

A Survey of Tank Facilities for Testing Oil Spill Dispersants

prepared for

Prince William Sound Regional Citizens' Advisory Council (PWSRCAC)
Anchorage, Alaska

by

Merv Fingas
Environmental Technology Centre
Environment Canada
Ottawa, Ontario

May, 2005

Abstract

This report is a survey of tank facilities that could be used for testing oil spill dispersants. The report begins with considerations for tank testing, followed by a list of requirements for tank testing, and data is then provided on a number of potential tanks.

There are many issues related to conducting dispersant tests in large tanks. These have been detailed in previous studies and are summarized in this report. This study stipulated the following basic requirements for tank facilities that are to be used for testing dispersants:

1. ability to filter or renew tank water;
2. ability to use the tank to conduct experiments;
3. ability to apply dispersants and take measurements;
4. availability of wave-making apparatus;
5. ability to calculate mass balance;
6. ability to control or manipulate water temperature; and
7. ability to run tests under different salinities.

The following additional features are also desirable:

8. proven track record of conducting high quality measurements;
9. previous mass balance calculations;
10. previous wave energy studies;
11. personnel experienced in sampling measurements;
12. certified hydrocarbon lab and chemists available;
13. appropriate volume of water;
14. readily accessible site; and
15. flexible scheduling.

In compiling this report, a survey of tanks was carried out. Most of the information came from the Internet or by contacting individuals. The tanks that were found to meet most of the criteria are the Texas A&M SERF tank at Corpus Christi and, to a lesser degree, the new EPA/BIO tank at Dartmouth, Nova Scotia.

Special features of the SERF tank include nine parallel tanks so that experiments can be carried out simultaneously, extensive water treatment facilities, an adjoining laboratory, and high-precision wave-generators. Disadvantages include the narrowness of the tanks, the lack of built-in water temperature controls, and the location in the south, although a design for a climate-controlled facility has been completed. SERF is the only facility that would be ready to go for dispersant testing according to the requirements noted in this report.

The new EPA/BIO tank at Dartmouth will also be of interest to the Prince William Sound Regional Citizens' Advisory Council as it is built especially for testing dispersants. The advantages of this facility include its location close to the sea. Disadvantages are that it is new and calibration, testing, and establishment of basic parameters will have to be completed before the facility is ready for use.

Sixty tanks are listed in this report. The most significant ones are listed and summarized and the tanks of particular interest are noted. Caution must be exercised in using any of these tanks as there may be extensive work and cost in establishing mass balances, wave energy studies, and procedures to clean the tank or replace the water.

Summary and Issues

There are many issues related to conducting dispersant tests in large tanks. These have been detailed in similar previous studies and are summarized in this report. This study stipulates the following basic requirements for tank facilities that are to be used for testing oil spill dispersants.

1. Ability to filter or renew tank water

Each time a dispersant test is conducted, a large amount of the dispersant rapidly enters the water column. The water in the tank therefore requires high-performance filtration after at least 3 experiments, and ideally, after each experiment. While the water in the tank could be replaced, the discharged water may have to be filtered to lower than the 15 ppm discharge limits.

2. Ability to use the tank to conduct experiments

There may be other impediments to using a tank for testing dispersants, including political ones. Clearance from local and state authorities may therefore be needed before proceeding.

3. Ability to apply dispersants and take measurements

To conduct dispersant trials, the water surface in the tank must be accessible so that oil and dispersant can be applied and measurements taken.

4. Availability of wave-making apparatus

As waves and turbulent energy are critical to dispersant effectiveness, a precision, repeatable wave-making apparatus must be available at the facility.

5. Ability to calculate mass balance

The tank facility should have the capability to calculate mass balance. If this has not already been done, it could take up to 4 years to accomplish.

6. Ability to control or manipulate water temperature

The temperature of the water must be controlled within a degree or two to achieve repeatable results. In addition, the air temperature above the oil must be maintained within a certain range of the desired water temperature.

7. Ability to run tests under different salinities

Salinities of between 20 and 33 o/oo are required to mimic open-sea conditions. The tank must be capable of holding and disposing of saline water.

The following additional features are also specified.

8. Proven track record of conducting high quality measurements

It takes years to develop the expertise required to take quality measurements.

9. Previous mass balance calculations

The facility should have a track record of actually performing mass balance measurements.

10. Previous wave energy studies

Wave energy studies are as complex as mass balance studies and require experience and expertise to ensure accuracy. These studies should have been previously carried out at a tank facility in order for that facility to be considered for testing dispersants.

11. Personnel experienced in sampling measurements

Personnel at the facility must have enough specialized training and years of experience to carry out the many complicated measurements required.

12. Certified hydrocarbon lab and chemists available

Governments now require that submitted data be sampled and measured by certified

chemists in certified laboratories using certified procedures. Such a facility is best located at or very near the tank.

13. Appropriate volume of water

A tank can be too small or too large for a given purpose. It is suggested that 20 to 200 m³ be the smallest size and 2000 to 5000 m³ the largest size of tank to be considered for testing dispersants.

14. Readily accessible site

Public transportation should be available to the facility so that it is readily accessible to the users.

15. Flexible scheduling

Flexibility in scheduling is required to cope with varying weather conditions and other seasonal variables.

In compiling this report, a survey of tank facilities was carried out. More than 100 tanks were found in the literature and Internet search and 60 are listed in the report. The facilities that meet most of the criteria are the Texas A&M SERF tank at Corpus Christi (previously called COSS or Coastal Oil Studies System) and, to a lesser degree, the new EPA/BIO tank at Dartmouth, Nova Scotia.

The SERF tank has been studied over the years with respect to establishing mass balance, energy levels, and several other factors. The tanks at this facility were specially built to study nearshore dispersant usage and have many features relevant to the Prince William Sound Regional Citizens' Advisory Council. These features include nine parallel tanks so that experiments can be conducted simultaneously, extensive water treatment facilities, an adjoining laboratory, and high-precision wave generators. Disadvantages include the narrowness of the tanks, the lack of built-in water temperature control, and the location in the south. It should be added, however, that a design for a climate-controlled facility has been completed. The latter two disadvantages might be overcome by running experiments in the winter and using cooling systems to maintain water temperature at the target levels. SERF is the only facility that would be ready to go for dispersant testing according to the requirements noted in this report.

The new EPA/BIO tank at Dartmouth will also be of interest to the PWSRCAC as it is built especially for dispersant testing. An advantage of this facility is its location close to the sea, ideal for drawing water and with cold water and air available several times during the year. The facility is adjacent to the Bedford Institute of Oceanography with immediate access to oil laboratories and experts in many fields. As the facility is new, however, calibration, testing, and establishment of basic parameters will have to be completed before credible results can be produced. The tank is also quite small – smaller than some of the 'small' facilities listed in this study.

Some tanks studied and discussed here almost meet the requirements, including OHMSETT, which is well known, and the Ocean Engineering Facility at Texas A&M in College Station. While this latter tank has been used for testing oil, it may not meet a number of the other requirements noted in this paper. While a number of small tanks are used for testing oil and dispersants, these facilities lack good characterization and don't meet several of the other requirements noted in this report. They are therefore not recommended as a first choice as the effort required to bring these tanks up to standard would be better put into a larger facility.

List of Acronyms

ANS	Alaska North Slope - Usually referring to the crude oil mixture at the end of the pipeline
ASMB	Alberta Sweet Mixed Blend - a crude oil from Alberta often used as a reference
BIO	Bedford Institute of Oceanography
CCD	Charged couple device
COSS	Coastal Oil Studies System - a test tank now called SERF
PAH	Polynuclear Aromatic Hydrocarbons
PWS	Prince William Sound
PWSRCAC	Prince William Sound Regional Citizens' Advisory Council
SAIC	Science Applications International Corporation
SERF	Shoreline Environmental Research Facility - a test tank operated by Texas A&M at Corpus Christi, Texas (formerly COSS)
TPH	Total Petroleum Hydrocarbons - A measurement of total oil in a sample
WAF	Water-Accommodated Fraction - The sum total of oil in a water sample including physically dispersed and soluble oil

Acknowledgements

The author thanks Lisa Ka'aihue of the Regional Citizens' Advisory Council of Prince William Sound, the contract manager for this project. The many persons who provided information on their tanks are acknowledged. The report was edited by Jennifer Charles of Environment Canada.

Table of Contents

Abstract	iii
Summary and Issues	v
List of Acronyms	vii
Acknowledgements	viii
1. Introduction and Considerations for Tank Testing	1
1.1 Mass Balance	2
1.2 Proper Controls	3
1.3 Energy Measurement and Calculation	4
1.3.1 Measurement of Energy	6
1.4 Scaling of Energy and Waves	7
1.5 Wave Reflection	8
1.6 Analytical Methods	8
1.7 Differential Plume Movement	10
1.8 Time Lag and Length of Time Plume is Followed	10
1.9 Mathematics of Calculation and Integration	10
1.10 Lower and Upper Limits of Analytical Methods	10
1.11 Thickness Measurements	11
1.12 Behaviour of Oil with Surfactant Content	11
1.13 Surfactant Stripping	12
1.14 Recovering Surface Oil	13
1.15 Background Levels of Hydrocarbons	13
1.16 Fluorescence of the Dispersant	13
1.17 Herding	14
1.18 Heterogeneity of the Slick and Plume	14
1.19 True Analytical Standards	14
1.20 Weathering of the Oil	14
1.21 Salinity and Temperature of the Water	15
2. Basic Requirements	15
2.1 Ability to Filter or Renew Tank Water	15
2.2 Ability to Use Tank to Disperse Oil	17
2.3 Ability to Apply Dispersants and Take Measurements	17
2.4 Wave-making Apparatus	17
2.5 Ability to Calculate Mass Balance	18
2.6 Ability to Control or Manipulate Water Temperature	18
2.7 Ability to Run Tests Under Different Salinities	18
2.8 Ability to Run a Given Test for as Long as One Day	18
2.9 Ability to Run Salt Water	19

3.	Additional Requirements	19
3.1	Proven Track Record of Conducting High Quality Measurements	19
3.2	Previous Mass Balance Calculations	19
3.3	Previous Wave Energy Studies	19
3.4	Certified Hydrocarbon Lab and Chemists Available	20
3.5	Personnel Experienced in Sampling Measurements	20
3.6	Appropriate Volume of Water	20
3.7	Readily Accessible Site	20
3.8	Flexible Scheduling	20
4.	Description of the Tanks	21
4.1	Tanks Meeting the Basic Requirements	21
4.1.1	Texas A&M SERF Tank or COSS	21
4.1.2	EPA/BIO Tank at Bedford Institute of Oceanography	21
4.2	Tanks Almost Meeting the Requirements	22
4.2.1	OHMSETT	22
4.2.2	Ocean Engineering Facilities at Texas A&M, College Station	24
4.3	Tanks Used for Dispersant Tests But No Longer Available	24
4.3.1	Esso/Imperial Oil Test Tank	24
4.3.2	Delft Hydraulics Test Flume	25
4.4	Small Tanks	27
4.4.1	Environment Canada Equipment Testing Tank	27
4.4.2	CEDRE Polludrome	27
4.4.3	SINTEF Elliptical Flume	28
4.4.4	SL Ross Tank	28
4.4.5	INRS-Oceanologie Dispersant Testing Tank	28
4.4.6	Other Large-scale Tests	28
4.5	Additional Information on Tank Testing	28
4.6	Other Tanks	29
5.	Summary and Recommendations	29
6.	References	34

Figures

1	Waves in the SERF facility	41
2	The SERF facility	41
3	EPA/BIO tank at Bedford, Nova Scotia	42
4	Exterior of the EPA/BIO tank	42
5	Testing in circular booms being conducted at the OHMSETT facility	43
6	Overhead view of the OHMSETT facility	43
7	Glass-walled wind-wave tank at Texas A&M in College Station, Texas	44
8	A dispersant test underway at the Imperial test tank in Calgary, Alberta	44
9	A skimmer being tested at Environment Canada's test tank	45

10	Settling tanks at the Polludrome tank at CEDRE	45
11	The tow/wave tank at the University of New Hampshire	46
12	The Iowa ice basin and tow tank in operation	46
13	The Iowa State tow tank	46
14	The wave-generator at Texas A&M wave tank	46
15	Oregon State circular wave-generation facility	47
16	Oregon State large wave flume	47
17	The University of Delaware wave tank	48
18	A tow tank at the U.S. Naval Academy	48
19	An ice tank at the National Research Council in St. John's, Newfoundland	48
20	A tow tank at the National Research Council in St. John's, Newfoundland	48
21	The Ocean Engineering Basin in St. John's, Newfoundland	48
22	A wave at the National Research Council test tank in Ottawa, Ontario	48
23	The Engineering Wave Basin at the National Research Council in Ottawa, Ontario ..	49
24	The Vizon tow tank in Vancouver, British Columbia	49
25	A large flume at the Delft facility in the Netherlands	49
26	A glass-lined flume at Delft	49
27	Schematic diagram of the large tow tank at the Hamburg Shipbuilding Facility	49
28	The Hamburg ice tank	50
29	Schematic of the Hamburg large tank for ice testing	50
30	The tow tank at INSEAN, Italy	50
31	Tandem tow tank schematic at SINTEF in Norway	51
32	The Marintek deep wave basin in Brest, France	51
33	The tow tank at the National Marine Institute in Japan	51
34	A 150-m tow tank at the National Marine Institute in Japan	51
35	A square wave basin at the National Marine Institute in Japan	51
36	A tow tank at VWS in Berlin	52
37	Tilting oil flume at VWS in Berlin	52
38	Environmental tank at VWS in Berlin	52

Tables

1	Results of Tank Effectiveness Tests	3
2	Summary of Tank Specifications	53
3	Tanks Meeting or Almost Meeting Basic Requirements	57
4	Summary of Tank Contacts	58

1. Introduction and Considerations for Tank Testing

Test tanks offer the potential for testing the effectiveness of oil spill dispersants on a scale that approaches or is the same as that in the field. The advantage of this is that the scale of the test, which is often a focal point of criticism for small tests, is no longer a major factor. The disadvantages of a tank test are that measurements are hard to make and important factors such as mass balance are equally difficult to achieve.

The following are several concerns about the behaviour of oil and dispersants as it relates to tank testing.

- Oil, treated or untreated, will move into several ‘compartments’ such as into the water, onto the tank walls, or into the air through evaporation. Without proper mass balance calculations, it could be presumed that the oil has dispersed.
- Because the oil goes into these various compartments, little treated oil remains on the surface whether significant dispersion occurs or not.
- It is very difficult to get a synoptic view of all the oil dispersed because of the heterogeneity of the oil distribution in the water. Furthermore, the dispersed droplets are still somewhat buoyant and are therefore not distributed equally with depth.
- The surfactants in dispersants leach out of the oil and the amount dispersed decreases with time. The measurement is therefore time-dependent.
- In addition to causing dispersion, the presence of surfactant alters the behaviour of oil in other ways. It causes the oil to spread out over the surface of the tank, often past visibility.

Due to these and many related complications, careful procedures must be developed to measure the amount of oil actually dispersed. The one reasonably accurate way to measure effectiveness in the water is to measure the concentration of oil in the water at least 6 hours after the dispersant has been applied. Brown et al. (1987) suggested that the value was only accurate after 24 hours, with the longer time allowing the oil concentration to be more homogeneous around the tank.

Lessons on tank testing can be taken from Imperial Oil in Calgary, Alberta (Brown et al., 1987; Brown and Goodman, 1988). Testing was developed in the Imperial Oil tank over a 7-year period. The mass balance problems were particularly noted during these tests. The SERF facility in Texas recently had similar difficulties and many of the lessons learned there are incorporated into this paper (Bonner et al., 2003). In addition to problems with mass balance, Bonner et al. (2003) note that the wave energy, spectrum, and several other factors in the tank required measurement and adjustment. Both the difficulties with mass balance and wave energy developments went on for about 5 years. It would be wise and beneficial to build on this series of experiments and improve on the techniques, rather than re-inventing them.

Test tanks are typically classified into several categories, based on their primary use with respect to ship models (Johnson, 1997). For oil spill dispersant work, the tank would properly be named ‘test tank’ which has no particular features compared to other types of tanks. Test tanks can have several dimensions or features and are not typically used for ship studies. A ‘towing tank’ (sometimes simplified to ‘tow tank’) is commonly used for ship studies. These are capable of towing a model, as the name implies. OHMSETT is the only towing tank used for oil spill work. The ‘manoeuvring basin’, which was originally designed for testing autonomous ship models, is another type of ship tank that can be used for oil spill work. Manoeuvring basins are

typically large - 600 by 400 m is not uncommon. A flume is another tank occasionally used for oil spill work. A flume is typically used to test the hydraulics associated with channels, estuaries, or rivers.

This report is a survey of tanks in North America and includes information on some prime European facilities that are capable of handling oil spill dispersant studies. The requirements for such facilities are given and the facilities are described. Requirements are given in two categories, basic or minimal and additional desirable requirements. The tanks themselves are presented in three categories: tanks that meet all basic requirements, tanks that could be modified or adapted, and those that are of interest but are unlikely to meet the requirements without modifications.

In compiling this report, most of the information came from the Internet or by contacting individuals. One of the problems in discussing the capabilities of a tank with respect to oil and dispersant use is that individuals may not be fully aware of the needs and consequences of using a particular tank for testing oil spill dispersants. Even if this requirement is explained, respondents often did not realize that such experiments could cause fouling in the tank nor were they aware of the many specific requirements and their costs. While much interest was shown in the survey, there were few responses to subsequent questions.

Caution must always be exercised in using new tanks as there may be years of work in establishing mass balances, wave energy studies, and procedures to clean the tank or the water. It may be more expensive to use an existing multi-million dollar tank than it would be to start all over again.

1.1 Mass Balance

It is very difficult to calculate mass balance in large test tanks and even more so in field trials. In the 1993 North Sea dispersant trials, the dispersed oil in the water column measured shortly after the dispersant treatment accounted for only 1.8 to 3.5% of the initial volume of the oil released (Lunel, 1994a, b). Similarly, only 0.1 to 0.2% could be accounted for under the control slick, so the difference between the two was emphasized, e.g., 16 to 27 times the amount of oil. It should be noted that the amount of oil remaining on the surface was not accurately measured as there are no techniques for doing so.

Even in enclosed test tanks, it is very difficult to establish a mass balance. Brown et al. (1987) reported on tank tests of dispersant effectiveness. Effectiveness was measured in two ways: by accumulating the concentrations of oil in the water column by fluorometric measurements and by removing and weighing oil on the surface. The results of these two measurements, the amount of oil unaccounted for, and the difference between the two measurements are shown in Table 1.

These data show that from 0 to 68% of the oil in the tank is unaccounted for. Furthermore, in two cases (2 and 3 in the table), the amount of oil was over-calculated, which shows the difficulty in attaining a mass balance, even in a confined test tank. Brown et al. (1987) noted that the problem was accentuated by the heterogeneities in oil concentration in the tank. Some of the oil unaccounted for may have been in regions where the concentrations of oil were higher than average. It should also be noted that surface removal exaggerated the amount of oil dispersed from a factor of 1 to 8, with an average of 4 times.

Table 1 Results of Tank Effectiveness Tests

Dispersant Oil Combination	Results of Effectiveness by Different Methods		Percentage Unaccounted for	Percent Difference Between Methods
	Water Column - 3 hour	Surface removal		
1	9	53	38	44
2	24	77	-1	53
3	33	77	-10	44
4	9	76	15	67
5	11	39	50	28
6	14	43	43	29
7	16	16	68	0

Another example of mass balance is the efforts of the SERF facility in Texas to account for the oil in their tank (Page et al., 1999). The group was initially able to account for only 10 to 33% of the oil originally placed in the tank. After considerable effort, the mass balance was improved to about 50 to 75%, again illustrating the problems of attaining a mass balance.

Mass balance is very important in test situations because the reliability of the data relates directly to the mass balance. If the mass balance is not accounted for, the numbers are meaningless. The above examples show that, even in the more controlled tank tests, mass balance can vary from a few percent and higher. If the measurement made does not account for the discrepancies in mass balance, then very high errors result. A typical example of this is using only the oil remaining on the surface as an indicator of dispersant effectiveness. Table 1 shows that, in a very highly controlled test series, this number can be from 0 to 67% greater than the oil actually dispersed.

As in the title of the Brown et al. (1987) paper, the question “where has all the oil gone?” must be answered. In summary, the mass balance problems revolve around analytical problems, loss of oil through thin, invisible sheens, calculation difficulties, loss of oil to tank walls, and large heterogeneities in oil concentrations in the water column.

1.2 Proper Controls

A proper control is needed in order to accurately assess a dispersant tank test. The control slick must be treated equally to the test slick in every respect except for the application of dispersant. The importance of the use of a control slick is illustrated by two field dispersant trials, the treatment of emulsified oil at the *Exxon Valdez* oil spill and the Beaufort Sea Trial, both of which could also be relevant to tank tests.

In the *Exxon Valdez* test of dispersant application to an emulsified oil slick, two slicks were chosen in the Gulf of Alaska, south of Seward. One was left as a control and the other was treated with large amounts of dispersant. Sampling was conducted from a ship and from aircraft, some of which were equipped with remote sensing gear. The slicks were observed for about 6 hours. The dispersant failed to break the emulsion or to disperse the oil. Coincidentally, the control slick broke up somewhat after about 5 hours, probably due to its greater exposure to waves as it was up-sea of the treated slick. Without a control, the experimental results could have been interpreted differently.

In the Beaufort Sea experiment, three slicks were laid and two were left as controls (Swiss et al., 1987). Two days later, three slicks were found at sea and each had the same

orientation and general geometry as one slick on the first day of the experiment. The dispersed slick was the largest, although the oil content was not known. The interpretation of the results would have been quite different if there were no controls and if the slick had not been followed for days.

1.3 Energy Measurement and Calculation

Turbulent and total energy are known to be very important when measuring oil spill processes. For example, it is thought that energy is the single most important variable in relation to chemical dispersion. It is therefore very important to characterize the energy regime in a tank.

Turbulence is the fluctuation of velocity (Fingas, 2004). If a velocity assemblage is viewed, the description of the overall velocity is given as:

$$U = \bar{U} + u' \quad (1)$$

where U is the overall velocity component,

\bar{U} is the average or constant velocity, and

u' is the fluctuating component or turbulence.

The intensity of turbulence is given by:

$$I = (u^2 + v^2 + w^2)^{1/2} \quad (2)$$

where I is the turbulence intensity, and

u , v , and w are the average turbulence in the x , y , and z directions.

The turbulent kinetic energy can be given by:

$$k = 1/2m(u^2 + v^2 + w^2) \quad (3)$$

where k is the kinetic energy,

m is the mass, typically one unit in the SIU system, and

u , v , and w are the average turbulent velocity components in the x , y , and z directions. One approximation to the average turbulence is the average standard deviation.

Turbulence in natural systems decays as the force that initiated it is no longer applied. Kolmogorov developed the classic decay law (Davidson, 2000):

$$u^2 \sim t^{-10/7} \quad (4)$$

where u is the turbulence, and

t is time.

The work imparted by wind can be estimated as (Boumeester and Wallace, 1986):

$$W = \rho_{\text{air}} g T U^{*2}/2\pi \quad (5)$$

where W is the work,

ρ_{air} is the density of the air,

g is gravity,

T is temperature of the air, and

U^* is wind stress, the actual impact of wind on a surface.

The energy dissipation rate per unit surface area can be estimated from (Boumeester and Wallace, 1986):

$$\epsilon = 15 U^3 \quad (6)$$

where ϵ is the dissipation rate, and

U is the wind speed.

Mellor (2003) developed the relationship between wave energy and amplitude as:

$$E = g a^2/2 \quad (7)$$

where E is the wave energy,

g is the gravitational constant, and

a is the wave amplitude.

A classic method of presenting energy and turbulence energy and decay is in the form of a power density curve or density function (Tanahashi et al., 2001). In this type of presentation, the energy or dissipation of energy is present versus a logarithm of wave number. The classic decrease in energy with wave number is 5/3. This is said to be a 'natural' decay or energy distribution as it is found in many natural systems.

Breaking waves have historically drawn a good deal of attention from researchers because of the visual appearance of the high energy. Measurements of this at sea and in test tanks have been attempted, but not quantified.

Bonner et al. (2003) have suggested several formulations that may be relevant to test tanks. The energy in a single wavelength per unit crest width can be represented by:

$$E = \rho g H^2 L / 8 \quad (8)$$

where E is the wave energy,

ρ is the water density (kg/m^3),

g is the gravitational constant (m^2),

H is the wave height (m), and

L is the wave length (m).

The energy per unit surface area can be given by:

$$E = \rho g H^2 / 8 \quad (9)$$

where E is the wave energy,
 ρ is the water density (kg/m^3),
g is the gravitational constant (m/s^2), and
H is the wave height (m).

The energy per unit volume can be given by:

$$E = \rho g H^2 / 8h \quad (10)$$

where E is the wave energy,
 ρ is the water density (kg/m^3),
g is the gravitational constant (m/s^2),
H is the wave height (m), and
h is the water depth (m).

Fingas (2004) has calculated and measured the energy in some laboratory vessels and estimated those in sea conditions.

1.3.1 Measurement of Energy

A review of measurement techniques is given in Fingas (2004) and some are summarized here. Most techniques measure only the velocity. The velocity requirements can be converted to energy using variations of the equations given in Section 1.3.

Thermal Anemometry - Thermal anemometers can be used to measure fluid velocity by sensing the changes in heat transfer from a small, electrically heated element immersed in the fluid (Fingas, 2004). In one form of the instrument, the constant temperature anemometer, the cooling effect produced by fluid flowing over the element is balanced by the electrical current to the element. The change in current is measured as voltage change and forms the anemometer output. The anemometer output is typically coupled to a computer, where the data can be collected and analyzed.

An important feature of thermal anemometers is their ability to measure very rapid changes in velocity. Frequency changes up to 30,000 Hz or fluctuations as short as 30 microseconds can be measured. This high frequency is accomplished by coupling very fine sensing elements such as a wire from 4 to 6 micrometers in diameter or a platinum thin-film deposited on a quartz substrate. Due to its small size, the probe is less obtrusive than probes of an older design, although it still interferes with fluid flow.

Particle Image Velocimetry - In particle image velocimetry (PIV), the flow as marked by micron-sized seeder particles is illuminated by a light sheet (Price et al., 2002). Two images of each particle are recorded within a short time interval. The image separating the two gives a local velocity vector. As the time interval is small compared to the flow-time scales, PIV can

deliver instantaneous velocity maps in a plane.

Illumination is typically accomplished using a laser, such as a YAG or argon laser. The laser can easily produce a very thin light sheet, thus avoiding problems of multiple targets. A light sheet is created using a cylindrical lens or series of lenses. Most modern systems use CCD cameras gated to the pulse repetition frequency of the laser.

The advantages of using PIV for applications in oil spills is that surface seeding can be employed, which results in data particular only to the surface of the water, such as would be true for an oil slick.

Laser Doppler Anemometry - The laser Doppler anemometer uses laser transmitters and receivers to interrogate a small volume of water or air. The transmitter produces periodic short laser pulses. Ambient scatterers such as bubbles or seeding material scatter a portion of the laser light. The receiver detects these scattered laser pulses if they are in the laser path. The frequency of the returned laser pulses are Doppler-shifted by the speed of the scattering particles. The return signals can then be demodulated to calculate speeds within the defined sample volume.

Acoustic Doppler Velocimetry - The acoustic Doppler velocimeter uses focussed acoustic transmitters and receivers to interrogate a small volume of water. The transmitter produces periodic short acoustic pulses. Ambient scatterers such as bubbles or seeding material scatter a portion of the acoustic energy. The receiver detects these scattered acoustic pulses if they are in the defined sample volume. The frequency of the returned acoustic pulses are Doppler-shifted by the speed of the scattering particles. The return acoustic signals can then be used to calculate speeds within the defined sample volume.

1.4 Scaling of Energy and Waves

Bonner et al. (2003) point out that the energy density of the tank should correspond to the energy density of the natural system it is to replicate. By equating the energy equations in equation (10) for the tank and the natural system, one arrives at:

$$H_{\text{model}}^2 = (h_{\text{model}}/h_{\text{natural}})H_{\text{natural}}^2 \quad (11)$$

where: H_{model} is the wave height in the tank model,
 h_{model} is the depth of the tank,
 H_{natural} is the wave height in the real system, and
 h_{natural} is the depth of the real system.

Bonner et al. (2003) suggest that the volumetric energy need only be scaled as the ratio of the heights of the water column, keeping the waves similar. This is useful for systems with similar geometries and dimensions. It is suggested here that it might be better to scale on the basis of surface energy as in equation (9). By this, one would scale on the basis only that wave height be kept constant.

1.5 Wave Reflection

One of the major problems in test tanks is the reflection of waves from the end walls of the tank, particularly the wall opposite to the wave propagation direction (Bonner et al., 2003). Reflection from side walls can also cause problems. For example, the SERF tank has a wave damper behind the wave generators which consists of a series of tubes. This absorbs over 90% of the applied energy as measured through a series of tests. A sand beach is used to absorb energy on the wave target side. Most tanks have an artificial beach specifically designed to absorb over 90% of the wave energy and some have added baffles on side walls to minimize wall effects. These devices are not practical for testing oil, however, as oil would become trapped in these baffles.

1.6 Analytical Methods

There are not many analytical methods that can be used in field situations. Fluorometers were successfully used very early in the field testing program, but without GPS, it was difficult to assess the position at which to take samples. Today, accurate GPS data coupled directly to fluorometer data can provide reasonable positional data for the fluorometric readings.

Some of the earlier trials used grab samples that were subsequently analyzed by ultraviolet (UV) or infrared (IR) absorption (Fingas, 1989). These methods are notoriously inaccurate and have long since been replaced by gas chromatography methods. Sample preservation also poses a problem. Samples must be chilled immediately to prevent loss of hydrocarbons. Standard procedures are now available, but these were not applied in early trials.

The use of fluorometry in the field has been examined in detail (Lambert et al., 2000, 2001a, 2001b). These studies show that fluorometry is a sensitive, but not necessarily accurate, means of oil determination. A fluorometer uses UV or near UV to activate aromatic species in the oil. The UV activation energy is more sensitive to the naphthalenes and phenanthrenes in the oil, whereas the near UV is more sensitive to large species such as fluorenes. The concentration of aromatics in the oil increases as the oil weathers and is dispersed. The apparent fluorescent quantity therefore increases in this process.

The calibration of fluorometric readings is critical (Lambert et al., 2000, 2001a, 2001b). The most important factor is how the oil is introduced to the fluorometer and the subsequent readings taken. How much oil the fluorometer sees is influenced by the solubility and dispersibility and the subsequent evaporation/volatilization of the particular oil. Typically, oil and dispersant are added to a container, e.g., a bucket, and pumped through a flow-through fluorometer. The amount of oil added is usually taken as the amount of oil read by the fluorometer. The problem with this method is that most of the oil is not dispersed into the water column and many soluble species are present, which would not be the case in the sea. Tests of these types of methods show that the fluorometer calibration curve is generally between 5 and 10 times greater than is the actual case. Thus, a reading of 15 ppm in the field is actually a reading of approximately 1.5 to 3 ppm. As this was generally the case in most past field trials, the actual ppm readings provided are far too high and cannot simply be converted into actual values.

A better method of calibrating a fluorometer is by introducing oil weathered to about the percentage expected in the field to a closed container. After about 15 minutes of pumping, take a sample and analyze it by a good GC method (Lambert et al., 2001b). Then continue adding the

weathered oil by increments and do the sampling and analysis at each increment. When the numbers are collected, this will form a relatively good calibration curve. Because of the differences in chemical composition, however, this calibration curve could also give results as high as twice that of the actual concentration. This is because the dispersant action increases the aromatic content, which is the fluorescent portion of the oil, compared to the remaining fractions of the oil that do not fluoresce.

The most reliable method of calibrating a fluorometer is to perform the above calibration procedure but repeat it throughout the actual experiment. It is relatively easy to collect almost simultaneous samples from the fluorometer as the flow from the output of the fluorometer can be captured and preserved for later analysis. This is generally done when the fluorometer reading is relatively stable to ensure that the sample and the fluorometric value correspond. The actual values and the previously prepared calibration curve can be compared to examine the differences in composition. It should be noted that this method was followed in the Protecmar V and VI trials in France (Bocard et al., 1986/1987). Examination of this data shows the lower oil concentrations actually achieved in a dispersant application.

The effects of running probes into the water column have not been fully examined. Although several devices have been created in the past to examine the sub-surface water column, weighted hose is usually the standby. Tests show that there is significant retention on Tygon tubing and that it may be necessary to pump for up to one hour to clear this line to the point of background measurements. Teflon tubing appears to show a lesser effect, although less testing has been conducted on this. There may be a serious effect on measurements depending on how the tubes or sampling devices are deployed. Tests conducted by the French during the Protecmar trials showed that there was a significant hull effect, with portions of the oil-in-water plume being driven downwards by a boat (Bocard et al., 1986). The solution was to run a sampler far from the boat hull using a specially built device. A Canadian group subsequently ran a fixed probe in front of a sampling vessel to overcome the hull effect problem (Gill et al., 1985).

Another complication with sampling is the retention of surface oil on the sampling tubes, weights, and pumps that are lowered into the water. As the equipment goes through the surface slick, which is always present, some of the surface oil is retained on the sampling equipment and is read as oil concentration at that depth. Some experimenters have dragged the submerged sampling train to the next sample point to avoid this problem, although this action may also drag oil on the outside of the sampling gear.

In summary, fluorometry is the only practical technique for measuring concentrations of oil in the water column in real time. The errors encountered increase the apparent value of the oil concentration in the water column. Incorrect calibration procedures can distort concentration values by up to 10 times their actual value. Correct calibration procedures have been defined (Lambert et al., 2001b) and involve performing accurate gas chromatographic (GC) measurements both in the laboratory and the field during the actual experiment. Furthermore, water sampling gear must be deployed in such a way as to avoid disturbing the underwater plume or carrying oil from one level or area to another. Taking samples for chromatographic analysis is an alternative to the use of fluorometers. While costly and providing poor spatial coverage, this method is highly accurate.

1.7 Differential Plume Movement

The dispersed oil plume can move in a different direction than the surface slick (Fingas, 2000). Furthermore, its geometry generally has little relation to the surface slick. It becomes very difficult to locate sample probes and later to try to quantify the oil in the plume, the extent of which is unknown. The best solution in the test tank is to let it equilibrate over 24 hours and then take samples at several points and average the results (Brown et al., 1987).

Some early experimenters did not recognize the differential plume movement and took measurements under the surface slick. They then integrated average concentrations over this large area. This can exaggerate dispersant effectiveness by as much as an order-of-magnitude because the area of the plume is often fractions of the area of the remaining slick.

1.8 Time Lag and Length of Time Plume is Followed

There are certain time characteristics of the dispersion process that must be understood. Firstly, it takes from 15 to 90 minutes for results of the dispersant application to become visible. Any action faster than that is attributable to herding, and not dispersion. The visible results of dispersant are generally taken as the appearance of a yellow to coffee-coloured plume in the water. Secondly, the dispersant may continue to act for up to an hour after application. Thirdly, the movement and dispersion of the plume are generally slow, although the plume is usually visible for about 3 hours and is never visible past about 8 hours. Finally, the oil in the plume will resurface slowly over the next several days. Since the resurfaced oil is usually thinner than the visibility limits, this will not be noticed unless new tracking methods are developed or very sensitive techniques are used.

In tanks, it is important to account for the slowly evolving behaviour of the slick. Brown et al. (1987) noted that they had to measure their test tank after 24 hours to yield a reasonable result. Measurements taken before about 6 hours were found to be of little value. The Beaufort Sea experiment is another example of observing slicks for a longer period of time. Three slicks were laid and two were left as controls (Swiss et al., 1987). Two days later, three slicks were found at sea, each of which had the same orientation and geometry as one slick on the first day of the experiment. The dispersed slick was the largest, although the oil content was not known. If the slick had not been followed for days, the results would have been interpreted quite differently.

1.9 Mathematics of Calculation and Integration

Several examples of the effects of integrating and averaging incorrectly are given in a former paper (Fingas, 1989). This effect is exacerbated if no zero-oil concentration values are measured in areas outside the plume. This is shown in Fingas (2002).

1.10 Lower and Upper Limits of Analytical Methods

The lower and upper limits of the analytical methods applied are another important factor, especially in test tanks. If the lower limit is exceeded, using these values can result in serious errors. The lower analytical limit should be taken as twice the standard deviation or about 0.3 ppm for an older fluorometer or 0.1 ppm for a newer unit. The use of double the standard deviation is standard laboratory practice and, in fact, newer practices sometimes advocate using three times the standard deviation. Values below this should be taken as no-

detect levels and zero should be chosen for calculation purposes.

The upper limit is equally important since the amount of oil in the water column could exceed the upper limit of some analytical procedures. If this occurred in practice, the effectiveness would be underestimated. Fluorometers are non-linear in concentrations approaching or exceeding about 100 ppm oil-in-water and therefore very high concentrations might be missed. However, such high concentrations have never been measured either in the field or lab.

1.11 Thickness Measurements

Several researchers have tried to estimate the amount of oil remaining on the surface by estimating oil thickness. One of the most common ways of doing this has been by touching the surface with a sorbent. The amount of oil in the sorbent was determined by a number of means such as colorimetric or infrared analysis, which was then presumed to relate directly to the oil thickness. Careful laboratory tests of these techniques, however, have shown that they do not yield a good quantitative thickness result (Goodman and Fingas, 1988; Louchouart et al., 2000a).

There are several reasons why removing oil from the surface with sorbents is not necessarily total. The edges of the sorbent may trap more oil, it may not be possible to calibrate the sorbents in the laboratory, and there may be poor extraction from the sorbent. Sorbents cannot be 'calibrated' in the laboratory because it is very difficult to get a uniform thickness of oil in a vessel in the lab. Often oil does not spread uniformly and forms blobs interconnected by sheen. Oil will be herded to one side even by the minimal air circulation in the laboratory. Also, most oils will form a concave lens with more oil on the edge. The use of sampling tubes and other similar devices is fraught with similar difficulties.

In summary, the thickness of oil on the surface of the test tank cannot be measured. Therefore, thickness cannot be measured as one way to determine dispersant effectiveness. Recent work by Bonner et al. (2002) has resulted in methods for estimating thin slicks as a way to examine mass balance.

1.12 Behaviour of Oil with Surfactant Content

Other than dispersion, surfactant in the dispersant makes it more difficult to contain the oil and makes the oil less adhesive. This also affects the ability to measure oil remaining on the surface.

If the oil is contained, dispersant applied, and the remaining oil measured, errors as large as an order-of-magnitude would occur because the oil would pass under the boom. The important value is the critical velocity of containment. This is the velocity at which oil is lost under the boom through several failure mechanisms. The critical velocity of containment can be given by (Lee and Kang, 1997):

$$U_{cr} = \{2 [g T_{o/w}(\rho - \rho_o)]^{1/2} (\rho + \rho_o)/(\rho\rho_o)\}^{1/2} \quad (12)$$

where: U_{cr} is the critical velocity,
 $T_{o/w}$ is the interfacial tension between oil and water,
 ρ is the water density, and

ρ_o is the oil density.

A very low ratio of dispersant or surfactant (about 1:100) will lower the interfacial tension to about half its previous value (Fingas, 2000). According to the equation, this would lower the critical velocity to about 0.7 of the previous value. If an experiment were set up that measured the oil left behind a containment boom when the oil was being held close to critical velocity, even a small amount of dispersant would release the oil. If the oil left were measured as an indication of the effectiveness of the dispersant, this effectiveness value would be highly exaggerated and would represent containment failure and not dispersion.

Adhesion is the other factor that changes when dispersant is added to oil. While quantitative studies have not been performed on this, practical tests have shown that it is difficult, if not impossible, to remove the remaining oil after dispersant application using a sorbent surface skimmer (Brown et al., 1987). Such a skimmer relies on the adhesion of the oil to remove it from the water surface. Again, because of the effect of the dispersant, it is likely that the oil remaining on the surface will be underestimated and the apparent effectiveness of the dispersant will be overestimated. While it is felt that this effect is not as important as that of containment failure, it is significant nevertheless.

The combination of errors resulting from using contained oil slicks and lack of mass balance is at least a factor of 4 as noted in Brown et al. (1987) and is possibly as great as no dispersion at all even though the surface appears to be clear.

1.13 Surfactant Stripping

It is relatively well known that there is an exchange of surfactants between the target droplet and the surrounding water (Heimenz and Rajagopalan, 1997). This results in destabilization of the emulsion. When the water is in a large ratio to the droplet concentration, surfactant is largely lost and destabilization is relatively rapid. In laboratory tests, the ratio of the oil to water then becomes important in simulating the conditions at sea. In the swirling flask test used here, the oil-to-water ratio is 1:1200, which may be somewhat representative of a more open situation. The relationship of the energy, the dilution, and other factors in the laboratory test to open water conditions is not well understood at this time.

Chemically dispersed oil has been known to destabilize due to the loss of surfactants to the water column. Once droplets lose a critical amount of surfactant, they are less likely to remain in the water column. This effect was measured in a study using ASMB and ANS crude oils and the dispersants Corexit 9500 and Corexit 9527 (Fingas et al., 2002). Resurfacing was consistent within each group of tests, static and shaken. The values for those samples shaken continuously fit an equation of the form, effectiveness = $a + b\sqrt{\text{time}}$. For the static tests, an equation of the form, effectiveness = $a + b/\sqrt{\text{time}}$, was the best. A method to generally predict this falloff in effectiveness with time was developed by correlating all the equations and preparing a two-level prediction scheme.

Results show that, under all conditions, significant amounts of oil resurface in the swirling flask after the initial dispersion takes place. While mixing tends to retain more oil in the water column, only about 10% more oil is retained in the water column than if the system is static. While it has not been determined what relationship this process may have to what may occur in the sea, resurfacing of oil has been noted in several sea trials. Provision should be made

to track the plume and test for resurfacing.

1.14 Recovering Surface Oil

Some experimenters have tried to recover surface oil in an attempt to directly determine effectiveness by presuming that the entire remainder is dispersed. This is incorrect because the loss from the surface includes the amount evaporated, the amount in very thin (often invisible) slicks, the amount that is physically unrecoverable, oil that adheres to booms or other surface objects, errors in the amounts of all the oil compartments, and oil that is simply unaccounted for.

Controlled tests in a test tank have shown that the difference between oil accounted for in the water column and the amount on the surface can vary from 0 to 80% (Brown et al., 1987; Brown and Goodman, 1988). Again, this represents the typical error of trying to perform a surface-only measurement. Once oil is treated with dispersant, it becomes less adhesive and therefore much more difficult to recover from the surface using typical skimmers and sorbents. This fact can contribute to the error.

Some experimenters have recovered surface oil (Page et al., 1999; Tissot et al., 2000). While a good experimental procedure, it should be noted for the reasons discussed here that this amount is fraught with error. Great care must be taken to ensure good recovery as well as subsequent interpretation of the results.

1.15 Background Levels of Hydrocarbons

The background level of hydrocarbons is important for several reasons. A good background value is needed to subtract concentration values and to know when to terminate integration of the spill. It is suggested that the same techniques, along with the grab samples for calibration, be applied in the area before dispersant application and also after, if practical, to determine the range of background values in the area. These values can then be assessed for use in correcting the values and for ending integration.

Another problem associated with background levels is that hydrocarbons will adhere to sample tubes and equipment, resulting in higher than background values at the end of a run through the plume. There is no easy solution to this problem. One of the solutions is to examine the values and look at where the signal drops off significantly, probably at the end of the plume, and use this value as a 'corrected' background. Some experimentation can be done at the scene of the measurements to define the carry-through of hydrocarbons in the system. It should be noted that, if the carry-through is not corrected for, gross errors could occur in the amount of oil calculated.

1.16 Fluorescence of the Dispersant

While the dispersant mixtures, per se, should not fluoresce, most of them show a significant signal when placed in a Turner Fluorometer (Lambert et al., 2001a). The reason for this fluorescence is the reflection of ultraviolet and other light into the detection path and the actual fluorescence of small amounts of fluorescent material either in the dispersant or picked up through the system. Most experimenters in the past have ignored the fluorescence of the dispersant because it was presumed that there was no contribution. Furthermore, in an actual application or experiment, the pickup of even a small amount of oil by the dispersant will result

in a significant signal. While this is difficult to correct for, one way is to correct all the readings to accurate GC analytical results.

1.17 Herding

Herding occurs when the oil is pushed aside by the dispersant (Merlin et al., 1989). This occurs when the spreading pressure of the dispersant is greater than that of the oil slick, especially when the oil slick is thin. The dispersant must directly contact the water surface in order to cause herding. This happens readily with thin oil slicks because aerially applied droplets are generally 300 to 1200 μm in size, while the oil slick could easily be as thin as 100 μm (appearing as a thick slick) (Merlin et al., 1989). Often little dispersion takes place in the presence of herding. The larger droplets land on the surface first and cause herding if the conditions are correct and then much of the dispersant that follows in smaller droplets then lands directly on the water.

1.18 Heterogeneity of the Slick and Plume

As slicks are rarely homogeneous in thickness, the dispersant applied may be insufficient in some areas or the dispersant may break through in other areas and cause herding (Merlin et al., 1989; Payne et al., 1993). Furthermore, slick heterogeneities will result in heterogeneities in the dispersant plume, which will again result in difficulties integrating the plume. If peak values are used, the effectiveness of the dispersant will be overestimated and vice versa. This difficulty can be overcome by integrating very small areas of the sub-surface plume. In tanks, this can be overcome somewhat by continuing water circulation for 24 hours before measuring (Brown et al., 1987).

1.19 True Analytical Standards

Certified laboratories that use certified petroleum hydrocarbon measurement techniques should be used when conducting tank studies. One of the most serious difficulties in older field and tank trials occurred when inexperienced staff tried to conduct chemical procedures. Analytical methods are complex and cannot be conducted correctly without chemists familiar with the exact procedures.

Furthermore, field instrumentation such as fluorometers must be calibrated using standard procedures and field samples during the actual trial. These samples must be taken and handled by using standard procedures. Certified standards must be used throughout the testing to ensure good Quality Assurance/Quality Control (QA/QC) procedures are followed.

In this era, it is unacceptable not to use certified methods, laboratories, and chemists.

1.20 Weathering of the Oil

Dispersant effectiveness decreases as the oil weathers. While the weathering trend is characteristic to a particular oil, every oil shows this decrease (Fingas et al., 2001). The oil used for dispersant tests should be weathered to an extent that represents a realistic situation, e.g., equivalent to about 1 day. The weathering of the oil will also assist in maintaining a more correct mass balance.

Fingas et al. (2001) tested several oils for effectiveness with the dispersant Corexit 9500 and found that the dispersant effectiveness drops off significantly with the weathered oils. The

effectiveness typically fell by about half after the oil was weathered to the equivalent of one day. For light oils, this weathering would be about 20% by weight and about 10% by weight for heavy oils.

The weathering effect was analyzed using mathematical regression. The effectiveness drops off as the oil is weathered and this drop appears to be similar for the various oils, that is the slope is similar for the curves. This was analyzed using the mathematical approach of curve fitting equations to the weathering curves and then comparing the slopes and regression coefficients. The most commonly fit curve (simplest mathematical equation) was a square root equation [$y = a + b \cdot \sqrt{x}$]. The decline in weathering was also correlated against oil density, viscosity, weathering equation, and the maximum extent of weathering. The regression coefficients were low, indicating that a simple correlation to a fundamental oil property was not possible. This also indicates that the dispersibility of the oil is related more to its composition than to its physical properties.

1.21 Salinity and Temperature of the Water

Recent studies show that there is an interrelationship between the effectiveness of the dispersant and the salinity and temperature of the water (Fingas and Ka'ahue, 2005). To accurately simulate the effectiveness in a field situation, both the temperature and the salinity must be within about 20% of the actual field conditions. The temperature of the air must also be related to conditions in the field. As the oil is warmed by the sun during the day, its temperature may rise several degrees above that of the water and the air. If the water is much colder than the air, the test does not really represent the cold temperature of the water, but rather that of the air.

2. Basic Requirements

As pointed out in Section 1, measuring dispersant effectiveness in a tank requires the use of advanced technologies, good scientific procedures, and knowledge obtained from past experiences. In addition, the tank must meet some basic physical requirements so that these technologies and procedures can be applied. These will be discussed in this section.

2.1 Ability to Filter or Renew Tank Water

Each time a dispersant experiment is performed, significant amounts of oil remain in the water and tank surfaces. It has been shown at past trials that no more than 3 tests can be performed, even in a large tank, before the water must be filtered or changed (Fingas and Ka'ahue, 2004a). If the water is filtered, both particulate oil and dissolved oil components and dispersants must be removed. An oil-water separator is not adequate to deal with either the oil or the dispersant.

Another alternative is to rapidly replace the water in the tank. This means that saline water must be readily available and that saline discharges will not cause problems, both of which imply that the tank must be beside the ocean. The discharge of water containing more than 15 ppm of salt is prohibited by national and international laws. Unless the dispersant is very diluted and the oil is removed with a separator, oil cannot be discharged from a typical tank.

The case of filtration at the OHMSETT facility is relevant to this discussion. Mullin (2004) describes the use of a powdered activated carbon filter to remove dispersant from the

water. It takes 2 to 3 days to reduce surfactant concentrations so that the indicator parameter of surface tension is low enough. It was noted that the filters built earlier to purify the water did not remove surfactant. Ross et al. (2000, 2001) noted that as little as a few ppm of dispersant in the water were enough to cause dramatic effects such as with the testing of skimmers. For example, a concentration of only 5 to 10 ppm reduced the oil interfacial tension and 50 ppm reduced interfacial tension by 40 to 50%. Ross et al. (2000, 2001) conclude that even small concentrations of dispersant in water are unacceptable for conventional testing equipment. It was noted, however, that surfactant concentrations of up to 400 ppm would not change dispersant effectiveness, based on testing that was not described in detail (Ross et al., 2001). They also noted that each such test at OHMSETT would add 10 ppm of surfactant to the tank and that 2 to 4 experiments in a row could be conducted without surfactant effects.

This situation is aggravated in small tanks because there could be a greater concentration of dispersant in the tank due to the smaller amount of water and less dilution. On the other hand, there is a smaller amount of water to filter or replace. For large tanks, it may be almost impossible to filter or replace the greater volume of water. It must be remembered that the limits for discharged water are 15 ppm of hydrocarbons. It may therefore be necessary to clean up the water before discharge even after one dispersant experiment in a given tank.

From the experiences at OHMSETT, it is noted that dispersants cannot be removed from water using ordinary filter agents. Most filter agents are designed to remove particulate material over about 5 μm . This will remove a portion of the particulate oil, but not the dissolved surfactant, dissolved oil, and smaller particulates, which are very much smaller (down to about 1/1000 of the 5 μm). These can be removed by adsorption to carbon or similar materials or ultra-filtration. A tank for testing dispersants must therefore be equipped with a good filtration system. The best procedure is to flush the tank and discharge the water after filtration before refilling the tank.

SAIC conducted a study to review the use of nano- and ultra-filtration for removing surfactants (SAIC, 2003; Cooper et al., 2003). Of the several flat-sheet membranes tested, two (NF 45 and G 20) showed good potential for surfactant removal. NF 20 showed a rejection rate of 99.9% with a permeate flux of 36 L/m²/h and G 20 showed a rejection rate of 98.9% with a permeate flux of 23.5 L/m²/h. Due to several other factors, the G 20 membrane was recommended as the membrane for possible expansion to full treatment. It was estimated that full treatment using membrane systems would cost up to \$1,000,000.

An advanced oxidation process was also tested for removing dispersants, but it was found ineffective (SAIC, 2003). Surface tension methods were used to quantify the dispersant in the water, noting that full analytical methods would be very expensive. The relationship between surface tension and dispersant concentration was found to be as follows for tap water:

$$\text{Surface Tension (dynes/cm)} = -4.26 \ln(\text{dispersant concentration in ppm}) + 65.3 \quad (1)$$

For OHMSETT water, this formula for Corexit 9500 became:

$$\text{Surface Tension (dynes/cm)} = -4.32 \ln(\text{dispersant concentration in ppm}) + 65.2 \quad (2)$$

For OHMSETT water, this formula for Corexit 9527 became:

$$\text{Surface Tension (dynes/cm)} = -4.25 \ln(\text{dispersant concentration in ppm}) + 61.4 \quad (3)$$

2.2 Ability to Use Tank to Disperse Oil

Even with the filtration described in Section 2.1, there may still be reasons that a tank cannot be used to test dispersants. There may be concerns about contamination of the side walls or discharging water, even though this water may already be filtered. There may not be a safe place to discharge the water or the environment in the discharge area may be sensitive.

Users and owners of tank facilities must check with a variety of agencies to determine that such dispersant experiments are permitted.

2.3 Ability to Apply Dispersants and Take Measurements

The tank requires certain features in order for oil and dispersant to be applied and measurements to be taken. A primary feature is that there must be access to the water surface from the sides of the tank and that individuals must be able to use tools to apply oil and dispersant and take surface and sub-surface samples. The water should not be too far below the tank wall so that the surface is accessible. While useful, a moveable bridge may not be required to apply oil and dispersant. When using a smaller tank, oil and dispersant can be applied to the surface using hand-operated sprays or similar devices and surface or sub-surface samples can be taken with extension rods.

There must be access to a certified laboratory and sample preservation facilities. As the samples deteriorate rapidly (within minutes to hours), special preservation techniques such as refrigeration and placement in sealed vials or immediate analysis are required.

2.4 Wave-making Apparatus

As noted in Section 3.1, waves and turbulent energy are required for dispersion to occur. As the energy provided in a test tank must be consistent, quantifiable, and repeatable, a specially designed, computer-controlled system is required. Such systems are available from a number of suppliers and have already been installed in some tanks. Older tanks often have ‘home-built’ systems that cannot meet this requirement.

In modern wave generators, some segments are often hydraulically or electrically driven. These segments are individually controlled by computers that manipulate them to produce the desired wave. Pressure sensors in the tank walls indicate wave height at distance. This information is fed back to the computers to tightly control the waves generated.

Along with precision wave-making, excellent wave-damping or absorbing is required at the opposite end of the tank so that waves are not reflected from the walls, thereby producing multiple interference patterns. Wave-damping is also required behind the wave generator to avoid reflections from the back wall. The side walls of the tank must be coated with low-resistance material, such as epoxy, to avoid creating drag interference patterns. Some high-precision hydraulic tanks also have side wave-dampers, although these are not recommended for oil experiments as they would quickly become fouled.

Tanks should also have completed a series of hydraulic studies to characterize the waves, interferences, energy, and reflections in the tank. These studies must be followed up with

corrective action if less-than-ideal circumstances are found. Several documents in the literature describe such studies (Page et al., 1998).

2.5 Ability to Calculate Mass Balance

Mass balance must be calculated and maintained in the best way possible. Because of the difficulty in accounting for all the oil, dispersant effectiveness should not be taken as the oil unaccounted for. In past experiments, the oil unaccounted for ranged from -20% (over-accounted) to more than 80%. In one set of experiments, Brown et al. (1987) showed that lack of mass balance exaggerated apparent effectiveness on average by a factor of 4 times. In some tanks, mass balance may be difficult or impossible to measure because of large sizes or many oil sinks, such as sediment, which can take up a great deal of oil.

It is recommended to PWSRCAC that only tanks that have calculated and maintained mass balance in the past be considered for testing dispersants. It may be far too difficult and time-consuming to begin a mass balance exercise at a facility where it has never been carried out before.

2.6 Ability to Control or Manipulate Water Temperature

As temperature is a very important factor for dispersant effectiveness, this parameter must be tightly controlled throughout the tests (Fingas, 2000). As the oil and dispersant are the important vectors to this test, both temperatures must be tightly controlled throughout the experiment. It is not enough to adjust only the water temperature. The oil must be applied to the water at the control temperature and the dispersant must be applied to the oil at the same temperature that is the subject of the simulation. These temperatures must be maintained as much as possible throughout the experiment. The air temperature should not be much above the desired water/oil/dispersant temperature. It is suggested the maximum differential should be 10°C, especially during the initial active dispersion period (up to 30 minutes). As oil is readily heated by the sun, the oil should not be applied and then left for a period of time. It is suggested that 15 minutes is a practical time for the oil to be left.

A cooling system is required to achieve this temperature control for the water and the application systems must be specially designed to deliver oil and dispersant at the desired temperatures and resulting viscosities.

2.7 Ability to Run Tests under Different Salinities

Salinity is an important variable in testing dispersant effectiveness (Fingas and Ka'aihue, 2005). Generally, the salinity of water in a test tank can only be increased by adding salt or pumping in water with a higher salinity. It can take several large truck loads of salt to raise the salinity of water in a large tank to that of typical seawater (33 o/oo). Acquisition, mixing, maintenance, disposal, and compensating for the corrosion of salt can substantially increase the cost of operation. Manipulating salinity between about 20 to 35 o/oo may be necessary to simulate the desired conditions of the target waters.

2.8 Ability to Run a Given Test for as Long as One Day

As there is a significant time lag of up to one hour before dispersant acts and as the dispersant partitions to the water and may subsequently resurface, it is important that dispersant

tests are run for as long as possible to obtain a true picture of the overall effectiveness (Fingas et al., 2002). It is suggested that tests are routinely run for up to one day, at least until the basic parameters are established. There is extensive literature on the length of test runs, all noting that longer times are better to establish a more realistic picture (Fingas, 2002). It is important to note which features of a tank allow for a longer run. For example, can the wave generator run all night unattended? If not, can a night crew be assigned this task?

Brown et al. (1987) noted that they had to measure their test tank after 24 hours to yield a reasonable result. It was found that measurements taken before about 6 hours were of little value.

2.9 Ability to Run Salt Water

As today's dispersants are not very effective in fresh water, regulatory agencies typically specify the use of salt water for testing them. Tank testing thus requires a salinity of 20 to 33 o/oo to simulate the target area salinity (Fingas and Ka'aihue, 2005). Tanks built for freshwater only cannot be converted as any metal fixtures will rapidly corrode. Furthermore, disposal of salt water inland is a problem. Prospective tanks for testing dispersants are therefore largely restricted to coastal areas or to highly specialized facilities inland.

3. Additional Requirements

A study on field testing provided a good overview of the requirements for testing in the field or in large tanks (Fingas, 2002). The study's key points relating to tank testing are summarized in this section.

3.1 Proven Track Record of Conducting High Quality Measurements

As it takes from two to four years to establish a sound system of measurements in tanks, only those facilities that have already gone through this exercise should be considered (Fingas, 2002). This is clearly evidenced in the literature from the experiences at the Imperial Oil and SERF tanks (Brown and Goodman, 1988; Bonner et al., 2003). It is also clear that there are no shortcuts to this as each facility has many nuances and it takes time to train personnel in the various tests and operations that must be conducted.

3.2 Previous Mass Balance Calculations

A significant portion of the time needed to establish the tank operations is associated with developing procedures for measuring the components necessary to establish mass balance (Brown and Goodman, 1988; Bonner et al., 2003). As a corollary to Section 3.1, experience in establishing a mass balance is a requirement for a tank facility. Again there are no shortcuts to this and staff experience is needed.

3.3 Previous Wave Energy Studies

Just as experience in analysis and mass balance is necessary, experience in calibrating the tank's wave-makers and measuring their energy is a necessary consideration (Bonner et al., 2003). This saves time and cost and is also required because the energy regime in the tank may not be repeatable or controllable, particularly with 'home-built' wave-makers. Such systems may produce highly variable results that may not be useful.

3.4 Certified Hydrocarbon Lab and Chemists Available

As stated in the literature, most governments and large organizations now require that any chemical measurements be conducted in certified laboratories with certified chemists using certified procedures (Fingas, 2002). This is necessary as oil measurements can easily be as much as 2 orders-of-magnitude away from the actual values. Certain oil analytical methods also have high variances and must be carefully implemented to ensure reliable results (CAEAL, 2003). Field methods are often highly variant and can be very misleading (see Section 1.6).

There are many certified labs with the required certified chemists, methods, and equipment to carry out trials. There is no reason not to use such services. It is suggested that the laboratory be close to the facility so samples do not have to be transported over long distances. Analysis must generally be carried out within 24 to 48 hours. Volatile hydrocarbon samples are notoriously difficult to preserve and maintain over longer periods of time.

3.5 Personnel Experienced in Sampling Measurements

As complicated as the mass balance calculations can be, the measurements leading to them are even more difficult. Staff at the facility must be experienced in performing the measurements as they are very subject to error when implemented (Goodman and Fingas, 1988; Louchouart et al., 2000; Fingas and Ka'ahue, 2004b). Chemical sampling should be performed by chemists familiar with the techniques and subsequent analysis so that samples are correctly handled (Fingas, 2002).

3.6 Appropriate Volume of Water

The tank in which experiments are conducted should contain at least 20 to 200 m³ and no more than 2000 to 5000 m³ of water. A tank that is too small may not result in representative values and is barely larger than some of the larger vessels in labs. A tank that is too large will result in severe cleaning and purification problems. A large tank must be cleaned after a maximum of 3 or 4 tests and small tanks must be cleaned after each test. In addition, either sophisticated cleaning techniques are required to remove the dispersant or the water must be completely renewed.

3.7 Readily Accessible Site

The tank facility must be conveniently accessible. Facilities that are not located near major airports can be costly in terms of lost time and extra transportation costs. Tanks located at a distance from the client can also be extremely costly in terms of transportation.

3.8 Flexible Scheduling

It must be ensured from the outset that the prospective tank has flexibility in scheduling. If the schedule is so tight that only a small time window can be booked months in advance, difficulties could arise in meeting the test dates. Scheduling may also depend on the weather, with some flex time required to ensure that suitable weather conditions coincide with the testing.

4. Description of the Tanks

The specifications of the tanks of interest to this study are given in Table 2 and those that either meet or almost meet the requirements are summarized in Table 3. Contact information for the tanks is provided in Table 4.

4.1 Tanks Meeting the Basic Requirements

4.1.1 Texas A&M SERF Tank or COSS

The Texas A&M tank began as a facility to study the nearshore dispersion of oil spills (Reilly et al., 1994; Kitchen et al., 1997; Aurand et al., 1999). The tank was first named the COSS facility, which stands for the Coastal Oilspill Simulation System and was later renamed SERF for Shoreline Environmental Research Facility. The facility has nine tanks, each 33.5 m long by 2.1 m wide and 2.4 m deep, with a typical water depth of 2 m. A typical tank is shown in Figure 1 and an overview of the facility is shown in Figure 2.

All tanks are equipped with 2 by 2 m computer-controlled wave generators with vast capabilities. The maximum wave height produced is about 0.6 m. A wave-absorbing assembly behind the wave generators prevents wave reflection from the back wall. Each tank also has inlets and outlets that simulate tides ranging up to 0.6 m when the tank is filled to a depth of 2 m. The testing period can be varied from 4 to 24 hours. It can be arranged to have additional water flushed through the system.

The SERF facility is equipped with a sophisticated water re-circulation system that includes oil measurement capabilities. Water can be treated to remove oil before it is discharged. At the present time, water is not temperature-controlled, but a design has been completed to add both water and air temperature control to one or more test cells (Bonner, 2005). Although this facility was built specifically to study nearshore dispersion, the shoreline is optional and can be replaced with artificial wave-absorbing beaches.

Scientists at the facility have worked for several years to develop mass balances for the facility and have closed the gap in lost oil to about 10%. Researchers started with a mass balance of about 70% loss. Several test methods were developed to perform this (Bonner et al., 2003; Cheng et al. 1999). Nevertheless, there are special problems in trying to achieve a mass balance at SERF. First, in one of its most common operating modes, it has a beach that can take up as much as 30% of the tank's volume. In one test, it was found that the beach retained 49% of the oil placed into the tank system (Page et al., 1999). The amount of oil in the sediments was determined by extracting the oil from the sand and then using standard methods for hydrocarbon analysis. The water was added as a flow-through and most of the oil passed through the system when chemical dispersants were used. A system was established of integrating hydrocarbons in the outflow (Bonner et al., 2003).

Determining mass balance also includes measuring the amount of oil on the surface and walls of the tank. New methods were developed for doing this. For the tank walls, 12 strips (80 by 2 cm) of polymer tank lining were placed on the walls (Page et al., 2000b). Two strips were designated as pre-oiled baseline, two were sampled at 0.5 hours after the start of the experiment, and the remaining 8 were used at the end of the experiment. It was found that oil on the walls could account for a significant amount of the oil mass balance. Two techniques were used to determine the surface oil. A new technique was developed using a Solid Phase Extraction (SPE) disk to quickly take a sample of oil from the surface (Louchouart et al., 2000; Kitchen et al.,

1997). A special skimmer called the Surf Cleaner was used to collect the remaining surface oil (Bonner et al., 2003).

Two factors are also necessary to study dispersants, the energy and the scaling of the system (Bonner et al., 2003; Page et al., 1998, 2000a). The results of the hydrodynamic study are published in these latter two references.

A significant part of the SERF tank's work has also been to study toxicity (Fuller et al., 1999, 2000; Fuller and Bonner, 2001). Organisms have been placed in cages in the tank and the tests run. For dispersant tests, the dispersant was pre-mixed with the oil. Shoreline cleaners were evaluated for toxicity in a similar manner (Fuller et al., 2000) For shoreline cleaning agents, a 1.8 by 1.5 m area on the beach was used. Tests were run up to one week, with the oil allowed to weather for up to one day on the beach test section.

4.1.2 EPA/BIO Tank at Bedford Institute of Oceanography

A facility was recently built at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, Canada specifically to study oil spill dispersants. The inside and outside of this tank are shown in Figures 3 and 4. The tank is 16 m long by 0.6 m wide and 2 m deep, with a typical water depth of 1.2 m (Kelifa, private communication, 2005). This small amount of water is used so that the water can be changed quickly by pumping from the adjacent Bedford Basin, which is connected to the Atlantic Ocean by Halifax Harbour.

An air bubble curtain beside the walls minimizes contact with the surface. The wave-generator is a flapper-type, computer-controlled precision device that can be programmed for a variety of breaking or non-breaking waves. The tank has a flow-through capability that can be used to simulate the diffusion of the sea.

The tank is new and, at the time of preparation of this report, did not have many runs with real oil and dispersant. It is recommended that use of this facility be delayed until further studies are carried out at the site.

4.2. Tanks Almost Meeting the Requirements

4.2.1 OHMSETT

OHMSETT (Oil and Hazardous Simulated Environmental Test Tank) was built as a tow tank to test booms and advancing skimmers (Mullin and Lane, 2000; Ross et al., 2000, 2001). It is a large tank, 203 m long, 20 m wide, and 3.4 m high, with a typical water depth of 32.4 m. The facility is shown in Figures 5 and 6.

This tank typically contains about 9,600 m³ of brackish water pumped from the nearby bay. Salt must be added to raise the salinity from 13 to 15 o/oo to a typical sea salinity of 33 o/oo. The facility is equipped with a bridge that moves at up to 3 m/s and can be attached to two other bridges on the tank. There is an adjacent meeting room, a shop, and a small lab but no detailed oil analysis capability is available at the facility. The tank must be accessed under high security conditions as OHMSETT is located on Naval Weapons Station Earle in New Jersey.

Some dispersant tests have been carried out at the site, using an area of about 18 by 50 m, which is about 20% of the tank's total water volume or surface area. Oil was applied from the main bridge at a speed of 1 km/h and dispersant sprayed at the back of the bridge. There is about a 10-second delay in applying dispersant. These tests have been criticized for lack of mass balance and certain types of measurements, for conducting repeated tests without cleaning, and

for using hot oil sprayed on the surface.

For cold-water tests, cooling systems were rented to chill the water to -1 to +4°C. Belore (2003) reports on a first series of tests in cold water at OHMSETT. A rectangular containment boom was set out and oil sprayed onto the area. A dispersant spray boom applied oil at various ratios behind the towing bridge. The oil was heated to enable flow. A series of heating coils maintained the water at temperatures of about -1°C. The average wave amplitude varied from 16.5 to 22.5 cm and the average period between 1.7 and 1.9 seconds. No mass balance was done and dispersant effectiveness was estimated based on the amount of oil recovered. Some fluorescence measurements were taken but were not used to provide quantitative input.

Owens and Belore (2004) report on a series of qualitative tests carried out at OHMSETT. Ice blocks of approximately 0.6 by 0.6 m and ice fragments were placed into boom circles 3 m in diameter. Fields consisting of 100% blocks, 50% blocks, and 50% fragments and 100% fragments were created to represent brash ice. Wave energy was applied at a 17 cm average wave height and 5.5 second period for 30 minutes. A second wave type of 33 cm average wave height and 4 second wave period was applied for 30 minutes. A third lower energy of 15 cm wave height with a period of 6 seconds was applied. As the lower energy did not cause any visual dispersion effects, it was not used further. Oil left in the rings was collected and used to estimate the total amount of oil remaining in the boom. No mass balance was carried out and no quantitative measures such as water column oil concentration or estimations of oil escaping under the boom were carried out. A series of 18 tests were carried out using Hibernia, Alaska North Slope, and Cayvo crude oils, both fresh and weathered. A nominal oil thickness of 2 mm was used in all tests.

Mullin (2004) reports on two series of tests conducted from 2002 to 2003, for a total of 26 experiments. The experiments were conducted in a similar manner to those described above. Mullin also describes the use of a powdered activated carbon filter to remove the dispersant from the water. Two to three days are required to reduce surfactant concentrations down so that the indicator parameter of surface tension is low enough. Ross et al. (2000, 2001) noted that a dispersant concentration as low as a few ppm in the water was enough to cause dramatic effects. For example, a concentration of only 5 to 10 ppm caused a reduction in oil interfacial tension and 50 ppm caused a reduction of 40 to 50% in interfacial tension. The authors conclude that even small concentrations of dispersant in water are unacceptable for testing conventional equipment. It was noted, however, that surfactant concentrations up to 400 ppm would not change dispersant effectiveness. This was based on some testing in the Warren Springs apparatus which was not described in detail (Ross et al., 2001). It was also noted that each OHMSETT test of the type described above would add 10 ppm of surfactant to the tank. They noted that 2 to 4 experiments could be conducted in a row without surfactant effects.

Ross et al. (2000, 2001) also reported on tests to remove surfactant from the OHMSETT water. They found that the product currently used for filtration, Diatomite FW-20, did not remove Corexit 9500 from the water. Better results were obtained with the cellulose filter air, Preco-Floc PB-100, which removed 50 to 60% of the Corexit 9500. Large-scale tests, however, showed that the cellulose filter aid was not effective. Bench-scale tests on carbon showed that 90 to 100% of the dispersant could be removed using activated charcoal.

When using a facility as large as OHMSETT, the problems of controlling variables are greatly increased. Because of the exposed surface, surface winds become a problem and oil can

readily be wind-herded to the site even during one test. The salinity control requires that several tons of salt must be added to raise it to 33 o/oo. Very large refrigeration equipment is needed to cool the tank and it takes several days to drain and refill the tank when the water is changed.

Several relevant studies have been carried out at OHMSETT. Fingas et al. (2003) and Fingas and Fieldhouse (2003) carried out a series of water-in-oil emulsification experiments, during which many wave spectra were taken using the sonic sensor aboard the bridge. These data show that the spectra vary widely in the tank, even with the same wave settings. The reasons for this were noted as being reflection from the wave target end as well as from the wall behind the wave generator. Wind was also found to be an important factor.

4.2.2 Ocean Engineering Facilities at Texas A&M, College Station

The tank at the Ocean Engineering Facility at Texas A&M, College Station in Texas is of interest for testing dispersants. This tank, which has already been used for oil spill studies, has glass walls and is 40 m long, 0.7 m wide, and 1 m deep. The tank is shown in Figure 7.

4.3 Tanks Used for Dispersant Tests But No Longer Available

Several previous works examined dispersant phenomena using tanks that no longer exist. This information can nevertheless provide some guidance on future tank testing.

4.3.1 Esso/Imperial Oil Test Tank

The Esso Tank in Calgary was the first large tank to be used to test dispersant effectiveness. The tank is 55 m long, 31 m wide, and 3.3 m deep up to a shallow portion of 1.9 m (Brown and Goodman, 1988, 1996; Brown et al., 1985, 1986, 1987). Figure 8 shows the tank being used for a dispersant test. A computer-controlled wave generator produced waves of up to 0.3 m and could be programmed to produce regular or irregular waves. An artificial beach was used to absorb wave energy.

While dispersant tests were done in a variety of ways, after extensive experimentation, a circular boom was used to maintain the oil at an appropriate thickness and hydrocarbon content was monitored using fluorometers. A particle-size analyzer was also used to measure the size of the oil droplets in the water column. The oil concentration was continuously monitored during an experiment by four or five flow-through fluorometers. At about 7 intervals, physical samples were withdrawn and extracted and concentrations were compared to standard dissolved amounts. It should be noted that this is no longer an acceptable method of calibration as it has been found that composition changes (Lambert et al., 2001b). The dispersed oil contains much more fluorescent material as a weight percentage than does the starting oil. Thus a simple comparison of a dispersed oil to the whole oil would result in an exaggeration of the amount of oil in the water column.

A seamless 10-m diameter circular boom was used to contain the oil at enough thickness before applying dispersant from a spray boom that passed in an arc over the oil. The nozzles on the spray boom were the same type as those on a full-size spray boom. The spray droplet size was monitored during initial setups and the pump pressure adjusted to ensure droplets were less than 1 mm. The wave generator was started after the oil was dispersed. Various mixing times were tried from 3 hours up to 24 hours. It was found that more than 3 hours were required to yield a more or less homogeneous oil concentration throughout the tank. Concentrations peaked

at about 1 hour after the dispersant application.

The group also conducted dispersion tests with ice present (Brown and Goodman, 1996). The group found that the presence of ice actually increased dispersant effectiveness, probably because of enhanced energy at microscales when wave energy causes ice to move and additional energy is imparted to the surface by this ice movement. Both brash ice and oil-in-leads were simulated. Using surface recovery methods doubled the estimates of effectiveness compared to those derived from fluorometry measurements.

The following are the group's findings about testing dispersants in tanks.

- a) Larger wave energies (0.2 m or more) were required to achieve dispersion.
- b) Little dispersion was achieved at lower wave energies (0.1 m or smaller).
- c) Long mixing times (>3 hours) were necessary to achieve a more homogeneous concentration of oil throughout the tank.
- d) Oil concentration peaked at about one hour and then fell.
- e) The estimated dispersant effectiveness corresponded to the oil concentration, that is if calculated at one hour, the effectiveness was greater than that calculated earlier or later.
- f) Significant amounts of oil re-surfaced after the one hour time, even with continued mixing.
- g) Due to the high surfactant content, only about 3 tests could be done in the tank before the water had to be replaced.
- h) Twenty-four hour effectiveness values on a light oil ranged from 6 to 33% dispersed. At the 3-hour mark, the effectiveness was approximately twice this. Dispersant effectiveness has to be defined as a function of the time it was estimated.
- i) Mass balance is difficult to achieve, but with effort, up to about 80% of the oil can be accounted for.
- j) The oil concentrations in the water column are very heterogeneous as is any remaining surface oil.
- k) Oil remaining on the surface is not easy to recover and recovered amounts cannot be used to accurately gauge effectiveness.
- i) Measuring the concentration of oil in the water column provides the most accurate measurement of dispersant effectiveness.
- j) While measurements should include oil on the surface, on tank surfaces, etc., these measurements are difficult to take and may not be accurate.
- k) Extensive measurements of the oil in the water column, as well as on the water surface and tank walls, are required to achieve a more accurate mass balance due to the heterogeneity of the samples.
- l) High dispersant dosage (> 0.03 O/D or 1:33) is required to yield measurable effectiveness. The more dispersant used, the more effectiveness is achieved.
- m) Most dispersant activity occurs 30 to 60 minutes after application. In test tanks, however, measurements at these times are prone to error due to the lack of sufficient mixing time.

4.3.2 Delft Hydraulics Test Flume

Delvigne (1985, 1994) of the Delft Hydraulics Laboratory (1984a, 1984b) reports on the facility set up in that laboratory to study chemical and natural dispersion. The first larger scale,

e.g., above laboratory-scale, tests were conducted at this facility. The flume was 15 m long, 0.5 m wide, and with a maximum water depth of 0.6 m. The tank was constructed of glass or resistoplast-coated steel so that oil would not adhere to the walls and affect the experiments. A precision wave-generator provided irregular or regular waves up to a maximum height of 0.2 m, as well as breaking waves. A flow circuit created a flow velocity of up to 0.8 m/s through the flume. A 4-m long test section was located about 2/3 of the way between the wave generator and the wave damper at the other end. Sprayers for oil and dispersant were held in a cart above the flume. The spray distance could be up to 3 m above the flume. The water could be varied from fresh to saline, although saline water was typically used. The flume was in a constant-temperature room of 16 to 17°C, but ice or warm water was added to adjust the temperature.

The flume was cleaned with hot water. The criterion set for cleanliness was that the surface tension of the water was to be 0.064 N/m compared to 0.071 for laboratory water.

Several measurements were routinely taken: wave pattern and orbital movement, current velocity, turbulence structure in the water mass, oil layer thickness, oil surface tension and oil-water interfacial tension, oil and dispersant viscosity, oil composition, oil concentration in the water column, droplet size of the dispersed oil, quantity of dispersant per unit area of slick, and droplet size distribution of the dispersant spray.

The following methods were used to accomplish these measurements.

Wave profile - a pressure transducer below the water surface

Water and wave velocity - Laser-doppler apparatus

Current velocity - current meter

Turbulence structure - Laser-Doppler apparatus

Oil layer thickness - Gauge needle hooked to ohmmeter

Interfacial tensions - Tensiometer

Viscosities - Viscometer

Oil composition - Gas chromatograph

Oil concentration in water - Infrared analysis after solvent extraction and also using laser beam absorption

Particle size - Malvern Laser Particle Size Analyzer - directly through flume

Dispersant amount - Sampling by cups and weighing

Dispersant particle size - Malvern laser instrument as above.

It is important to note the extensive nature of the measurements taken by Delvigne. These measurements were taken more than 20 years ago and most test tanks today are not capable of measuring these parameters in such detail. At that time, many of the techniques and instruments were very new. Some of these measurements could be performed with relative ease today, using new equipment. The data from this flume was used to develop a widely used natural dispersion model. The chemical dispersion data was relatively unused by others.

Most of these factors can be taken into consideration or problems avoided if the testing follows the extensive studies of the past. In particular, the tank test studies described by Brown et al. (1987) dealt with several of these issues and showed how dispersant effectiveness could be measured in a test tank.

The calibration of tank hydrodynamics and calculation of mass balance are also dealt with extensively in Bonner et al. (2003). The suggested method is that the fresh, unweathered oil be

placed in the test tank and allowed to weather for 12 to 24 hours. The oil should be contained only to enhance contact, not as an analytical method. After the oil is placed, dispersant is applied at the desired ratio. Approximately 6 hours after the application, a series of fluorometers are run through the tank at depths of about 1 m apart and at various spacings across the cross-section. Discrete water samples are then taken from the fluorometers and the exact readings of the fluorometer recording (best done electronically) during the time that samples are taken. These samples are then correctly preserved and analyzed for total petroleum hydrocarbons (TPH). The calibration curve for the fluorometer is derived from these measurements. It is important that sampling, preservation, and analysis be done using certified methods, by certified chemists, and in certified labs.

The 6-hour sampling data are compared to the 24-hour sampling data that are taken in exactly the same manner. The effectiveness is then estimated from integration at the 24-hour mark. The 3-hour sample period is for checking and would be conducted only in the first test or two.

After the 24-hour period, the oil on the surface is driven to one corner where it is recovered with a skimmer for weighing. Elastol is occasionally used to assist in recovering the surfactant-treated oil. A mass balance is then achieved by comparing the oil recovered in the whole tank, the amount estimated on the walls, and the amount in the water column. The oil in the water column is the only amount dispersed. The mass balance is used to judge the validity of the particular run and not the effectiveness of a specific dispersant.

The tank filtration system is turned off during the experiment and is turned on only after the surface oil is recovered. Only about 4 experiments can be done before all the water must be changed due to the presence of surfactants.

The wave maker is left on for the full 24 hours.

The hydrocarbon background is determined in the same way as the dispersant concentration just before the dispersant experiment.

4.4 Small Tanks

4.4.1 Environment Canada Equipment Testing Tank

Since 1987, Environment Canada has had a 30 m³ tank for testing oil spill equipment and related products (Cooper, 2005). It was used occasionally for testing dispersants in its early years. The tank is 8.5 m long, 3 m wide, and 1.2 m deep with a false floor covering two drive units, which provide a current of up to 1.5 knots. A wave-maker can be placed in the tank and provides waves up to 0.2 m high. A steel walkway around the tank is used for dealing with equipment and a moveable bridge can be used to access equipment or take samples. Fresh water is typically used in the tank, although salt water has also been used. The facility is close to certified hydrocarbon laboratories and has a lot of equipment, including separators, that is used to conduct a variety of testing. A skimmer test being conducted in this tank is shown in Figure 9.

4.4.2 CEDRE Polludrome

Another elliptical flume is located at the Cedre SINTEF facility in Brest, France (Guyomarch et al., 1999a, b, 2002). The circumference is 12 m with a 6-m major axis. The flume is 0.6 m wide and 1 m deep. The water is circulated around the tank. The Polludrome is equipped with a tank to supply water for simulated tidal cycles and has a straight section in which a model

shoreline can be placed. The tank is used primarily for weathering studies but has been used for several dispersant studies. A settling tank at this facility is shown in Figure 10.

4.4.3 SINTEF Elliptical Flume

The SINTEF facility in Trondheim, Norway is equipped with an elliptical flume. Its circumference is 9 m with a 4-m major axis. The flume is 0.5 m wide and 0.4 m deep. The water is circulated around the tank. This tank is used primarily for weathering studies.

4.4.4 SL Ross Tank

The SL Ross tank in Ottawa, Ontario, Canada is 11 m long and 1.2 m wide (Belore, 1985, 1986, 1987). A simple paddle wave generation system is located at one end and a wave-dissipating beach is located at the other end. The paddle wave generator is connected to a variable speed motor to adjust wave periods. Dispersant spray booms and other measuring equipment are located on a cart and can be towed over the tank. Dispersant can also be applied with an overhead swinging boom. The facility uses an air-bubble system to contain oil to a central region. During dispersant trials, the oil is confined to about 1/8 of the surface area. Water samples can be taken from the tank through three ports 15 cm, 40 cm, and 65 cm below the surface. An observation window is located in the same area as the sampling ports.

Belore (2002) describes the use of the tank to test the effectiveness of Corexit 9500 on Hibernia oils at temperatures of 0 to 1°C. The tank was filled to a depth of 0.85 m of 32 o/oo salt water. A refrigeration unit maintained water temperature and insulation was also added to the tank. Oil remaining at the end of the test was sorbed and weighed to estimate dispersant effectiveness.

4.4.5 INRS-Oceanologie Dispersant Testing Tank

A meso-scale simulator, modelled after the MacKay laboratory apparatus was built in Rimouski by the Institute for Research on Water (Pelletier et al., 1987). The energy was imparted using the same method as the MacKay test, that of a high-velocity air flow. A series of dispersant tests were conducted in the tank including effectiveness, biodegradation, and weathering tests. Seawater was drawn from the St. Lawrence estuary and the unit was maintained at low temperatures ranging from -1.7 to 7°C. This tank was disassembled in the late 1980s.

4.4.6 Other Large-scale Tests

Godon and Milgram examined the potential of mixing dispersant directly into ship tanks using a tank that measured 1.2 m² and up to 2.4 m deep, for a maximum volume of 3,500 L (Godon and Milgram, 1986). The study may be applicable to testing dispersant in water studies as the mixing parameters are developed for large scale.

4.5 Additional Information on Tank Testing

It is important during any experiment to alter only one variable at a time. Otherwise, the outcome may be a result of the combination of the inputs, leading to confusion as to the effect of a given variable.

The experiences of Bonner et al. (2003) show that there are major losses of oil in three areas that have not been previously considered in performing a mass balance and which can account for over 50% of the oil loss in certain cases. These are adhesion to walls, adhesion to sediments, and formation of invisible slicks. Methods for measuring each of these oil losses were developed and

applied. The adhesion to the walls was measured by placing strips of wall material into the test tank and later removing and quantifying the oil on these strips. It was noted that the age and conditions of these strips were important as the more weathered strips would hold more oil than the newer, unweathered strips.

Bonner et al. (2003) noted that the sediment, even that from the apparently clean tank bottom, must be collected and oil content measured. Oil in thin slicks was measured using a solid-phase extraction disk held by vacuum to retain both the disk and oil adhered to the disk.

Scaling of wave energy is another distinct issue (Bonner et al., 2003). Dispersant effectiveness is largely affected by energy inputs and therefore it is important to scale and control this in a test tank. In the laboratory, energy input to the dispersant/oil mixture can be very tightly controlled, but it can be highly variable in a test tank and subject to influences such as winds. Bonner et al. (2002) provide mathematical tests of energy scaling and means to estimate wave reflection, which is another source of variability.

The use of containment while dispersant effectiveness is being measured in a test tank should be reviewed. Containment undoubtedly increases the turbulent energy at the boundary between contained and uncontained oil. Since this would not occur at sea or in most laboratory tests, this extra high energy may result in atypical results.

4.6 Other Tanks

Some tanks show promise for further research. Of particular interest are the tanks at the University of New Hampshire, one of which is shown in Figure 11. The respondents to the inquiry indicated that this might be used for oil spill experiments. The Oregon State large-wave flume, which is shown in Figure 16, is of particular interest. The remaining questions on this tank relate to filtration, salinity, and fouling. The tanks at the National Research Council in St. John's, Newfoundland, as shown in Figures 19 and 20, also have potential. These tanks were used for oil tests some time ago and thus some knowledge and capability does exist. The ice tank at the Hamburg Ship Building Centre, which is shown in Figures 28 and 29, is another tank that has been used for oil tests and may have potential (Wessels, 1992). However, logistics would certainly be a problem with this tank. One final tank worthy of mention is the environmental tank at VWS in Berlin, which is especially designed for testing oil and hazardous materials. This tank is shown in Figure 38.

5. Summary and Recommendations

In summary, this report reviewed the following basic considerations of tank testing.

1. Mass balance

Mass balance should be calculated and maintained in the best way possible. Because of the difficulty in accounting for all the oil, the oil not accounted for should not be taken as an indicator of dispersant effectiveness. In past experiments, the oil unaccounted for ranged from -20% (over-accounted) to over 80%. In one set of experiments, Brown et al. (1987) showed that a lack of mass balance would exaggerate apparent effectiveness on average by a factor of 4 times.

2. Proper controls

Dispersant effectiveness must always be directly related to an identical test, preferably conducted at the same time under identical conditions as the test with dispersants. It should be noted that dispersants cause other changes in oil behaviour and a simple comparison to an untreated control may not be valid.

3. Energy measurement and calculation

Turbulent and non-turbulent energy are the most important parameters when measuring the effectiveness of oil spill dispersants. These important variables must therefore be measured and controlled in the tank that is used. The concepts of energy are reviewed in this report and ways that energy can be measured and characterized are summarized.

4. Scaling of energy and waves

The scaling of energy and waves in the test tank to the target energy and waves in the sea is another topic related to energy. As a full-scale representation of at-sea waves or sea energy is inappropriate, scaling must take place. Bonner et al. (2003) developed a scaling equation that relates waves in a test tank to those at sea.

5. Wave reflection

A major problem in tanks is that the reflection of waves from tank ends produces a complex interference pattern which in turn produces inconsistent and often undesired waves. Installing absorbing structures at both ends is one possible solution.

6. Analytical methods

There are few analytical methods that can be directly applied outside the laboratory. Fluorometry is one of these but the instrument must be calibrated using standard sample analysis taken at the same time in the field. Furthermore, this calibration must be carried out using certified methods by a certified chemist in a certified laboratory.

7. Differential plume movement

The geometry and movement of the dispersed oil plume are different than that of the surface slick and the surface slick cannot be used to guide sampling of the dispersed oil plume.

8. Time lag and length of time plume followed

There is a time lag of 15 to 90 minutes before significant dispersion takes place. Furthermore, because of resurfacing of oil, the plume loses oil over a 2-day period. These dynamics must be considered in designing experiments.

9. Mathematics of calculation and integration

It has been shown that several errors can be made in integration. Averages should not be used over wide areas and only the specific dispersant plume should be integrated.

10. Lower and upper limits of analytical methods

The analytical methods used must have the dynamic range to cover background levels to the peak dispersant plume value, generally from 0.1 to 100 ppm.

11. Measuring thickness

As there are no valid and reliable techniques for measuring the thickness of surface oil, any value is an estimation and may easily be wrong by an order-of-magnitude. This makes it difficult to perform mass balance on the basis of surface measurements. Thin slick quantities have been estimated using specially developed techniques (Bonner et al., 2003).

12. Behaviour of oil with surfactant content

Oil with surfactant content behaves differently than oil without. The critical containment velocity of such oil is much less and its adhesion to sorbent-surface skimming devices is poor. If containment is used near critical velocity, the oil is simply released after dispersant treatment, not dispersed.

13. Surfactant stripping

Surfactants partition out of the oil droplets over time, de-stabilizing the dispersed droplets and causing oil to resurface. This occurs slowly and possibly over a wide area. Furthermore, slicks

resulting from this phenomena are probably not thick enough to be observed.

14. Recovering surface oil

There are a number of problems in recovering surface oil to calculate mass balance, including the loss of sheen, invisible sheen, and evaporation loss. The surfactants also cause poor adhesion. Using a recovery-enhancer can assist in obtaining a large percentage of the oil.

15. Background levels of hydrocarbons

The background levels of hydrocarbons must be used to correct measurements. The levels may vary widely and should be treated with the same caution as actual data.

16. Fluorescence of dispersant

The dispersant itself yields a fluorescent value, sometimes as much as 5 ppm. This is largely due to light scattering in the Turner fluorometer and should be corrected for.

17. Herding

Herding of oil occurs when larger droplets break through the slick and the surface pressure of the dispersant pushes oil aside. Herding is a major interference in conducting dispersant field trials and should be considered in tank tests.

18. Heterogeneity of slick and plume

Neither the slick nor the plume are homogeneous in distribution and concentration. This must be taken into account in the field trial. Taking measurements over small spatial areas will improve the quality of the final result.

19. True analytical standards

There are certified labs using certified methods with chemists certified to take these measurements. These and certified analytical standards should be used to make the measurements.

20. Weathering of the oil

Dispersant effectiveness drops off significantly as the oil weathers. Tank tests of dispersants should use oil that is weathered to such a degree that it approximates actual conditions.

21. Salinity

As noted in several studies, salinity is very important to the resulting dispersant effectiveness. Adding salt may provide the control to increase salinity, although saline water can only be readily discharged in areas close to the sea. It is easier to control salinity in a smaller tank.

22. Temperature

As was noted, the temperature of the water and the air above should approximate the target test temperatures. Solar heating of the oil should be avoided by conducting the experiment immediately after oil deposition or by carrying out the test during cloudy conditions.

Although there are many test tanks available, only a few meet the basic requirements outlined in this report. Others may be able to meet the specifications by changing their procedures, especially those related to dealing with a soiled tank. The following are the basic requirements for tank facilities that are to be used for testing oil spill dispersants.

1. Ability to filter or renew tank water

Each time a dispersant test is conducted, a large amount of the dispersant rapidly enters the water column. After a day or two, most of the dispersant is in the water column. The water in the tank therefore requires high-performance filtration after at least 3 experiments, and ideally, after each experiment. While the water in the tank could be replaced, the discharged water may have to be filtered to lower than the 15 ppm discharge limits.

2. Ability to use the tank to conduct experiments

There may be other impediments to using a tank for testing dispersants, including political

ones. Clearance from local and state authorities may therefore be needed before proceeding.

3. Ability to apply dispersants and take measurements

To conduct dispersant trials, the water surface in the tank must be accessible so that oil and dispersant can be applied and measurements taken. There must also be access to laboratories within a reasonable distance or time.

4. Availability of wave-making apparatus

As waves and turbulent energy are critical to dispersant effectiveness, a precision, repeatable wave-making apparatus must be available at the facility.

5. Ability to calculate mass balance.

The tank facility should have the capability to calculate mass balance. If this has not already been done, it could take up to 4 years to accomplish.

6. Ability to control or manipulate water temperature

The temperature of the water must be controlled within a degree or two to achieve repeatable results. In addition, the air temperature above the oil must be maintained within a certain range of the desired water temperature.

7. Ability to run tests under different salinities

Salinities of between 20 and 33 o/oo are required to mimic open-sea conditions. The tank must be capable of holding and disposing of saline water.

The following additional features are also desirable.

8. Proven track record of conducting high quality measurements

It takes years to develop the expertise required to take quality measurements. Only those facilities that have this reputation should be considered.

9. Previous mass balance calculations

In addition to having the capability to calculate the mass balance, the facility should also have a track record of actually performing these measurements.

10. Previous wave energy studies

Wave energy studies are as complex as mass balance studies and require experience and expertise to ensure accuracy. These studies should have been previously carried out at a tank facility in order for that facility to be considered for testing dispersants.

11. Personnel experienced in sampling measurements

Personnel at the facility must have enough specialized training and years of experience to carry out the many complicated measurements required.

12. Certified hydrocarbon lab and chemists available

Governments now require that submitted data be sampled and measured by certified chemists in certified laboratories using certified procedures. Such a facility is best located at or very near the tank.

13. Appropriate volume of water

A tank can be too small or too large for a given purpose. It is suggested that 20 to 200 m³ be the lowest size and 2000 to 5000 m³ the largest size of tank to be considered for testing dispersants.

14. Readily accessible site

Public transportation should be available to the facility so that it is readily accessible to the users.

15. Flexible scheduling

Flexibility in scheduling is required to cope with varying weather conditions and other seasonable variables.

The facilities that meet most of the criteria are the Texas A&M SERF tank at Corpus Christi (previously called COSS or Coastal Oil Studies System) and, to a lesser degree, the new EPA/BIO tank at Dartmouth, Nova Scotia.

The SERF tank has been studied over the years with respect to establishing mass balance, energy levels, and several other factors. The tanks at this facility were specially built to study nearshore dispersant usage and have many features relevant to the Prince William Sound Regional Citizens' Advisory Council. These features include nine parallel tanks so that experiments can be conducted simultaneously, extensive water treatment facilities, an adjoining laboratory, and high-precision wave generators. Disadvantages include the narrowness of the tanks, the lack of built-in water temperature control, and the location in the south. It should be added, however, that a design for a climate-controlled facility has been completed. The latter two disadvantages might be overcome by running experiments in the winter and using cooling systems to maintain water temperature at the target levels. SERF is the only facility that would be ready to go for dispersant testing according to the requirements noted in this report.

The new EPA/BIO tank at Dartmouth will also be of interest to the PWSRCAC as it is built especially for dispersant testing. An advantage of this facility is its location close to the sea, ideal for drawing water and with cold water and air available several times during the year. The facility is adjacent to the Bedford Institute of Oceanography (BIO) with immediate access to oil laboratories and experts in many fields. As the facility is new, however, calibration, testing, and establishment of basic parameters will have to be completed before credible results can be produced. The tank is also quite small – smaller than some of the 'small' facilities listed in this study.

Some tanks studied and discussed here almost meet the requirements, including OHMSETT, which is well known, and the Ocean Engineering Facility at Texas A&M in College Station. While this latter tank has been used for testing oil, it may not meet a number of the other requirements noted in this report.

While a number of small tanks are used fairly regularly for testing oil and dispersants, these facilities lack good characterization and don't meet several of the other requirements noted in this paper. These smaller tanks would be easier to bring to full service than a larger tank, but it could take several months to several years to do this. They are therefore not recommended as a first choice as the effort required to bring these tanks up to standard would be better put into a larger facility.

Sixty tanks are listed here. More than 100 tanks were found in the literature and Internet search. The most significant ones are listed and summarized and the tanks of particular interest are noted. It should be added that caution must be exercised in using any of these tanks as it could take years and extensive work and cost to establish mass balances, conduct wave energy studies, and establish procedures to clean the tank or replace the water.

Other tanks of particular interest are the tanks at the University of New Hampshire as described in Table 2 and illustrated in Figure 11. The respondents to the inquiry indicated that this might be used for oil spill experiments. The Oregon State large-wave flume is also of particular interest (shown in Figure 16). The remaining questions on this tank relate to filtration, salinity, and fouling. The tanks at the National Research Council in St. John's, Newfoundland, as shown in Figures 19 and 20, also have potential as they were used to test oil quite some time ago. The ice tank at the Hamburg Ship Building Centre has been used to test oil and may have potential for testing dispersants. One final tank worthy of mention is the environmental tank at VWS (Berlin Model Basin) in Germany, which is especially designed for testing oil and hazardous material. This tank is shown in Figure 38.

In summary, the best option for testing dispersants at this time is the SERF facility at Corpus Christi, Texas. The test time and conditions could be adjusted to suit the climatic conditions and cooling units could be installed to maintain temperature.

6. References

Aurand, D., G. Coelho, J. Clark and G. Bragin, "Goals, Objectives and Design of a Mesocosm Experiment on the Environmental Consequences of Nearshore Dispersant Use", in *Proceedings of the Twenty-second Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 629-643, 1999.

Belore R., "Effectiveness of the Repeat Application of Chemical Dispersants on Oil", *Environmental Studies Revolving Fund*, Report No. 6, National Energy Board, Calgary, AB, 30 p, 1985.

Belore, R., "Large-scale Laboratory Studies of Dispersant Effectiveness, Application and Mixing", in *Proceedings of the Ninth Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 527-542, 1986.

Belore, R., "Mid-scale Testing of Dispersant Effectiveness", in *Proceedings of the Tenth Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 329-342, 1987.

Belore, R., "Wave Tank Tests to Determine the Effectiveness of Corexit 9500 Dispersant on Hibernia Crude Oil Under Cold Water Conditions", in *Proceedings of the Twenty-fifth Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 735-740, 2002.

Belore, R., "Large Wave Tank Dispersant Effectiveness Testing in Cold Water", in *Proceedings of the 2003 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 381-385, 2003.

Bocard, C., G. Castaing, J. Ducreux, C. Gatellier, J. Croquette and F. Merlin, "Summary of Protecmar Experiments, The French Dispersant Offshore Trials Program", *Oil and Chemical Pollution*, Vol. 3, pp 471-484, 1986/87.

Bonner, J., C. Page and C. Fuller, "Meso-Scale Testing and Development of Test Procedures to Maintain Mass Balance", *Marine Pollution Bulletin*, Vol. 47, no 9-12, pp. 406-414, 2003.

Bonner, J., Private Communication, 2005.

Boumeester, R.J.B. and R.B. Wallace, "Oil Entrainment by Breaking Waves" in *Proceedings of the Ninth Arctic and Marine Oilspill (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 39-49, 1986.

Brown, H.M. and R.H. Goodman, "Dispersant Tests in a Wave Basin: Four Years of Experience",

in *Proceedings of the Eleventh Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 501-514, 1988.

Brown, H.M. and R.H. Goodman, “The Use of Dispersants in Broken Ice”, in *Proceedings of the Nineteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp 453-460, 1996.

Brown, H.M., R.H. Goodman and G.P. Canevari, “Dispersant Effectiveness in Cold Water”, in *Proceedings of the Eighth Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 245-259, 1985.

Brown, H.M., N.M. To and R.H. Goodman, “Experimental and Theoretical Basin Studies of Dispersant Effectiveness in Cold Water”, in *Proceedings of the Ninth Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 635-651, 1986.

Brown, H.M., R.H. Goodman and G.P. Canevari, “Where Has All the Oil Gone? Dispersed Oil Detection in a Wave Basin and at Sea”, in *Proceedings of the 1987 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 307-312, 1987.

CAEAL, “Standard Method for Oil TPH Analysis”, Canadian Association of Environmental Analysis Laboratories, Toronto, ON, 2003.

Cheng, C.Y., A. Ernest, R. Aguilar and J.S. Bonner, “Materials Balance on a Chemically-Dispersed Oil and a Whole Oil Exposed to an Experimental Beach Front”, in *Proceedings of the Twenty-second Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 645-658, 1999.

Cooper, D., K. Volchek, S. Cathum, H. Peng and J. Lane, “Trace Dispersant Detection and Removal”, in *Proceedings of the Twenty-sixth Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 799-812, 2003.

Cooper, D., Private Communication, 2005.

Davidson, P.A., “Was Loitsyansky Correct? A Review of the Arguments”, *Journal of Turbulence*, Vol. 1, pp 1-14, 2000.

Delft Hydraulics Laboratory, “Laboratory Facility for the Simulation of the Natural and Chemical Dispersion of Oil”, M1933-2, Delft, The Netherlands, 88 p, 1984a.

Delft Hydraulics Laboratory, “A Series of Flume Experiments on the Natural and Chemical Dispersion of Oil”, M1933-3, Delft, The Netherlands, 72 p, 1984b.

Delvigne, G.A.L., “Experiments on Natural and Chemical Dispersion of Oil in Laboratory and Field Circumstances”, in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 507-514, 1985.

Delvigne, G.A.L., “Natural and Chemical Dispersion of Oil”, *Journal of Advanced Marine Technology Conference*, Vol. 11, pp 23-40, 1994.

Dickins, D. and L. Solsberg, “An Evaluation of Canadian Towing Tanks and Manoeuvring Basins as Substitute Test Facilities for OHMSETT”, Manuscript Report prepared for Environment Canada and U.S. Minerals Management Service, 1989.

Fingas, M.F., “Field Measurement of Effectiveness: Historical Review and Examination of Analytical Methods”, in *Oil Dispersants: New Ecological Approaches*, STP 1018, L.M. Flaherty (ed.), American Society for Testing and Materials, Philadelphia, PA, pp 157-178, 1989.

Fingas, M.F., “Use of Surfactants for Environmental Applications”, in *Surfactants: Fundamentals and Applications to the Petroleum Industry*, Laurier L. Schramm, (ed.), Chapter 12, Cambridge University Press, pp 461-539, 2000.

Fingas, M.F., “A White Paper on Oil Spill Dispersant Field Testing”, Prince William Sound Regional Citizens' Advisory Council (PWSRCAC) Report, Anchorage, AK, 40 p., 2002.

Fingas, M.F., “Energy and Work in Laboratory Vessels”, in *Proceedings of the Twenty-seventh Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 1-18, 2004.

Fingas, M.F. and B. Fieldhouse, “Studies of the Formation Process of Water-in-Oil Emulsions”, *Marine Pollution Bulletin*, Vol. 47, pp 369-396, 2003.

Fingas, M.F. and L. Ka’aihue, “Dispersant Tank Testing - A Review of Procedures and Considerations”, in *Proceedings of the Twenty-seventh Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 1003-1016, 2004a.

Fingas, M.F. and L. Ka’aihue, “Review of Monitoring Protocols for Dispersant Effectiveness”, in *Proceedings of the Twenty-seventh Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 977-1002, 2004b.

Fingas, M.F. and L. Ka’aihue, “Literature Review of the Variation of Dispersant Effectiveness with Salinity”, in *Proceedings of the Twenty-eighth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 1043-1084, 2005.

Fingas, M.F., B. Fieldhouse, L. Sigouin, Z. Wang and J. Mullin, “Dispersant Effectiveness Testing: Laboratory Studies of Fresh and Weathered Oils”, in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 551-556, 2001.

Fingas, M.F., L. Sigouin, Z. Wang and G. Thouin, “Resurfacing of Oil with Time in the Swirling Flask”, in *Proceedings of the Twenty-fifth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 773-783, 2002.

Fingas, M.F., B. Fieldhouse and Z., Wang, “The Long Term Weathering of Water-in-Oil Emulsions”, *Spill Science and Technology Bulletin*, Vol. 8, No. 2, pp 137-143, 2003.

Fuller, C. and J.S. Bonner, “Comparative Toxicity of Oil, Dispersant and Dispersed Oil to Texas Marine Species”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 1243-1241, 2001.

Fuller, C., J. Bonner, T. McDonald, G. Bragin, J. Clark, D. Aurand, A. Hernandez and A. Ernest, “Comparative Toxicity of Simulated Beach Sediments Impacted With Both Whole and Chemical Dispersions of Weathered Arabian Medium Crude Oil”, in *Proceedings of the Twenty-second Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 659-670, 1999.

Fuller, C., J. Bonner, S. Dellamea, S. Ussery, P. Tissot, P. Louchouart, C. Page and T. McDonald, “Ecological Evaluation of Shoreline Cleaners Used on Oiled Mesocosm Sandy Beaches”, in *Proceedings of the Twenty-third Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 795-803, 2000.

Gill, S.D., R.H. Goodman and J. Swiss, “Halifax '83 Sea Trial of Oil Spill Dispersant Concentrates”, in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 479-482, 1985.

Godon, A. and J.H. Milgram, “In-Tank Mixing Study”, in *Proceedings of the Ninth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 543-562, 1986.

Goodman, R.H. and M.F. Fingas, “The Use of Remote Sensing in the Determination of Dispersant Effectiveness”, *Spill Technology Newsletter*, Vol. 13, No. 3, pp 55-58, 1988.

Guyomarch, J., O. Kerfourn and F.-X. Merlin, “Dispersants and Demulsifiers: Studies in the Laboratory, Harbour and Polludrome”, in *Proceedings of the 1999 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 195-202, 1999a.

Guyomarch, J., F.-X. Merlin and S. Colin, “Study of the Feasibility of Chemical Dispersion of Viscous Oils and Water-in-Oil Emulsions”, in *Proceedings of the Twenty-second Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 219-230, 1999b.

Guyomarch, J., E. Mamaca, M. Champs and F.-X. Merlin, “Oil Weathering and Dispersibility Studies: Laboratory, Flume, Mesocosms and Field Experiments”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, pp 166-177, 2002.

Heimenz, P.C. and R. Rajagopalan, *Principles of Colloid and Surface Chemistry*, Marcel Dekker, Inc., New York, NY, 1997.

Johnson, B., *International Towing Tank Conference: ITTC Symbols and Terminology List*, U.S. Naval Academy, Annapolis, MD, 1997.

Kelifa, A., Private Communication, March 15, 2005.

Kitchen, R.B., J.S. Bonner, R.L. P. Tissot, T.J. McDonald, C.B. Fuller and C. Page, “Quantitative Determination of Oil Films/Slicks from Water Surfaces Using a Modified Solid-phase Extraction (SPE) Sampling Method”, in *Proceedings of the Twentieth Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 1327-1407, 1997.

Lambert, P., B. Fieldhouse, Z. Wang, M.F. Fingas, M. Goldthorp, L. Pearson and E. Collazzi, “Preliminary Results from the Laboratory Study of a Flow-through Fluorometer for Measuring Oil-in-water Levels”, in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 69-98, 2000.

Lambert, P., M. Goldthorp, B. Fieldhouse, Z. Wang, M. Fingas, L. Pearson and E. Collazzi, “A Review of Oil-in-Water Monitoring Techniques”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 1375-1380, 2001a.

Lambert, P., B. Fieldhouse, Z. Wang, M. Fingas, M. Goldthorp, L. Pearson and E. Collazzi, “A Laboratory Study of Flow-through Fluorometer for Measuring Oil-in-Water Levels”, in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 23-45, 2001b.

Lee, C.M. and K.H. Kang, “Prediction of Oil Boom Performance in Currents and Waves”, *Advanced Fluids Engineering Research Centre*, Phang, Korea, 24 p, 1997.

Louchouart, P., J.S. Bonner, P. Tissot, T.J. McDonald, C. Fuller and C. Page, “Quantitative Determination of Oil Films/Slicks from Water Surfaces Using a Modified Solid-phase Extraction (SPE) Sampling Method”, in *Proceedings of the Twenty-third Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 59-68, 2000a.

Louchouart, J.S. Bonner, R.L. Autenrieth, K.C. Donnelly and A.N. Ernest, “Introducing COSS: A New and Unique Oil Spill Research Facility”, in *Proceedings of the Twenty-third Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 59-68, 2000b.

Lunel, T., “Dispersion of a Large Experimental Slick by Aerial Application of Dispersant”, in *Proceedings of the Seventeenth Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 951-966, 1994a.

- Lunel, T., “Field Trials to Determine Quantified Estimates of Dispersant Efficiency at Sea”, in *Proceedings of the Seventeenth Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 1011-1021, 1994b.
- Mellor, G., “The Three-Dimensional Current and Surface Wave Equations”, *Journal of Physical Oceanography*, Vol. 33, pp 1978-1989, 2003.
- Merlin, F., C. Bocard and G. Castaing, “Optimization of Dispersant Application, Especially by Ship”, in *Proceedings of the 1989 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 337-342, 1989.
- Mullin, J.V. “Dispersant Effectiveness Experiments Conducted on Alaska and Canadian Crude Oils in Very Cold Water”, in *Proceedings of Interspill 2004*, 17 p, 2004.
- Mullin, J.V. and J.A. Lane, “R&D Users Guide to the OHMSETT Oil Spill Response Test Facility”, *Spill Science and Technology*, Vol. 6, p 77-87, 2000.
- Owens, C.K. and R.S. Belore, “Dispersant Effectiveness Testing in Cold Water and Brash Ice”, in *Proceedings of the Twenty-seventh Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 819-841, 2004.
- Page, C., P. Sumner, R. Autenrieth, J. Bonner and T. McDonald, “Hydrodynamic Characterization of the COSS (Coastal Oil Spill Simulation System)”, in *Proceedings of the Twenty-first Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 89-99, 1998.
- Page, C., P. Sumner, R. Autenrieth, J. Bonner and T. McDonald, “Materials Balance on a Chemically-Dispersed Oil and a Whole Oil Exposed to an Experimental Beach Front”, in *Proceedings of the Twenty-second Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 645-658, 1999.
- Page, C.A., J.S. Bonner, P.L. Sumner, T.J. McDonald, R.L. Autenrieth and C.B. Fuller, “Behaviour of a Chemically-Dispersed Oil and a Whole Oil on a Near-Shore Environment”, *Water Research*, Vol. 34, pp 2507-2516, 2000a.
- Page, C., C. Fuller, R. Autenrieth, J. Bonner, P. Louchouart, P. Tissot and T. McDonald, “Materials Balance on an Oil Washed from a Sandy Substrate Using Shoreline Cleaners”, in *Proceedings of the Twenty-third Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 697-708, 2000b.
- Payne, J.R., T. Reilly, R.J. Martrano, G.P. Lindblom, M.H. Kennicutt II and J.M. Brooks, “Spill of Opportunity Testing of Dispersant Effectiveness at the *Mega Borg* Oil Spill”, in *Proceedings of the 1993 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 791-793, 1993.

Pelletier, E., C. Brochu, J.E. Desnoyers and J.H. Vandermeulen, “The Effects of Chemical Dispersion on Long-term Weathering of Crude Oil in Cold Seawater”, in *Proceedings of Oceans 87*, Halifax, NS, pp 1620-1623, 1987.

Price, S.J., D. Sumner, J.G. Smith, K. Leong and M.P. Paidoussis, “Flow Visualization Around a Circular Cylinder Near to a Plane Wall”, *Journal of Fluids and Structures*, Vol. 16, pp 175-191, 2002.

Reilly, T.J., N.C. Kraus, W.R. Wise and R. Jamail, “COSS: A Mesoscale Test Bed for Nearshore Spill Research”, *Spill Science and Technology*, Vol. 1, pp 165-167, 1994.

Ross, S.L., I.A. Buist, S.G. Potter and R.C. Belore, “Feasibility of Using OHMSETT for Dispersant Testing and Research”, in *Proceedings of the Twenty-third Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 709-731, 2000.

Ross, S., I. Buist, S. Potter, R. Belore and A. Lewis, “Dispersant Testing of OHMSETT: Feasibility Study and Preliminary Testing”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 461-466, 2001.

SAIC, “Process for the Removal of Spent Oil Spill Dispersants from Test Water at the National Oil Spill Response Test Facility”, Report for the United States Department of the Interior, Minerals Management Service, Herndon, VA, 37 p, March, 2003.

Swiss, J.J., N. Vanderkooy, S.D. Gill, R.H. Goodman and H.M. Brown, “Beaufort Sea Oil Spill Dispersant Trial”, in *Proceedings of the Tenth Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 307-328, 1987.

Tanahashi, M., S. Iwase and T. Miyauchi, “Appearance and Alignment with Strain Rate of Coherent Fine Scale Eddies in Turbulent Mixing Layers”, *Journal of Turbulence*, Vol. 2, pp 1-17, 2001.

Tissot, P., C. Fuller, P. Louchouart, J. Bonner, S. Dellamea and D. Bujnoch, “Quantitative Method for Surface Oil Measurement and Recovery Based on a New Type of Low Impact Skimmer”, in *Proceedings of the Twenty-third Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 353-366, 2000.

Wessels, E., “New Test Basin for Experimental Studies on Oil Spills in Ice”, in *Proceedings of the Fifteenth Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp 271-279, 1992.

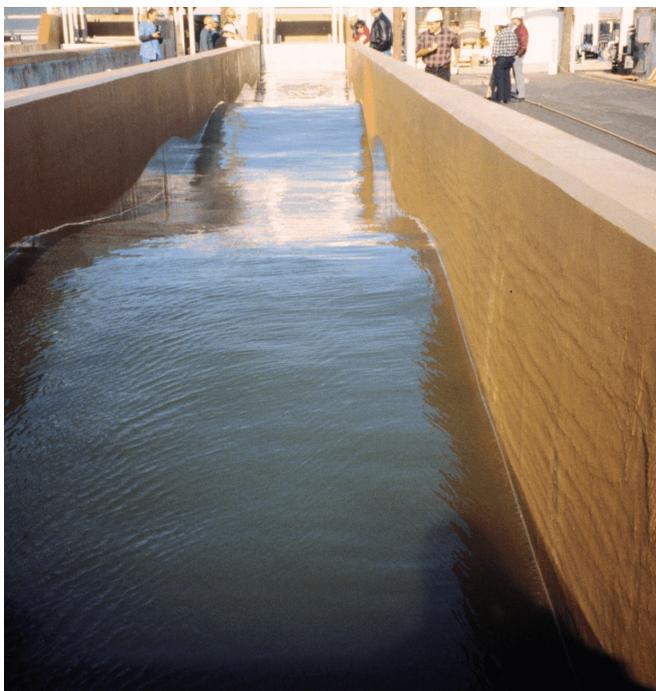


Figure 1 Waves in the SERF facility at Corpus Christi, Texas



Figure 2 The SERF facility - The nine test tanks are visible at the top of the photo, the laboratory is the white building below the tanks, and the upright tanks are the oily water treatment vessels.



Figure 3 EPA/BIO tank at Bedford, Nova Scotia

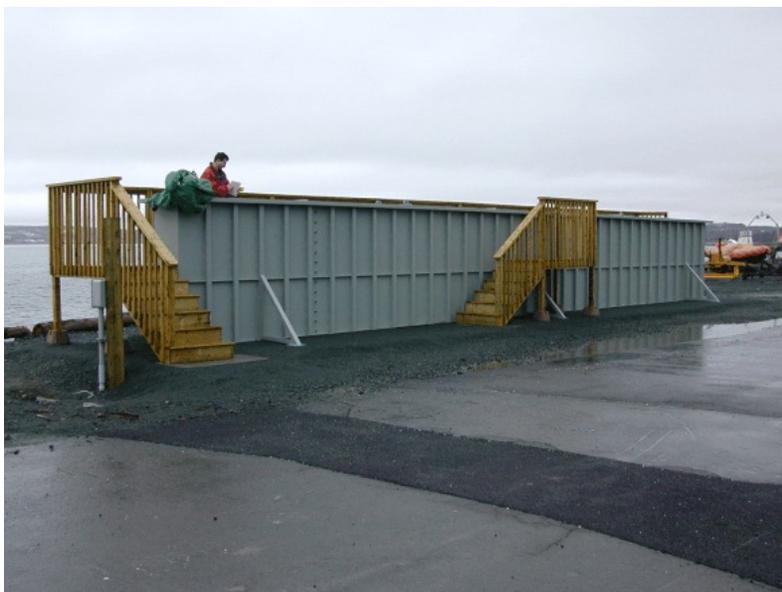


Figure 4 Exterior of the EPA/BIO tank



Figure 5 Testing in circular booms being conducted at the OHMSETT tank. The towed bridge is used to discharge oil and take samples.



Figure 6 Overhead view of the OHMSETT facility



Figure 7 Glass-walled wind-wave tank at Texas A&M in College Station, Texas

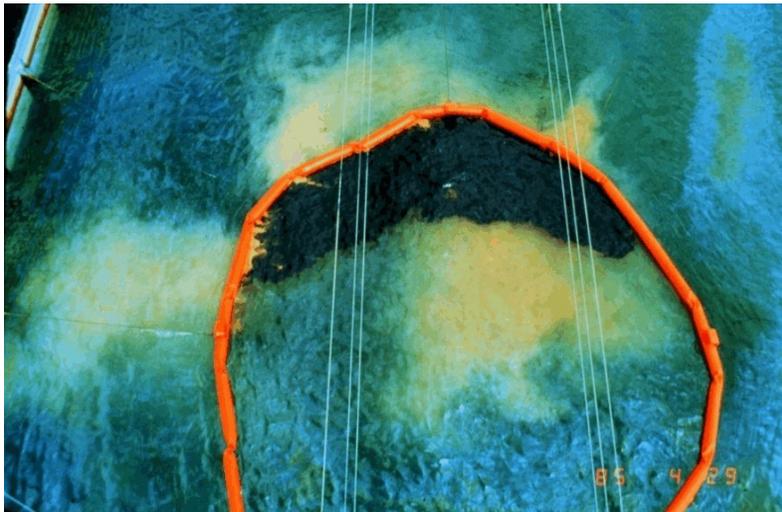


Figure 8 A dispersant test underway at the Imperial test tank in Calgary, Alberta. This tank has since been demolished.



Figure 9 A skimmer being tested at Environment Canada's test tank.



Figure 10 Settling tanks at the Polludrome tank at CEDRE, Brest, France

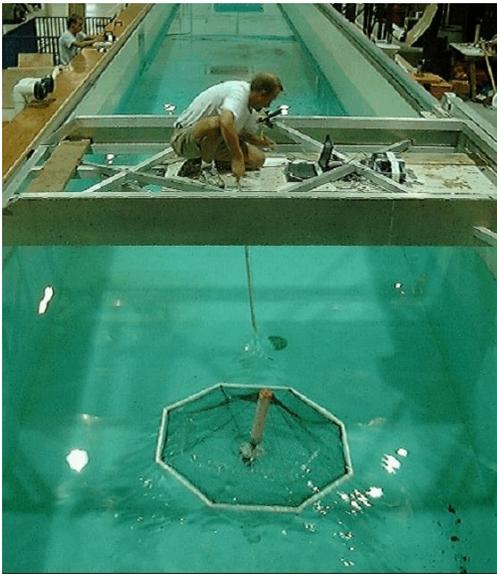


Figure 11 The tow/wave tank at the University of New Hampshire



Figure 12 The Iowa ice basin and tow tank in operation



Figure 13 The Iowa State tow tank, which is 100 m long.



Figure 14 The wave-generator at Texas A&M wave tank in College Station



Figure 15 Oregon State circular wave generation facility



Figure 16 Oregon State large wave flume. This tank may be a candidate for dispersant testing.

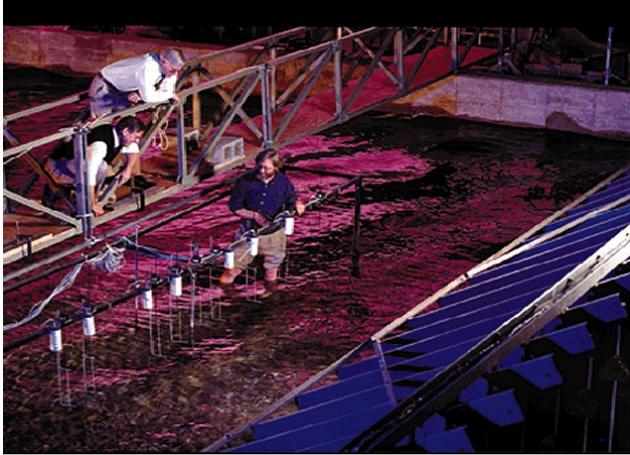


Figure 17 The University of Delaware wave tank



Figure 18 A tow tank at the U.S. Naval Academy. Tow tanks are often used to study ship models



Figure 19 An ice tank at the National Research Council in St. John's, Newfoundland



Figure 20 A tow tank at the National Research Council in St. John's, Newfoundland



Figure 21 The Ocean Engineering Basin in St. John's, Newfoundland



Figure 22 A wave at the National Research Council test tank in Ottawa, Ontario



Figure 23 The Engineering Wave Basin at the National Research Council in Ottawa, Ontario



Figure 24 The Vizon tow tank in Vancouver, British Columbia.



Figure 25 A large flume at the Delft facility in the Netherlands



Figure 26 A glass-lined flume at Delft

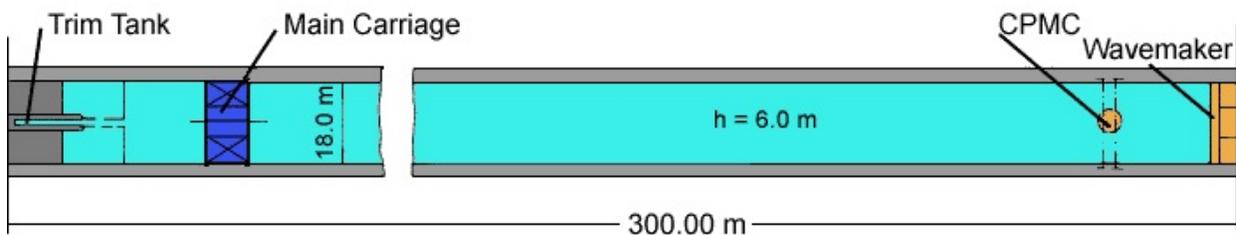


Figure 27 Schematic of the large tow tank at the Hamburg Shipbuilding Facility



Figure 28 Montage of photographs of the Hamburg ice tank. The photo at right shows an oil skimmer being tested.

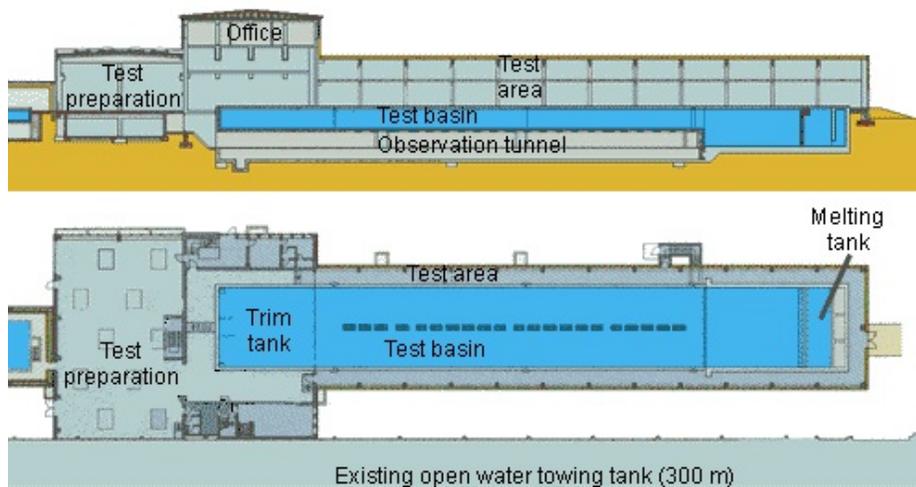


Figure 29 Schematic of the Hamburg large tank for ice testing



Figure 30 The tow tank at INSEAN, Italy. At 470 m, this is the longest tank of its type.

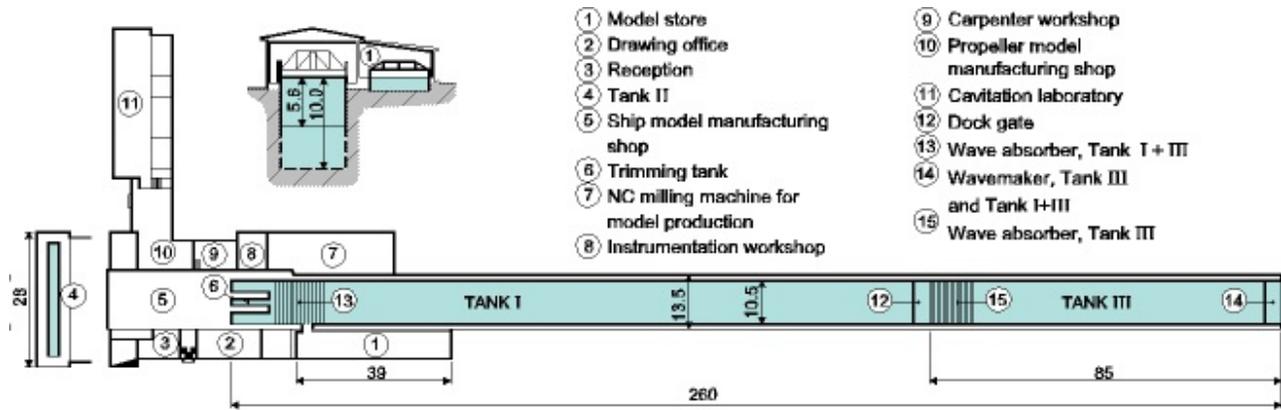


Figure 31 Tandem tow tank schematics at SINTEF in Norway



Figure 32 The Marintek deep wave basin in Brest, France



Figure 33 The tow tank at the National Marine Institute in Japan. This tank has the largest water volume of its type.



Figure 34 A 150-m tow tank at the National Marine Institute in Japan



Figure 35 A square wave basin at the National Marine Institute in Japan



Figure 36 A tow tank at VWS in Berlin



Figure 37 Tilting oil flume at VWS in Berlin



Figure 38 Environmental tank at VWS in Berlin. This tank is used to test behaviour and cleanup of oil and other hazardous materials.

Table 2 Summary of Tank Specifications																			
Basic Specifications							Wave Generator							Lab					
Facility	Location	Total Water Volume (m ³)	Length (m)	Width (m)	Water Depth (m)	Tank Height (m)	Tank Type	Notes	Water Type	Potential for Dispersant Use	Type	Wave Range	Breaking waves?	Max. Run Length	Wave Absorbers	Oil Lab	Certifiable	Phys. Meas.	Avail.
Ocean Engineering Program	College Station, TX	50	38	1	1.3		Wave tank	Glass-walled and bridge		3									
Ocean Engineering Program	College Station, TX	310	58	1.6	3.3		Tow tank	Moveable bridge		4		Up to 0.6 m	Yes						
Ocean Engineering Program	College Station, TX	220	28	10	0.8		Wave tank	Moveable bridge	Can also generate currents	4									
Oregon State	Corvallis, Oregon	1800	104	3.7	4.6		Wave flume	Bridge		4	Hydraulic ram	Up to 1.6 m	Yes	Cannot use for roll					
University of	Newark, DE	400	20	20	1.1		Wave basin			4	Elemental								
University of	Newark, DE	20	33	0.6	0.76		Wave tank			4									
US Naval Academy	Annapolis, MA	9800	124	15.2	5.2		Tow tank	Moveable bridge		4									
US Naval Academy	Annapolis, MA	200	40	2.6	1.8		Tow tank	Moveable bridge		4									
US Naval Academy	Annapolis, MA	100	14	16	0.6		Test tank			4									
Canadian Tanks																			
National Water Institute	Burlington, ON	1600	122	5	2.7		Tow tank			4									
National Water Institute	Burlington, ON	600	103	4.5	1.25		Wind-wave flume			4									
National Water Institute	Burlington, ON	46000	3.6	3.6	3.6		Special tank			2	Can be used for roll			Observation windows on all sides					
NRC	St. John's, NF	10800	90	10	12		Ice tank	In refrigerated room		4	Multi-segmented			Cannot use for roll					
NRC	St. John's, NF	16800	200	12	7		Tow tank	Bridge		4		Up to 1 m	Yes	Cannot use for roll					
NRC	St. John's, NF	7700	75	32	3.2		Engineering basin	Recirculating system		4		Up to 0.8 m	Yes	Cannot use for roll					
NRC	Ottawa, ON	500	97	2	2.7		Wave flume	Moveable bridge		3		Up to 1.1 m	Have carried out oil tests before, but salt cannot be used						
NRC	Ottawa, ON	4500	50	30	3		Wave basin	Structure test		4	60-segment	Up to 2 m	Have carried out oil before, but salt cannot be used						
NRC	Ottawa, ON	1300	63	14	1.5		Wave basin	Coastal engineering		4		Up to 0.5 m	Have carried out oil before, but salt cannot be used						
NRC	Ottawa, ON	100	63	1.2	1.2		Wave flume			3		Up to 0.35 m	Have carried out oil before, but salt cannot be used						
Ocean Engineering Research Centre	St. John's, NF	500	58	3	3	4	Tow tank	Moveable bridge		3									
Vancouver Soc	Vancouver, BC	600	67	3.7	2.4		Tow tank	Bridge		4		Up to 0.25 m							
Vancouver Soc	Vancouver, BC	1900	30	26	2.4		Major engineering basin			4		Up to 0.25 m							

Table 2 Summary of Tank Specifications																			
Facility	Basic Specifications						Tank Height (m)	Tank Type	Notes	Water Type	Potential for Dispersant Use	Wave Generator					Lab		
	Location	Total Water Volume (m ³)	Length (m)	Width (m)	Water Depth (m)	Wave Type						Wave Range	Breaking waves?	Max Run Length	Wave Absorbers	Oil Lab	Certifiable	Phys Meas	Avail
VISION SciTec	Vancouver, BC	200	67	4	0.75		Tow tank				+								
Overseas Tanks																			
DeM Hydraulics	DeM, Holland	8400	240	5	7		Tow tank	Moveable bridge			+	Paddle	Up to 2.5 m	Yes		Yes			
DeM Hydraulics	DeM, Holland	100	56	1	1.2		Flume	Wave-compensating			+	Compensating	Up to 0.4 m	Yes		Yes			
DeM Hydraulics	DeM, Holland	1200	40	40	0.75		Basin				+	80-element	Up to 0.35 m	Yes		Yes			
HSVA	Hamburg, Germany	32400	300	18	6		Tow tank	Bridge	Fresh		+		Up to 0.5 m	Yes		Yes			
HSVA	Hamburg, Germany	2730	78	10	3.5	Depth varies from 2.5 to 5 m	Ice tank	Has been used for oil	Fresh		3	2 m/hour freezing rate							
HSVA	Hamburg, Germany	270	30	6	1.5	Circular flume	Environmental test tank	Has been used for oil	Fresh to brackish		3	Has oil separator							
HSVA	Hamburg, Germany	1920	80	8	3	Turn-around	Tow tank	Bridge plus turn-around	Fresh		+		Up to 0.3 m	Yes		Yes			
INSEAN	Rome, Italy	41200	470	13.5	6.5	7	Tow tank	Moveable bridge up to 15 m/s			+								
Manoeuvring tank	Gosport, Hampshire, U.K.	40900	61	122	5.5		Test tank		Fresh		+	Elemental computer-controlled	Up to 0.2 m	Yes		Yes			
Marinlek-Sink 1	Trondheim, Norway	10300	175	10.5	5.6	Tank I	Tow tank	Tank land illare in tandem			+		Up to 0.3 m	Yes		Yes			
Marinlek-Sink 1	Trondheim, Norway	100	25	2.8	1	Tank II	Tow tank	All have bridges			+		Up to 0.9 m	Yes		Yes			
Marinlek-Sink 1	Trondheim, Norway	8900	85	10.5	10	Tank III	Tow tank	All have bridges			+		Up to 0.9 m	Yes		Yes			
Marinlek-Sink 1	Trondheim, Norway	37500	75	50	10		Ocean basin				+		Up to 0.9 m	Yes		Yes			
METRI	Brest, France	9700	50	12.5	15.5	Note: deep depths of 20 and 15	Deep wave pool	Moveable bridge and cranes			+		Up to 0.45 m						
METRI	Brest, France	600	50	4	3		Tow tank	Moveable bridge			+		Up to 0.45 m						
National Marine Research Institute	Japan	57600	400	18	8		Tow tank	Moveable bridge			+								
National Marine Research Institute	Japan	3900	150	7.5	3.5		Tow tank	Moveable bridge			+								
National Marine Research Institute	Japan	28800	80	80	4.5		Test tank				+								
VWS	Berlin, Germany	9600	250	8	4.8		Tow tank	Moveable bridge up to 12 m/s			+	Dual flap hydraulic	Up to 0.4 m	Yes		Yes			
VWS	Berlin, Germany	1100	120	8	1.1		Tow tank	Moveable bridge			+		Up to 0.12 m	Yes		Yes			
VWS	Berlin, Germany	30	25	1	1		Tilting oil flume	Moveable bridges	Closed water circuit for oil		3			Yes		Yes			

Table 3 Tanks Meeting or Almost Meeting Basic Requirements																	
Basic Requirements										Optional Features							
Facility	Location	Filter or Quick Refill	Ability to Use Tank	Ability to Conduct Application and Measurements	Wave-making Apparatus	Ability to do Mass Balance	Water Temperature Control	Ability to Run Salinities	Test Periods Up to One Day	Science Track Record	Mass Balance History	Technical Personnel	Oil Lab	Wave Energy Studies	Large Volume of Water	Readily Accessible	Scheduling
SERF	Corpus Christi, TX	both	yes	yes	yes	yes	possible	yes	yes	high	high	high	full	yes	medium	yes	relatively clear
EPABIO	Dartmouth, NS	refil	yes	yes	yes	yes	possible	yes	yes	new	new	new	full	yes	low	yes	relatively clear
Tanks almost meeting specifications																	
OHMSETT	Leonardo, NJ	no	yes	yes	yes	maybe	possible	yes	yes		none	some	no	no	yes	yes	relatively full
WWS, tilting oil-flume	Berlin, Germany	both	yes	yes	yes	maybe	possible	yes	yes			some		yes	medium	yes	relatively clear
WWS - Environmental test flume	Berlin, Germany	both	yes	yes	yes	maybe	possible	yes	yes			some		yes	medium	yes	relatively clear

Table 4 Summary of Tank Contacts							
Facility	Location	Alternate Name	Other Location Info	Web Site	Main Reference	Contact	E-mail
COEL	University of New Hampshire	Chase Ocean Engineering Laboratory		http://www.marine.unh.edu/		Andy McLeod	marine.information@unh.edu
EPA/BIO	Dartmouth, NS		Near BIO	http://www.dfo-mpo.gc.ca/science/booger-crepge/main_e.htm		Ken Lee	LeeK@mar.dfo-mpo.gc.ca
Florida Atlantic University	Boca Raton, FL			http://www.ocean.fau.edu/facilities/facility.html			
IHR	Iowa City, Iowa	University of Iowa		http://www.ihr.uiowa.edu/facilities/			ihr@uiowa.edu
Ocean Engineering Program	College Station, TX	Several tanks		http://edge.tamu.edu/aboutOE/aboutOEOme.htm#Facilities			lori@civil.tamu.edu
OHMSETT	Leonardo, NJ	Oil and Hazardous Materials Simulated Environmental Test Tank	One hour south of New York City	http://www.ohmsett.com/	Mullin, J.V. and J.A. Lane, "R&D Users Guide to the OHMSETT Oil Spill Response Test Facility", Spill Science and Technology, Vol. 6, pp. 77-87, 2000.	J. Mullin	joseph.mullin@mms.gov
Oregon State	Conallis, OR	Wave Research Laboratory		http://wave.oregonstate.edu/Research/		Daniel Cox	Daniel.Cox@orst.edu
Polludrome	Brest, France	CEDRE facility		http://www.le-cedre.fr/index_gb.html		Guyomarch	contact@cedre.fr
SAIC/EETO	Ottawa, ON			etc-cte.ec.gc.ca		D. Cooper	david.coop@saiccanada.com
SERF	Corpus Christi, TX			http://www.serftamus.edu/	Louchouart, J.S. Bonner, R.L. Autenrieth, K.C. Donnelly and A.N. Ernest, "Introducing COSS: A New and Unique Oil Spill Research Facility", in Proceedings of the Twenty-third Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, 0	C. Page	cpage@serftamus.edu
Sintef	Trondheim, Norway			http://www.sintef.no/static/ch/environmetlab/laboratory.htm		Per Daling	per.s.daling@sintef.no
SL Ross	Ottawa, ON			http://www.sloss.com/		R. Belore	info@sloss.com
University of Delaware	Newward, DE	Two tanks		http://www.coastal.udel.edu/facilities.html			kirby@udel.edu
US Naval Academy	Annapolis, MA	Several tanks		http://www.usna.edu/Hydrmechanics/		Mr. John Hill	jrhill@usna.edu
Facilities used for oil but no longer available							
NRC M42	Ottawa, ON	Manoeuvring basin			Dickins, D., and L. Solsberg, An Evaluation of Canadian Towing Tanks and Manoeuvring Basins as Substitute Test Facilities for OHMSETT, Manuscript Report prepared for Environment Canada and US Minerals Management Service, 1989.		

Table 4 Summary of Tank Contacts							
Facility	Location	Alternate Name	Other Location Info	Web Site	Main Reference	Contact	E-mail
Esso Tank	Calgary, AB	Manoeuvring Basin			Brown, H.M. and R.H. Goodman, "Dispersant Tests in a Wave Basin: Four Years of Experience", in Proceedings of the Eleventh Arctic Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, ON, pp 501-514, 1988.		
Other Facilities							
Delft Hydraulics	Delft, Holland	Several tanks		http://www.wldelft.nl/facil/			
HSVA	Hamburg, Germany	Several tanks		http://www.hs.va.de/			info@hs.va.de
INSEAN	Rome, Italy			http://www.insean.it/facilities/home.HTM			@insean.it
Manoeuvring tank	Gosport, Hampshire, U.K.			http://www.marine.gov.uk/		I. Grant	idgrant@dera.gov.uk
Marintek-Sintef	Trondheim, Norway	Several tanks		http://www.sintef.no/content/page3_44_2.asp			marintek@marintek.sintef.no
METRI	Brest, France	Several tanks	Part of Ifremer	http://www.ifremer.fr/metri/		Yvon Leguen	yvon.le.guen@ifremer.fr
National Marine Research Institute	Japan	Several tanks		http://www.nmri.go.jp/			info@nmri.go.jp
National Water Institute	Burlington, ON	Two tanks		http://www.nwri.ca/factsheets/rsbe.htm#fands			
NRC	St. Johns', NF	Several tanks	Institute for Ocean Technology	http://www.iot-ito.nrc-cnrc.gc.ca		Noel Murphy	noel.murphy@nrc-cnrc.gc.ca
NRC	Ottawa, ON	Several tanks		http://chc.nrc-cnrc.gc.ca/english/Coastal/Facilities/CTest_facilities_e.html		Andrew Cornett	Andrew.Cornett@nrc-cnrc.gc.ca
Ocean Engineering Research Centre	St. Johns', NF		At Memorial University	http://www.engr.mun.ca/research/centres/OERC/			
Vizon SciTec	Vancouver, BC	Several tanks	Formerly BC Research	http://www.vizonscitec.com/shipdynamics/default.htm			
WWS	Berlin, Germany	Several tanks	Technical University	http://www.tu-berlin.de/wws/			postbox@wws.tu-berlin.de
Wellenkanal	Hannover, Germany	Large wave channel (GWK)		http://sun1.rzn.uni-hannover.de/tzk/			office@tzk.uni-hannover.de

