Review of a Decade of Dispersant Operational Research Conducted under Simulated At-sea Conditions at Ohmsett

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Abstract
For more than 40 years spill researchers have used large outdoor wave tanks like Ohmsett to simulate at-sea conditions for purposes of oil spill research and testing. Ohmsett is the largest of these wave tanks, but only in the past decade have researchers used it to study chemical dispersion of oil spills. Over that time, Ohmsett researchers have addressed decision-makers' questions that could not be resolved using bench-scale methods and were difficult to address in sea tests. They focused on factors that limit operational effectiveness of dispersants; persistence of dispersant in treated oil slicks; procedures for monitoring effectiveness of dispersant applications; and ability to extrapolate from bench-scale tests to predict dispersant performance at sea. This paper is a brief review of this work and of the challenges of using wave-tank testing to predict spills behaviour at sea.

1 Introduction
Prior to the 2011 Deepwater Horizon spill in the Gulf of Mexico, more than 20 years had passed since North American oil spill researchers had conducted dispersant studies at sea. As a consequence, the new generation of oil spill researchers/planners had little experience with using dispersants on spills or in sea trials. Decision-makers were therefore forced to try to extrapolate from results of small-scale laboratory tests to try to predict dispersant performance and oil behaviour, a practice recognized to be unreliable. In 1999, the U.S. Minerals Management Service (now called Bureau of Ocean Energy Management, Regulation, and Enforcement or BOEMRE) addressed this problem by opening their large, outdoor wave tank (Ohmsett) to simulate at-sea conditions for studying operational questions associated with dispersants. Over the past decade more than 15 operationally oriented research projects have been completed at Ohmsett. This paper is an overview of the work.

Medium and large wave tanks have been used from time to time for oil spill and dispersant research. One of the earliest tanks used for dispersant work was the outdoor tank at Esso Resources Canada Limited in Calgary (Brown et al., 1987; MacNeill et al., 1985). Over the last decade at least five wave-tanks of various sizes have been used on a regular basis for dispersant work, including:

a) S.L. Ross Wave Tank;
b) SINTEF Circulating Flume,
c) DFO/EPA Tank at the Bedford Institute of Oceanography,
d) Shoreline Environmental Research Facility (SERF); and
e) Ohmsett.
See Table 1 below for information about these. Most have been used for research on basic spill behaviour. Ohmsett, which is the largest by far, has been used for systematic studies of operational questions posed by spill responders and regulators for decades in planning and training.

Large tank facilities like Ohmsett have the advantage of allowing research on oil spill behaviour to be conducted under simulated at-sea conditions and at near sea-scale in a safe and controlled way. At the same time it poses challenges, such as: a) requiring far larger quantities of oil and dispersant than laboratory or meso-scale testing; and b) requiring researchers to determine empirically how Ohmsett conditions (e.g., waves) compare to actual conditions at sea.

Early Ohmsett studies examined the importance of the viscosity of oil and emulsions in limiting dispersant effectiveness and laid the groundwork for later work, which included:

a) Addressing operational questions related to dispersant application by aircraft;
b) Investigating the mechanisms by which factors such as oil viscosity limit dispersant effectiveness;
c) Studying the persistence of dispersants in oil slicks when spills are treated on calm water; and
d) Using Ohmsett testing to better inter-relate results of effectiveness testing in bench-scale, at Ohmsett and at sea.

This paper provides an overview of this work.

**Table 1. Wave tanks used for oil spill and dispersant research, 1980s to present**

<table>
<thead>
<tr>
<th>Name</th>
<th>Dimensions(^a), m</th>
<th>Operated by</th>
<th>Example Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esso Resources Wave Basin</td>
<td>L = 54.5, W = 30.8, D = 1.9 to 3</td>
<td>Esso Resources Canada Ltd, Calgary, Alberta</td>
<td>MacNeill et al., 1985 Brown et al., 1987</td>
</tr>
<tr>
<td>Delft Oil flume</td>
<td>L = 15, W = 0.5, D = 0.45</td>
<td>Delft Hydraulics Laboratory, Delft, Netherlands</td>
<td>Delvigne, 1989 Delvigne and Sweeney, 1988</td>
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<tr>
<td>Shoreline Environmental Research Facility (SERF),</td>
<td>L = 33.5, W = 2.1, D = 2.4</td>
<td>Shoreline Environmental Research Facility, Corpus Christi Texas</td>
<td>Bonner et al., 2003.</td>
</tr>
<tr>
<td>Sintef Circulating Flume</td>
<td>L = 8.7, 0.5, D = 0.5</td>
<td>SINTEF, Trondheim, Norway</td>
<td></td>
</tr>
<tr>
<td>SL Ross Wave Tank</td>
<td>L = 10, W = 1.3, D = 1.3</td>
<td>SL Ross Laboratory, Ottawa, Canada</td>
<td>Belore et al., 2000</td>
</tr>
<tr>
<td>DFO Canada / U.S. EPA Tank</td>
<td>L = 32, W = 0.5, D = 1</td>
<td>Bedford Institute of Oceanography, Dartmouth Nova Scotia</td>
<td>Li et al., 2008 Boufadel et al., 2008a,b</td>
</tr>
<tr>
<td>Ohmsett</td>
<td>L = 203, W = 20, D = 3.4</td>
<td>Naval Weapons Station EARL, Leonardo, New Jersey</td>
<td>This paper</td>
</tr>
</tbody>
</table>

\(^a\) L = length, W = width, D = depth
2 Ohmsett and the Testing Protocol

2.1 Ohmsett

BOEMRE’s National Oil Spill Response Test Facility, known as Ohmsett (Figure 1), located at the Naval Weapons Station Earle in Leonardo, New Jersey, is a large, outdoor, aboveground tank containing 9,841 m$^3$ (=2.6 million U.S. gallons) of seawater. Controlled and reproducible ocean wave environments are simulated through the use of a wave generating system. The system is capable of generating both smooth, regular waves and breaking waves of varying wavelengths and amplitudes. The tank is spanned by a moveable bridge that serves as a platform for discharging test oils and dispersant, towing oil measuring devices through the tank and housing personnel and equipment used to run the tests and measure outcomes. Prior to 2008 the mechanical wave-generator system was controlled mechanically, so that wave conditions could be controlled only by altering the throw and frequency of the wave paddle. In 2008, a computer-control system was installed allowing more sophisticated control of waves. A portion of the work described below was conducted prior to 2008.

![Figure 1. Minerals Management Service’s National Oil Spill Response Test Facility, Ohmsett.](image)

2.1.1 Dispersant Effectiveness Protocol

The Ohmsett dispersant effectiveness test protocol was developed in 2000 (SL Ross, 2000a, b) and has been refined in numerous subsequent studies (e.g., SL Ross, 2003; SL Ross et al., 2005; 2009). Dispersant performance is quantified by measuring how effectively dispersant increases the dispersion of oil slicks during a standard test. Each test involves control and
experimental runs. In each case an oil slick is laid down in a standard way, sprayed with dispersants (or not in the case of the control) and exposed to waves for a standard period. After this the waves are stopped and all oil remaining on the surface is collected, its volume measured and the proportion of oil dispersed during the test is calculated. The proportion dispersed in the experimental run is compared to the control to determine the effect of dispersant treatment.

In recent years, tests have been conducted in a 150-m long section in the centre of the 203-metre tank that is boomed at both ends to contain the surface oil. Tests involve the following.

1. A wave field of known characteristics is established prior to discharging the oil with a dominant wave frequency of approximately 33 to 34 waves per minute, wavelength of 5 m and significant wave height of 0.4 m. This was the least energetic wave field possible with the wave generator system in place in 1999. Asher (2005) and Veron et al. (2009) described characteristics of the wave fields in the Ohmsett tank.

2. A slick containing a known quantity of test oil (≈20 US gallons or 75L), of standard width and thickness, is discharged on the centre of the tank from a manifold on the bridge as it moves down the tank.

3. Unless otherwise required, the slick is sprayed with dispersant within seconds after discharge at a controlled dosage (approximately one part dispersant to 20 parts oil (DOR=1:20)) using a spray bar similar to those used in spraying from vessels offshore.

4. The dispersant-treated oil slick is exposed to breaking waves for a standard period, usually 30 minutes. In highly effective tests, slicks generally disperse quickly and completely immediately upon contact with breaking waves producing a light brown-colored cloud of dispersed oil in the water (sometimes referred to as “café-au-lait” or “coffee-with-cream”). Slicks generally disperse within the first five minutes of the test. On the other hand, in very ineffective tests the slicks do not disperse, but break into patches of thick oil that remain clearly visible throughout the test, while the dispersant itself mixes in the water.

5. At the end of the 30-minute mixing period, the wave generator is stopped, the wave field subsides and all oil remaining on the water surface and walls of the tank is carefully herded to one end of the tank for collection and measurement. The proportion of oil dispersed in each test, the dispersant effectiveness (DE), is estimated using the oil volume collected at the end of the test and the volume initially discharged. The oil volume collected is corrected for losses through evaporation (estimated using the change in oil properties over the test) and gains due to water uptake (emulsification). Dispersant dosages in each experiment are calculated using the volumes of oil discharged and dispersant sprayed corrected to reflect the proportion of the dispersant sprayed that actually landed on the oil slick.

As mentioned, all tests involve experimental (dosed with dispersant) and control (no dispersant) runs. Controls quantify the amounts of oil lost from the slick through physical dispersion and adherence to sidewalls or containment booms. Control runs are identical to experimental runs except that no dispersant is applied. Losses in controls range from 12 to 28% and are independent of the type of oil used. In control tests, when breaking waves encounter slicks, they tear holes in the slicks revealing clear water underneath. Café-au-lait clouds are never observed. Some oil may become entrained in the form of visibly large, visibly discrete droplets. In experimental tests, losses range from this level up to 100%, depending on the test conditions. Effectiveness in experimental tests depends strongly on oil properties.
The basic elements of the protocol have remained unchanged over the decade since first developed although some minor modifications have been made. These are discussed in the project reports where the modifications were first introduced.

To date, virtually all Ohmsett experiments have used the products Corexit 9527 and Corexit 9500. Although other dispersant products are listed in the U.S. National Contingency Plan Product Schedule (EPA, 2011), Corexit 9500 and 9527 make up virtually all of the dispersants stockpiled in the U.S. and Canada (S.L. Ross, 2009). Because Ohmsett testing has been focused on US operational questions, the decision was made to use only dispersants stockpiled in large amounts in the US. The only exception has been that the products Superdispersant 25 and Agma 379 were included with Corexit 9500 in the 2003 study comparing results of Ohmsett testing with those of at-sea tests conducted in the United Kingdom in the same year (SL Ross et al., 2005). Research into the effect of dispersant type on effectiveness, using other dispersants from the NCP Product Schedule, has been included in the Ohmsett research plan for 2011-12.

3 Operational Effectiveness Factors

The majority of Ohmsett work has focused on the main questions facing dispersant planners as spelled out in a number of dispersant use guidelines documents. These can be reduced to three, namely:

1. Is the oil/emulsion dispersible?
2. Are the mixing conditions sufficient to bring about effective dispersion?
3. Is the dispersant/dose effective?

The work addressing these questions is outlined below.

3.1 Dispersibility of Oils

3.1.1 Effects of Oil Viscosity

Early workers demonstrated that the most important oil property influencing dispersant performance in laboratory tests was the viscosity of oils or water-in-oil emulsions (Lee et al., 1981). Lee et al. showed that for water-free blends of fuel oils spanning a broad range of viscosities, oils with viscosities < 2000 cP were highly dispersible using the Warren Spring Laboratory test method (WSL), but above 2000 cP dispersibility declined with increasing oil viscosity and was reduced to nil at oil viscosities of 10,000 cP. These authors also showed that for non-viscous oils that were dispersible when fresh, weathering and emulsification increased their viscosity causing dispersibility to decline in bench-scale testing. For emulsions of some oils, dispersibility declined to nil at viscosities >10,000 cP, as in water-free oils, but for others emulsions continued to be somewhat dispersible at viscosities well above 10,000 cP. Daling (1988) produced results similar to Lee et al. (1981) in tests of emulsions of several oils in several testing methods, including WSL. Dispersibility of some emulsions was reduced to nil at viscosities of 10,000 cP or less, while at least one oil continued to be somewhat dispersible at emulsion viscosities up to 40,000 to 50,000 cP. Daling suggested that there may not be a single limiting viscosity for emulsions and that a dispersant’s ability to break the emulsion might be the limiting factor. Canevari (1985) argued that for water-free unemulsified oils the limiting effect of viscosity may be relatively simple, but the process might be more complex for emulsified oils. The initial work Ohmsett presented here focused on what Canevari (1985) viewed as the simpler problem, namely the limiting effect of oil viscosity on chemical dispersion in water-free oils.
Work on the more complex problem of dispersion of emulsions is ongoing and will be published at a later date.

Early workers developed a rule-of-thumb about the relationship of oil viscosity to effectiveness based on Lee et al. In short, “dispersants [were] most effective for oil viscosities less than about 2000 cSt and almost no dispersion occurs over 10,000 cSt” (Cormack et al., 1986/87). That rule has been applied for several decades, but was itself based largely on laboratory tests rather than systematic work in the field, so its limitations were also uncertain. More modern work on dispersibility of water-free oils using modern bench-scale methods and dispersant products has confirmed the early work demonstrating the dominating effect of oil viscosity on effectiveness (Canevari et al., 2001; Stevens and Roberts, 2003). Other modern authors have shown relationships between oil properties other than viscosity and dispersibility in bench scale tests. For example, Fingas et al. (2003) showed a statistical relationship between dispersion performance and content of low molecular weight hydrocarbons in low-viscosity oils using the Swirling Flask Testing (SFT) method. Canevari et al (2001) showed a strong negative correlation between dispersion performance and concentration of \( n \)-paraffins in oils in the 1000 to 8000 cP range using the EXDET test method. The latter commented that this relationship appeared to be over-ridden by the effect of oil viscosity in some oils. While these studies are potentially useful in understanding the dispersion mechanism, it is not clear how they might be used for operational decision-making. For that reason Ohmsett work has focused on oil viscosity.

As mentioned above relatively recent work by Canevari et al. (2001) and Stevens and Roberts (2003) using modern methods and products found that limiting oil viscosities in bench-scale tests were somewhat higher than in Lee et al. (1981). Our Ohmsett work sought to critically re-examine the limiting effect of oil viscosity in water-free oils under “simulated at-sea conditions”.

Ohmsett work tested the dispersibility of 12 water-free crude oils ranging in viscosity from 67 cP to 40,100 cP at test temperature. Oils were obtained from producing wells on the Pacific Outer Continental Shelf (Pacific OCS). Results showed an effectiveness-viscosity curve with three phases when oil slicks were treated Corexit 9500 at a dispersant-to-oil ratio (DOR) of 1:20 (Figure 2). Specifically:

1. Oils with viscosities less than 2500 cP, yielded virtually 100% dispersion effectiveness in all cases.
2. Oils with viscosities greater than 33,000 cP yielded negligible dispersant-aided effectiveness; that is, effectiveness that indistinguishable from controls.
3. Oils with viscosities from 2500 cP to as high as 18,690 cP yielded incomplete dispersion; that is effectiveness less than 100 percent, but greater than controls.

![Figure 2. Effect of oil viscosity on dispersion in Ohmsett tests in 2005 and 2008](image-url)
In other words, virtually 100% of experimental slicks of oils with viscosities < 2500 cP dispersed quickly and completely. Any part of the treated slick that contacted breaking waves dispersed immediately (first five minutes) producing characteristic light brown clouds of dispersed oil in the water (referred to as “café-au-lait”). In the 2008 study the “café-au-lait” clouds contained average oil concentrations ranging from 36 to 69 ppm. Oil droplets in the clouds had an average volume-mean-diameter (VMD) of 8 to 37 microns (Table 2). This contrasted with control tests (no dispersant) that produced no visible oil clouds in the water. Breaking waves entrained only a few large, visible droplets, producing low oil concentrations (2 to 5 ppm) in the water and with much larger droplet sizes (VMD = 100 to 191 microns). Thick patches of oil remained clearly visible on the surface throughout each control run.

Dispersant-treated slicks of highly viscous oils > 33,000 cP, behaved much like the control tests, except that the dispersant turned the water milky and patches of thick oil remained visible on the water surface throughout these tests.

In tests with oils of intermediate viscosity (i.e. 2500 to 33,000 cP), breaking waves sheared dispersant-treated slicks into black or brown-black clouds of visibly coarse oil droplets. In some tests patches of thick oil remained clearly visible throughout the test, while in others oil slicks appeared to disperse completely early in the test only to reform on the surface later in the test, possibly due to resurfacing of the larger droplets of dispersed oil. In the partial-dispersion tests in 2008 (Old Heritage and Gina oils in Table 2) oil concentrations in the water were similar to the highly effective tests of less viscous oils, but the oil droplet sizes appeared to be markedly larger in the more viscous oils.

These studies showed that the limiting oil viscosity for chemical dispersion under simulated at-sea conditions in Ohmsett testing was in the 18,690 cP to 33,400 cP range. This was similar to the limiting viscosity observed with Corexit 9500 in several different modern bench scale test methods (Canevari et al., 2001; Fiocco et al., 1999).

The very high level of effectiveness observed with non-viscous oils at Ohmsett (near 100%) might appear to differ from bench-scale test data where effectiveness index values are less than 100% in tests with oils in this same viscosity range. The difference may lie in the design of the tests. At Ohmsett, test conditions have been developed to simulate operating conditions for oil spills at sea. On the other hand, in bench-scale methods conditions (mixing energy, mixing time, settling time) simulate some dispersion processes, but have been purposely adjusted to yield intermediate effectiveness values with effective dispersants and dispersible oils, so that better-performing products can be readily distinguished from poorer ones. A detailed comparison of Ohmsett results to those of bench-scale methods is presented in a later section.

This work confirmed and expanded on knowledge of dispersant limitations learned from earlier bench-scale testing work and lead to Ohmsett studies that:

a) examined the mechanism by which oil viscosity limits oil dispersibility (see below); and

b) compared results of various bench-scale test methods with each other and with those gathered under simulated at-sea conditions at Ohmsett (see below).

Preliminary work examining the limiting effect of viscosity on dispersibility of emulsions has been initiated and upcoming work will use tests at Ohmsett and in bench-scale methods to determine whether the limiting viscosity of oil depends on dispersant type.
Table 2 Summary of oil conditions in the water in control and treated tests, 2008.

<table>
<thead>
<tr>
<th>Oil</th>
<th>Oil Viscosity, CP&lt;sup&gt;a&lt;/sup&gt;</th>
<th>DOR b</th>
<th>Dispersed/Lost %, volume</th>
<th>Mean Oil Conc. ppm</th>
<th>Peak Oil Conc. ppm</th>
<th>Oil Drop Size D50, µm</th>
<th>Droplet Volume &lt; 70 µm&lt;sup&gt;c&lt;/sup&gt; %</th>
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</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Eureka</td>
<td>2565</td>
<td>0</td>
<td>24</td>
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<td>Gina H7</td>
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<td>14</td>
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<td>Treated</td>
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<td>67</td>
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<td>73</td>
<td>60</td>
</tr>
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</table>

a. Oil viscosities were measured at test temperature using a Thermo-Haake VT550 rotational viscometer at a shear rate of 10/sec, as per Daling (1988).
b. DOR = dispersant-to-oil ratio
c. Percent of droplets less than 70 µm diameter by volume

3.1.2 Mechanism by which Oil Viscosity Limits Effectiveness

Upon completion of the viscosity-dispersibility studies, work was initiated to investigate the mechanism by which oil viscosity might limit dispersion. This was done in order to aid dispersant designers in developing products that would be more effective on heavier oils. One simple mental model of oil-dispersant interaction is that when dispersants are sprayed:

a) dispersant droplets land on oil slicks and mix into them (“mixing one”);

b) the surfactant molecules in the dispersant partition into the oil, move to and orient themselves at the oil-water interface; and

c) the surfactants reduce the oil-water interfacial tension allowing the oil to be sheared into small droplets by waves and mixed into the upper mixing zone of the water column (“mixing two”).

This simple mental model suggested that at least two mechanisms might be acting to limit dispersant performance in viscous oils. First, in viscous oils dispersant might be prevented from mixing into the oil (“mixing one”). Rather dispersant droplets landing on the oil might be held up on the oil surface to be washed away by waves. Second, even if dispersants mix into the oil, the
visco-elastic forces in viscous oil might resist the shearing forces of waves and prevent the oil being broken into small droplets and mixed into the water ("mixing two"), regardless of the effect of the surfactants on oil-water interfacial tension. Ohmsett work to date has addressed only "mixing one".

The aim of the "mixing-one" study was to determine whether "mixing one" alone might account for viscous oils’ resistance to dispersion. The study involved ensuring that "mixing one" occurred by blending Corexit 9500 directly into viscous oil before discharging it onto the water surface, rather than by spraying it on the slick after discharge. Dispersion behaviour was measured in the conventional way by spraying dispersant on to the oil slicks after discharge, then exposing the treated slicks to breaking waves. The tests were then repeated using the same oils, but pre-mixing the Corexit 9500 into the oil before discharge. All slicks were treated at two dose levels, 1:20 and 1:10. If resistance to "mixing one" alone was limiting dispersion, then mixing dispersant into the oil should overcome it and allow the oils to disperse better in pre-mixed tests than in spraying tests. Three viscous oils from the Pacific OCS area were tested: a) Platform Ellen-Well A040 crude oil, viscosity = 18,495 cP at 15 °C; b) Platform Gail –Well E010 crude oil, viscosity = 11,000 cP at 15 °C; and c) Platform Irene – co-mingled oil from the Lompoc Pipeline = viscosity 46,000 cP at 15 °C.

Results are summarized in Table 3. Tests on the least viscous oil, Gail/E010, produced incomplete dispersion in the spraying tests at DORs of 1:20 and 1:10, namely 84 and 88%, respectively. Unexpectedly, premixing dispersant into the oil did not increase dispersion effectiveness. Rather effectiveness was markedly lower in the premixed tests, 38 and 73%. Oil concentrations in the water were markedly lower in the pre-mixed tests than in the sprayed tests and the oil droplet sizes were markedly larger, confirming the findings that pre-mixing produced lower effectiveness. Tests with the other two viscous oils produced similar results.

In short, this work showed that resistance to "mixing-one" alone was not sufficient to explain the resistance of these viscous crude oils to chemical dispersion. The implication is that in viscous oils, the visco-elastic forces within the oil might be sufficient to oppose the shearing forces of the breaking waves to reduce dispersion effectiveness, regardless of the presence of dispersant surfactants. This is remarkable because, in the pre-mixed tests the dispersant not only added surfactants to the oil, but the low-viscosity hydrocarbon carrier in the dispersant reduced the viscosity of the oil-dispersant mix (Table 3). An alternative hypothesis was that the viscosity of the oil may prevent the pre-mixed surfactants from moving through the oil to the oil water interface and so could not reduce oil-water interfacial tension. In either case, the results suggest that simply reformulating a dispersant so it could penetrate better into viscous oil may not be sufficient to improve its overall effectiveness against highly viscous oils. The fact that sprayed dispersant produced some effective dispersion suggests that there may have been sufficient dispersant-oil interaction on the outer surface of the slick to facilitate effective dispersion of at least the surface layers of the slick. This suggests that an alternative mental model of oil-dispersant interaction in viscous oil might be needed to adequately understand their resistance to chemical dispersion.

### 3.2 Ohmsett Mixing Energy and Influence on Effectiveness

Ohmsett work regarding mixing energy has been approached on two fronts: a) characterizing the wave environment and relating Ohmsett waves to those at sea; and b) studying the effect of wave energy on effectiveness.
Table 3. Effect of Pre-mixing versus Spraying on Effectiveness on Viscous oils in Ohmsett Tests

| Oil                  | DOR Maximun | DO (mm) | Oil Type | Test # | Test Date | Oil Viscosity @ 15ºC (cP) | Oil Viscosity @ 15ºC (cP) | Oil Dispersant Mix Concentration (ppm) | Ave. Elevated Oil Conc. by LISST (ppm) | Oil Drop Size (AvgD50 μ) | Peak Oil Conc. (> 70 microns) (ppm) | Dispersant Effectiveness % | Volume % < 70 microns |
|----------------------|-------------|---------|----------|--------|-----------|--------------------------|---------------------------|------------------------------------------|-------------------------------------|----------------------------|------------------------|----------------------------|--------------------------|-------------------------|
| Gail E010            | 1:15        | 1:30    | Spray    | 10     | Na        | 11,000                   | 10,470                    | 84                                        | 73                                  | 41                        | 357                    | 70                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Gail E010            | 1:10        | 1:32    | Spray    | A¹     | Na        | 11,000                   | 10,470                    | 88                                        | 68                                  | 72                        | 582                    | 55                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Gail E010            | 1:20        | 1:20    | Pre-Mix  | 11     | Na        | 11,000                   | 10,470                    | 88                                        | 68                                  | 72                        | 582                    | 55                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Gail E010            | 1:10        | 1:10    | Pre-Mix  | 12     | Na        | 11,000                   | 7,090                     | 73                                        | 33                                  | 146                      | 208                    | 23                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Ellen A040           | 1:17        | 1:49    | Spray    | 7      | Na        | 18,495                   | 90                        | 90                                        | 53                                  | 81                       | 570                    | 54                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Ellen A040           | 1:11        | 1:32    | Spray    | 8      | Na        | 18,495                   | 92                        | 92                                        | 51                                  | 52                       | 362                    | 67                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Ellen A040           | 1:20        | 1:20    | Pre-Mix  | 9      | Na        | 18,495                   | 15,060                    | 31                                        | 28                                  | 194                      | 166                    | 33                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Ellen A040           | 1:10        | 1:10    | Pre-Mix  | 6      | Na        | 18,495                   | 10,400                    | 67                                        | 31                                  | 136                      | 200                    | 30                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Irene-Co-mingled     | 1:16        | 1:79    | Spray    | 4      | Na        | 46,000                   | 92                        | 92                                        | 51                                  | 52                       | 362                    | 67                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Irene-Co-mingled     | 1:5         | 1:27    | Spray    | 3      | Na        | 46,000                   | 73                        | 73                                        | 40                                  | 57                       | 477                    | 63                       |                          | 3.2.1 Characterizing Ohmsett Waves |
| Irene-Co-mingled     | 1:20        | 1:20    | Pre-Mix  | 2      | Na        | 46,000                   | 32,240                    | 46                                        | 14                                  | 258                      | 19                     | 8                        |                          | 3.2.1 Characterizing Ohmsett Waves |
| Irene-Co-mingled     | 1:10        | 1:10    | Pre-Mix  | 5      | Na        | 46,000                   | 26,030                    | 45                                        | 17                                  | 182                      | 102                    | 24                       |                          | 3.2.1 Characterizing Ohmsett Waves |

¹Data from test 2 of 2010 test program (S.L. Ross, 2010)

3.2.1 Characterizing Ohmsett Waves

The objectives of characterizing the waves at Ohmsett were to: a) be able to generate wave fields of known properties for testing; and b) to relate the mixing characteristics of Ohmsett waves to those at sea. In 2006, Asher (2005) conducted a descriptive study of waves under combinations of wave maker settings. For each of three wave paddle stroke distances, he identified the lowest wave paddle frequency at which breaking waves developed and characterized the wave conditions produced using different combinations of wave paddle throw distance and paddle frequency. Asher showed that for a 3-inch wave paddle stroke, a paddle frequency of 30 counts per minute (cpm) produced regular, glassy, smooth, non-breaking waves and a frequency of 33 cpm produced breaking waves. Veron et al. (2008) assessed wave energies produced at 33 cpm and related them at sea conditions, concluding that:

1. Surface turbulence (breaking wave) conditions in the test protocol (quantified by ultrasonic altimetry of wave displacement and infrared imagery of surface temperature) were consistent with open ocean conditions at low to moderate wind speeds (less than 25 knots).
2. Subsurface turbulence conditions in the test protocol (by acoustic Doppler velocimetry) were typical of steep waves created by strong winds operating over short fetches.

Veron et al. (2008) highlighted the apparent discrepancy between surface and subsurface mixing conditions in Ohmsett waves, but explained that the contrast in the two measurements resulted from attempting to compare conditions in the Ohmsett tank, where fetches are short, to open sea conditions where fetches are very long.

In a separate study dispersant effectiveness results using the Ohmsett protocol were compared to those produced in at-sea tests in breaking waves in sea states of Beaufort 3 and 4 (winds of 7-10 and 11-15 knots) using identical oils and dispersants. Lewis (2004) found that in
at-sea tests 2075-cP fuel oil treated with Corexit 9500 dispersed quickly and completely, but a more viscous 7100-cP fuel oil did not. Tests at Ohmsett produced high levels of effectiveness for both 2075- and 7100-cP oils (SL Ross et al., 2005). One possible explanation for the apparently higher level of dispersant effectiveness in the standard Ohmsett test compared to sea tests with winds of 7 to 15 knots, might be that the mixing energy level at Ohmsett may be greater than Beaufort sea states 3 and 4. This is consistent with Veron’s analysis that showed that Ohmsett waves may be typical of sea conditions in winds of up to 25 knots.

3.2.2 Influence of Ohmsett Mixing Energy on Effectiveness

The importance of mixing energy on dispersion performance is well known (NRC, 2005) and has been demonstrated frequently in bench-scale tests. Effectiveness of dispersants in breaking waves has been documented at sea (Lewis, 2004; Colcomb et al., 2005) and in wave tanks (e.g. MacKay, 1995; S.L. Ross et al., 2005). However, in dispersant training classes, decision-makers have questioned potential dispersant effectiveness at low sea states, particularly in non-breaking waves. That subject was a source of concern during the Deepwater Horizon spill (Gulf of Mexico, 2011). Wave tank studies by MacNeill et al. (1985) showed negligible effectiveness in non-breaking waves of low amplitude (10 and 20 cm wave heights) in the Esso Resources Canada wave tank. This was consistent with preliminary Ohmsett studies testing viscous IFO oils in non-breaking waves (Trudel et al., 2005). The first Ohmsett study into the effect of wave energy examined dispersant effectiveness in non-breaking waves on non-viscous oils.

The study objectives were to determine:

a) if chemical dispersants could be effective in non-breaking waves of the type produced at Ohmsett; and

b) if so, if there was an oil viscosity limit to dispersibility in breaking waves.

A series of 17 standard Ohmsett dispersant effectiveness tests were conducted using five oils, ranging in viscosity from 14 to 1825 cP. Oils were treated with Corexit 9500 applied at DORs of 1:10 to 1:20. The non-breaking wave environment used was the highest energy, non-breaking wave environment available at the Ohmsett facility based on Asher (2005). Wave-maker settings of 3-inch paddle stroke at frequency of 29-30 cpm produced regular, smooth, glassy non-breaking waves (height =33 cm, wave length=7.1 m). Effectiveness was assessed using three methods, visual observations, measurements of oil concentration in water, and droplet-size distributions.

The principal observation in the study was that there was no apparent chemical dispersion caused by non-breaking waves during 30-minute tests with any oil, regardless of oil viscosity (Trudel et al., 2007, Table 4). In all tests, the volumes of oil recovered after each test were high; there was no visual evidence of “café-au-lait” clouds of dispersed oil in the water; and in-situ instrumentation detected no evidence of dispersed oil. Even the least viscous oil, Galveston 209 (viscosity = 14 cP), did not disperse in non-breaking waves. Based on their viscosity, all of these oils would have dispersed quickly and completely in breaking waves. One of the oils was shown to disperse quickly and completely in breaking waves in another study (S.L. Ross and MAR Inc 2010). In addition, in this study small amounts of turbulence caused by a small cable being dragged through the treated oil slicks caused small “café-au-lait” clouds of dispersed oil in its wake.
## Table 4. Summary of Direct Measurements and Visual Observations of Dispersant performance in All Ohmsett Tests in Non-Breaking Waves

<table>
<thead>
<tr>
<th>Oil Type</th>
<th>Viscosity cP @ 15°/10s⁻¹</th>
<th>Dispersant Type</th>
<th>Measured DORM</th>
<th>Oil Volume Spilled (Litres)</th>
<th>Vol. Emulsion Rec’d (Litres)</th>
<th>Water Content Rec’d Emulsion (Wt %)</th>
<th>Volume Oil Rec’d (%)</th>
<th>Volume Oil Disp’d (%)</th>
<th>DE (%)</th>
<th>Visual, a @ 0-10 minutes</th>
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</thead>
<tbody>
<tr>
<td>GA 209</td>
<td>14</td>
<td>Control</td>
<td>0</td>
<td>74.9</td>
<td>66.4</td>
<td>2</td>
<td>65.1</td>
<td>86.9</td>
<td>13.1</td>
<td>13.1</td>
</tr>
<tr>
<td>GA 209</td>
<td>14</td>
<td>Control</td>
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<td>80.24</td>
<td>72.0</td>
<td>1</td>
<td>71.2</td>
<td>88.8</td>
<td>11.2</td>
<td>11.2</td>
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<tr>
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<td>Corexit 9500</td>
<td>1:10</td>
<td>71.33</td>
<td>283.1</td>
<td>83.9</td>
<td>45.5</td>
<td>63.8</td>
<td>36.2</td>
<td>36.2</td>
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<tr>
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<td>14</td>
<td>Corexit 9500</td>
<td>1:9</td>
<td>66.2</td>
<td>226.2</td>
<td>66.1</td>
<td>76.6</td>
<td>115.7</td>
<td>-15.7</td>
<td>-15.7</td>
</tr>
<tr>
<td>IFO 30</td>
<td>252</td>
<td>Control</td>
<td>0</td>
<td>72.84</td>
<td>75.9</td>
<td>11</td>
<td>67.6</td>
<td>92.8</td>
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<td>7.2</td>
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<tr>
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<td>Control</td>
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<td>76.82</td>
<td>76.7</td>
<td>4</td>
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<td>4.1</td>
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<tr>
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<td>252</td>
<td>Corexit 9500</td>
<td>1:13</td>
<td>76.41</td>
<td>253.1</td>
<td>66.5</td>
<td>84.8</td>
<td>111.0</td>
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<td>-11.0</td>
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<tr>
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<td>252</td>
<td>Corexit 9500</td>
<td>1:30</td>
<td>77.09</td>
<td>227.8</td>
<td>66.0</td>
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<td>-0.5</td>
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<tr>
<td>EB 873</td>
<td>683</td>
<td>Control</td>
<td>0</td>
<td>72.98</td>
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<tr>
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<td>Corexit 9500</td>
<td>1:13</td>
<td>73.11</td>
<td>268.9</td>
<td>65.4</td>
<td>93.0</td>
<td>127.2</td>
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<td>-27.2</td>
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<tr>
<td>WD 30</td>
<td>1067</td>
<td>Control</td>
<td>0</td>
<td>70.78</td>
<td>74.3</td>
<td>24</td>
<td>56.5</td>
<td>79.8</td>
<td>20.2</td>
<td>20.2</td>
</tr>
<tr>
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<td>1067</td>
<td>Corexit 9500</td>
<td>1:20</td>
<td>75.31</td>
<td>Nd⁰</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>Corexit 9500</td>
<td>1:20</td>
<td>76.54</td>
<td>183.5</td>
<td>51</td>
<td>89.9</td>
<td>117.5</td>
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<td>Control</td>
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<td>23.3</td>
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</tr>
<tr>
<td>Harmony</td>
<td>1825</td>
<td>Corexit 9500</td>
<td>1:15</td>
<td>73.66</td>
<td>189.8</td>
<td>56.1</td>
<td>83.3</td>
<td>113.0</td>
<td>-13.0</td>
<td>-13.0</td>
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<tr>
<td>Harmony</td>
<td>1825</td>
<td>Corexit 9500</td>
<td>1:15</td>
<td>71.88</td>
<td>Nd⁰</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

a. Visual assessment based on four-point scale of Lewis 2004: 1= no visible dispersion; 2= slow and partial dispersion; 3=moderately rapid dispersion; 4= very rapid and total dispersion.
b. No dispersion observed visually during test, but heavy rain following test appeared to cause rapid and total dispersion of the test slick leaving no oil to collect.
c. No dispersion observed visually in this test, but at the end of the test an error in the shut-down sequence creating a single breaking wave which caused near-complete dispersion of the test oil.
These results were consistent with the earlier work by MacNeill et al. (1985). Clearly, regular non-breaking waves do not appear to cause dispersion in oils that would be highly dispersible in breaking waves. While this result suggests that little dispersion is likely in non-breaking waves, it is important to recognize that the regular, non-breaking waves in these tests were smooth and glassy, and lacking the wavelets commonly observed on non-breaking waves at sea. It is not clear what effect these wavelets might have on dispersion. In addition, from an operational point of view, it is important to recognize that adding dispersant to oil slicks on calm water at sea causes slicks to spread and grow very thin, and might ultimately dissipate. This thinning and dissipation process may be as effective in dissipating slicks in the long run, though it may be more difficult to verify.

3.3 Type and Dose of Dispersant

The type and dose of dispersant have been shown to influence dispersant effectiveness in bench scale tests (e.g. Desmarquest et al., 1985; Fingas et al., 1995) and at-sea tests (e.g. Lewis, 2004). As mentioned above, until the Deepwater Horizon spill there had been little justification for testing different dispersants at Ohmsett because only Corexit 9527 and 9500 were stockpiled in North America. To date Ohmsett work focused on dispersant dosage testing the effectiveness of low-dose applications of dispersant typical of application by large, fixed wing aircraft.

Current plans for dispersant use on large spills in the U.S. call for spraying from large fixed-wing aircraft. Although vessel-based systems can spray high doses of dispersant on thick slicks in a single pass, the dosage possible from a single pass from an aircraft is quite low. Aircraft can deliver only the equivalent of a 0.0075 mm thick layer of dispersant on the sea and thus can fully dose (DOR=1:20) slicks that are only 0.15 mm thick. The thick parts of oil slicks can be 10 to 100 times thicker than this. Indeed, oil patches studied in the Deepwater Horizon spill were much thicker than this (generally >5 mm thick as per Belore et al., 2011). The actual dispersant dose under these conditions might range from 1:200 to 1:2000. The questions posed in this study were:

a) Are dispersant doses ineffective until repeated passes produces a threshold DOR for effectiveness or do low dispersant doses (1:200 to 1:1000) disperse small fractions of slicks; and

b) What is the behaviour of oil receiving repeated low doses of dispersants? Can existing monitoring protocols identify effectiveness under multiple, low dose conditions?

Ohmsett tests examined effectiveness of multiple low dispersant doses on slicks of low- to medium-viscosity crude oils. Four oils ranging in viscosity from 30 to 4300 cP (at test temperature) were used (SL Ross and MAR Inc., 2010). The standard Ohmsett test protocol was used, except that dispersant was applied in multiple low-doses rather than a single high dose. Oil slicks were laid down in the standard way and sprayed immediately with dispersant at a dose of 1:100 to 1:700 depending on the test. Effectiveness of the initial application was observed for approximately five minutes in breaking waves, simulating the time required for a large aircraft to reposition for a second spray pass. After five minutes an additional low dose was applied using a hand wand. The process was repeated until four or five applications had been accomplished. Spraying Systems Company 800050 and 650025 flat fan nozzles were used. All tests were conducted using Corexit 9500 dispersant. The dispersant coverage applied in each pass during the test program was approximately 0.0094 mm. Effectiveness of individual spray applications was evaluated qualitatively by visual and by instrumental means using a Sequoia Scientific LISST 100X particle size analyzer (LISST) and Turner Cyclops C3 in-situ fluorometer (C3). The overall effectiveness of all passes was assessed by collecting oil remaining at the end of a 30-minute test.
Test results are summarized in Table 5. In all cases, the initial low-dose application resulted in a partial dispersion of the oil as evidenced by appearance of small café-au-lait clouds of dispersed oil, while some of the test slick persisted on the water surface. The remaining oil spread quickly to cover a broad area of the tank. “Café-au-lait” coloured dispersions were observed on each subsequent low-dose application. The cumulative effect of these multiple applications was to produce a high level of overall effectiveness, most in the 80 to 95% range. Based on these observations it appears that:

a) Single low doses of dispersant (1:100 to 1:700) produced partial dispersion; and

b) Multiple, low-dose applications of dispersant were effective in dispersing even thicker slicks.

During actual spills, repeated low dose spraying on weathered oil slicks might be expected to provide additional advantages. Potentially the initial application might break emulsions and/or inhibit further emulsification. This could be expected to increase the effectiveness of repeated treatment.

![Table 5. Effectiveness of low repeated doses of dispersants](image)

3.4 Other Research

### 3.4.1 Persistence of Dispersant in Oil Slicks on Calm Seas

The use of dispersants on oil spilled on calm seas is not recommended in some plans because, as was shown above, there may be insufficient ‘mixing energy’ to cause immediate dispersion of the oil. Allen and Dale (1995) argued that dispersants should not be used at wind speeds of less than 10 knots. In the Deepwater Horizon spill regulators discouraged dispersant use at times when waves were less than a specified height. While dispersant-treated oil may not disperse immediately at low sea states, it might disperse at a later time when the seas become rougher. In some circumstances, such as where spilled oil may be contained in relatively thick layers in the ‘leads’ between ice floes, dispersant spraying in calm weather might be a feasible and effective oil spill response technique. The National Research Council report “Oil Spill Dispersants; Efficacy and Effects” (NRC, 2005) (page 67 and 283) identified this topic as being worthy of further research.

Surfactants, the active ingredients in dispersants are partially soluble in both oil and water. At sea, where there is a very large surplus of water, surfactants would be expected to leach out of dispersant-treated slicks on calm water into the surrounding water. Several authors have studied the leaching of dispersant surfactants from treated oil slicks water (Knudsen et al., 1994; Hokstad et al.,...
1996; Resby et al., 2007). In planning, an important consideration is the rate at which dispersant is lost when treated slicks sit on calm seas. Is it lost in hours, days or weeks?

One Ohmsett study examined the persistence of dispersants in treated slicks. Dispersant was pre-mixed into oil that was laid down in 5-mm-thick oil slicks contained in a small circular boom. Slicks were allowed to sit on calm water for more than 96 hours before being exposed to breaking waves (Lewis et al., 2010). In some of these tests, the effect of water movement on dispersant persistence was tested, simulating slicks being moved across the water surface by light winds. In these studies the persistence of dispersant in the oil was monitored daily by testing dispersibility of oil samples using the WSL test method.

In one test series dispersibility of IFO 30 fuel oil in WSL tests declined rapidly from 60% to 10% in 96 hours. The decline was slightly faster in slicks exposed to moving water versus calm water and faster for thinner slicks than in thicker. When exposed to breaking waves, freshly-treated slicks dispersed quickly and completely, while those aged on calm water for four days displayed only slow and partial dispersion.

In short the study showed that if a 5-mm thick slick of dispersible oil were to be treated with dispersants and then sat on calm water, dispersant performance might decline from complete to partial within 4 days. The decline was more rapid for thinner slicks.

4 Relating Ohmsett Results to Other Testing Methods

One objective of using Ohmsett to simulate at-sea conditions for dispersant research was to study the relationship between bench-scale testing and dispersant performance at sea. A number of authors have studied this relationship, including Daling and Lichtenthaler (1986) and Mackay and Chau (1987). Daling and Lichtenthaler found a poor relationship between laboratory and at-sea results and suggested that laboratory test methods should be developed to better simulate at-sea conditions. Obviously test methods at Ohmsett simulate at-sea conditions as well as possible given the limitations of the tank. The challenge was to design studies to compare dispersant performance in bench-scale tests with those at Ohmsett. Because oil viscosity exerts a strong influence on dispersant performance, our first attempt at comparing bench-scale tests to Ohmsett involved comparing oil viscosity-dispersibility curves from each (Trudel et al., 2010). Several authors had developed oil viscosity-dispersibility curves using a range of methods, including EXDET, IFP, MNS and WSL test methods (e.g. Canevari et al., 2001; Fiocco et al., 1999; Stevens and Roberts, 2003). All studied fresh, unemulsified oils. These results were compared to Ohmsett. Only studies using Corexit 9500 at DORs of 1:20 or 1:25 were used and only studies in which testing and viscosity measurements were completed at the same temperature were included (Table 6). Comparable data sets for the Swirling Flask Test (SFT) and new Baffled Flask test method could not be found, but a dataset was developed for the SFT using data from Environment Canada’s oil properties database (EC, 2011).

Results from all studies are summarized in Figure 3. Effectiveness-viscosity curves were fitted by eye by the present authors. As discussed above, the dispersibility-viscosity curve for testing at Ohmsett tests had three phases:

1. Dispersibility was at or near 100% for oil viscosities < 2500 cP;
2. Dispersibility declined with increasing viscosity in the 2500 to 20,000 cP range; and was indistinguishable from controls at viscosities >20,000 cP.

For most bench-scale methods, MNS, IFP, EXDET and SFT data sets, effectiveness values were greatest for the least viscous oils, declined with increasing oil viscosity and were effectively zero for the most viscous oils tested. The oil viscosity at which effectiveness declined to control levels can only be approximated from these data because the number of oils tested at viscosities >
10,000 cP was small and there were large gaps across the viscosity range. For IFP and EXDET methods, limiting viscosities were in the 13,780 to 20,920 cP and 8700 to 19,710 cP ranges, respectively. The value in the MNS test was clearly higher, in the 20,920 to 47,000 cP range, while that for the SFT was clearly much lower, between 735 to 3250 cP. Limiting viscosity in Ohmsett tests was in the 18,690- to 33,000-cP range, which was consistent with EXDET, IFP and MNS methods.

For oils in the viscosity range 2500 to 20,000 cP, the range in which partial effectiveness was observed at Ohmsett, dispersion effectiveness-viscosity performance was clearly much higher in the MNS methods than at Ohmsett and the SFT method was much lower, effectively indistinguishable from control values. Results of IFP and EXDET methods were similar to those at Ohmsett.

Data sets for MNS, IFP, and EXDET lacked results for oils < 1000 cP, so comparisons for these was not possible. The effectiveness-oil viscosity curve for from WSL testing in this range (Figure 3, Stevens and Roberts, 2003) differed from the others in that low viscosity oils apparently yielded low levels of effectiveness, increased with increasing viscosity to a maximum at 2000 to 5000 cP, and then declined somewhat with further increasing viscosity. The apparent low effectiveness result for the lighter, non-viscous oils in the WSL method has been a well-known feature of the WSL method since the 1970s (Martinelli and Lynch, 1980). Evidently droplets of the non-viscous, low-density oils, though effectively dispersed, float quickly out of suspension during the one-minute settling period allowed prior to sampling. The somewhat viscous oils and denser oils also disperse effectively, but the droplets of the denser oils rise more slowly and so remain in suspension throughout the one-minute settling period yielding a higher effectiveness index value. Stevens and Roberts study using the WSL method did show a moderate level of effectiveness for a 93,000-cP fuel oil. The high level of effectiveness (40%) for an oil with a very high viscosity, 93,000 cP, had not been observed in any other study for any other method. Additional work will clearly be needed to verify this result.

This analysis suggested a general relationship in dispersant effectiveness values among bench level testing methods. In general, effectiveness was strongly influenced by oil viscosity in all methods. Generally, effectiveness at any given oil viscosity varies with test method as follows: MNS>IFP>EXDET>SFT. This is consistent with Sullivan et al. (1993) who ranked methods based on mixing energy as follows: MNS>IFP≈EXDET≈SFT, suggesting that variations among methods may be due primarily to mixing energy. In SFT and WSL effects of mixing energy may be obscured by the complicating factor of a settling phase where some of the larger droplets of dispersed oil settle out. This complication, though improving the reproducibility of the test results, complicates the task of relating test results to dispersant performance at sea. Based on this limited data set, it appears that Ohmsett results using the standard protocol are most similar to those from the EXDET and IFP methods.

This study had deficiencies in that it:

a) compared tests on different oils tests under different temperatures;

b) lacked results for oils <1000 cP for several methods; and

c) lacked data on the Baffled Flask Test method.

A further study is in nearing completion in which many methods currently in use in North America and Europe are compared with Ohmsett using a common set of oils spanning a broad range of viscosities and standard test conditions.
Figure 3. Comparison of published oil-dispersibility vs oil viscosity curves developed in different effectiveness testing apparatus.
Table 6. Temperatures of oils in Figure 3.

<table>
<thead>
<tr>
<th>Test Method a</th>
<th>Effectiveness test temperature, ° C</th>
<th>Viscosity Measurement Temperature, ° C</th>
<th>Reference</th>
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<tbody>
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<td>WSL</td>
<td>15</td>
<td>15</td>
<td>Stevens and Roberts 2003</td>
</tr>
<tr>
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</tr>
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<td>Canevari et al 2001</td>
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<td>SFT</td>
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<td>Ohmsett 2008</td>
<td>27</td>
<td>27</td>
<td>Trudel et al. 2010</td>
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a. WSL=Warren Spring Laboratory Method (LaboFina Method), MNS=Mackay-Nadeau-Steelman method, IFP=institute francais de petrol, EXDET=Exxon Dispersant Effectiveness Test method, SFT=Swirling Flask Test Method.

5 Summary

In 1999 BOEMRE made Ohmsett available to conduct dispersant research under simulated at-sea conditions. Over the past decade more than 15 operationally oriented research projects have been completed. Initial work developed the dispersant effectiveness testing protocol. Most subsequent work has addressed operational issues:

a) The main factors that control operational effectiveness, including oil/emulsion properties, dispersant type and dose and wave energy; and

b) Methods for monitoring effectiveness in spill response operations.

In addition work has been completed to address:

a) The mechanisms by which oil viscosity limits dispersant effectiveness; and

b) Persistence of dispersants in oil slicks treated on calm water.

The Ohmsett dispersant effectiveness test protocol was developed in 2000 (S.L. Ross, 2000a, b) and has been refined in studies (e.g., S.L. Ross, 2003; S.L. Ross et al., 2005).

Research on the limiting effect of oil viscosity on dispersant effectiveness involved testing dispersibility of 12 water-free crude oils (from Pacific OCS) ranging in viscosity from 67 cP to 40,100 cP at test temperature. Results showed an effectiveness-viscosity curve with three phases when oil slicks were treated Corexit 9500 at a dispersant-to-oil ratio (DOR) of 1:20.

Specifically:

1. Oils with viscosities less than 2500 cP, yielded virtually 100% dispersion effectiveness in all cases.

2. Oils with viscosities greater than 33,000 cP yielded negligible dispersant-aided effectiveness; that is, effectiveness that was indistinguishable from controls.

3. Oils with viscosities from 2500 cP to as high as 18,690 cP yielded incomplete dispersion; that is effectiveness was greater than controls, but less than 100 percent.

Some work has been completed on emulsions and more is planned.

In order to gain insights into the relationship between results of bench-scale tests and those at Ohmsett, these results were compared to similar oil viscosity-effectiveness curves developed using a variety of bench-scale dispersion effectiveness test methods. The analysis suggested a general relationship exists a) among bench-scale testing methods and b) between
these methods and Ohmsett. Generally, effectiveness at any given oil viscosity varies with test method as follows: MNS>IFP>EXDET>SFT, a relationship that reflects (to a degree) the level of mixing energy in the test. Based on this limited data set, it appears that Ohmsett results using the standard protocol are most similar to those from the EXDET and IFP methods. Further work is proceeding to refine this relationship.

Work was initiated to investigate the mechanism by which oil viscosity might limit dispersion. One simple mental model of oil-dispersant interaction is that when dispersants are sprayed, dispersant droplets land on slicks and mix into them (“mixing one”), surfactant molecules in the dispersant partition into the oil, move to and orient themselves at the oil-water interface and reduce oil-water interfacial tension. This allows the oil to be sheared into small droplets by waves and mixed into the upper mixing zone of the water column (“mixing two”). Ohmsett work showed that resistance to “mixing-one” alone was not sufficient to explain the resistance of these viscous crude oils to chemical dispersion. The implication is that in viscous oils, the visco-elastic forces within the oil might be sufficient to oppose the shearing forces of the breaking waves thereby reducing dispersion effectiveness, regardless of the presence of dispersant surfactants. An alternative hypothesis is that the viscosity of the oil may prevent the pre-mixed surfactants from moving through the oil to the oil water interface and so could not reduce oil-water interfacial tension. In either case, the results suggest that simply reformulating a dispersant so it could penetrate better into viscous oil may not be sufficient to improve its overall effectiveness against highly viscous oils. The fact that sprayed dispersant produced some effective dispersion, while premixed dispersant did not, suggests that there may have been dispersant-oil interaction on the outer surface of the slick to facilitate effective dispersion of at least the surface layers of the slick. This suggests that an alternative mental model of oil-dispersant interaction in viscous oil might be needed to adequately understand their resistance to chemical dispersion.

Ohmsett work regarding mixing energy has been approached on two fronts:

a) characterizing the wave environment and relating Ohmsett waves to those at sea; and

b) studying the effect of wave energy on effectiveness.

Veron et al (2008) assessed wave energies produced at the wave-maker setting used in the standard protocol (a wave paddle stroke of 3.0 inches and frequency of 33 cpm) and related them at sea conditions. He concluded that:

a) Surface turbulence (breaking wave) conditions in the test protocol were consistent with open ocean conditions at low to moderate wind speeds (less than 25 knots); and

b) Subsurface turbulence conditions in the test protocol were typical of steep waves created by strong winds operating over short fetches.

He highlighted the apparent discrepancy between surface and subsurface mixing conditions in Ohmsett waves, but explained that the contrast in the two measurements resulted from attempting to compare conditions in the Ohmsett tank, where fetches are short, to open sea conditions where fetches are very long.

One study of the effect of wave energy on effectiveness involved comparing effectiveness of tests in breaking waves to that in non-breaking waves. The principal finding in that study was that there was no apparent chemical dispersion caused by non-breaking waves during 30-minute tests with any oil, regardless of oil viscosity.
One part of Ohmsett work focused on dispersant dosage, studying the effectiveness of the low-dose applications of dispersant delivered by large, fixed wing aircraft. In all tests, the initial low-dose dispersant applications resulted in partial dispersion of test slicks producing small café-au-lait clouds of dispersed oil, but leaving at least some of the test slick on the water surface. The cumulative effect of three or four repeat applications was to produce a high level of overall effectiveness in the 80 to 95% range. Future work will compare effectiveness of dispersant products on the US NCP Product Schedule.

The persistence of dispersants in treated slicks was studied by dosing slicks and then allowing them to soak on calm seas for many days. Five-mm thick slicks of treated dispersible oil dispersed quickly and completely when fresh. However, effectiveness declined markedly after 96 hours of soaking. The rate of decline was faster with thinner slicks.

6 References


Mackay, D., and A. Chau, “The Effectiveness of Chemical Dispersants: A Discussion of Laboratory and Field Test Results”, Oil and Chemical Pollution, 3(6): 405-415. 1987.


SL Ross Environmental Research Ltd., Net Environmental Benefit Analysis of Dispersants for Cleaning Oil Spills from Production Platforms on the Newfoundland Grand Banks, Canadian Association of Petroleum Producers, St. John's, Newfoundland, 2009.


