1)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	40	5	11.3
Train 2	4	30	12	-
Train 3	-	-	-	-

Waves

		Top LISST			Bottom LISST		
(#)	Time (HH:MM)	Conc. (ppm)	D50 (µm)	Vol < 75 µm (%)	Conc. (ppm)	D50 (µm)	Vol < 75 µm (%)
1	11:43	2.3	72.8	32%	2.6	88.5	35%
2	11:48	6.1	9.2	98%	9.5	7.4	100%
3	11:53	10.4	26.9	70%	8.7	7.8	100%
4	11:58	8.1	26.1	83%	5.8	13.8	98%
5	12:03	2.2	9.1	99%	7.6	37.1	56%
6	12:08	6.1	33.3	79%	5.2	22.9	84%
7	12:13	3.4	20.6	97%	3.1	11.4	99%

Oil Recovered Start 9:55
End 10:09

Mass (kg)	Volume (L)	Effectiveness (%)
0.0	0.0	100%

Test Number	8				**Weather Conditions**				
Date	29-Apr-21				Temp.	Wind Spd.	Wind Dir.	Sky	
Time	14:30				(°C)	(m/s)	(°)		
Test Type	Dispersant				26.1	2.6	204	Sunny	
Test Oil	HOOPS								

Oil Distributed Start 9:05

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.4	29.4	8.1	3.6

Dispersant Applied Start 9:15

1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave One (BW3)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	40	5	11.3
Train 2	5	30	12	5.8
Train 3	4	20	18	-

Waves		Top LISST			Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	14:58	0.7	72.7	56%	4.3	49.7	49%
2	15:03	14.1	11.1	100%	28.1	13.1	97%
3	15:08	5.9	9.4	100%	16.0	10.1	98%
4	15:13	3.4	11.0	100%	11.3	13.5	94%
5	15:18	4.1	24.3	86%	7.9	10.3	100%
6	15:23	11.4	62.8	47%	11.0	19.6	97%
7	15:28	12.1	57.4	52%	10.1	19.2	98%

Oil Recovered Start 9:55

End 10:09

Mass (kg)	Volume (L)	Effectiveness (%)
0.7	1.8	97%

Test Number	9							
Date	30-Apr-21			**Weather Conditions**				
Time	9:00			Temp. (°C)	Wind Spd. (m/s)	Wind Dir. (°)	Sky	
Test Type	Dispersant							
Test Oil	HOOPS			20.9	11.0	295	Sunny	

Oil Distributed Start 9:05

Mass (kg)	Volume (L)	Area (m^2)	Thickness (mm)
26.2	29.2	9.0	3.3

Dispersant Applied Start 9:15

1.5 L Corexit EC9500A via spray wand

Wave Settings Breaking Wave One (BW1)

	Cycles (#)	CPM	Amp. (in)	Delay (s)
Train 1	5	40	5	11.3
Train 2	4	30	12	-
Train 3	-	-	-	-

Waves

		Top LISST			Bottom LISST		
	Time	oncentration	D50	Vol < 75 µm	oncentration	D50	Vol < 75 µm
(#)	(HH:MM)	(ppm)	(µm)	(%)	(ppm)	(µm)	(%)
1	9:54	44.5	112.2	11%	19.1	90.5	30%
2	9:59	10.8	75.5	49%	1.4	194.3	10%
3	10:04	0.1	132.1	0%	1.3	301.2	5%
4	10:10	0.0	257.8	0%	1.7	311.6	4%
5	10:15	0.0	N/A	N/A	0.7	244.6	11%
6	10:20	0.0	N/A	N/A	1.5	295.7	5%
7	10:25	0.0	N/A	N/A	1.9	315.7	4%

Oil Recovered Start 9:55
End 10:09

Mass (kg)	Volume (L)	Recovery (%)
22.9	8.1	87%