Weather Windows for Oil Spill Countermeasures

for

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by

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Abstract

Oil spill countermeasures are affected by weather such that, in some cases, these countermeasures cannot continue under adverse weather conditions. A literature review was carried out to determine if there were data related to the performance of all countermeasure techniques under varying weather conditions. Although the literature did not provide any quantitative guides for the performance of countermeasures under varying weather conditions, data could be extracted to enable assessment of changes in their performance related to weather conditions. Many estimates or traditional limits are found in the literature, but these vary considerably and may not be useful.

Wind and wave height are the most important factors influencing countermeasures. These two factors are related and, given sufficient time for the sea to become 'fully-arisen', can be inter-converted. These factors must sometimes be considered separately, however, so that specific weather effects can be examined. Other weather conditions affecting countermeasures include currents and temperature. Currents are the critical factor for certain countermeasures such as booms. Temperature primarily affects the performance of dispersants and has been shown to have only minimal effect on other countermeasures. Formation of ice, however, is a problem with most countermeasures.

Booms are the type of countermeasures most susceptible to weather conditions. Conventional booms will fail at a current of 0.5 m/s (1 knot) regardless of the boom's design or other conditions. This is due to inherent hydrodynamic limitations. There is wave-associated degradation of this value which is dependent on design. Failure data for some typical booms are summarized.

Skimmers show degradation of recovery potential with increasing wave height and also with relative current. Skimmer performance is very specific to a given skimmer. A number of skimmer performance curves have been developed for this study. Some skimmers only function effectively in absolutely calm waters while others have recovered oil in sea states of up to 5 or 6 (wave heights of up to 3 m or 10 feet with corresponding winds of up to 15 m/s or 30 knots). Sufficient data exist to predict performance with waves and currents for over 30 specific skimmers and over 10 generic types. Advancing skimmers often recover more oil with increasing tow rate as this increases the encounter rate with the oil.

The weather affects dispersant application and effectiveness in three ways: the amount of dispersant that contacts the target is highly wind-dependent; the amount of oil dispersed is very dependent on ocean turbulence and other energy; and the amount of oil remaining in the water column is dependent on the same energy. Nomograms for relative dispersant effectiveness have been created. At high sea energies, natural dispersion is very much a factor for lighter oils.

The weather affects in-situ burning in two ways: the ability to ignite oil in a given wind and the ability to sustain ignition in a given wind. While there are few data on these, the probability of ignition was estimated based on prior experience.

The effects of weather on other countermeasure methods have been summarized.

Wind and Wave Conversion Nomogram

Wind Velocity				Beaufort Scale	Range (m/s)	Waves and a Fully-Arisen Sea		
m/s	knots	km/hr	mi/hr			Sea States	Wave Height m	ft
0	0	0	0					
1	2	3.5	2.2	1	.5-1.5	0	0	0.05
2.5	5	8.8	5.6	2	2-3	1	0.1	0.18
4.3	8.5	15.1	9.6	3	3-5		0	0.06
5	10	17.5	11.2			2	0.3	0.88
6	12	21	13.4	4	5.5-8		0.5	1.4
6.8	13.5	23.8	15.2				0.6	1.8
7	14	24.5	15.7			3	0.7	2
8	16	28	17.9				1	2.9
9	18	31.5	20.2	5	8.5-10.5	4	1.3	3.8
9.5	19	33.3	21.3				1.4	4.3
10	20	35	22.4			5	1.7	5
11	22	38.5	24.6	6	11-13		2.1	6.4
12	24	42	26.9				2.6	7.9
12.3	24.5	43.1	27.6			6	2.7	8.2
13	26	45.5	29.1				3.2	9.6
14	28	49	31.4	7	14-12.5		3.6	11
15	30	52.5	33.6			7	4.6	14
15.3	30.5	53.6	34.3				4.6	14
16	32	56	35.8				5.3	16
17	34	59.5	38.1	8			6.3	19
18	36	63	40.3				6.9	21
18.5	37	64.8	41.4				7.6	23
19	38	66.5	42.6				8.3	25
20	40	70	44.8			8	9.2	28
21	42	73.5	47	9			10.2	31
22	44	77	49.3				11.9	36
23	46	80.5	51.5			9	13.2	40
24	48	84	53.8	10			14.5	44
25	50	87.5	56				16.2	49
25.8	51.5	90.3	57.8				17.2	52
26	52	91	58.2				17.8	54
27	54	94.5	60.5				19.5	59
28	56	98	62.7	11			21.1	64
29.8	59.5	104.3	66.8				24.1	73
32	64	112	71.7	12			26.4	80

Water and Velocity Conversion Nomogram

m/s	knots	km/hr	miles/hour	feet/sec
0	0	0	0	0
0.1	0.2	0.3	0.2	0.3
0.2	0.4	0.8	0.4	0.7
0.3	0.6	1.1	0.7	1
0.4	0.8	1.4	0.9	1.3
0.5	1	1.8	1.1	1.6
0.6	1.2	2.2	1.3	2
0.7	1.4	2.6	1.6	2.3
0.8	1.6	2.9	1.8	2.6
0.9	1.8	3.3	2	3
1	2	3.7	2.2	3.3
1.1	2.2	4	2.5	3.6
1.2	2.4	4.3	2.7	3.9
1.3	2.6	4.8	2.9	4.3
1.4	2.8	5.1	3.1	4.6
1.5	3	5.4	3.4	4.9
1.6	3.2	5.8	3.6	5.2
1.7	3.4	6.2	3.8	5.6
1.8	3.6	6.6	4	5.9
1.9	3.8	6.9	4.3	6.2
2	4	7.3	4.5	6.6
2.1	4.2	7.7	4.7	6.9
2.2	4.4	8	4.9	7.2
2.3	4.6	8.3	5.1	7.5
2.4	4.8	8.8	5.4	7.9
2.5	5	9.1	5.6	8.2
2.6	5.2	9.4	5.8	8.5
2.7	5.4	9.9	6	8.9
2.8	5.6	10.2	6.3	9.2
2.9	5.8	10.6	6.5	9.5
3	6	10.9	6.7	9.8
3.1	6.2	11.3	6.9	10.2
3.2	6.4	11.7	7.2	10.5
3.3	6.6	12	7.4	10.8
3.4	6.8	12.3	7.6	11.1

List of Acronyms

ANS	Alaska North Slope - Usually refers to the crude oil mixture at the end of the pipeline
APSC	Alyeska Pipeline Service Company - The company that operates the Alyeska pipeline and the Valdez terminal
ASMB	Alberta Sweet Mixed Blend - A crude oil consisting of various low-in-sulphur crude oils
Corexit 9527	Brand name of a dispersant from Exxon
Corexit 9500	Brand name of a dispersant from Exxon
EPA	United States Environmental Protection Agency
IFO	Intermediate Fuel Oil - A mixture of Bunker C and diesel used for ship propulsion
IFP	The French Petroleum Institute - Usually used here as a description of their laboratory test
NOAA	National Oceanic and Atmospheric Administration (U.S.)
ORR	Oil recovery rate - The total oil recovered by a skimmer in a specified period of time, usually one hour
PWSRCAC	Prince William Sound Regional Citizens’ Advisory Council
RE	Recovery efficiency - The amount of oil recovered by a skimmer as a percent of the total fluid recovered
SERVS	Ship Escort Response Vessel System - A co-op operating in Prince William Sound
TE	Throughput efficiency - The percentage of oil recovered by a skimmer compared to the oil presented to the skimmer

Summary and Issues

Spill countermeasures are affected by weather conditions, often adversely. A literature review was carried out to determine if there were data related to the performance of all countermeasures under varying weather conditions. Although the literature did not show any quantitative guides for the performance of countermeasure techniques or equipment under varying weather conditions, data could be extracted to provide assessment of changes in performance with weather conditions. Many estimates or traditional limits are found in the literature, but these vary considerably and may not be useful. Examples of these estimates include statements that skimmers will not work in waves over 1 or 6 m (3 to 20 ft) and that burning cannot be carried out in winds over 10 m/s (20 knots). Many of these statements are completely without basis.

Wind and wave height are the most important factors influencing countermeasures. These two factors are related and, given a typical sea, can be inter-converted. Sometimes they must be considered separately, however, so that specific weather effects can be examined. Other weather conditions include currents and temperature. Currents are the critical factor for countermeasures such as booms. Temperature primarily affects dispersants and has been shown to have only minimal effect on other countermeasures, other than if icing occurs.

For each countermeasure, it was possible to find some performance data as it related to wind and waves. These data then allow for calculation of how the relative performance deteriorates or changes with increasing wind or relative current. These factors are then averaged to yield curves of performance change with increasing wind or current. This data is then used to predict when the performance of a particular technique reaches 50 or 25% of its initial value. These performance curves are summarized in Table 1. It should be emphasized that this table gives overall averages only and not specific unit performance, a factor that varies widely.

Table 1 **Summary Table of Performance Changes with Weather**

	Relative Change in Performance with:					
	Wave Height		**Current Speed**		**Wind**	
	50% value m	**25% value** m	**50% value** m/s	**25% value** m/s	**50% value** m/s	**25% value** m/s
Type of Countermeasure						
Typical booms	1.5	2	0.5	0.7	3	4
Harbour skimmers	1.5	2	0.6	1	7	10
Offshore skimmers	2.5	5	4	7	7	10
Fast current skimmers	2	4	5	8	10	15
Chemical dispersion					10 to 18	22
Ignition (probability of ignition reduction)					18	24

Booms are the countermeasures most susceptible to weather conditions. Booms will fail at a current of 0.5 m/s (1 knot) regardless of design, due to inherent hydrodynamic limitations. There is wave-associated degradation of this value which is dependent on design.

Skimmers show degradation of recovery potential with increasing wave height and also with relative current. Skimmer performance is very individual and a number of skimmer performance curves have been developed for this study. Some skimmers can only function effectively in absolutely calm waters while others have recovered oil in sea states of up to 5 or 6 (wave heights of up to 3 m or 18 feet with corresponding winds of up to 15 m/s or 30 knots). Sufficient data exist to predict performance with waves and currents for over 30 specific skimmers and over 10 generic types.

The weather affects dispersant application and effectiveness in three ways: the amount of dispersant that contacts the target is highly wind-dependent; the amount dispersed on the surface is very dependent on ocean turbulence and other energy; and the amount remaining in the water column is dependent on the same energy. Nomograms for relative effectiveness have been created. At high sea energies, many lighter oils can disperse naturally.

The weather affects in-situ burning in two ways: the ability to ignite oil in a given wind and the ability to sustain ignition in a given wind. Estimates were made based on prior experience.

Figure 1 shows the overall effects of wind on oil spill countermeasures. All values shown in the figure are relative values. Under optimal conditions, the relative value would be 100% times the specific effectiveness to yield an actual working effectiveness. Generally, increasing wind decreases relative effectiveness, although the relative chemical dispersion rises as more energy is available to disperse oil. When winds increase to over approximately 10 m/s (20 knots), chemical dispersion decreases as more and more dispersants are lost rather than deposited on the oil surface. Booms are the most affected by winds and current. Skimmers vary widely in their susceptibility to wind and waves.

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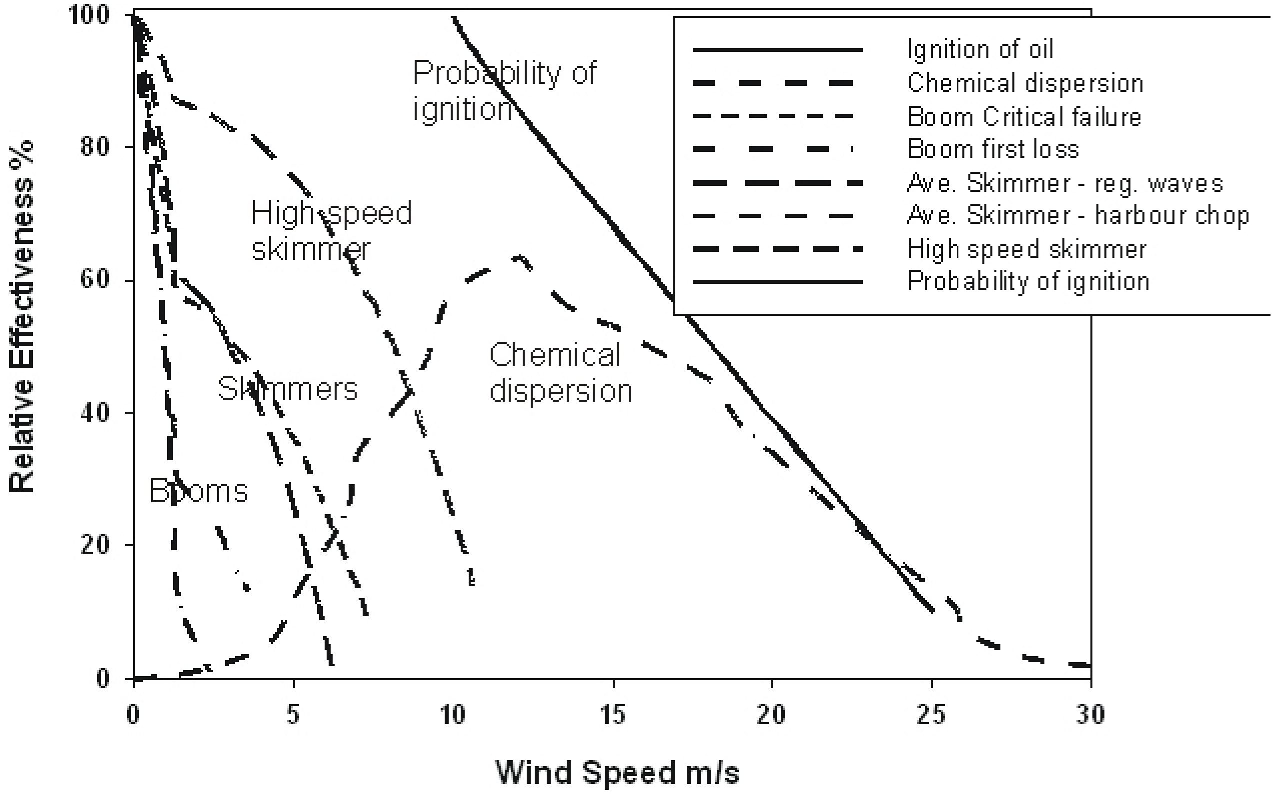

Figure 1 Summary of Wind Effects on Countermeasures

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1. Introduction

1.1 Objectives

The objectives of this report are to review the literature and develop an assessment of the effectiveness of oil spill countermeasures in relation to variations in weather and other environmental conditions.

1.2 Scope

This review covers the literature published up to November 2003. The study focuses primarily on literature related to issues of the effectiveness of oil spill countermeasures in relation to variations in weather and other environmental conditions.

1.3 Organization

The report begins with a summary of oil spill countermeasures and how they might be affected by weather. This is followed in turn with a specific review of data that is available. In Section 3, a summary is given of the development of simple models or estimation techniques for summarizing and predicting relative performance with weather conditions.

2. Review of Effectiveness of Countermeasures with Variations in Weather and Other Environmental Factors

2.1 Introduction

Weather has been recognized as one of the most important factors in predicting oil spill fate and behaviour (Lehr et al., 1999). Weather has not, however, been well recognized in designing oil spill countermeasures (API, 2000; Pearson, 2000).

The traditional concept of 'Windows of Opportunity', or other concepts similarly named, began with the topic of dispersants in about the mid-1990s. This concept largely related to the window of opportunity for dispersal as time progressed and the oil became more weathered and less dispersible. As time progresses, the window of opportunity to disperse closes (Fiocco and Lessard, 1997). Thus, the prime variable for generating the window was weathering with time. Subsequently, some of the same concepts, but only including the same parameters, were extended to physical recovery and containment (Nordvik, 1995, 1999; Nordvik et al., 2002; Champ et al., 1997; Champ, 2002). The windows of opportunity for ANS oil, based on weathering only, were stated by Champ et al. (1997) to be 0 to 36 hours for burning, 0 to 36 hours for dispersing, 0 to 18 hours for oil-water separator, and 26 to 120 hours for reduced dispersant effectiveness.

Before the publication of the window of opportunity concept, it was not included in logistic planning nor was weather considered essential in planning oil spill countermeasures (Hann, 1979).

Historically, most references to 'windows of opportunity' were to the time factor. The biggest concern was the evaporation of the oil which leads to large increases in viscosity and therefore increased difficulty in recovery and other countermeasures. The secondary time window is that of spreading. A typical crude oil can spread over dozens of square kilometres on the first day after the spill (Jeffery, 1971; Thalich and Xizobo, 2001). Furthermore, once spreading progresses, the thickness approaches or is less than 1 µm, a thickness which cannot be dealt with by any form of countermeasure. Oil that had been at sea for a period of time was sometimes thought to be lost and countermeasures were hopeless (Beynon, 1969). It has only recently been recognized that many of these problems do not occur with heavy oils (Dicks et al., 2002).

The presence of ice, although not strictly a weather condition, can severely affect the recovery of standard equipment (Lamp, 1971)

The ability to perform multiple tasks at sea is typically recognized, although the ability to use chemical dispersants and mechanical recovery are not compatible with one another (Harris, 1999).

The costs of spills have not been evaluated in terms of weather conditions (Etkin, 1999, 2001; Etkin and Tebeau, 2003). There is insufficient information in the literature with which to judge the effect of weather conditions on the costs and general progress of oil spill cleanup. Harper et al. (1995) reviewed costs and did not include the effects of weather. Harper et al. also noted that the costs of offshore cleanup are less by a factor of 2.5 to 4 than shoreline cleanup. In-situ burning is estimated to be about 5 times cheaper than offshore recovery and 10 times cheaper than shoreline cleanup.

2.2 Spreading Compared to Weathering

Spreading, which is a function of time and oil properties, will result in thin slicks, which may not be recoverable, burnable, or dispersible (Lystad and Martinson, 1981). Oceanic processes including Langmuir circulation and the presence of ocean fronts may result in the collection of material, thus reversing the effects of spreading to a certain degree (Thorpe, 2000; McWilliams and Sullivan, 2000; Lehr and Simecek-Beatty, 2000; Simecek-Beatty and Lehr, 2000). Initial spreading equations such as those by Fay do not consider weather factors such as wind and waves and consequently under-predict the spreading when wind is a factor (Brown and Goodman, 1995).

2.3 Important Components of Weather

A review of factors relevant to the effectiveness of countermeasures in relation to changes in weather shows that wind speed and the resulting wave heights are the most important factors. Current or speed of water movement is not usually the result of changing weather, but will be covered briefly in this report. Temperature affects countermeasures such as dispersion but is not as significant in terms of other countermeasures. Temperature can be significant if it results in icing. The relevant temperature changes at sea are only from 5 to 20°C. This spread in water temperature in North America does not cause viscosity changes that are significant in relation to skimmers and especially not to booms.

Wind is the component that generates waves and by itself can cause significant changes in oil behaviour (Bayoumi and Ghalwash, 1999). Wind can also change the rate of surface drift of oil. Youssef and Spaulding (1994) found through modelling that the drift factor (normally taken as 3.5%) varies with wind. In shallow water, the drift factor increases with increasing wind speed. The deflection angle, however, was found to be insensitive to variations in depth, but increasing slightly as wind speed increases.

For waves, the most important component to consider is the type of wave (Shonting, 1979; Fredriksson et al., 1996). A regular wave does not impose as great a constraint on performance as does an irregular wave. This will be considered here as a large amount of data was generated in the OHMSETT facility with regular waves as well as ‘harbour chop’, and the difference can be shown in performance degradation. At sea, many different types of wave energies have been recognized. For example, breaking waves display more energy than non-breaking waves (Boumeester and Wallace, 1985, 1986). Goodman (1994) noted that wave energy was a most important factor, but one that was not understood. Cheng et al. (1998) designed waves for a test tank and noted that wave shape was an important factor. Payne et al. (1991a) studied the weathering of the *Exxon Valdez* oil in the field and in test tanks. They note that weather, especially the waves, is an important factor in the fate and behaviour of the oil. Simecek-Beatty et al. (2002) developed a model of chemical dispersion and use the fact that the mixing layer is 1.5 times the wave height. This shows that wave height is a strong predictor of dispersion amount.

Weather data is stated by some to be a very important factor as it relates to spill countermeasures (Simecek-Beatty and Timmons, 1995; Webb, 1995). Elliot and Jones (2000) review the prediction of oil spill behaviour and fate during the *Sea Empress* incident and note that the use of coarse-grid, non-operational data resulted in prediction errors. They note that accuracy could be improved by using high quality and high resolution weather data.

2.4 Oil Properties Regardless of Weathering

Oil properties play a large role in the behaviour and fate of oil at sea, including how the oil relates to changes in the weather. Buist et al. (1989) studied waxy crudes from Eastern Canada and found that, from a countermeasures perspective, they behaved differently than other oils, regardless of small differences in temperature. Fingas et al. (2003) noted that the dynamics of Orimulsion were changed by variations in temperature. The lower the temperature, the more Orimulsion surfaced.

2.5 Review of Booms and Boom Testing

Booms are very susceptible to winds, currents, and waves, probably more so than any other oil spill equipment or technique (Fingas, 2000a).

A boom is a floating mechanical barrier designed to stop or divert the movement of oil on water. Booms resemble a vertical curtain with portions extending above and below the water line. Most commercial booms consist of four basic components: a means of flotation, a freeboard member (or section) to prevent oil from flowing over the top of the boom, a skirt to prevent oil from being swept underneath the boom, and one or more tension members to support the entire boom.

Most booms are also fitted with one or more tension members which run along the bottom of the boom and reinforce it against the horizontal load imposed by waves and currents. Tension members are usually made of steel cables or chains but sometimes consist of nylon or polyester ropes. The boom fabric itself is not strong enough to withstand the powerful forces to which booms are subjected, except in protected waters. For example, the force on a 100-m long section of boom could be as much as 10,000 kg, depending on sea conditions and the construction of the boom.

2.5.1 Types of Booms

The three basic types of booms are fence and curtain booms, which are common, and external tension member booms, which are relatively rare. Booms are also classified according to where they are used, i.e., offshore, inshore, harbour, and river booms, based on their size and ruggedness of construction. The fence boom is constructed with a freeboard member above the float. Although relatively inexpensive, these booms are not recommended for use in high winds or strong water currents. Curtain booms are constructed with a skirt below the floats and no freeboard member above the float. Curtain booms are most suitable for use in strong water currents. External tension member booms, which are constructed with a tension member outside the main structure, are used in strong currents and in water containing ice or debris.

The characteristics of booms that are important in determining their operating ability are the buoyancy-to-weight ratio or reserve buoyancy, the heave response, and the roll response. The buoyancy-to-weight ratio or reserve buoyancy is determined by the amount of flotation and the weight of the boom. This means that the float must provide enough buoyancy to balance the weight of the boom with the force exerted by currents and waves, thereby maintaining the boom's stability. The greater a boom's reserve buoyancy, the greater its ability to rise and fall with the waves and remain on the surface of the water. The heave response is the boom's ability to conform to sharp waves. It is indicated by the reserve buoyancy and the flexibility of the boom. A boom with good heave response will move with the waves on the surface of the water and not be alternately submerged and thrust out of the water by the wave action. The roll response refers to the boom's ability to remain upright in the water and not roll over.

Sorbent booms are specialized containment and recovery devices made of porous sorbent material such as woven or fabric polypropylene, which absorbs the oil while it is being contained. Sorbent booms are used when the oil slick is relatively thin, i.e., for the final 'polishing' of an oil spill, to remove small traces of oil or sheen, or as a backup to other booms. Sorbent booms require considerable additional support to prevent breakage under the force of strong water currents. They also require some form of flotation so they won't sink once saturated with oil and water.

Fire-resistant booms are used when oil is burned on site. These booms are made of specialized materials that withstand high heat fluxes. They are subject to the same current and wave limitations as other booms. Often they are of heavy construction and lack much reserve buoyancy and thus may be more subject to waves and currents.

2.5.2 Uses of Booms

Booms are used primarily to contain oil, although they are also used to deflect oil. When used for containment, booms are often arranged in a U, V, or J configuration. The U configuration is the most common and is achieved by towing the boom behind two vessels, anchoring the boom, or by combining these two techniques. The U-shape is created by the current pushing against the centre of the boom. The critical requirement is that the current in the apex of the U does not exceed 0.5 m/s or 1 knot, which is referred to as the critical velocity. This is the speed of the current flowing perpendicular to the boom, above which oil will be lost from the boom.

In open water, the U configuration can also be achieved by allowing the entire boom system to move down-current so that the velocity of the current, as opposed to that of the boom, does not exceed the critical velocity. If this velocity is exceeded, first small amounts of oil and then massive amounts will be lost. This leads to several types of boom failure which are described in Section 2.5.3.

If used in areas where the currents are likely to exceed 0.5 m/s or 1 knot, such as in rivers and estuaries, booms are often used in the deflection mode. It is relatively well-known that currents in estuaries such as would be found in Prince William Sound can exceed 3 m/s (6 knots). The boom is then deployed at various angles to the current, so that the critical velocity is not exceeded. The oil can then be deflected either to areas where it can be collected or to less sensitive areas.

2.5.3 Boom Failure

A boom's performance and its ability to contain oil are affected by water currents, waves, and winds. Either alone or in combination, these forces often lead to boom failure and loss of oil. Eight common ways in which booms fail are summarized here.

Entrainment Failure - This type of failure is caused by the speed of the water current and is more likely to happen with a lighter oil. When oil is being contained by a boom in moving water, if the current is fast enough, the boom acts as a dam and the surface water being held back is diverted downwards and accelerates in an attempt to keep up with the water flowing directly under the boom. The resulting turbulence causes droplets to break away from the oil that has built up in front of the boom, referred to as the oil headwave, pass under the boom, and resurface behind it. The water speed at which the headwave becomes unstable and the oil droplets begin to break away is referred to as the critical velocity. It is the speed of the current flowing perpendicular to the boom, above which oil losses occur. For most booms riding perpendicular to the current, this critical velocity is about 0.5 m/s (about 1 knot).

Drainage Failure - Similar to entrainment, this type of failure is related to the speed of the water current, except that it affects the oil directly at the boom. After critical velocity is reached, large amounts of the oil contained directly at the boom can be swept under the boom by the current. Both entrainment and drainage failure are more likely to occur with lighter oils. One or both of these two types of failure can occur, depending on the currents and the design of the boom.

Critical Accumulation - This type of failure usually occurs when heavier oils, which are not likely to become entrained in water, are being contained. Heavier oils tend to accumulate close to the leading edge of the boom and are swept underneath the boom when a certain critical accumulation point occurs. This accumulation is often reached at current velocities approaching the critical velocities, but can also be reached at lower current velocities.

Splashover - This failure occurs in rough or high seas when the waves are higher than the boom's freeboard and oil splashes over the boom's float or freeboard member. It can also occur as a result of extensive oil accumulation in the boom compared to the freeboard.

Submergence Failure - This type of failure occurs when water goes over the boom. Often the boom is not buoyant enough to follow the wave motion and some of the boom sinks below the water line and oil passes over it. Submergence failure is usually the result of poor heave response, which is measured by both the reserve buoyancy and the flexibility of the boom. Failure due to submergence is not that common as other forms of failure, such as entrainment, usually occur first. Submergence is increased as waves and current increase.

Planing - Planing occurs when the boom moves from its designed vertical position to almost a horizontal position on the water. Oil passes over or under a planing boom. Planing occurs if the tension members are poorly designed and do not hold the boom in a vertical position or if the boom is towed in currents far exceeding the critical velocity. The potential for planing also increases as waves and currents increase.

Structural Failure - This occurs when any of the boom's components fail and the boom lets oil escape. Sometimes structural failure is so serious that the boom is carried away by the current. This does not happen often in normal currents and conditions. Floating debris, such as logs and ice, can contribute to structural failure.

2.6 Review of Skimmers and Skimmer Testing

Skimmers are mechanical devices designed to remove oil from the water surface. They vary greatly in size, application, and capacity, as well as in recovery efficiency (Fingas, 2000a). Skimmers are classified according to the area where they are used, for example, inshore, offshore, in shallow water, or in rivers, and by the viscosity of the oil they are intended to recover, that is heavy or light oil. Skimmers are available in a variety of forms, including independent units built into a vessel or containment device and units that operate in either a stationary or mobile (advancing) mode. Some skimmers have storage space for the recovered oil and some of these also have other equipment such as separators to treat the recovered oil.

The effectiveness of a skimmer is rated according to the amount of oil that it recovers, as well as the amount of water picked up with the oil. Removing water from the recovered oil can be as difficult as the initial recovery. Effectiveness depends on a variety of factors including the type of oil spilled, the properties of the oil such as viscosity, the thickness of the slick, sea conditions, wind speed, ambient temperature, and the presence of ice or debris.

2.6.1 Skimmer Performance

A skimmer's performance is affected by a number of factors including the thickness of the oil being recovered, the extent of weathering and emulsification of the oil, the presence of debris, and weather conditions at the time of recovery operations.

A skimmer's overall performance is usually determined by a combination of its recovery rate and the percentage of oil recovered. The oil recovery rate (ORR) is the volume of oil recovered under specific conditions. It is measured as volume per unit of time, e.g., m^3/h, and is usually given as a range. If a skimmer takes in a lot of water, it is detrimental to the overall efficiency of an oil spill recovery operation. The results of recent performance testing on various types of skimmers are given in Table 2. The change in performance with weather is not given in this table, but will be addressed in Sections 2.6.2 and 3.4 of this report. Other factors that are measured are the throughput efficiency (TE), which is the percentage of the oil recovered compared to the amount of oil presented to a skimmer, and the recovery efficiency (RE), which is the amount of oil in the recovered fluid. The recovery efficiency is important as extra water in the recovered product will necessitate handling and separation.

In addition to these characteristics, other important measures of a skimmer's performance include the amount of emulsification caused by the skimmer, its ability to deal with debris, ease of deployment, ruggedness, applicability to specific situations, and reliability.

2.6.2 Effect of Weather Conditions on Skimmers

Weather conditions at a spill site have a major effect on the efficiency of skimmers. Most skimmers work best in calm waters. Depending on the type of skimmer, some will not work effectively in waves greater than 1 m or in currents exceeding 1 knot. Most skimmers do not operate effectively in waters with ice or debris such as branches, seaweed, and floating waste. Some skimmers have screens around the intake to prevent debris or ice from entering, conveyors or similar devices to remove or deflect debris, and cutters to deal with sea weed. Very viscous oils, tar balls, or oiled debris can clog the intake or entrance of skimmers and make it impossible to pump oil from the skimmer's recovery system.

2.6.3 Types of Skimmers

Skimmers are classified according to their basic operating principles: oleophilic surface skimmers; weir skimmers; suction skimmers or vacuum devices; elevating skimmers; submersion skimmers; and vortex or centrifugal skimmers. Each type of skimmer has distinct advantages and disadvantages.

Oleophilic surface skimmers, sometimes called sorbent surface skimmers, use a surface to which oil can adhere to remove the oil from the water surface. This oleophilic surface can be in the form of a disc, drum, belt, brush, or rope, which is moved through the oil on the top of the water. A wiper blade or pressure roller removes the oil and either deposits it into an onboard container or the oil is directly pumped to storage facilities on a barge or on shore. The oleophilic surface itself can be steel, aluminum, fabric, or plastics such as polypropylene and polyvinyl chloride. Oleophilic skimmer concepts are illustrated in Figure 2.

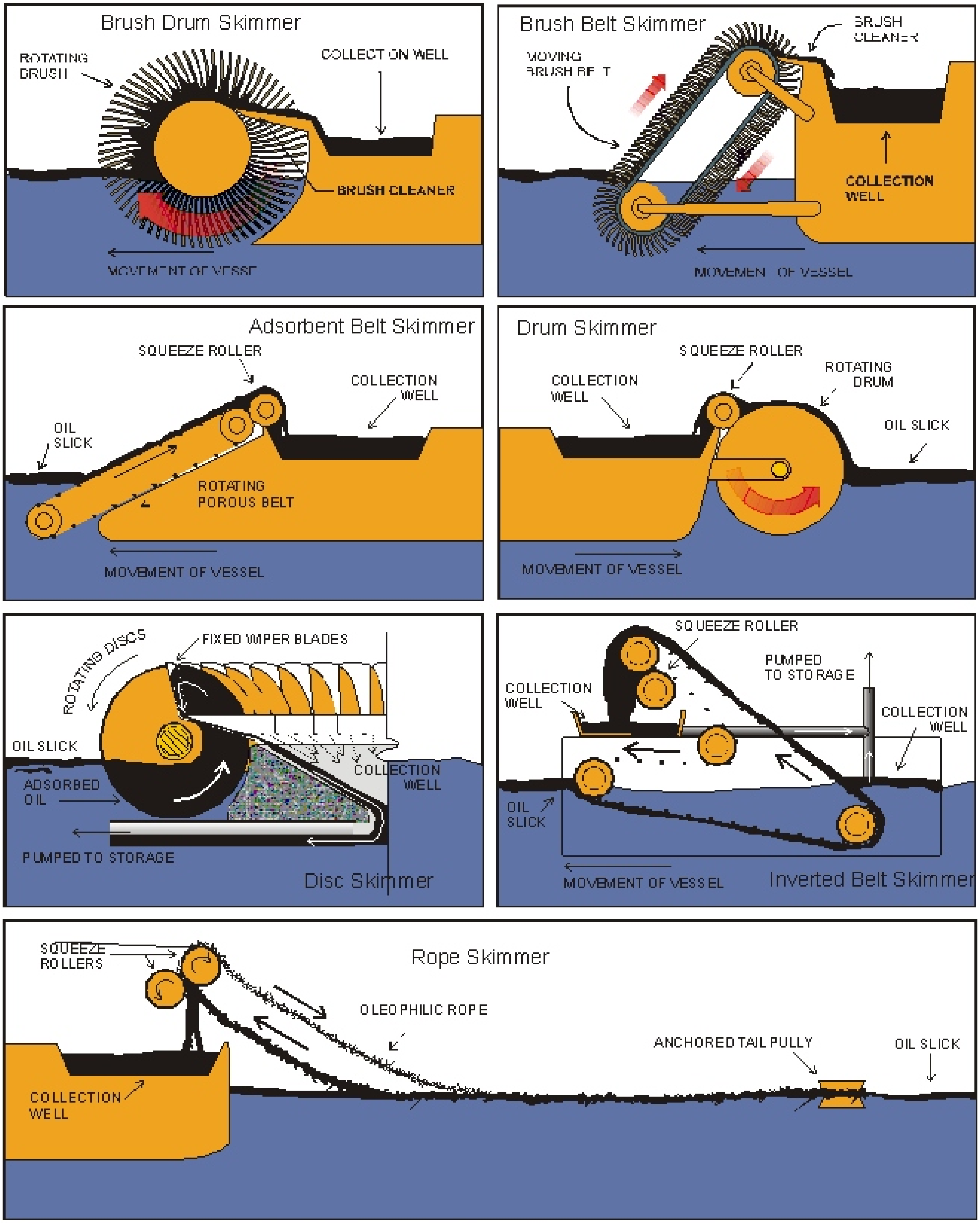


Figure 2 - Oleophilic Skimmers (from Fingas, 2000)

Table 2 Performance of Typical Skimmers

	Recovery Rate (m^3/hr) for given oil type*				Percent
Skimmer Type	**Diesel**	**Light Crude**	**Heavy Crude**	**Bunker C**	**Oil****
Oleophilic Skimmers					
small disc	0.4 to 1	0.2 to 2			80 to 95
large disc		10 to 20	10 to 50		80 to 95
brush	0.2 to 0.8	0.5 to 20	0.5 to 2	0.5 to 2	80 to 95
large drum		10 to 30			80 to 95
small drum	0.5 to 5	0.5 to 5			80 to 95
large belt	1 to 5	1 to 20	3 to 20	3 to 10	75 to 95
inverted belt		10 to 30			85 to 95
rope		2 to 20	2 to 10		
Weir Skimmers					
small weir	0.2 to 10	0.5 to 5	2 to 20		20 to 80
large weir		30 to 100	5 to 10	3 to 5	50 to 90
advancing weir	1 to 10	5 to 30	5 to 25		30 to 70
Elevating Skimmers					
paddle conveyer		1 to 10	1 to 20	1 to 5	10 to 40
Submersion Skimmers					
large	0.5 to 1	1 to 80	1 to 20		70 to 95
Suction Skimmers					
small	0.3 to 1	0.3 to 2			3 to 10
large trawl unit		2 to 40			20 to 90
large vacuum unit		3 to 20	3 to 10		10 to 80
Vortex/Centrifugal Skimmers					
centrifugal unit	0.2 to 0.8	0.2 to 10			2 to 20

** Recovery rate depends very much on the thickness of the oil, type of oil, sea state, and many other factors.*

*** This is the percentage of oil in the recovered product. The higher the value, the less the amount of water and thus the better the skimmers' performance.*

Oleophilic skimmers pick up very little water compared to the amount of oil recovered, which means they have a high oil-to-water recovery ratio. They therefore operate efficiently on relatively thin oil slicks. They are not as susceptible to ice and debris as the other types of skimmers. These skimmers are available in a range of sizes and work best with light crude oils, although their suitability for different types of oil varies with the design of the skimmer and the type of oleophilic surface used.

The **disc skimmer** is a common type of oleophilic surface device. The discs are usually made of either polyvinyl chloride or steel. Disc skimmers work best with light crude oil and are well suited to working in waves and among weeds or debris.

The **drum skimmer** is another type of oleophilic surface skimmer. The drums are made of either a proprietary polymer or steel. The drum skimmer works relatively well with fuels and light crude, but is ineffective with heavy oils.

Belt skimmers are constructed of a variety of oleophilic materials ranging from fabric to conveyor belting. Most belt skimmers function by lifting oil up from the water surface to a recovery well. As the motion of the belt through the water drives oil away from the skimmer, however, oil must be forced to the belt manually or with a water spray. Belt skimmers have been designed to overcome this problem, including one that pumps the oily water through a porous belt and the inverted belt skimmer which carries the oil under the water. The oil is subsequently removed from the belt by scrapers and rollers after the belt returns to a selected position at the bottom of the skimmer. Belt skimmers of all types work best with heavier crudes. Belt skimmers are large and are usually built into a specialized cleanup vessel.

Brush skimmers use tufts of plastic attached to drums or chains to recover the oil from the water surface. The oil is usually removed from the brushes by wedge-shaped scrapers. Brush skimmers are particularly useful for recovering heavier oils, but are ineffective for fuels and light crudes. Some skimmers include a drum for recovering light fuels and a brush for use with heavier oils. These skimmers can also be used with limited amounts of debris or ice. Brush skimmers are available in a variety of sizes, from small portable units to large units installed on specialized vessels or barges.

Rope skimmers remove oil from the water surface with an oleophilic rope of polymer, usually polypropylene. Some skimmers have one or two long ropes which are held in the slick by a floating, anchored pulley. Others use a series of small ropes that hang down to the water surface from a suspended skimmer body. The rope skimmer works best with medium viscosity oils and is particularly useful for recovering oil from debris- and ice-laden waters. Rope skimmers vary in size from small portable units to large units installed on specialized vessels or barges.

Weir skimmers are a major group of skimmers that use gravity to drain the oil from the surface of the water into a submerged holding tank. In their simplest form, these devices consist of a weir or dam, a holding tank, and a connection to an external or internal pump to remove the oil. Many different models and sizes of weir skimmers are available. A weir skimmer is illustrated in Figure 3.

A major problem with weir skimmers is their tendency to rock back and forth in choppy water, alternately sucking in air above the slick and water below. This increases the amount of water and reduces the amount of oil recovered. Some models include features for self-levelling and adjustable skimming depths so that the edge of the weir is precisely at the oil-water interface, minimizing the amount of water collected. Offshore weir skimmers have been constructed and these usually divert the top surface of the water and oil to a calm area. This can increase the weir skimmer’s capability to very high sea states.

Weir skimmers do not work well in ice and debris or in rough waters and they are not effective for very heavy oils or tar balls. Weir skimmers have also been built into booms and have been moderately successful in providing high recovery rates of lighter crudes.

Suction or vacuum skimmers use a vacuum or slight differential in pressure to remove oil from the water surface. Often the 'skimmer' is only a small floating head connected to an external source of vacuum, such as a vacuum truck. The head of the skimmer is simply an enlargement of the end of a suction hose and a float. Two suction skimmers are illustrated in Figure 4.

Suction skimmers are similar to weir skimmers in that they sit on the water surface, generally use an external vacuum pump system such as a vacuum truck, and are adjusted to float at the oil-water interface. They also tend to be susceptible to the same problems as weir skimmers. They are prone to clogging with debris which can stop the oil flow and damage the pump. They also experience the problem of rocking in choppy waters which causes massive water intake, followed by air intake. Their use is restricted to light to medium oils.

Despite their disadvantages, suction skimmers are the most economical of all skimmers. Their compactness and shallow draft make them particularly useful in shallow water and in confined spaces. They operate best in calm water with thick slicks and no debris. Very large vacuum pumps, called air conveyors, and suction dredges have been used to recover oil, sometimes directly without a head. Both these adaptations, however, have the same limitations as smaller suction skimmers.

Elevating skimmers or devices use conveyors to lift oil from the water surface into a recovery area. A paddle belt or wheel or a conveyor belt with ridges is adjusted to the top of the water layer and oil is moved up the recovery device on a plate or another moving belt. The operation is similar to removing liquid from a floor with a squeegee. The oil is usually removed from the conveyer by gravity. When operating these skimmers, it is difficult to maintain the conveyor at the water line. In addition, they cannot operate in rough waters or in waters with large pieces of debris, and cannot deal with light or very heavy oils. Elevating skimmers work best with medium to somewhat heavy oils in calm waters. They are generally large and are sometimes built into specialized vessels. Two concepts for elevating skimmers are shown in Figure 5.

Submersion skimmers use a belt or inclined plane to force the water beneath the surface. The belt or plane forces the oil downward toward a collection well where it is removed from the belt by a scraper or by gravity. The oil then flows upward into the collection well, and is removed by a pump. Submersion skimmers move faster than other skimmers and can therefore cover a large area, making them suitable for use at larger spills. They are most effective with light oils with a low viscosity and when the slick is relatively thin. Disadvantages include a poor tolerance to debris compared to other skimmers and they cannot be used in shallow waters. Submersion skimmers are larger than other types of skimmers and are usually mounted on a powered vessel. The submersion skimmer concept is shown in Figure 6.

2.6.4 Other Devices

Many other devices are used to recover oil. Several skimmers combine some of the principles of operation already discussed. For example, one skimmer uses an inverted belt both as an oleophilic skimmer and a submersion skimmer. A fish trawl has been modified by adding an oil outlet. Once the trawl is filled, however, usually with water, it is almost impossible to maintain a dynamic balance in the trawl so that further oil can enter. Regular fishing nets and fishing boats have been used to recover extremely large tar balls, but the oil fouls the nets, making disposal or expensive cleanup necessary. Garbage-collecting vessels have been successfully used to remove oiled debris or tar balls.

Special purpose ships have been built specifically to deal with oil spills. Several ships have been built with a hull that splits to form a V-shaped containment boom with skimmers built into the hull, although this requires very expensive design features so the ship can withstand severe weather conditions. Other ships have been built with holes in the hull to hold skimmers, with sweeps mounted on the side to direct oil to the skimmer area. Many small vessels have been custom-built to hold skimmers.

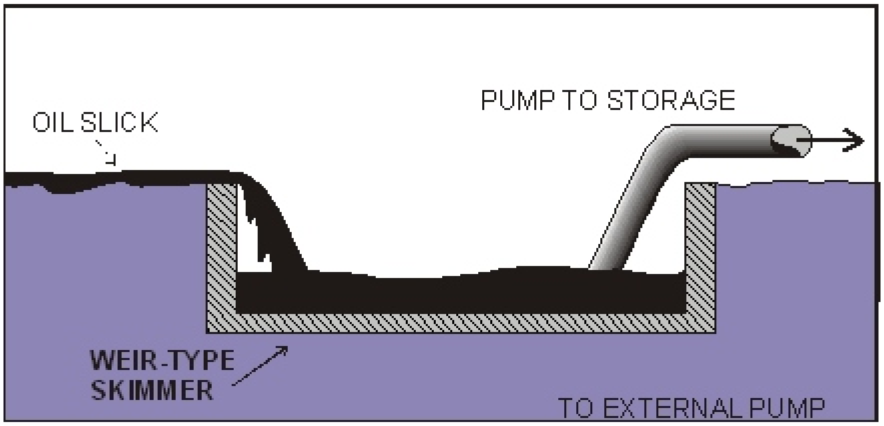


Figure 3 Weir Skimmer (from Fingas, 2003)

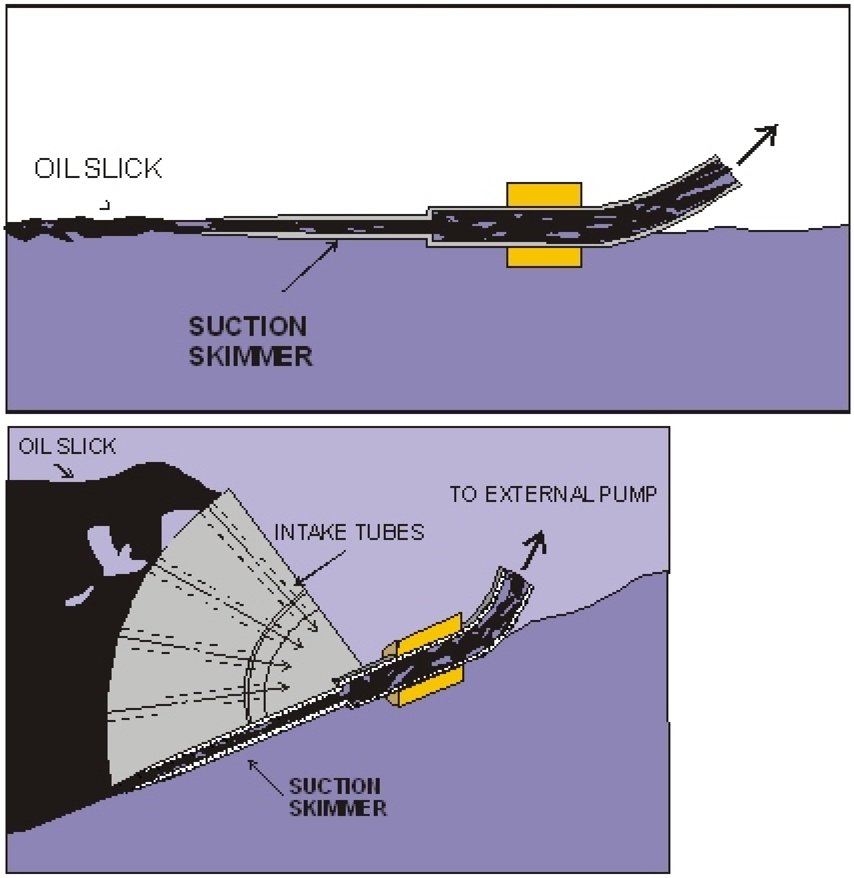


Figure 4 Suction Skimmers (from Fingas, 2003)

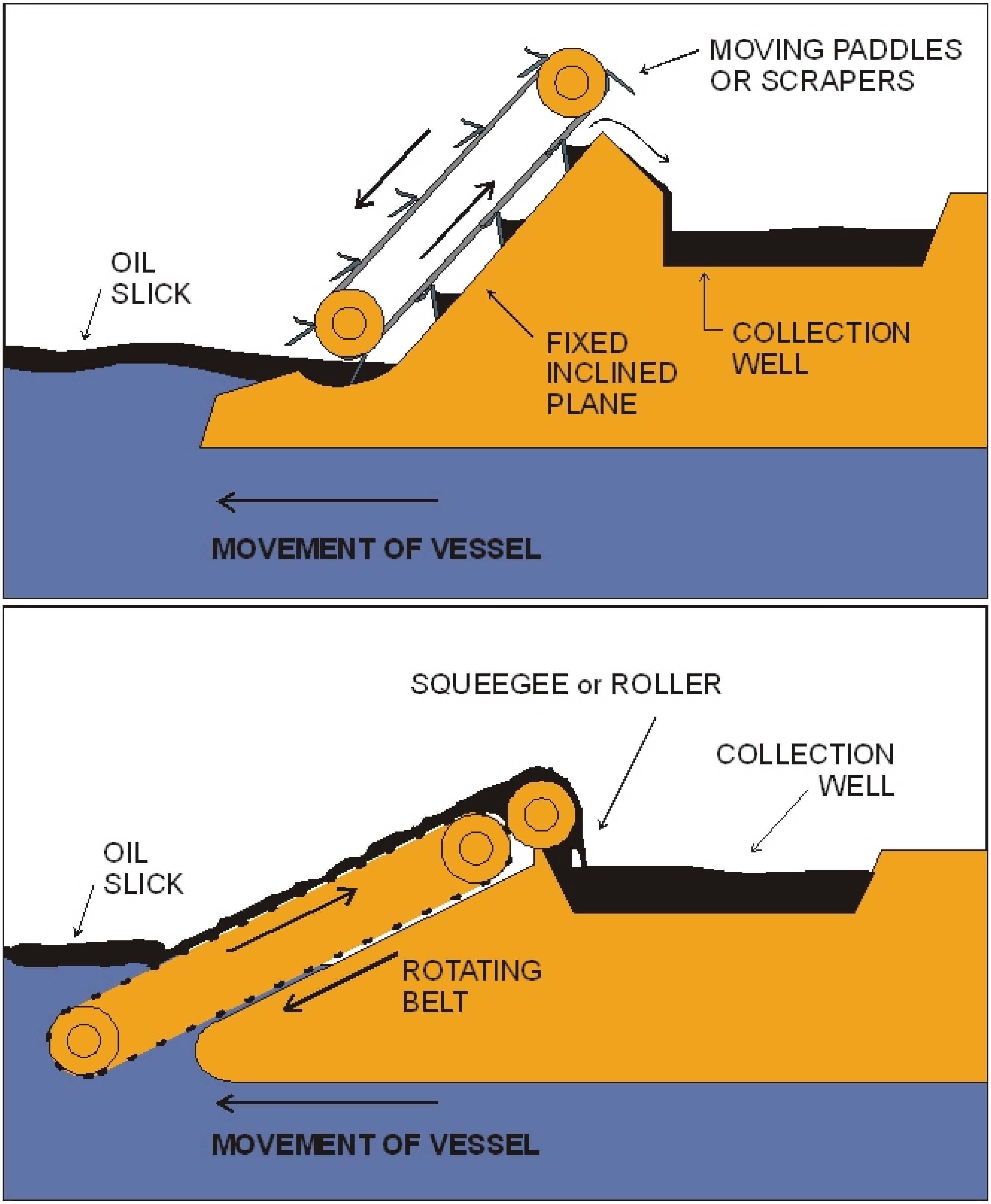


Figure 5 Elevating Skimmers (from Fingas, 2003)

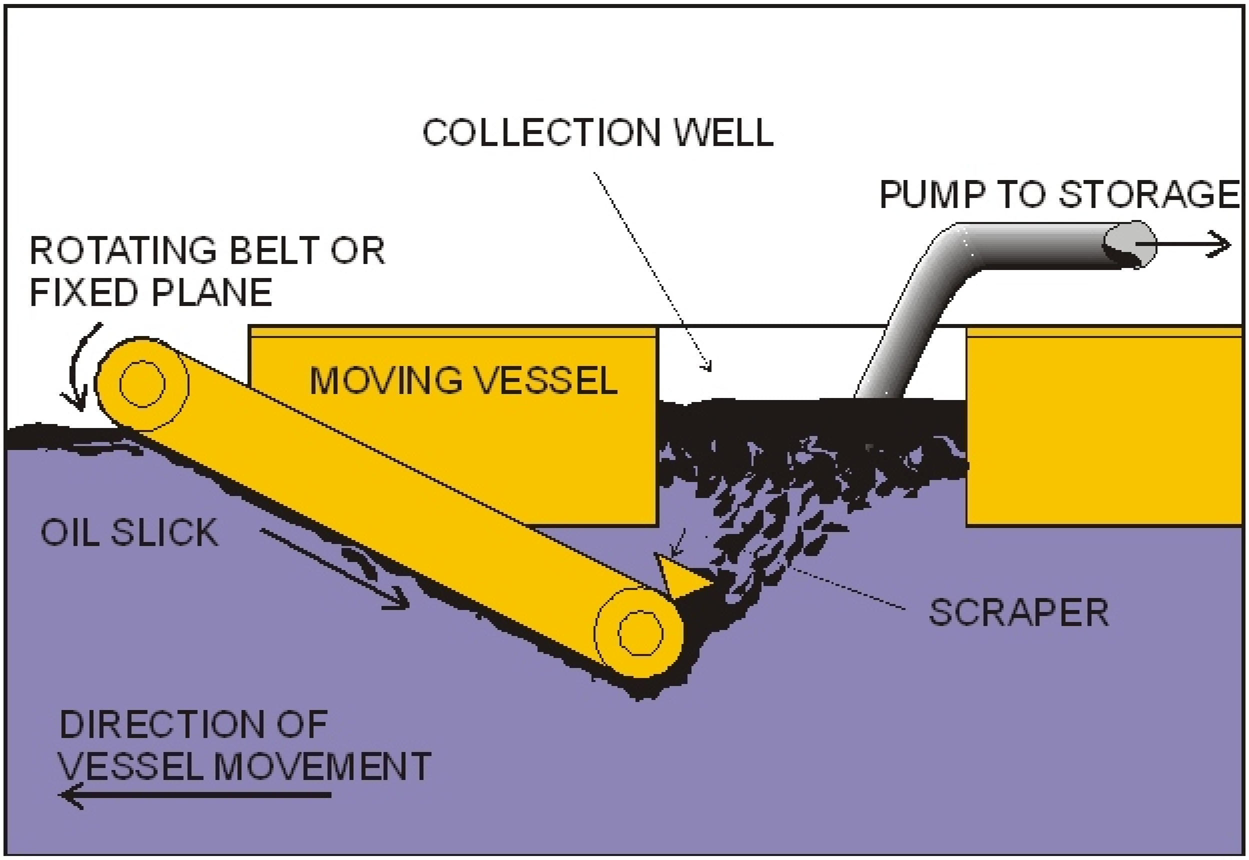


Figure 6 Submersion Skimmer

2.7 Sorbents

Sorbents are materials that recover oil through either absorption or adsorption. They play an important role in oil spill cleanup and are used in the following ways: to clean up the final traces of oil spills on water or land; as a backup to other containment means, such as sorbent booms; as a primary recovery means for very small spills; and as a passive means of cleanup. An example of such passive cleanup is when sorbent booms are anchored off lightly oiled shorelines to absorb any remaining oil released from the shore and prevent further contamination or re-oiling of the shoreline.

The performance of sorbents is measured in terms of total oil recovery and water pickup, similar to skimmers. "Oil recovery" is the weight of a particular oil recovered compared to the original weight of the sorbent. For example, highly efficient synthetic sorbent may recover up to 30 times its own weight in oil and an inorganic sorbent may recover only twice its weight in oil. The amount of water picked up is also important, with an ideal sorbent not recovering any water.

The effect of weather on sorbents is unclear as sorbents are typically used as a final polishing tool. As this task is critical under most circumstances, sorbent use could wait until the weather allowed.

2.8 Dispersants and Other Chemical Treating Agents

Dispersant is a common term used to label chemical spill-treating agents that promote the formation of small droplets of oil which 'disperse' throughout the top layer of the water column. Dispersants contain surfactants, chemicals like those in soaps and detergents, that have molecules with both a water-soluble and oil-soluble component. Depending on the nature of these components, surfactants cause oil to behave in different ways in water. Surfactants or surfactant mixtures used in dispersants have approximately the same solubility in oil and water, which stabilizes oil droplets in water so that the oil will disperse into the water column. This can be desirable when an oil slick is threatening a particularly sensitive shoreline.

The effectiveness of a dispersant is determined by measuring the amount of oil that it puts into the water column and comparing it to the amount of oil that remains on the water surface. When a dispersant is working, a white to coffee-coloured plume of dispersed oil appears in the water column and can be seen from ships and aircraft. This plume can take up to half an hour to form. If there is no such plume, it indicates little or no effectiveness.

Effectiveness is influenced by many factors, including the composition and degree of weathering of the oil, the amount and type of dispersant applied, sea energy, salinity of the water, and water temperature. The composition of the oil is the most important of these factors, followed closely by sea energy and the amount of dispersant applied. Dispersion is not likely to occur when oil has spread to thin sheens. Below a certain thickness, the applied dispersant will interact with the water and not the oil.

Weather affects dispersant application and effectiveness in three ways: the amount of dispersant that contacts the target is highly wind-dependent; the amount of oil dispersed is very dependent on ocean turbulence and other energy; and the amount of oil remaining in the water column is dependent on the same energy. The higher the wind, the less dispersant will be applied to the oil from an aerial platform. The greater the sea energy, the more oil will be dispersed downwards and the more that will stay dispersed.

Some oils are prone to natural dispersion, particularly those that contain large amounts of saturates. For example, diesel fuel which contains mostly saturates, disperses both naturally and when dispersant is added. The amount of diesel that disperses when dispersants are used compared to the amount that would disperse naturally depends primarily on the amount of dispersant entering the oil. On the other hand, oils that consist primarily of resins, asphaltenes, and larger aromatics or waxes will disperse poorly even when dispersants are applied and will in fact separate to some degree and remain on the surface. For this reason, certain products such as Bunker C are very difficult or impossible to disperse with chemical treating agents available today. The major factor in natural dispersion is sea energy in the form of waves and turbulence.

Laboratory studies have found that there is a trade-off between the amount (or dose) of dispersant applied and the sea energy at the time of application. In general, it was found that more dispersant is needed when the sea energy is low to yield the same amount of dispersion as when the sea energy is high.

The relationship between the amount of dispersant applied and the sea energy has been studied. A very large amount of dispersant is required when sea energy is low. In fact, this amount of dispersant would be very difficult to get into oil under most normal circumstances. At low sea energies and with oils that disperse poorly, more dispersant is required at the interface between the oil and the water, to the point that a typical application of surfactant would not be adequate.

2.8.1 Application of Dispersants

Dispersants are applied either 'neat' (undiluted) or diluted in sea water in the case of many boat and ship application systems. Aerial spraying, which is done from small and large fixed-wing aircraft as well as from helicopters, is the most popular application method. Spray systems on small aircraft used to spray pesticides on crops can be modified to spray dispersant. Such aircraft can perform many flights in one day and in many different conditions. Their capacities vary from about 250 to 1,000 L of dispersant. Transport aircraft with internal tanks can carry from 4,000 to 12,000 L of dispersant.

Large transport aircraft such as Hercules fitted with portable spray systems can carry about 20,000 L which could treat 400,000 L of oil at a dispersant-to-oil ratio of 1:20. At a thickness of 0.5 mm, this oil would cover about 400,000 m^2 or 0.4 km^2. This treatment could be applied in as little as an hour after loading the dispersant and as many as eight flights could be flown in a day, depending on the distance from the airport to the spill.

Spray systems are available for boats, varying in size from 10- to 30-m wide spray booms to tanks from 1,000 to 10,000 L. As dispersant is almost always diluted with sea water to maintain a proper flow through the nozzle, extra equipment is required on the vessel to control dilution and application rates. About 10,000 to 100,000 L of dispersant can be applied a day, which would cover an area of 1,000,000 m^2 or 1 km^2. As this is substantially less than could be sprayed from a single aircraft, spray boats are rarely used for a large spill. Smaller spray vessels are rarely used.

The essential elements in applying dispersant are to supply enough dispersant to a given area in droplets of the correct size and to ensure that the dispersant comes into direct contact with the oil. Droplets larger than 1,000 µm will break through the oil slick and cause the oil to collect in small ribbons, which is referred to as herding. This can be detected by the rapid clearance of the oil in the dispersant drop zone without the formation of the usual white to coffee-coloured plume in the water column. This is very detrimental and wastes the dispersant. Herding can also occur on thinner slicks when the droplets of dispersant are smaller. The distribution of smaller droplets of dispersant is not desirable especially when spraying from the air as small droplets will blow away with the wind and probably not land on the intended oil slick.

Finally, it is very difficult with aerial equipment to spray enough dispersant on a given area to yield a dispersant-to-oil ratio of about 1:20. The rate at which the dispersant is pumped and the resulting droplet size are critical and a slick must often be under-dosed with dispersant rather than creating very small droplets. Tests have shown that re-applying dispersant to the same area several times is one way of ensuring that enough dispersant is applied to the oil.

Dispersants must always be applied with a system designed specifically for the purpose. If pesticide spray equipment is used, small droplets form that may blow away and not enough dispersant is deposited onto the oil slick. Unless suitably modified, fire monitors or regular hoses from ships may not result in correct droplet sizes or quantities of dispersant per unit area. Furthermore, the high velocity of the water/dispersant mixture can herd the oil away, resulting in the loss of dispersant to the water column, where it has little effect on oil floating on top of the water.

2.9 In-Situ Burning

In-situ burning is an oil spill cleanup technique that involves controlled burning of the oil at or near the spill site. The major advantage of this technique is its potential for removing large amounts of oil over an extensive area in less time than other techniques. The technique has been used at actual spill sites for some time, especially in ice-covered waters where the oil is contained by the ice.

The most obvious disadvantage of burning oil is concerns about toxic emissions from the large black smoke plume produced. The second disadvantage is that the oil will not ignite and burn unless it is thick enough. Most oils spread rapidly on water and the slick quickly becomes too thin for burning to be feasible. Fire-resistant booms are used to concentrate the oil into thicker slicks so that the oil can be burned. This is then subject to the same wind and wave limitations as physical recovery.

2.9.1 Ignition of Oil

Early studies of in-situ burning focussed on ignition as being the key to successful burning of oil on water. It has since been found that ignition can be difficult under high winds (Fingas and Punt, 2000). More recent studies have shown that slick thickness is actually the most important factor required for oil to burn and that almost any type of oil will burn on water or land if the slick is thick enough. Ignition may be difficult, however, at winds greater than 20 m/s (40 knots). The weather thus becomes a key factor in a successful burn operation.

In general, heavy oils and weathered oils take longer to ignite and require a hotter flame than lighter oils. This is also the case for oil that contains water, although oil that is completely emulsified with water may not ignite at all. While the ignitability of emulsions with varying water concentrations is not well understood, oil containing some emulsion can be ignited and burned. Several burns have been conducted in which some emulsion or high water content in the oil did not affect either the ignitability of the oil or the efficiency of the burn. Chemical emulsion breakers can be used to break down enough of the emulsion to allow the fire to get started. As it is suspected that fire breaks down the water-in-oil emulsion, water content may not be a problem once the fire is actually burning.

Most ignition devices burn long enough and generate enough heat to ignite most oils. Several igniters have been developed, ranging from simple devices made of juice cans and propellant to sophisticated helicopter-borne devices. The state of the art in ignition technology is the helitorch, a helicopter-slung device which dispenses packets of burning, gelled fuel that produce a flame of 800ºC lasting for up to 6 minutes. The device was developed to start back-fires for the forestry industry. It must be added, however, that many of these devices have not been tested under high wind conditions. Simple home-made devices have functioned relatively well under higher wind conditions given that they sheltered the initial flame.

2.9.2 Use of Containment

Oil can be burned on water without using containment booms if the slick is thick enough (2 to 3 mm) to ignite. For most crude oils, however, this thickness is only maintained for a few hours after the spill occurs. Oil on the open sea rapidly spreads to an equilibrium thickness, which is about 0.01 to 0.1 mm for light crude oils and about 0.05 to 0.5 mm for heavy crudes and residual oils. Such slicks are too thin to ignite and containment is required to concentrate the oil so it is thick enough to ignite and burn efficiently.

Special fire-resistant booms are available to contain oil when using burning as a spill cleanup technique. As they must be able to withstand heat for long periods of time, these booms are constantly being tested for fire resistance and containment capability and designs are modified in response to test results. Fire-resistant booms require special handling, especially stainless steel booms because of their size and weight. Furthermore, these booms are more subject to wind and waves than the best regular booms.

Booms are also used by spill responders to isolate the oil from the source of the spill. When considering burning as a spill cleanup technique, the integrity of the source of the spill and the possibility of further spillage is always a priority. If there is any possibility that the fire could flash back to the source of the spill, such as an oil tanker, the oil is usually not ignited. Oil is sometimes contained by natural barriers such as shorelines, offshore sand bars, or ice. Several successful experiments and burns of actual spills have shown that ice acts as a natural boom so that in-situ burning can be carried out successfully for spills in ice. Oil against a shoreline can be burned if the shoreline is in a remote area and consists of cliffs, rock, gravel, or sandy slopes and is a safe distance from any combustible material, such as forests, grass cover, or wooden structures. This then makes burning much more feasible under adverse weather conditions.

2.10 Shoreline Cleanup

The fate and behaviour of oil on shorelines is influenced by many factors, some of which relate to the oil itself, some to characteristics of the shoreline, and others to conditions at the time the oil is deposited on the shoreline, such as weather and waves (Fingas, 2000a). These factors include the type and amount of oil, the degree of weathering of the oil, both before it reaches the shoreline and while on the shoreline, the temperature, the state of the tide when the oil washes onshore, the type of beach substrate, i.e., its material composition, the type and sensitivity of biota on the beach, and the steepness of the shore.

Other important factors are the existence of a high tide berm on the beach, if the oil is deposited in the intertidal zone, and whether the particular length of shoreline is exposed to or sheltered from wave action. An exposed beach will often 'self-clean' before a cleanup crew can perform the task, which can result in the released oil being transported to other beaches or even back to the same beach.

The extent of oil coverage often depends on the stage of the tide when the oil is deposited on the shoreline. At high tide, oil can be deposited above the normal tide line and often spreads over a broad intertidal area. The least amount of oiling occurs when the oil is deposited on the shoreline during the falling tide, although this is less likely to occur as the water is moving away from the shoreline. The nature of the intertidal zone, i.e., its composition and slope, will often dictate the fate of the oil. If large amounts of oil are not retained in the intertidal zone, then the oil will have less impact on the area.

The fate of oil on shorelines also depends on the wave regime. Oil can be removed and carried away by energetic waves within days, whereas it can remain for decades in sheltered areas. For example, some of the oil spilled from the *Arrow* in 1970 remains in the sheltered coves of Nova Scotia to this day. Similarly, a significant amount of oil spilled from the *Metul*a in 1974 remains on sheltered beaches in Chile. In both cases, the oil was Bunker C and weathering produced a crust on top of the oil. Under this crust, the oil is still relatively fresh, even after decades.

Beaches are a dynamic environment that change in profile during seasonal storms. This can result in oil being buried on the beach in layers, often as deep as 1 metre, or buried oil can be brought to the surface.

Oil stranded on shorelines, especially above the high tide line, weathers with time and becomes more adhesive, viscous, and difficult to remove. If nutrients are present and the oil is crude, limited biodegradation can take place, but this occurs slowly and only a small percentage of the oil may be removed in one to two years. As oil stranded above the high tide line is above the limit of normal wave action, physical removal can occur only during storm events.

2.10.1 Recommended Cleanup Methods

Some recommended shoreline cleanup methods are natural recovery, manual removal, flooding or washing, use of vacuums, mechanical removal, tilling and aeration, sediment reworking or surf washing, and the use of sorbents or chemical cleaning agents. Many of these methods are only practical if weather conditions permit.

Sometimes the best response to an oil spill on a shoreline may be to leave the oil and monitor the natural recovery of the affected area. This would be the case if more damage would be caused by cleanup than by leaving the environment to recover on its own. This option is suitable for small spills in sensitive environments and on a beach that will recover quickly on its own such as on exposed shorelines.

2.10.2 Types of Shoreline

The type of shoreline is crucial in determining the fate and effects of an oil spill as well as the cleanup methods to be used (Environment Canada, 1998). In fact, the shoreline's basic structure and the size of material present are the most important factors in terms of oil spill cleanup. There are many types of shorelines, all of which are classified in terms of sensitivity to oil spills and ease of cleanup. The types discussed here are: bedrock, man-made solid structures, boulder beaches, pebble-cobble, mixed sand-gravel beaches, sand beaches, sand tidal flats, mud tidal flats, marshes, peat and low-lying tundra, and mangrove.

Bedrock shorelines consist of rock that is largely impermeable to oil, although oil can penetrate through crevices or fractures in the rock. For this reason and because plant and animal life is scarce, bedrock shorelines are not particularly vulnerable to oil spills. Oil is more likely to be deposited in the upper tidal zone. If the shore is exposed to wave action, a significant amount of oil is likely to be removed after each tidal cycle.

Shorelines consisting of man-made solid structures include retaining walls, harbour walls, ramps, and docks and are generally made of rocks, concrete, steel, and wood. This type of shoreline is usually considered impermeable to oil. Man-made structures are very similar to bedrock and are the least sensitive of any shoreline to oil.

Boulder beaches consist primarily of materials that are more than 256 mm in diameter. These beaches are not altered by any conditions other than ice, human activity, or extreme wave conditions. Boulder beaches often give way to mud or sand tidal flats in the lower intertidal zone. Because of the large spaces between individual boulders, oil can be carried down to the sediments and remain there for years. Boulder beaches are considered to be moderately sensitive to oil and do not recover rapidly from oiling.

Pebble-cobble beaches consist of materials ranging in size from 2 to 256 mm. Some fine materials may be present in the interstitial areas between pebbles and there may also be large boulders in the area. Oil readily penetrates pebble-cobble beaches through the open spaces between the rocks. Retention of the oil may be low as it is often flushed out from the interstitial areas by natural tide or wave action. Oil will likely concentrate on the upper reaches, however, where there is little flushing action. As wave action constantly rearranges or reworks the sediments, few animals and plants are present, especially in the middle intertidal zone.

A mixed sand-gravel beach consists of a variety of materials from 0.1 to 64 mm in size. These beaches are often called gravel beaches, because the larger gravel appears to predominate.

Sand beaches are what most people envision as a 'beach' and they are found in every part of North America. On many coasts, they are often located between other types of beaches. Sand is defined as a particle 0.1 to 2 mm in diameter, consisting of several different sizes and types of minerals. Coarse sand is usually defined as 0.5 to 2 mm in size and fine sand is less than 0.5 mm. Oil can easily become buried in sand and over time this can result in layers of sand and oil, referred to as 'chocolate layer cake'. This is particularly true in the case of frequent storms.

Sand tidal flats consist of material similar to sand beaches but are at shallow angles and never drain completely. They contain a lot of silt or very fine material. The surface layer of sand flats, which consists of a few centimetres, is dynamic and unstable.

Peat and low-lying tundra are similar types of shoreline found in the Arctic regions. Although different, they have similar sensitivity and cleanup methodologies. Peat is a spongy, fibrous material formed by the incomplete decomposition of plant materials. Peat erodes from tundra cliffs and often accumulates in sheltered areas, as does oil. Oil does not penetrate wet peat, but dry peat can absorb large amounts of oil. Low-lying tundra is normally dry land but is flooded by the sea at certain times of the year.

3. Review of Literature on Spill Countermeasures and Weather

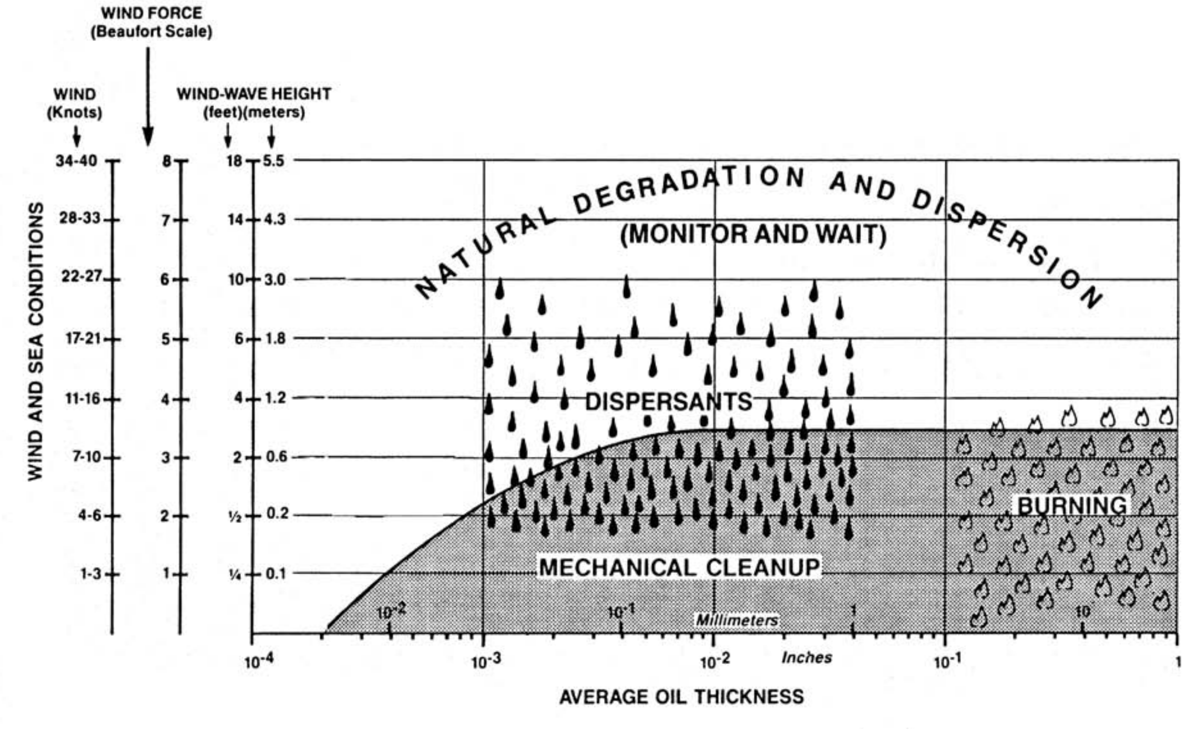
3.1 *A priori* Decision Guides

A number of '*a priori*' guides have been issued. A classic and very good *a priori* guide is described by Al Allen in 1988, the concept of which is summarized in Figure 7. As shown in the figure, the guide is meant to be used as an intermediate in calculating volume rates for each countermeasure analyzed.

The logic that Allen (1988) uses is summarized here. For burning, it is assumed that a sufficient thickness (2 to 3 mm) is needed for oil to burn and that ignition cannot be carried out at winds greater than about 10 m/s (20 knots) but that, once ignited, burns can be sustained much past this value. Allen notes that mechanical cleanup techniques typically work best on thick oil layers in calm seas and that this drops off quickly at winds of 7 to 10 m/s (Beaufort 3 to 4). The thickness relationships are also crucial as shown in Figure 7. High-seas skimming equipment may have an extended envelope, but this is not defined. Allen notes that, as short-period wind-waves build to 0.6 to 0.9 m (2 to 3 feet), booms will suffer significant losses due to entrainment and splashover.

The lower bound of dispersant use was estimated to be a wind of about 5 m/s (Beaufort 2) on the basis of the mixing required. The upper limit of dispersant application was estimated to be about 12 to 14 m/s wind (Beaufort 5 to 6) on the basis of the benefits compared to natural dispersion which should be great at this sea level. These weather options are later combined by Allen (1988) with a volume recovery versus spill thickness to provide an assessment basis for offshore countermeasures.

Figure 7 A Classic Weather Windows Diagram (Allen, 1988)



ExxonMobil (2000) lists the weather limitations (upper limit) for dispersant application as: work boats (tugboat type) - wind speed 3 to 11 m/s (7 to 21 knots), significant wave height 0 to 3 m (1 to 9 feet); single-engine airplanes - wind speed 8 to 11 m/s (17 to 21 knots), significant wave height 2 to 3 m (6 to 9 feet); medium-sized helicopters - wind speed 9 to 11 m/s (17 to 27 knots, significant wave height 2 to 8 m (6 to 17 feet); and large multiple-engine airplanes - wind speed 15 to 18 m/s (30 to 35 knots), significant wave height 9 to 12 m (17 to 23 feet).

DeCola (2003) presents a survey of world guidelines and decision trees for dispersant use. Of the about 30 guides or decision trees presented, only two decision trees note restrictions on weather conditions. The US EPA Region 6 guideline indicates an upper limit of 13 m/s (25 knots) on dispersant use and the Washington/Oregon guidelines specify a lower limit of a sea state of 1 and an upper sea state of 4 (1 to 10 m/s winds). The latter guideline also specifies an upper limit of 0.5 m/s current for mechanical countermeasures.

Koops and Huisman (2002) give *a priori* limits of Beaufort 6 for skimmers and other mechanical recovery, a limit between 2 to 8 Beaufort (2 to 20 m/s wind) for dispersion, and a lower threshold of greater than 3 Beaufort for natural dispersion. Koops (1988) gives the limit of skimmers as 1.5 m wave heights and notes that swell has no effect on the capability to mechanically recover.

The Mechanical Equipment Calculator, part of NOAA's Spill Tools on the internet, does not include the effects of weather on containment and recovery, although effectiveness is calculated in the program (Gregory et al., 1999).The program includes primarily the inputs of slick thickness and efficiency.

Dempsey (2002) suggests a limit of a wind speed of 12 m/s (25 knots) and a sea state with a wave height not exceeding 3 m for offshore work.

Reed (Reed et al., 1995, a,b,c) described the OSCAR spill model and noted the mechanical recovery efficiencies in the model were set as 80% with a 5 m/s wind and 60% with a 10 m/s wind.

3.2 General Countermeasures

Most authors presume low limits for at-sea countermeasures. The presumption is typically that countermeasures cannot be conducted if the sea is not dead calm (O'Brien, 2002; Steen et al., 2002). Steen et al. suggest a limit of 1 m waves, while at the same symposium, Koops and Huisman (2002) suggest a limit of five times that amount.

Det Norske Veritas in co-operation with the Norwegian Pollution Authority has developed standards for the certification of oil spill recovery technologies (Johanesson and Mjelde, 2001). The certification focusses on test methods specifically geared to smaller test tanks as exist in Norway and not on developing minimum specifications for such equipment.

3.3 Booms

Schulze and Lane (2001) and Schulze (2003) review the performance of booms and summarize 20 years of testing. They note that it is important to relate first-loss velocity as well as test oil viscosity, freeboard, boom draft, and boom buoyancy-to-weight ratio. Much of the boom testing was conducted in OHMSETT where the results of boom testing have varied over the years. Devitis and Hannon (1995) note that the results of testing have gone up over the years, that is the first-loss tow velocity has increased. Particularly, Devitis and Hannon note that there was a jump between the 1982 and 1992 results. During that period, no testing was conducted in OHMSETT and, when it resumed, the first loss failures jumped from about 0.5 to 0.6 m/s. However, Devitis and Hannon note that the range of results are about the same and the differences may stem from the fact that the earlier results were conservative and, secondly, that boom designs have improved somewhat. The results of testing from 1975 to 1982 and the procedures for offshore testing for oil spill containment booms were reviewed by Nash and Hillger (1988). The first loss speed ranged from 0.1 to 0.57 m/s for a calm situation and from 0 to 0.56 m/s for regular waves and 0 to 0.38 m/s for chop. Testing results from OHMSETT are summarized in Table 3.

The classic failure of oil spill containment booms at currents of about 0.4 m/s (0.8 knots) is well established by hydrodyamic models and tests. Much of this theory was established by Wicks (1969). Milgram and van Houten (1978) summarized the classic theories and demonstrated these in a test tank. Delvigne (1989) described boom failure by critical accumulation of viscous oils. Delvigne also noted that the classical droplet breakaway failure varied as a square of the current velocity. Tedeschi (1999) reviews booms and notes that the typical failure is at winds of 8 to 9 m/s (15 to 18 knots). Fitzmaurice (1993) reviews containment and failure modes and suggests that multiple boom configurations might be used to avoid critical accumulation. Van Dyck (1994), Clavelle and Rowe (1993), An et al. (1997), Goodman et al. (1997); Brown et al. (1997), Fang and Wong (2000), Swift et al. (2000a), and Grilli et al. (2000) utilized models to study failure modes. None included waves as a failure mode. Chen (1998) also reviews containment and proposed to raise containment limits by using porous nets in front of the booms to slow the currents. Johnston et al. (1993) identified a boom failure mechanism just before critical accumulation occurs with heavy oils. This mode is characterized by a surging under the boom. Zhu and Strunin (2002) propose a new containment model utilizing the Froude number submergence depth and the amount of oil trapped by the barrier.

The effect of waves has been studied by Van Dyck and Bruno (1995). They conducted a series of tow tank tests which show that short wavelength waves are the most difficult sea conditions for a floating boom to follow, even at optimum tow speeds or relative currents. It was found that wave height was not the limiting parameter, provided the wave length/height ratio is 12:1 or greater. Short length/height ratios lead to breaking waves where the height of the breaker must not exceed the available freeboard of the floating boom or there will be significant oil loss. Optimum catenary tow speeds are verified to be near 0.5 knot full scale for all wave sizes tested.

Lee and Kang (1997) review the performance of booms in currents and waves. They suggest that the effect of waves is to increase the horizontal current velocity. They present a graphical algorithm to predict the failure resulting from symmetrical waves. Kordyban (1992) developed a model to examine the effect of waves on boom failure. His approach is similar to Lee and Kang and a sinusoidal wave increases the effective velocity. Marks et al. (1971) analyzed the forces on a boom and calculated the total force was directly related to the wave amplitude as well as 12 other factors.

Milgram (1977) reviewed the specific mechanical design features of booms. He derived the following relationship to predict fabric tearing force as:

$$f_r = (C_r \rho g (d+b)^2 \ell H^{1/3})/10 \qquad (1)$$

where: f_r = tearing force,
C = flow around the boom,

ρ = density of oil or contained product,
g = gravitational constant,
d and b = constants related to fabric strength, and
H = the significant wave height.

Milgram notes that fabric tearing is the most significant type of physical damage to the boom and that it relates to the one-third power of the significant wave height.

Several workers have noted that the wave period is a serious factor in determining boom capabilities in waves (Oebius, 1999). Oebius noted that a height-to-period ratio of 0.04 is optimal for boom containment, but that shorter periods such as 0.056 would result in loss of containment.

Potter et al. (1999) studied the towing forces on booms. The first formulation that they review has the wave height as a direct and linear factor. The second formulation has the wave height as a constant that varies with boom and wave type. A typical constant for wave height is about 2 for a calm condition, 3.5 for regular waves, and 4 for harbour chop. Allen-Jones (1997) reviewed the towing forces and suggested that the direct use of significant wave height might be appropriate. Schulze and Potter (2002) subsequently conducted a series of tests in OHMSETT to measure the tow forces. This resulted in a new estimator of tow force which includes the tension caused by the force of water being directly proportional to the significant wave height.

Several attempts have been made to increase the containment capability of booms in fast waters using energy dissipative devices (Wooten, 1973; Dorrler et al., 1975; Jensen et al., 1975; Zhang et al., 1999). Wong and Witmer (1995) used an elliptical shape to increase containment capability. Fang and Wong (2001) used a ramp and a series of vertical barriers to create a calm recovery area.

Sloan et al. (1994) and Nordvik et al. (1995a, b) tested several booms offshore in the New York/New Jersey area. Findings included the result that many of the booms tested were not suitable for the conditions encountered in offshore waters, and that the wave height was only one of the factors that caused an excess of tow forces for the boom designs. It was also noted that there was a strong relationship between tow speed submergence initiation and reserve buoyancy and that the calculation methods for tow force underestimated the tow force. It was suggested that this might be a result of not adding the second tow vessel's acceleration. Nash and Molsberry (1995) discuss the offshore testing and note that the size of the system is a factor. They observed that larger booms performed better in an offshore environment.

Suzuki et al. (1985) tested booms in ice and found that the ice presence actually increased the critical tow speed. The critical tow speed with ice present generally increased from 0.4 to 0.5 m/s depending on a variety of conditions.

3.3.1 Typical Booms

Yazaki (1983) described the Japanese government requirements for two types of booms as being able to contain oil in winds of 10 or 20 m/s (type C, small harbour, or type D, larger, boom); wave heights of 1 and 1.5 m, and 0.25 and 0.5 m/s current.

Brown et al. (1993) noted that booms would fail at tow velocities of 0.25 m/s if the oil was heavier.

3.3.2 Special and High Current Booms

Getman (1977) reports on the tests of three fast current oil recovery devices - the Shell ZRV skimmer, the Seaward streaming fibre skimmer, and the French Cyclonet 050. Getman noted that the Shell ZRV performed well in a high current and in a wave train and the other two devices performed poorly in a wave train.

Bitting (1993) reports on the testing of the NOFI Vee-Sweep system noting that this device retains oil at higher speeds than most other devices. Hansen (2000a, 2001) measured the performance of a number of devices including sorbent booms in fast water. The JBF 6001 and Current Buster worked up to 3 and 3.5 m/s currents respectively. Hansen (2002) described a series of tests to measure the performance of fast water booms and deflectors.

Brekne et al. (2003) describe a boom designed to work in up to 2.5 m significant wave height and 20 m/s winds (50 knots). This new specialized boom, known as the Uniboom, uses a net for the lower portion of the skirt and is self-inflating. No subsequent data was actually provided on measured performance.

Williams and Cooke (1985) studied and tested bubble barriers for containing and burning oil. They found that the depth of slick contained varied as the square of the current velocity. For example, in 8 to 10 m/s wind, the floating bubble barrier held a 3.2 cm slick several metres away.

Eryuzlu and Hauser (1977) describe the use of floating deflectors to move oil out of currents to calm areas. A prototype deflector was tested in currents from 0.8 to 2.1 m/s and successfully deflected oil simulant to a calm area.

Folsom and Johnson (1977) describe a streamlined boom which was claimed to contain or deflect oil at currents up to 3 m/s.

Nash and Johnson (1981) report on the use of plunging water jets to converge oil slicks. They found they could converge slicks at current speeds of up to 3 m/s using this technology.

Brown et al. (1992, 1993) and Brown and Goodman (1998) report on the study and testing of several high-speed containment concepts including vertical cylinders, vertical slats with and without a back wall, vertical walls with fins at an angle, a hydrofoil, and horizontal structures including inclined screens and a variety of filters. Several of these innovations improved the containment ability, but no single system was recommended.

Swift et al. (2000b) reported on tests of an inclined submergence bow plane device which retained oil at currents up to 1.03 m/s.

3.4 Skimmers

Extensive testing of skimmers has been conducted in the OHMSETT facility. Tests from the 1970s are summarized in Smith and Lichte (1981) and Farlow and Griffiths (1981). Additional data are given in Lichte et al. (1981) and Lichte (1979). These tests are summarized again in Schulze (1998). Schulze is used as the prime source of data here, as summarized in Table 4.

Watkins (1995) notes that a measure of the effectiveness of a skimmer is the ability to recover the most oil in the least time. Suzuki et al. (1989) tested model skimmers at scale models and described the flow mathematically. Guenette and Buist (1993) reported on extensive testing of the Lori brush skimmer.

While it is acknowledged that skimmers may have similar limits as booms [about 0.5 m/s (1 knot)], these limitations can be overcome by several means, most typically by moving the skimmer at a lesser relative velocity to the oil on the sea. Several workers have proposed skimmer designs to overcome these limitations. Several earlier works used air herding or sheltering of the recovery area (Ayers et al., 1975; Freestone et al., 1975; Neal et al., 1975; Widawsky, 1975).

Clauss and Kühnlein (1991) proposed and demonstrate the use of massive wave-shielding hulls and energy-absorbing designs to allow at-sea recovery. Ueda et al. (2001) tested a model skimmer that avoids the effects of waves by diverting oil into a calm area. Hara et al. (2002) propose to use a moon pool inside a vessel to increase the wave limit from 1 to 2 or 3 m wave height. Akahoshi et al. (2002) suggest the current limit of sea recovery is a wave height of 2.5 m and propose to use a compensating float-pump system to deal with motion of the recovery platform. Hvidbak and Gunter (2002a) note that heavy oil imposes additional restrictions on recovery at sea.

Provant (1992) described the capabilities of the recovery equipment for the weather conditions of Prince William Sound. Provant provides tables of expected wave heights with winds in the sound. The degradation of performance of skimmers is given as: sea height up to 0.9 m, 80%; 1 to 2 m, 70%; 2.1 to 2.7 m, 50%; and over 2.8 m, 10%.

Nordvik (1999b) described modifications of the Transrec oil recovery system to improve its recovery efficiency and to enable high seas recovery. The unit recovered 15 to 85% of the oil presented to it during individual tests in 1.5 m waves and was thought to be capable of operating in waves up to 4 m.

Nordvik (1995) suggested limits for windows of opportunity for skimmers based on viscosity increase. Nordvik suggested a limit of 3 to 10 hours for a disc skimmer and 10 hours for a brush skimmer for the heavy oil BCF 17. For BCF 24, the window was estimated to be 2 to 3 days for a disk skimmer and after 3 days for a brush skimmer. These limits were based on the viscosity number generated from an oil viscosity model.

A test of skimmers and booms in cold weather conditions showed no differences from warmer weather tests of the same skimmers (Environment Canada, 1984). Shum and Borst (1985) tested a rope-mop skimmer in a test tank with ice and found that the recovery rates were not affected by up to 50% ice concentration. After 50% ice concentration, the mouth of the skimmer became jammed with ice. These tests show that the most significant factor in temperature is the formation of ice.

Gates and Corradino (1985) described a test of a weir skimmer in a test tank. The recovery did not deteriorate significantly when waves were increased from .18 to .47 m.

3.4.1 Harbour/Small Skimmers

The standard specifications for a harbour skimmer are that they should be able to achieve the specified performance with a 0.3 m wave (Smith et al., 1989). Velocity of the skimming surface is important and studies have shown that significant performance improvements in a skimmer can be achieved if the rotation speed is slowed (Christodoulou and Turner, 1987). Yazaki (1983) noted that the government of Japan specified that small skimmers must be able to operate at winds of 10 m/s and up to 0.5 m wave height and larger skimmers at winds of up to 15 m/s and wave heights of up to 1.2 m.

3.4.2 Offshore/Larger Skimmers

Nordvik (1995) noted successful recoveries on the open seas at up to 10 to 13 m/s winds and in waves up to 2.5 m/s. Peigne (1985) reports on the test of the Sirene and ESCA offshore skimming systems. Both systems were able to recover oil during offshore tests in winds up to 10 m/s and the accompanying waves of 1 to 2 m. Leigh (1973) described efforts to build and test two skimming devices to withstand sea state 5 (equivalent to winds of 10 to 14 m/s and wave heights of about 2 m). The two devices were a disc-drum skimmer and a weir basin that sheltered the basin face from oncoming waves.

Wilson (1981) reported on the testing of a high seas weir boom and noted that high recoveries were obtained in seas with up to 3 m waves and winds of up to 15 m/s. Up to 7,500 tons of oil or emulsion were collected in high seas.

3.4.3 Special/High Current Skimmers

Schwartz (1979) describes some of the first tests on higher-speed skimmers, noting the performance decrease with both waves and tow speed. Hansen (2002) described a series of tests to measure the performance of fast-water skimmers. The “Ocean Buster” skimmer, a unit using a weir and calm area behind the weir, has been successfully tested at tow speeds up to 2 m/s (4 knots) (Brekne et al., 2003). The same skimmer was tested in seas up to 3 m significant wave height at a tow speed of 0.8 m/s (1.5 knots). Coe (1999) describes a similar effort in which the USCG high-speed skimmer capability was increased up to 3 m/s (6 knots) by using a deflector.

3.4.4 Skimming Ships

Several Dutch efforts have taken place over the past 20 years to use dredger vessels with their systems for the recovery of oil (Ouwerkerk et al., 1995). Recent efforts have focussed on modifications to the input system to allow the dredger vessels to use their own pumps, thereby utilizing this enormous capacity. The heart of the system is the floating unit known as a dredge skimmer, which replaces the regular draghead. This skimmer follows the wave movements and the suction pipeline is kept in position about 2 m under the water level by the suction tube gantries. A sweeping arm is connected to the skimmer through a double hinge, allowing the arm freedom of movement horizontally and vertically. Koops et al. (1985) describe the use of the earlier versions of these skimming vessels to recover the heavy oil during the *Katina* oil spill. The modified dredges recovered oil in waves of up to 2 m, at which point the sweeping operation was stopped to avoid damage. Recent versions of the vessel recovered up to 13,000 L of pure heavy oil during a 3-month period at the *Prestige* spill.

3.5 Dispersants

Over 10 years ago, neither weathering of the oil nor weather itself were considered in planning for dispersant application (Lindstedt-Siva, 1987). More recently, dispersant applications have been assessed using only weathering and not weather as a criterion for results (Scholz et al., 1999; Lewis and Aurand, 1997; Aurand, 1995; Trudel et al., 2001, 2003). Nordvik (1995) proposed a weathering-based window of 26 hours for ANS crude and 2 hours for Bonnie Light. A period of reduced dispersibility was estimated to be 26 to 120 hours for ANS crude and 2 to 4 hours for Bonnie Light. After 4 hours, Bonnie Light was deemed not dispersible. Several workers (Lewis et al, 1994, 1995a, b, 1998a, b) noted that the weathering of the oil itself was a major factor in dispersant effectiveness.

Martinelli and Lynch (1980) reviewed the factors affecting chemical dispersion and noted that the two most important factors are the oil composition and sea energy. Martinelli and Lynch concluded that temperature was semi-important and several other factors were not investigated. Farmwald and Nelson (1982) tested the effect of temperature on dispersibility of Prudhoe Bay crude and found a variable temperature effect. Daling (1988), Daling et al. (1995), and Brandvik et al. (1991) measured dispersant effectiveness in the laboratory and found that, as temperature was lowered, effectiveness fell by as much as 20%. The researchers also noted that photolysis of the oil resulted in less effectiveness.

Salt (2001) reviews the use of dispersant application aircraft at night and concludes that only daylight operations would be safe.

Lunel and Lewis (1999) propose that the bottom threshold for dispersibility be established as 15% for moderate sea conditions and 30% for calm sea conditions. Lunel et al. (1995a) suggest that winds of 0 to 5 m/s be classified as low energy and winds of 6 to 10 m/s be classified as high energy. The natural dispersion on a medium fuel oil was 0.8% at low energy and 3% at high energy. The dispersion for the medium fuel oil for Slickgone was 8% at low energy and 17% at high energy. Scholz et al. (1999) suggest a minimum threshold of energy of a sea state of 1 to 5 (corresponding to winds of 2.5 to 12 m/s and waves of 0.1 to 2 m).

At higher sea states, many crude oils will disperse naturally. Most of the oil spilled during the *Braer* incident, which was a Gulfaks crude oil, dispersed naturally (Thomas and Lunel, 1993; Lunel 1995a, b). Lunel noted that the winds were of force 8 to 10 (16 to 26 m/s, yielding waves of about 6 to 12 m and gusts of wind up to 35 m/s) during that incident. It is important to note that the oil, Gulfaks, was dispersible and that the same conditions applied to a Bunker C, for example, would not result in significant dispersion. Lunel also stated that natural dispersion is slower and moves only to about 1 m depth. This had been stated earlier by Cormack and Nichols (1977). Fuentes et al. (1995) studied natural dispersion in a turbulent laboratory apparatus and found that natural dispersion increased with increased oil weathering. The oil was a lighter Arabian crude. The winds during the *Sea Empress* incident were up to 20 m/s and thus much of the dispersion that occurred during that incident may have been natural (Lunel et al., 1996).

Natural dispersion has been studied and described by several other workers (Reed et al., 1995c; Sebastiao and Soares, 1995). Mackay et al. (1980) described the natural dispersion of oil as:

$$\text{Fraction dispersed} = 0.11(W+1)^2\ (1 + 50\mu^{1/2}ds_t)\text{-}1 \qquad (2)$$

where W is the wind speed in m/s,

μ is the viscosity in mPa.s,

d is the slick thickness in cm, and

S_t is the oil-water interfacial tension in dyne cm^{-1}.

Most recent models use the equations of Delvigne and Sweeney (1988):

$$Q = C\ D^{0.57}\ S\ F\ d^{0.7}\ \Delta d \qquad (3)$$

where Q is the entrainment rate of oil droplets,

C is an empirical constant dependent on oil type,

D is the dissipated breaking wave energy,

S is the fraction of the sea surface covered by the oil,

F is the fraction of the sea hit by breaking waves,

d is the oil particle diameter, and

Δd is the oil particle diameter interval.

The wave energy, D is given by:

$$D = 0.0034\rho g H^2 \qquad (4)$$

where D is the energy in J/m^2,
ρ is the density of seawater,
g is the gravitational constant, and
H is the rms value of wave height.

Thus in both the Mackay and the Delvigne formulation, the amount of oil that enters the water varies as the square of the wave height. Delvigne and Hulsen (1994) subsequently developed a small laboratory method to measure the dispersibility of an oil.

Koops (1988) also presents a formulation for natural dispersion:

$$V_{disp} = Vo(1 - e^{-7.6\ 10^{-5}}\, Ht/Vo^{0.62}) \qquad (5)$$

where V_{disp} is the volume of oil dispersed naturally,
Vo is the initial oil volume,
H is the significant wave height, and
t is the time.

In the Koops formulation, the oil dispersion varies linearly with the wave height.

Mackay (1985) later developed a relationship for breaking waves only and the parameter that determined the rate of dispersion was only the amount of dispersant applied.

The effectiveness of Corexit 9500 and Corexit 9527 was tested on Alaska North Slope crude oil at various salinities and temperatures representative of conditions found in Southern Alaskan waters (Moles et al., 2001). The oil was weathered to different degrees. Tests were conducted in a swirling flask at temperatures of 3, 10, and 22°C with salinities of 22 and 32°/oo. Analysis was by GC. The authors concluded that, at the common temperatures found in the estuaries and marine waters of Alaska, the dispersants were largely ineffective. They also found that there was an interactive effect between temperature and salinity. A high effectiveness for ‘emulsion’, an uncharacterized mixture of oil and water, was attributed to ‘osmotic shock’ because of the difference in the salinity of preparation (33 °/oo) and the test salinity.

Deposition of dispersant droplets depends on the droplet sizes discharged from the nozzles. Lindblom and Cashion (1983) presented a relationship that describes the droplet sizes:

$$VMD = k\ (\mu a\ \sigma^{b}\ \rho^{c}\ V^{d}\ D^{e}) \qquad (6)$$

where VMD is the droplet volume mean diameter,
μ is the dispersant viscosity,
σ is the surface tension,
ρ is the density of the dispersant,
V is the exit velocity relative to the surrounding airstream,
D is the nozzle diameter, and
k, a, b, c, d, e are empirical constants.

It should be noted that d varies from -0.6 to -1.3 depending on dispersant, thus the effect of increasing wind velocity is to decrease the droplet diameter discharged.

Smedley (1981) studied the deposition of dispersants from DC-4 and Canadair spray aircraft. Smedley noted that droplets less than 100 µm and sometimes up to 500 µm may be entrained in aircraft vortices and may not be deposited near the intended target. Tests also showed that crosswinds cause poor deposition.

Fay (1993) reported on a series of tests on the MASS spray system at Crosbytown, Texas. Fay notes that 20 to 80% of the dispersant was lost and did not hit the targeted area. Giammona et al. (1994) conducted a major campaign to measure the deposition of dispersant from several aircraft platforms near Alpine, Texas. These data have been used here to provide prediction of the relation of wind to deposition efficiency and thus weather cutoffs.

Lewis (1995) calibrated a helicopter bucket system finding that the standard conditions of 30 m/s (60 knots) forward speed and altitude of 14 m (50 feet) resulted in about 70% deposition. A forward speed of 8 m/s (15 knots) and 6 m (12 feet) resulted in better or optimal deposition, although the ground effect of the helicopter rotors was extreme. A deposition of about 3 to 6 mL/m^2 was obtained at the standard conditions, with a loss of about 20% of the material due to wind drift under the prevailing weather conditions of 2 to 5 m/s winds. At this wind speed the deposition was about 3.4 mL/m^2 (about 3.5 US gal/acre) with a swath width of about 21 m. Reducing the air speed to 15 m/s (30 knots) and an altitude of 7 m (25 feet) increased the dosage rate to 14 mL/m^2 (about 14 US gal/acre) with a deposition rate of at least 70%. Brandvik et al. (1997) tested a new helicopter bucket but did not gauge the effect of wind.

Payne et al. (1991b) studied the use of dispersant on the Pac Baroness and noted that winds of 7 to10 m/s caused problems in deposition. Furthermore, it was impossible to tell if the dispersant hit the slick or was blown off by the cross wind. Payne et al. (1993) studied the test application of dispersant on the *Mega Borg* spill and noted that there was significant wind drift of the dispersants. Lunel (1994a; 1994b; 1995a; 1995b; 1995c; 1995d; 1998; Lunel et al. 1995a, b; 1996; 1997; Lunel, 2001; Lunel and Davies, 1996: Lunel and Wood, 1996) noted in several sea trials that winds of 5 to 10 m/s were not a problem for aerial application, although targeting is a problem and that this is best done with the aid of remote sensing. Guyomarch et al. (2002) describe a field experiment in which the wind ranged from 3 to 20 m/s. This wind was not noted as a factor.

Several workers noted that dispersion using spray booms on vessels was relatively unaffected by winds up to 15 m/s (Lichtenthaler and Daling, 1983).

3.5.1 Other Agents

Pope et al. (1985) tested surface collecting agents and evaluated them over a range of temperatures. The efficiencies of the agents only decreased slightly with air temperatures down to less than 0ºC. The effect of wind of 2 to 3 m/s was to assist in herding.

3.6 In-situ Burning

Buist et al. (2003) studied the burn rates and conditions of some Alaskan oils with and without ice. Buist (2003) discussed the windows of opportunity for in-situ burning. He proposes that the maximum wind speed for successful ignition is 10 to 12 m/s, although no basis for this is given. Later in the paper, Buist also proposes a series of weathering percentages and water content for which oils would or would not burn or where efficiency is severely hampered. Further limitations discussed include operational limits and that VFR flying rules for the helicopter would require greater than 4 km visibility and a minimum 300 m ceiling. Buist et al. (1998) studied in-situ burning in a test tank on the North Slope of Alaska and found that the wave steepness reduced both the burn rate and effectiveness. Bech et al. (1993) found that increasing wave action reduced efficiency.

Thornborough (1997) described a series of in-situ burns conducted off the United Kingdom in 1996. The trial was specifically designed to examine the limits of ignition and combustion under sea conditions. Burn 1 was ignited using a small hand-held unit with a sea state of 4/5 (waves of 1 to 2 m), wind of 10 to 13 m/s (20 to 25 knots), and a current speed of 0.9 m/s (1.8 knots). The boom and the ignition were successful and were not significantly hampered by the prevalent weather conditions. The second burn was ignited using a Helitorch at sea state of 4 (waves about 1.5 m), wind of 10 m/s (20 knots), a current of 0.9 m/s (1.8 knots) and again at 120 degrees from the current direction and that of the towing vessel. The second burn involved oil containing 25% water. The burning fuel from the Helitorch reached the sea surface from a height of 60 to 70 feet (20 to 25 m) and a helicopter speed of 10 to 13 m/s (20 to 25 knots). Above this height and speed, the gelled gasoline did not stay ignited.

Nordvik et al. (2002; 2003) reviewed windows of opportunity for burning, noting that the lower flammability limit and weathering of the oil are important. This paper also proposes an upper wind limit of 10 to 12 m/s (20 knots) for the ignition of the oil. The source of this limit, other than a related report, is not given. A weathering diagram generated from the IKU model is given as the means for estimating the weathering time at which the flash point is reasonable, given a certain wind velocity. Nordvik (1995) had proposed a window based on formation of emulsion for ANS crude of 36 hours and of 1 hour for Bonnie Light crude.

3.6.1 Ignition

Farmwald and Nelson (1982) tested the effect of temperature on flammability and ignition of Prudhoe Bay crude and found temperature had little effect. Guenette and Wighus (1996) reported that ignition was difficult when winds exceeded 10 m/s. Bech et al. (1993) found that ignition was difficult with emulsified oils. D'Atri and King (1993) conducted a burn in cold conditions and found that gelled gasoline did not work, however, a propane weed-burner worked well.

Guenette and Thornborough (1997) reported on the use of two types of igniters used off the coast of the United Kingdom. Burn 1 was ignited using a small hand-held unit with a sea state of 4/5 (waves of 1 to 2 m), wind of 10 to 13 m/s (20 to 25 knots), and a current speed of 0.9 m/s (1.8 knots). The boom and the ignition were successful and not significantly hampered by the prevalent weather conditions. The second burn was ignited using a Helitorch at sea state of 4 (waves about 1.5 m), wind of 10 m/s (20 knots), a current of 0.9 m/s (1.8 knots), and again at 120 degrees from the current direction and that of the towing vessel. The hand-held unit consisted of a jar of gelled gasoline and a flare. The unit is floated out to the oil after lighting the flare, the flame from the flare melts the wall of the plastic and then ignites the gelled gasoline. The second device used a modified helitorch in which the fluid included an emulsion breaker as well as the usual gelled fuel.

Moffat and Hankins (1997) tested a flare-type igniter specially built for oil spills. The flares showed a temperature of 1370°C at the centre and this was maintained for a 3-minute burn. The igniter was used to ignite diesel fuel in ambient temperatures of 3°C with winds of 8 to 10 m/s.

Burns certainly could be ignited at higher wind speeds given that the initial burn is sheltered from the wind. It is known, that once ignited, fires can burn at very high wind velocities (Fingas and Punt, 2000). In fact, a device for performing this feat was built and tested in the early 1980s (Fingas and Punt, 2000).

3.6.2 Fire-resistant Boom

Meikle (1983) reported on the test of a ceramic fire-resistant boom. Measurements were taken of the loss rate versus tow speed, as well as the rate of burning at different tow speeds. These are reported in Table 3. Buist et al. (1983) also reported on the testing of a fire-resistant boom. The boom was successfully tested in a towing mode up to wave heights of 4 m and contained oil in currents up to 0.4 m/s.

Bitting and Coyne (1997) and Hansen (2000b) reported on the tests on fire-resistant booms as containment booms. Many of the booms showed performance near that of conventional booms. The first loss and critical failure velocities were reported. McCourt et al. (1997) tested a series of fire-resistant booms for ruggedness while exposed to a propane fire and found that most booms could tolerate the propane fires.

3.7 Others

Pumps and transfer devices are not really limited by the weather, but are significantly affected by viscosity which increases as the oil weathers. Lower temperatures would, of course, increase viscosity and make pumping more difficult. Cooper and Mackay (2002) and Hvidbak and Gunter (2002b) review viscous pumping technologies.

Nordvik (1995) proposed a window of opportunity limit for using sorbents based on weathering and increased viscosity of oil. Nordvik suggested a viscosity of 15,000 mPa.s would constitute a reasonable upper limit. The window of opportunity for heavy oil such as BCF-17 and BCF-24 became 4 and 10 days respectively. The effectiveness was felt to be reduced to 50% after 36 hours.

Nordvik (1995) also proposed a window of opportunity limit for centrifugal separators based on the closing density gap between oil and seawater. This limit was calculated to be 18 hours for ANS and 24 hours for Bonnie Light. Provant (1992) studied the effects of wave height on separation by decanting. Provant rated the decrease in performance with wave height as: wave height up to 0.9 m, 0.8 decanting factor (eg. 80% effective); waves of 1 to 2 m, 0.8; waves of 2.1 to 2.7 m, 0.7; and over 2.8 m, 0.6.

McCourt and Shier (1998) studied the sediment interaction on the Yukon River and found in laboratory experiments that there were temperature and energy relationships. The mean oil loading was 0.006 goil/gsolids at an arc (shaking angle) of 4 degrees, 0.1 at 7 degrees, and 0.11 at 10 degrees. This is explained by increasing contact and coalescence. The loading went from the 0.11 noted at 15°C up to 0.26 goil/gsolids at 2°C.

3.8 Ice Conditions

While it was not one of the purposes of this study to examine the cleanup efficiencies with ice as this is more than a factor of weather, some data were found that make it possible to calculate the degradation of certain recovery techniques with increasing ice concentrations (Grenon, 2000). Abdlenour et al. (1985) summarized tests of a water-spray boom/weir combination in increasing ice conditions. Shum and Borst (1985) tested a rope mop in ice-infested conditions and found a sharp drop off in effectiveness.

Several workers have noted that ice, not temperature is an issue (Arita et al, 1998; Grenon, 2000). Tsang and Vanderkooy (1979) describe the development of an ice boom which shows the capability of deflecting ice floes on rivers and allowing oil to pass through. The boom was successfully tested in heavy ice concentrations and with currents up to 0.2 m/s.

4. Development of Models for Effectiveness of Countermeasures

4.1 Overall

The basic procedure to develop a model for countermeasures effectiveness was to use literature data on testing of examples of the particular countermeasure and then correlate this data with the weather factor. The main advantage of this method is that it yields a relatively realistic outlook on the actual relationship between performance and the weather factor under consideration. The main disadvantage is that often there are no data on the performance of oil spill countermeasures at high winds, waves, or extreme temperatures. Thus, to a certain extent, the existing quantitative data may be extrapolated past the typical measurement points.

4.2 Booms

The quantitative data obtained for boom performance with weather is summarized in Table 3. The variance of critical velocity and wave height can be seen in the table. An analysis of the variation of critical loss rate and wave height shows some correlation. This allows one to use the values presented in Table 3 directly to predict the decrease in first loss and critical velocities. Figure 8 shows the decrease in first loss and critical tow velocities with increasing wave height, using the averages of all booms and then the average of fire-resistant booms. The decrease in performance of booms with increasing wave height as shown in Figure 8 is expected and has been relatively well known for several years. The correlation between various performance parameters for booms is shown in Table 5. It can be seen that there is a poor correlation between viscosity, wave height, and first loss speed.

4.3 Skimmers

The quantitative data obtained for skimmer performance with weather is summarized in Table 4. These data largely come from Schulze (1998) and represent data collected over 25 years of skimmer testing.

Table 4 shows the three most important values of skimmer performance, ORR, TE, and RE. The Oil Recovery Rate (ORR) is the quantitative rate in volume per unit time, usually m^3/hour and is corrected for water recovery. The throughput efficiency (TE) is applicable only to advancing skimmers. The throughput efficiency is the percentage of oil presented to a skimmer versus that recovered, in percent. The recovery efficiency (RE) is the percent of oil recovered out of the total oil and water recovered.

Table 4 also shows the calculations of the rate of change of the ORR, TE, and RE with increasing current and wave height. These are calculated directly from the data shown in Table 4. The rate of change is taken when other parameters of the test including viscosity and oil type, tow rate, and wave height and type, are held constant.

Table 6 shows the summary and calculated averages of the data from Table 4. There is some change in the performance of skimmers with ice concentration.

Table 3 Tests of Boom Performance with Changing Weather Conditions

			Current/Tow Speed		Wave Height Summary					
boom	Reference	Year of Test	First Loss Speed m/s	Critical Speed m/s	Speed/wave /s	Oil Type	Oil Viscosity mPa. S	Number of **Tests**	Wave height m	Wave Conditions
Typical booms										
Fence - catenary	Schulze 2001	1977	0.2				300	8	calm or 0.3	or long regular waves
Fence - catenary	Schulze 2001	1977	0.23		0.17		300		0.6	short regular waves
Fence - diversionary	Schulze 2001	1977	0.6				300		calm	
Fence - diversionary	Schulze 2001	1977	0.7		-0.7		300		0.3	long regular waves
Fence - diversionary	Schulze 2001	1977	0.5		1.3		300		0.6	short regular waves
Fence - catenary	Schulze 2001	1991	0.45				64		calm	
Fence - catenary	Schulze 2001	1991	0.5				64		calm	
Fence - catenary	Schulze 2001	1991	0.6				64		calm	
Curtain - catenary	Schulze 2001	1977	0.45				333	16	calm or 0.3	or long regular waves
Curtain - catenary	Schulze 2001	1977	0.25		1.3		333		0.6	short regular waves
Curtain - diversionary	Schulze 2001	1977	0.6				1462		calm or 0.3	or long regular waves
Curtain - diversionary	Schulze 2001	1977	0.4		1.3		1462		0.6	short regular waves
Curtain - catenary	Schulze 2001	1977	0.45				230		calm	
Curtain - catenary	Schulze 2001	1977	0.35		0.7		230		0.3	long regular waves
Curtain - diversionary	Schulze 2001	1977	0.4				336		calm	
Curtain - diversionary	Schulze 2001	1977	0.45		0.3		336		0.3	long regular waves
Curtain - diversionary	Schulze 2001	1977	0.38		0.5		336		0.6	short regular waves
Curtain - catenary	Schulze 2001	1977	0.4				649	calm, or short or long reg waves		
Curtain - diversionary	Schulze 2001	1977	0.4				333	calm, or short or long reg waves		
Curtain - catenary	Schulze 2001	1977	0.45				97	calm, or short or long reg waves		
Curtain - diversionary	Schulze 2001	1977	0.7				235	calm, or short or long reg waves		
Curtain EF- catenary	Schulze 2001	1977	0.35				194	calm, or short or long reg waves		
Curtain EF- diversionary	Schulze 2001	1977	0.45				134	calm, or short or long reg waves		
Selfinf - catenary	Schulze 2001	1977	0.25				300/177		calm	
Selfinf - catenary	Schulze 2001	1977	0.3				300/177		0.3	long regular waves
Selfinf - catenary	Schulze 2001	1977	0.4		-0.35		300/177		0.6	short regular waves
Selfinf - catenary	Schulze 2001	1977	0.2				300/10		calm or 0.3	or long regular waves

Table 3 ctd   Tests of Boom Performance with Changing Weather Conditions

			Current/Tow Speed		Wave Height Summary					
boom	Reference	Year	First Loss Speed	Critical Speed	Speed/wave	Oil	Oil Viscosity	Number of	Wave height	Wave
		of Test	m/s	m/s	/s	Type	mPa. S	**Tests**	m	Conditions
Selfinf - catenary	Schulze 2001	1977	0.35		-0.5		300/10		0.6	short regular waves
Selfinf - diversionary	Schulze 2001	1977	0.75				300/238		calm	
Selfinf - diversionary	Schulze 2001	1977	0.5		0.85		300/238		0.3	long regular waves
Selfinf - diversionary	Schulze 2001	1977	.6-.8		0.15		300/238		0.6	short regular waves
Selfinf - diversionary	Schulze 2001	1977	0.2		1		300/238		0.3	harbour chop
Selfinf - catenary	Schulze 2001	1980	.4/.55				1026/3000		0.2	long regular waves
Selfinf - catenary	Schulze 2001	1980	0.45				1026/3000		0.2	long regular waves
Selfinf - catenary	Schulze 2001	1980	.4/0.57		0.13		1026/3000		0.4	long regular waves
Selfinf - catenary	Schulze 2001	1991	0.5				10/64		calm	
Press-inf- diversionary	Schulze 2001	1993	.5/.7				100/370		calm	
Press-inf- diversionary	Schulze 2001	1993	0.7/0.9				100/9300		calm	
Press-inf- diversionary	Schulze 2001	1993	0.7/0.65		0.55				0.3	long regular waves
Press-inf- diversionary	Schulze 2001	1993	0.8/0.9		-0.25		100/9900		0.6	short regular waves
Press-inf- diversionary	Schulze 2001	1993	0.7/0.8		0.25		100/9900		0.3	harbour chop
Press-inf- diversionary	Schulze 2001	1993	0.62/0.8				100/9900		calm	
Press-inf- diversionary	Schulze 2001	1993	0.5/0.8		0		900/7500		0.3	harbour chop
Press-inf- diversionary	Schulze 2001	1993	0.6/0.8				900/10400		calm	
Press-inf- diversionary	Schulze 2001	1993	0.6/0.7		0.2		900/3600		0.6	short regular waves
Press-inf- diversionary	Schulze 2001	1993	0.72/0.88				100/850		calm	
Press-inf- diversionary	Schulze 2001	1993	0.63/0.7				300/870		calm	
Press-inf- diversionary	Schulze 2001	1993	0.65/0.8		0.15		300/870		0.3	long regular waves
Press-inf- diversionary	Schulze 2001	1993	0.63/0.85		0.35		300/630		0.3	harbour chop
Press-inf- diversionary	Schulze 2001	1993	0.6/0.7				300/1050		calm or 0.3	or long regular waves
Press-inf- diversionary	Schulze 2001	1993	0.5/0.62		0.35		300/1050		0.3	harbour chop
Press-inf- catenary	Schulze 2001	1991	0.6				10/64		calm	
Press-inf- catenary	Schulze 2001	1991	0.45				10/64		calm	
Press-inf- catenary	Schulze 2001	1991	0.75				10/64		calm	

Table 3 ctd Tests of Boom Performance with Changing Weather Conditions										
			Current/Tow Speed		**Wave Height Summary**					
boom	Reference	Year of Test	First Loss Speed m/s	Critical Speed m/s	Speed/wave /s	Oil Type	Oil Viscosity mPa. S	Number of **Tests**	Wave height m	Wave Conditions
Fire-resistant booms										
Fence	Schulze 2001	1997	0.5	0.63			600/3000		calm	
Fence	Schulze 2001	1997	0.35	0.45	0.63		600/3000		0.24	regular waves
Fence	Schulze 2001	1997	0.55	0.65	-0.17		600/3000		0.3	long regular waves
Fence	Schulze 2001	1997	0.48	0.55	0.067		600/3000		0.2	harbour chop
Fence	Schulze 2001	1997	0.48	0.66			500/2900		calm	
Fence	Schulze 2001	1997	0.37	0.53	0.46		500/2900		0.24	regular waves
Fence	Schulze 2001	1997	0.48	0.6	0		500/2900		0.3	long regular waves
Fence	Schulze 2001	1997	0.5	0.53	-0.07		500/2900		0.2	harbour chop
Fence	Schulze 2001	1999	0.45	0.6			400/200		calm	
Fence	Schulze 2001	1999	0.38	0.45	0.29		400/200		0.24	regular waves
Fence	Schulze 2001	1999	0.45	0.6	0		400/200		0.3	long regular waves
Fence	Schulze 2001	1999	0.45	0.6	0		400/200		0.2	harbour chop
Intern foam	Schulze 2001	1999	0.48	0.63			360/1940		calm	
Intern foam	Schulze 2001	1999	0.42	0.55	0.25		360/1940		0.24	regular waves
Intern foam	Schulze 2001	1999	0.55	0.74	-0.23		360/1940		0.3	long regular waves
Intern foam	Schulze 2001	1999	0.53	0.65	-0.19		360/1940		0.2	harbour chop
Press inflat	Schulze 2001	1997	0.45	0.61			500/1730		calm	
Press inflat	Schulze 2001	1997	0.4		0.21		500/1730		0.24	regular waves
Press inflat	Schulze 2001	1997	0.54		-0.3		500/1730		0.3	long regular waves
Press inflat	Schulze 2001	1997	0.5		-0.17		500/1730		0.2	harbour chop
exterior tension	Schulze 2001	1999	0.45	0.63			360/2064		calm	
exterior tension	Schulze 2001	1999	0.3	0.48			360/2064		0.24	regular waves
exterior tension	Schulze 2001	1999	0.5	0.65			360/2064		0.3	long regular waves
exterior tension	Schulze 2001	1999	0.35	0.55			360/2064		0.2	harbour chop
Ceramic	Meikle 1983	1982	1.1			heavy	1300		calm	
Ceramic	Meikle 1983	1982	1.1		0	heavy	1300		0.2	
Ceramic	Meikle 1983	1982	0.9		0.5	heavy	1300		0.4	
Ceramic	Meikle 1983	1982	0.7		2	heavy	1300		0.2	harbour chop

Table 4 Tests of Skimmer Performance with Changing Weather Conditions

			Current /Tow Speed Summary				Wave Height Summary					Oil	Slick			Wave				
Skimmer	Reference	Year	Slope ORR	ORR Slope	Slope TE	Slope RE	Slope ORR	ORR Slope	Slope TE	Slope RE	Oil	Viscosity	Thick.	# of	Speed	height	Wave	ORR	TE	RE
		of Test	m^2s/h	%s/m	%s/m	%s/m	m^2/h	%/m	%/m	%/m	Type	mPa. S	mm	Tests	m/s	m	Conditions	m^3/h	%	%
Harbour&small skimmers																				
Skimming Barrier	Schulze, 1998	1977										200	120	3	0.25	calm		58.2		56
Skimming Barrier	Schulze, 1998	1977					36	61.9		71.7		200	120	5	0.25	0.3	harbour chop	47.4		34.5
Skimming Barrier	Schulze, 1998	1977	-115.4	-198.3		-134.6						200	120	2	0.38	calm		73.2		73.5
Skimming Barrier	Schulze, 1998	1977	-57.6	-99		-12.8						200	120	6	0.5	calm		72.6		59.2
Skimming Barrier	Schulze, 1998	1977					-18	-30.9		41.3		200	120	2	0.38	0.3		63.6		43.6
Skimming Barrier	Schulze, 1998	1977					-45	-77.3		23.7		200	120	4	0.5	0.3	regular	71.7		48.9
Skimming Barrier	Schulze, 1998	1977					0	0		50.3		200	120	4	0.5	0.3	regular	58.2		40.9
Skimming Barrier	Schulze, 1998	1977					15.2	26.1		49.4		200	120	1	0.25	0.5	regular	50.6		31.3
Skimming Barrier	Schulze, 1998	1977					12.6	-27.8		34.6		200	120	4	0.5	0.5	regular	66.3		41.9
Skimming Barrier	Schulze, 1998	1977					18.8	-17.2		38.8		200	120	4	0.5	0.5	regular	63.2		39.8
Skimming Barrier	Schulze, 1998	1977					25.3	43.5		46.7		200	120	2	0.25	0.6	harbour chop	43		28
Skimming Barrier	Schulze, 1998	1977					-85	-8		60.2		200	120	3	0.38	0.6	harbour chop	61		37.4
Skimming Barrier	Schulze, 1998	1977					30	10.3		40.7		200	120	6	0.5	0.6	harbour chop	54.6		34.8
Skimming Barrier	Schulze, 1998	1977					30.7	11.5		41.5		200	120	6	0.5	0.6	harbour chop	54.2		34.3
Sirene Skimming Barrier	Schulze, 1998	1979										545	3.1	1	0.38	calm		18	100	23
Sirene Skimming Barrier	Schulze, 1998	1979	-87.5	-486.1	175	-158.3						545	3.3	1	0.5	calm		28.5	79	42
Sirene Skimming Barrier	Schulze, 1998	1979	-41.6	-231.1	288	-104						545	3.2	1	0.63	calm		28.4	28	49
Sirene Skimming Barrier	Schulze, 1998	1979	5.9	33	240.5	-8.1						545	3	1	0.75	calm		15.8	11	26
Sirene Skimming Barrier	Schulze, 1998	1979					-1	-5.6	1.7	18.2		545	3.2	1	0.38	0.6	harbour chop	18.6	99	31
Sirene Skimming Barrier	Schulze, 1998	1979					-35.8	-199.1	85	-48.5		545	3.3	1	0.63	0.6	harbour chop	39.5	49	71
Sirene Skimming Barrier	Schulze, 1998	1979					-25.7	-142.6	115	-26.8		545	2.6	1	0.75	0.6	harbour chop	33.4	31	58
Sirene Skimming Barrier	Schulze, 1998	1979					23.3	129.6	306.7	86.3		545	2.7	2	1	0.3	harbour chop	11	8	16
Sirene Skimming Barrier	Schulze, 1998	1979					3.2	17.8	2	29.8		545	3.2	1	0.38	0.5	regular	16.4	99	27
Sirene Skimming Barrier	Schulze, 1998	1979					-35.4	-196.7	94	-26.2		545	2.7	1	0.63	0.5	regular	35.7	53	55
Sirene Skimming Barrier	Schulze, 1998	1979										178	3.1	1	0.38	calm		16.6	99	22
Sirene Skimming Barrier	Schulze, 1998	1979	-155	-933.7	258.3	-183.3						178	3.3	1	0.5	calm		35.2	68	44
Sirene Skimming Barrier	Schulze, 1998	1979	16	96.4	244	-80						178	3.1	1	0.63	calm		12.6	38	42
Sirene Skimming Barrier	Schulze, 1998	1979	7	42.3	237.8	-5.4						178	2.6	1	0.75	calm		14	11	24
Sirene Skimming Barrier	Schulze, 1998	1979					1.8	10.8	0	2		178	3.2	1	0.38	0.5	regular	15.7	99	21
Sirene Skimming Barrier	Schulze, 1998	1979					-46.4	-279.5	96	-74		178	3.1	1	0.5	0.5	regular	39.8	51	59
Sirene Skimming Barrier	Schulze, 1998	1979					-21.6	-130.1	158	-44		178	3.5	1	0.63	0.5	regular	27.4	20	44
Sirene Skimming Barrier	Schulze, 1998	1979					1.6	9.6	170	-14		178	2.5	1	0.75	0.5	regular	15.8	14	29
Sirene Skimming Barrier	Schulze, 1998	1979					1.3	7.7	0	-4.3		178	3.1	1	0.38	0.7	harbour chop	15.7	99	25
Sirene Skimming Barrier	Schulze, 1998	1979					-4	-24.1	82.9	-17.1		178	2	1	0.5	0.7	harbour chop	19.4	41	34
Sirene Skimming Barrier	Schulze, 1998	1979					-11.4	-68.8	61.4	-64.3		178	3.3	1	0.63	0.7	harbour chop	24.6	56	67
Sirene Skimming Barrier	Schulze, 1998	1979					0	0	122.9	-10		178	2.9	1	0.75	0.7	harbour chop	16.6	13	29
Lori Brush Skimmer	Schulze, 1998	1979									med. oil	600	ns	1	0.75	calm		0.31		60
Lori Brush Skimmer	Schulze, 1998	1979	-0.6	-182.8		-86.7					med. oil	600	ns	1	1.05	calm		0.48		86

Table 4 ctd. Tests of Skimmer Performance with Changing Weather Conditions

			Current/Tow Speed Summary				Wave Height Summary					Oil	Slick			Wave				
Skimmer	Reference	Year	Slope ORR	ORR Slope	Slope TE	Slope RE	Slope ORR	ORR Slope	Slope TE	Slope RE	Oil	Viscosity	Thick.	# of	Speed	height	Wave	ORR	TE	RE
		of Test	m^2s/h	%s/m	%s/m	%s/m	m^2/h	%/m	%/m	%/m	Type	mPa. S	mm	Tests	m/s	m	Conditions	m^3/h	%	%
Lori Brush Skimmer	Schulze, 1998	1979	-0.8	-258.1		-40					med.oil	600	ns	1	1.3	calm		0.75		82
Lori Brush Skimmer	Schulze, 1998	1979	-0.9	-279.6		-24					med.oil	600	ns	1	1.5	calm		0.96		78
Lori Brush Skimmer	Schulze, 1998	1979	-0.3	-82.9		-5.7					med.oil	600	ns	1	1.8	calm		0.58		66
Lori Brush Skimmer	Schulze, 1998	1979					-0.3	-80.6		-131.3	med.oil	600	ns	1	0.75	0.16	regular	0.35		81
Lori Brush Skimmer	Schulze, 1998	1979					-2.6	-842.3		-83.3	med.oil	600	ns	1	1	0.18	regular	0.78		75
Lori Brush Skimmer	Schulze, 1998	1979					-2.5	-821.1		-72.7	med.oil	600	ns	1	1.3	0.22	regular	0.87		76
Lori Brush Skimmer	Schulze, 1998	1979					-2	-645.2		-56	med.oil	600	ns	1	1.5	0.25	regular	0.81		74
Lori Brush Skimmer	Schulze, 1998	1979					-1.1	-349.5		-33.3	med.oil	600	ns	1	1.8	0.24	regular	0.57		68
Scoop Weir Skimmer	Schulze, 1998	1978									heav.oil	1000	ns	2	0.25	calm		9.2	100	57
Scoop Weir Skimmer	Schulze, 1998	1978	-6.9	-75.3	0						heav.oil	1000	ns	1	0.38	calm		10.1	100	87
Scoop Weir Skimmer	Schulze, 1998	1978	13.6	147.8	220						heav.oil	1000	ns	3	0.5	calm		5.8	45	100
Scoop Weir Skimmer	Schulze, 1998	1978	13.4	145.9	176.3						heav.oil	1000	ns	4	0.63	calm		4.1	33	
Scoop Weir Skimmer	Schulze, 1998	1978					-4.7	-50.7	30		heav.oil	1000	ns	1	0.38	0.3	regular	10.6	91	
Scoop Weir Skimmer	Schulze, 1998	1978					7.5	81.5	71.7		heav.oil	1000	ns	1	0.25	0.6	harbour chop	4.7	57	100
Scoop Weir Skimmer	Schulze, 1998	1978					6.3	68.8	53.3		heav.oil	1000	ns	3	0.38	0.6	harbour chop	5.4	68	
Scoop Weir Skimmer	Schulze, 1998	1978					4.2	45.3	51.7		heav.oil	1000	ns	3	0.5	0.6	harbour chop	6.7	69	95
Scoop Weir Skimmer	Schulze, 1998	1978					7.5	81.5	118.3		heav.oil	1000	ns	2	0.63	0.6	harbour chop	4.7	29	
Disc skim. -flat-CCG tes	Schulze, 1998	1993									lt.crude	5 to 50	10		0	calm				99
Disc skim. -flat-CCG tes	Schulze, 1998	1993								85	lt.crude	5 to 50	10		0	0.4	regular			65
Disc skim. -flat-CCG tes	Schulze, 1998	1993								63.8	lt.crude	5 to 50	10		0	0.8	harbour chop			48
Disc skim. -flat-CCG tes	Schulze, 1998	1993									lt.crude	5 to 50	25		0	calm				96
Disc skim. -flat-CCG tes	Schulze, 1998	1993								32.5	lt.crude	5 to 50	25		0	0.4	regular			83
Disc skim. -flat-CCG tes	Schulze, 1998	1993								38.8	lt.crude	5 to 50	25		0	0.8	harbour chop			65
Disc skim. -T-disk -CCG	Schulze, 1998	1993									lt.crude	5 to 50	10		0	calm				99
Disc skim. -T-disk -CCG	Schulze, 1998	1993								47.5	lt.crude	5 to 50	10		0	0.4	regular			46
Disc skim. -T-disk -CCG	Schulze, 1998	1993								51.3	lt.crude	5 to 50	10		0	0.8	harbour chop			24
Disc skim. -T-disk -CCG	Schulze, 1998	1993									lt.crude	5 to 50	25		0	calm				100
Disc skim. -T-disk -CCG	Schulze, 1998	1993								37.5	lt.crude	5 to 50	25		0	0.4	regular			85
Disc skim. -T-disk -CCG	Schulze, 1998	1993								67.5	lt.crude	5 to 50	25		0	0.8	harbour chop			46
Paddle skimmer	Schulze, 1998	1977									heav.oil	1900	26		0	calm		9.4	91	84
Paddle skimmer	Schulze, 1998	1977					23	244.7	105	330	heav.oil	1900	26		0	0.2	regular	4.8	70	18
Rope Mop stationary	Schulze, 1998	1977									lt.crude	6	20		0	calm		2.6		89
Rope Mop stationary	Schulze, 1998	1977					-1.5	-57.7		35	lt.crude	6	20		0	0.6	harbour chop	3.5		68
Rope Mop stationary	Schulze, 1998	1977									lt.crude	14	20		0	calm		3.1		79
Rope Mop stationary	Schulze, 1998	1977					-1.7	-53.8		15	lt.crude	14	20		0	0.6	harbour chop	4.1		70
Rope Mop stationary	Schulze, 1998	1977									lt.crude	79	20		0	calm		10		98
Rope Mop stationary	Schulze, 1998	1977					-7	-225.8		10	lt.crude	79	20		0	0.6	harbour chop	7.3		73
Rope Mop towed single	Schulze, 1998	1978									med.oil	793	5		0.75	calm		4.6		55
Rope Mop towed single	Schulze, 1998	1978	-4.2	-90.9		-1.8					med.oil	793	5		1.3	calm		6.9		56

Table 4 ctd. Tests of Skimmer Performance with Changing Weather Conditions

			Current/Tow Speed Summary				Wave Height Summary					Oil	Slick			Wave				
Skimmer	Reference	Year	Slope ORR	ORR Slope	Slope TE	Slope RE	Slope ORR	ORR Slope	Slope TE	Slope RE	Oil	Viscosity	Thick.	# of	Speed	height	Wave	ORR	TE	RE
		of Test	m^{2}s/h	%s/m	%s/m	%s/m	m^2/h	%/m	%/m	%/m	Type	mPa. S	mm	Tests	m/s	m	Conditions	m^3/h	%	%
Rope Mop towed single	Schulze, 1998	1978	0.5	7.2		105					med.oil	793	5		1.5	calm		6.8		35
Rope Mop towed single	Schulze, 1998	1978					-8	-173.9		-40	med.oil	793	5		0.75	0.15	regular	5.8		61
Rope Mop towed single	Schulze, 1998	1978	-3.1	-53.3		14.5	-4	-58		20	med.oil	793	5		1.3	0.15	regular	7.5		53
Rope Mop towed single	Schulze, 1998	1978	5.5	73.3		-10	2.7	39.2		-133.3	med.oil	793	5		1.5	0.15	regular	6.4		55
Rope Mop towed single	Schulze, 1998	1978					-6.5	-141.3		3.3	med.oil	793	5		0.75	0.6	harbour chop	8.5		53
Rope Mop towed single	Schulze, 1998	1978	5.1	59.9		7.3	2	29		11.7	med.oil	793	5		1.3	0.6	harbour chop	5.7		49
Rope Mop towed single	Schulze, 1998	1978	3.5	61.4		15	3	44.1		-18.3	med.oil	793	5		1.5	0.6	harbour chop	5		46
Oil Mop ZRV	Schulze, 1998	1976									lt.crude	65	4 ave		1.25	calm		7	36	23
Oil Mop ZRV	Schulze, 1998	1976	0	0	84	0					lt.crude	65	4 ave		1.5	calm		7	15	23
Oil Mop ZRV	Schulze, 1998	1976	-0.6	-8.6	18	-2					lt.crude	65	4 ave		1.75	calm		7.3	27	24
Oil Mop ZRV	Schulze, 1998	1976					3.7	52.4	-10	21.7	lt.crude	65	4 ave		1.5	0.6	harbour chop	4.8	21	10
Oil Mop ZRV	Schulze, 1998	1977									heav.oil	3000	3	3	0.5	calm		4.3	71	52
Oil Mop ZRV	Schulze, 1998	1977	-7.2	-167.4	44	-50					heav.oil	3000	3	6	1	calm		7.9	49	77
Oil Mop ZRV	Schulze, 1998	1977	-8.5	-197.7	7	-23					heav.oil	3000	3	2	1.5	calm		12.8	64	75
Oil Mop ZRV	Schulze, 1998	1977					-9.5	-220.9	-15	28.3	heav.oil	3000	3	4	0.5	0.6	harbour chop	10	80	35
Oil Mop ZRV	Schulze, 1998	1977									lt.crude	3	3	9	1	calm		9.4	65	66
Oil Mop ZRV	Schulze, 1998	1977	-8.1	-86.2	-2	4					lt.crude	3	3	2	2	calm		17.5	67	62
Oil Mop ZRV	Schulze, 1998	1977	-3	-31.9	14.7	12					lt.crude	3	3	3	2.5	calm		13.9	43	48
Oil Mop ZRV	Schulze, 1998	1977					0	0	-11.7	20	lt.crude	3	3	4	1	0.6	harbour chop	9.4	72	54
Oil Mop ZRV	Schulze, 1998	1977	-3.5	-37.2	16	13	7.7	43.8	18.3	35	lt.crude	3	3	5	2	0.6	harbour chop	12.9	56	41
Oil Mop ZRV	Schulze, 1998	1977					5	28.6	2.5	21.3	lt.crude	3	3	2	2	0.8	regular	13.5	65	45
Marco Belt skimmer	Schulze, 1998	1976									heav.oil	837	8 to 11	6	0.5	calm		11.5	85	57
Marco Belt skimmer	Schulze, 1998	1976	-24.2	-210.4	-10	-18					heav.oil	837	8 to 11	5	1	calm		23.6	90	66
Marco Belt skimmer	Schulze, 1998	1976	-9.1	-79.1	23	-19					heav.oil	837	8 to 11	4	1.5	calm	harbour chop	20.6	62	76
Marco Belt skimmer	Schulze, 1998	1976					1.3	11.6	15	-28.3	heav.oil	837	8 to 11	1	0.5	0.6	harbour chop	10.7	76	74
Marco Belt skimmer	Schulze, 1998	1976	-2.4	-22.4	62	46	19.5	82.6	75	25	heav.oil	837	8 to 11	1	1	0.6	harbour chop	11.9	45	51
Marco Belt skimmer	Schulze, 1998	1976	-1.8	-16.8	48	37	13.5	65.5	56.7	65	heav.oil	837	8 to 11	1	1.5	0.6	harbour chop	12.5	28	37
Marco Belt skimmer	Schulze, 1998	1976							20.8	18.3	heav.oil	837	8 to 11	1	0.5	1.2	harbour chop	.	60	35
Marco Belt skimmer	Schulze, 1998	1976			40	2			41.7	26.7	heav.oil	837	8 to 11	1	1	1.2	harbour chop	9.9	40	34
Marco Belt skimmer	Schulze, 1998	1977									heav.oil	784	3	1	0.25	calm		3	74	87
Marco Belt skimmer	Schulze, 1998	1977	-12.4	-413.3	12	32					heav.oil	784	3	22	0.5	calm		6.1	71	79
Marco Belt skimmer	Schulze, 1998	1977									heav.oil	784	6	1	0.5	calm		9.9	71	84
Marco Belt skimmer	Schulze, 1998	1977	-8.8	-293.3	12	-2					heav.oil	784	3	5	0.75	calm		7.4	68	88
Marco Belt skimmer	Schulze, 1998	1977	-25.2	-254.5	8	-16					heav.oil	784	6	1	0.75	calm		16.2	69	88
Marco Belt skimmer	Schulze, 1998	1977	-6.9	-231.1	29.3	8					heav.oil	784	3	31	1	calm		8.2	52	81
Marco Belt skimmer	Schulze, 1998	1977	-17.4	-175.8	20	-4					heav.oil	784	6	1	1	calm		18.6	61	86
Marco Belt skimmer	Schulze, 1998	1977	-2.6	-85.3	40	12					heav.oil	784	3	8	1.5	calm		6.2	24	72
Marco Belt skimmer	Schulze, 1998	1977					-0.8	-27.8	43.3	61.7	heav.oil	784	3	5	0.5	0.6	harbour chop	3.5	48	50
Marco Belt skimmer	Schulze, 1998	1977					-1.2	-38.9	71.7	63.3	heav.oil	784	3	1	0.75	0.6	harbour chop	3.7	31	49

Table 4 ctd. Tests of Skimmer Performance with Changing Weather Conditions

			Current/Tow Speed Summary				Wave Height Summary					Oil	Slick			Wave				
Skimmer	Reference	Year	Slope ORR	ORR Slope	Slope TE	Slope RE	Slope ORR	ORR Slope	Slope TE	Slope RE	Oil	Viscosity	Thick.	# of	Speed	height	Wave	ORR	TE	RE
		of Test	m^{2}s/h	%s/m	%s/m	%s/m	m^2/h	%/m	%/m	%/m	Type	mPa. S	mm	Tests	m/s	m	Conditions	m^3/h	%	%
Marco Belt skimmer	Schulze, 1998	1977					9.5	96	95	65	heav. oil	784	6	2	1	0.6	harbour chop	4.2	14	45
Marco Belt skimmer	Schulze, 1998	1977					0.5	16.7	35.8	34.2	heav. oil	784	3	2	0.5	1.2	harbour chop	2.4	31	46
Marco Belt skimmer	Schulze, 1998	1977					-0.3	-8.3	38.3	33.3	heav. oil	784	3	1	0.75	1.2	harbour chop	3.3	28	47
Fixed Submersion plane	Schulze, 1998	1978									k. oil	19	3	2	0.75	calm		14.8	51	
Fixed Submersion plane	Schulze, 1998	1978	-40	-270.3	-36						k. oil	19	3	2	1	calm		24.8	78	
Fixed Submersion plane	Schulze, 1998	1978	-31.7	-214.4	-20.8						k. oil	19	3	3	1.5	calm		38.6	77	
Fixed Submersion plane	Schulze, 1998	1978	-13.1	-88.6	1.1						k. oil	19	3	5	2	calm		31.2	49	
Fixed Submersion plane	Schulze, 1998	1978	-5.8	-39.4	10.7						k. oil	19	3	2	2.5	calm		25	27	
Fixed Submersion plane	Schulze, 1998	1978					20	135.1	56.7		k. oil	19	3	2	0.75	0.3	harbour chop	8.8	34	
Fixed Submersion plane	Schulze, 1998	1978	-1.6	-18.2	28		52	209.7	170		k. oil	19	3	2	1	0.3	harbour chop	9.2	27	
Fixed Submersion plane	Schulze, 1998	1978	-9.6	-109.1	2.7		75.3	195.2	150		k. oil	19	3	5	1.5	0.3	harbour chop	16	32	
Fixed Submersion plane	Schulze, 1998	1978	-14.3	-162.7	-6.4		15	48.1	23.3		k. oil	19	3	4	2	0.3	harbour chop	26.7	42	
Fixed Submersion plane	Schulze, 1998	1978					11.2	75.5	18.3		k. oil	19	3	1	0.75	0.6	harbour chop	8.1	40	
Fixed Submersion plane	Schulze, 1998	1978					17.6	118.9	52		k. oil	19	3	1	0.75	0.5	regular	6	25	
Fixed Submersion plane	Schulze, 1998	1978	-8.4	-140	4		33.4	134.7	108		k. oil	19	3	1	1	0.5	regular	8.1	24	
Fixed Submersion plane	Schulze, 1998	1978	1.2	20	20		67	173.6	134		k. oil	19	3	1	1.5	0.5	regular	5.1	10	
Fixed Submersion plane	Schulze, 1998	1978									heav. oil	1230	10	1	1	calm		87.8	90	
Fixed Submersion plane	Schulze, 1998	1978	217.2	247.4	12						heav. oil	1230	10	2	1.25	calm		33.5	87	
Fixed Submersion plane	Schulze, 1998	1978	107.8	122.8	36						heav. oil	1230	10	2	1.5	calm		33.9	72	
Fixed Submersion plane	Schulze, 1998	1978	51.2	58.3	29						heav. oil	1230	10	4	2	calm		36.6	61	
Fixed Submersion plane	Schulze, 1998	1978									heav. oil	1230	3	1	0.5	calm		3.2	8	
Fixed Submersion plane	Schulze, 1998	1978	-18.8	-585.9	-78.4						heav. oil	1230	3	3	1.38	calm		19.7	77	
Fixed Submersion plane	Schulze, 1998	1978	-46.6	-1456.3	-148						heav. oil	1230	3	3	1	calm		26.5	82	
Fixed Submersion plane	Schulze, 1998	1978									heav. oil	1230	3	1	0.75	0.3	harbour chop	8	32	
Fixed Submersion plane	Schulze, 1998	1978	-28.4	-355	-60		38	143.4	116.7		heav. oil	1230	3	2	1	0.3	harbour chop	15.1	47	
Fixed Submersion plane	Schulze, 1998	1978	-16.3	-203.3	-20						heav. oil	1230	3	1	1.5	0.3	harbour chop	20.2	47	
Fixed Submersion plane	Schulze, 1998	1978									heav. oil	1230	3	1	0.75	0.6	harbour chop	7.2	29	
Fixed Submersion plane	Schulze, 1998	1978	-37.2	-516.7	-104		16.7	62.9	45		heav. oil	1230	3	1	1	0.6	harbour chop	16.5	55	
Fixed Submersion plane	Schulze, 1998	1978	3.5	48.1	24						heav. oil	1230	3	1	1.5	0.6	harbour chop	4.6	11	
Fixed Submersion plane	Schulze, 1998	1978									heav. oil	1230	3	2	0.75	0.5	regular	4.3	20	
Fixed Submersion plane	Schulze, 1998	1978	-4.7	-109.8	-6.4						heav. oil	1230	3	1	2	0.5	regular	10.2	28	
Fixed Submersion plane	Schulze, 1998	1978	0.9	21.7	16						heav. oil	1230	3	1	1.5	0.5	regular	3.6	8	
DIP 2001	Schulze, 1998	1973									Alberta crude	8	.7 ave	1	1.3	calm		2.7	88	30
DIP 2001	Schulze, 1998	1973					-1.3	-49.4	65		Alberta crude	8	.7 ave	1	1.6	0.6	regular	3.5	49	20
DIP 2001	Schulze, 1998	1975									Arab crude	24	1	1	0.5	calm		1.1	94	96
DIP 2001	Schulze, 1998	1975	0.4	36.4	34						Arab crude	24	0.5	1	1	calm		0.9	77	94
DIP 2001	Schulze, 1998	1975					0	0	-10		Arab crude	24	1	1	0.5	0.4	natural	0.9	81	95
DIP 2001	Schulze, 1998	1975	-1.8	-200	6		-2.3	-250	7.5		Arab crude	24	1	1	1	0.4	natural	1.8	78	96

Table 4 ctd. Tests of Skimmer Performance with Changing Weather Conditions

			Current /Tow Speed Summary				Wave Height Summary					Oil	Slick			Wave				
Skimmer	Reference	Year of Test	Slope ORR m^3s/h	ORR Slope %s/m	Slope TE %s/m	Slope RE %s/m	Slope ORR m^3/h	ORR Slope %/m	Slope TE %/m	Slope RE %/m	Oil Type	Viscosity mPa. S	Thick. mm	# of Tests	Speed m/s	height m	Wave Conditions	ORR m^3/h	TE %	RE %
Stationary skim. - Manta	Schulze, 1998	1975									DOP	79	20	6		calm		20.1		27
Stationary skim. - Manta	Schulze, 1998	1975					8.2	40.6		8.3	DOP	79	20	1		0.6	harbour ch	15.2		22
Stationary skim. - Skimp	Schulze, 1998	1980									medium	200	7	3		calm		2.5		8
Stationary skim. - Skimp	Schulze, 1998	1980					1.9	76.9		3.8	medium	200	7	1		0.26	regular	2		7
Stationary skim. - Skimp	Schulze, 1998	1980									medium	200	23	2		calm		4		31
Stationary skim. - Skimp	Schulze, 1998	1980					2.7	67.3		15.4	medium	200	29	3		0.26	regular	3.3		27
Stationary skim. - Skimp	Schulze, 1998	1980									medium	200	16	3		calm		8.4		29
Stationary skim. - Skimp	Schulze, 1998	1980					4.2	50.1		15.8	medium	200	16	1		0.19	regular	7.6		28
Slurp Skimmer	Schulze, 1998	1975									crude	24	1	1		calm		0.17		5
Slurp Skimmer	Schulze, 1998	1975					-1	-558.8		-30	crude	24	1	1		0.2	natural	0.36		11
Slurp Skimmer	Schulze, 1998	1975									crude	24	5	1		calm		0.46		15
Slurp Skimmer	Schulze, 1998	1975					0	-10.9		0	crude	24	5	1		0.2	natural	0.47		15
Slurp Skimmer	Schulze, 1998	1975									Emulsion	3500	5	1		calm		0.49		25
Slurp Skimmer	Schulze, 1998	1975					0.4	71.4		55	Emulsion	3500	5	1		0.2	natural	0.42		14
Harbour mate weir skim.	Schulze, 1998	1993									Diesel	4.5	10			calm		0.2		5
Harbour mate weir skim.	Schulze, 1998	1993									Diesel	4.5	25			calm		1.3		28
Harbour mate weir skim.	Schulze, 1998	1993					-3.5	-1750		5	Diesel	4.5	10			0.4	regular	1.6		3
Harbour mate weir skim.	Schulze, 1998	1993					0.3	19.2		10	Diesel	4.5	25			0.4	regular	1.2		24
Harbour mate weir skim.	Schulze, 1998	1993					0	0		2.5	Diesel	4.5	10			0.8	harbour ch	0.2		3
Harbour mate weir skim.	Schulze, 1998	1993					0.6	48.1		22.5	Diesel	4.5	25			0.8	harbour ch	0.8		10
Harbour mate weir skim.	Schulze, 1998	1993									crude	50 to 300	10			calm		0.08		1
Harbour mate weir skim.	Schulze, 1998	1993									crude	50 to 300	25			calm		1.3		21
Harbour mate weir skim.	Schulze, 1998	1993					0	-31.3		0	crude	50 to 300	10			0.4	regular	0.09		1
Harbour mate weir skim.	Schulze, 1998	1993					2	153.8		32.5	crude	50 to 300	25			0.4	regular	0.5		8
Harbour mate weir skim.	Schulze, 1998	1993					0	-31.3		-1.3	crude	50 to 300	10			0.8	harbour ch	0.1		2
Harbour mate weir skim.	Schulze, 1998	1993					0.3	19.2		2.5	crude	50 to 300	25			0.8	harbour ch	1.1		19
Destroil weir skimmer	Schulze, 1998	1979									heavy	810	5	5		calm		16.2		69
Destroil weir skimmer	Schulze, 1998	1979					10	61.7		21.3	heavy	810	5	2		0.47	harbour ch	11.5		59
Destroil weir skimmer	Schulze, 1998	1979					24.2	149.4		78.9	heavy	810	5	2		0.19	regular	11.6		54
Destroil weir skimmer	Schulze, 1998	1979					-18.1	-111.6		-92.3	heavy	810	5	1		0.26	regular	20.9		93
Destroil weir skimmer	Schulze, 1998	1979									light	9	5	2		calm		18.4		77
Destroil weir skimmer	Schulze, 1998	1979					34.2	186		123.1	light	9	5	1		0.26	regular	9.5		45
GT-185	Schulze, 1998	1988									Bunkers	11700				calm		21		76
GT-185	Schulze, 1998	1988					15	71.4		65	Bunkers	11700				0.4	regular	15		50
GT-185	Schulze, 1998	1988									Terra Nov	100-600				calm		30		100
GT-185	Schulze, 1998	1988					1.7	5.6		26.7	Terra Nov	100-600				0.3	regular	29.5		92
GT-185	Schulze, 1998	1988					37.5	125		125	Terra Nov	100-600				0.4	regular	15		50
Walosep	Schulze, 1998	1988									Bunkers	>100k				calm		38		2
Walosep	Schulze, 1998	1988					70	184.2		0	Bunkers	>100k				0.4	regular	10		2

Table 4 ctd. Tests of Skimmer Performance with Changing Weather Conditions

			Current/Tow Speed Summary				Wave Height Summary					Oil	Slick			Wave				
Skimmer	Reference	Year	Slope ORR	ORR Slope	Slope TE	Slope RE	Slope ORR	ORR Slope	Slope TE	Slope RE	Oil	Viscosity	Thick.	#of	Speed	height	Wave	ORR	TE	RE
		of Test	m^2s/h	%s/m	%s/m	%s/m	m^2/h	%/m	%/m	%/m	Type	mPa. S	mm	Tests	m/s	m	Conditions	m^3/h	%	%
Veegarm towed weir	Schulze, 1998	1980											1		0.25	calm		11	100	8
Veegarm towed weir	Schulze, 1998	1980	-28	-254.5	0	-48							1		0.5	calm		18	100	20
Veegarm towed weir	Schulze, 1998	1980	-7	-63.6	8	-10							1		1.25	calm		18	92	18
Veegarm towed weir	Schulze, 1998	1980	-22.7	-206.1	0	-5.3							1		1	calm		28	100	12
Veegarm towed weir	Schulze, 1998	1980											2		0.25	calm		11	100	18
Veegarm towed weir	Schulze, 1998	1980	-56	-509.1	0	-16							2		0.5	calm		25	100	22
Veegarm towed weir	Schulze, 1998	1980	-10	-90.9	18	-10							2		1.25	calm		21	82	28
Veegarm towed weir	Schulze, 1998	1980	-26.7	-242.4	30.7	-13.3							2		1	calm		31	77	28
Veegarm towed weir	Schulze, 1998	1980	-17	-154.5	50	-6							2		1.25	calm		28	50	24
Veegarm towed weir	Schulze, 1998	1980	-4.8	-43.6	56	-3.2							2		1.5	calm		17	30	22
Veegarm towed weir	Schulze, 1998	1980											5		0.25	calm		18	100	35
Veegarm towed weir	Schulze, 1998	1980	-80	-444.4	0	-20							5		0.5	calm		38	100	40
Veegarm towed weir	Schulze, 1998	1980	-5	-27.8	22	-5							5		1.25	calm		23	78	40
Veegarm towed weir	Schulze, 1998	1980	-24	-133.3	50.7	-5.3							5		1	calm		36	62	39
Veegarm towed weir	Schulze, 1998	1980									light	9	2		0.25	calm		5.4	100	5
Veegarm towed weir	Schulze, 1998	1980	4.8	88.9	0	0					light	9	2		0.5	calm		4.2	100	5
Veegarm towed weir	Schulze, 1998	1980	1.4	25.9	70	1					light	9	2		1.25	calm		4	30	4
Veegarm towed weir	Schulze, 1998	1980	-0.3	-4.9	90.7	1.3					light	9	2		1	calm		5.6	32	4
Veegarm towed weir	Schulze, 1998	1980									heavy	1300	2		0.25	calm		14	100	9
Veegarm towed weir	Schulze, 1998	1980	-8	-57.1	0	4					heavy	1300	2		0.5	calm		16	100	8
Veegarm towed weir	Schulze, 1998	1980	6	42.9	18	2					heavy	1300	2		1.25	calm		8	82	7
Veegarm towed weir	Schulze, 1998	1980					0.5	4.8	31.6	6.8					0.25	1.9	regular	10	40	5
Veegarm towed weir	Schulze, 1998	1980	-8	-80	-8	-8	6.8	27.4	30.5	7.9					0.5	1.9	regular	12	42	7
Veegarm towed weir	Schulze, 1998	1980	4	40	40	-2									0.75	1.9	regular	8	20	6
Veegarm towed weir	Schulze, 1998	1980					-20	-181.8	0	25					0.25	0.2	regular	15	100	13
Veegarm towed weir	Schulze, 1998	1980	-12	-80	0	-16	35	140	0	25					0.5	0.2	regular	18	100	17
Veegarm towed weir	Schulze, 1998	1980	-12	-80	20	-14									0.75	0.2	regular	21	90	20
Veegarm towed weir	Schulze, 1998	1980	-6.7	-44.4	34.7	-5.3	55	177.4	15	55					1	0.2	regular	20	74	17
Veegarm towed weir	Schulze, 1998	1980					2.1	39	210.5	0	light	9	2		0.25	0.19	harbour chop	5	60	5
Veegarm towed weir	Schulze, 1998	1980	2	40	152	0	-1.6	-37.6	410.5	0	light	9	2		0.5	0.19	harbour chop	4.5	22	5
Veegarm towed weir	Schulze, 1998	1980	2	40	96	2	0	0	94.7	0	light	9	2		0.75	0.19	harbour chop	4	12	4
Veegarm towed weir	Schulze, 1998	1980	0	0	64	1.3	3.2	56.4	105.3	0	light	9	2		1	0.19	harbour chop	5	12	4
Veegarm towed weir	Schulze, 1998	1980					4.2	30.1	26.3	0	heavy	1300	2		0.25	0.19	harbour chop	13.2	95	9
Veegarm towed weir	Schulze, 1998	1980	-7.6	-57.6	140	4	4.7	29.6	210.5	0	heavy	1300	2		0.5	0.19	harbour chop	15.1	60	8
Veegarm towed weir	Schulze, 1998	1980	-0.6	-4.5	138	4	-28.9	-361.8	294.7	0	heavy	1300	2		0.75	0.19	harbour chop	13.5	26	7
Veegarm towed weir	Schulze, 1998	1980					12.5	89.3	12.5	-2.5	heavy	1300	2		0.25	0.4	harbour chop	9	95	10
Veegarm towed weir	Schulze, 1998	1980	14	155.6	200	16	26.3	164.1	137.5	5	heavy	1300	2		0.5	0.4	harbour chop	5.5	45	6
Veegarm towed weir	Schulze, 1998	1980	8	88.9	154	12	7.5	93.8	160	7.5	heavy	1300	2		0.75	0.4	harbour chop	5	18	4
Veegarm towed weir	Schulze, 1998	1980					2.2	41.2	60.3	0	light	9	2		0.25	0.63	harbour chop	4	62	5
Veegarm towed weir	Schulze, 1998	1980	-10	-250	104	4	-3.7	-86.9	101.6	1.6	light	9	2		0.5	0.63	harbour chop	6.5	36	4

Table 4 ctd. Tests of Skimmer Performance with Changing Weather Conditions

Skimmer	Reference	Year of Test	Current/Tow Speed Summary Slope ORR m²s/h	ORR Slope %s/m	Slope TE %s/m	Slope RE %s/m	Wave Height Summary Slope ORR m²/h	ORR Slope %/m	Slope TE %/m	Slope RE %/m	Oil Type	Oil Viscosity mPa.S	Slick Thick. mm	# of Tests	Speed m/s	Wave height m	Wave Conditions	ORR m³/h	TE %	RE %
RST Advancing weir	Schulze, 1998	1992									medium	380		6	0.38	calm		23.7		97
RST Advancing weir	Schulze, 1998	1992					50	211	0	11.1	medium	380		7	0.38	0.27	regular	10.2		94
Offshore skimmers																				
Transrec	Nordvik, 1999	995-1998									various			2	5	1			80	
Transrec	Nordvik, 1999	995-1998							1.3		various			2	5	1.5			78	
Transrec	Nordvik, 1999	995-1998							5		various			2	5	2			70	
Transrec	Nordvik, 1999	995-1998							6		various			2	5	2.5			65	
Special skimmers															2 to 5					
USCG HSS	Hansen, 2002	1999			27						Sundex				3 to 4	calm			98 to 18	
USCG HSS	Hansen, 2002	1997			-10						Sundex				2 to 4	calm			69 to 79	
NOFI	Hansen, 2002	1999			8						Sundex				2 to 5	calm			98 to 90	
UNH FS	Hansen, 2002	2000			17						Sundex				3 to 4	calm			98 to 46	
USCG ZRV	Hansen, 2002	1977			11						Sundex				2 to 4	calm			72 to 61	
LPI fixed plane	Hansen, 2002	1978			6						Sundex				3 to 5	calm			82 to 61	
Fastflo	Hansen, 2002	1999			14						Sundex				2 to 5	calm			72 to 45	
USCG HSS	Hansen, 2002	1997			18						Hydrocal				2 to 5	calm			83 to 29	
USCG HSS	Hansen, 2002	1999			22						Hydrocal				2 to 3	calm			72 to 6	
USCG HSS	Hansen, 2002	2000			11						Hydrocal				2 to 3.5	calm			72 to 61	
NOFI	Hansen, 2002	1999			0						Hydrocal				2 to 5	calm			91 to 91	
USCG ZRV	Hansen, 2002	1977			6						Hydrocal				2 to 3	calm			66 to 49	
High Speed Circus	Hansen, 2002	1999			40						Hydrocal				2 to 4	calm			90 to 50	
Stream Stripper	Hansen, 2002	2000			12						Hydrocal					calm			80 to 66	
Sorbent booms			L/m												1			7		
boom 1	Hansen 2001	2000													1		calm	8		
boom 1	Hansen 2001	2000													1.5		calm	14		
boom 1	Hansen 2001	2000	-3												1		calm	12		
boom 1	Hansen 2001	2000													1		calm	14		
boom 2	Hansen 2001	2000													1		calm	10		
boom 2	Hansen 2001	2000	3												1		calm	13		
boom 2	Hansen 2001	2000	0												1.7		calm	10		
boom 2	Hansen 2001	2000	7												1.7		calm	11		
boom 2	Hansen 2001	2000	7												2.5		calm	10		
boom 2	Hansen 2001	2000	9												2.5		calm	6		
boom 2	Hansen 2001	2000													1		calm	13		
boom 3	Hansen 2001	2000													1		calm	6		
boom 3	Hansen 2001	2000	7												1.7		calm	7		
boom 3	Hansen 2001	2000	8												2.5		calm	6		
boom 3	Hansen 2001	2000	11												2.5		calm	6		

Table 5 **Correlation of Performance and Test Parameters for Booms**

	First Loss Speed	Critical speed/wave	Oil Viscosity	Wave height
First Loss Speed	1.00	-0.01	**0.39**	**-0.40**
Critical/wave	-0.01	1.00	**0.55**	-0.05
Oil Viscosity	**0.39**	**0.55**	1.00	-0.13
Wave height	**-0.40**	-0.05	-0.13	1.00

--those items noted in bold show somewhat significant correlation

Table 6 Summary Skimmer Performance with Changing Weather Conditions

	Current/Tow Speed Summary			Wave Height Summary						Regular waves			Harbour chop		
Skimmer	% ORR/curr	TE/curr	RE/curr	% ORR/wave	TE/wave	RE/wave	ORR	TE	RE	% ORR/wave	TE/wave	RE/wave	% ORR/wave	TE/wave	RE/wave
	%s/m	%s/m	%s/m	%/m	%/m	%/m	m^3/h	%	%	%/m	%/m	%/m	%/m	%/m	%/m
Overall Average	**-112**	**62**	**-26**	**-54**	**59**	**17**	12	**64**	**50**	**-80.1**	**53.1**	**16.1**	**15.3**	**90.8**	**22.2**
Skimming Barrier	-148.7		-73.7	-0.7		45.4	60		43	-21.2		39.7	26.9		54.8
Sirene Skimming Barrier	-246.5	240.6	-89.9	-62.2	92.5	-13.8	23	53	38	-74.3	106.5	-20	-46.5	115.5	-6.2
Lori Brush Skimmer	-200.9		-39.1	-547.7		-75.3	1		75	-647.7		-75.3			
Scoop Weir Skimmer	72.8	132.1		45.3	65		7	66	88	-60.7	30		77.3	81.1	
Disc Skimmers - flat and T						53			71			50.6			56.7
Paddle skimmer							7	81	51						
Rope Mop stationary				-23.2	105	78.3	5		80				-68.9		32.9
Rope Mop towed single	9.6		21.7	-43.5		-8.5	7		51	-64.2		-61.1	-56.2		7.5
Oil Mop ZRV	-75.6	26	-6.6	-19.2	-3.2	25.3	10	52	45	28.6	2.5	21.3	-41.6	-4.6	26.3
Marco Belt skimmer	-178.2	25.8	7.1	24.7	49.3	36.4	10	54	63				24.7	49.3	36.4
Fixed Submersion plane	-187.6	-14.8		129.7	87.4		19	44		142.4	98		124.3	82.9	
DIP 2001	-81.8	20		-99.8	20.8		2	78	72	-149.7	20.8				
Stationary Skimmer - Skim pak				58.7		10.8	8		22	64.8		11.7	40.6		8.3
Ship Skimmer				-166.1		8.3	0.4		14	-166.1		12.5			
Harbourmate weir skimmer				-196.5		9.2	1		10	-402.1		15.8	12		6.6
weir skimmers, Destroil, GT-185				84		43.5	19		59	87.1		54.4	61.7		21.3
Veegam towed weir	-79.5	53.4	-4.7	13.2	111.9	7.7	14	68	14	33.6	25.7	23.9	5.2	152	2.3
Transrec					4			73			4.1				
Various high speed skimmers		13						75							

Calculated and Summarized Values

	Positive values only						Average					
	regular waves			Harbour chop			regular waves			Harbour chop		
	% ORR/wave	TE/wave	RE/wave	% ORR/wave	TE/wave	RE/wave	% ORR/wave	TE/wave	RE/wave	% ORR/wave	TE/wave	RE/wave
	%/m	%/m	%/m	%/m	%/m	%/m	%/m	%/m	%/m	%/m	%/m	%/m
Overall Average	**90.8**	**54.9**	**50**	**67.4**	**96.7**	**32.5**	**5.4**	**54**	**33.1**	**41.4**	**93.8**	**27.4**
Skimming Barrier	26.1		39.7	38.6		54.8	2.5		39.7	32.8	0	54.8
Sirene Skimming Barrier	12.7	106.5	15.9	68.7	115.5	52.3	-30.8	106.5	-2.1	11.1	115.5	23.1
Lori Brush Skimmer							-273.9		-37.7			
Scoop Weir Skimmer		30		77.3	81.1		-25.4	30	0	77.3	81.1	
Disc Skimmers - flat and T			50.6			56.7			50.6			56.7
Paddle skimmer	-	-	-	-	-	-						
Rope Mop stationary	244.7	105	330	61.9		32.9	122.4	52.5	165	-3.5	0	32.9
Rope Mop towed single	39.2		20	29		7.5	-12.5		-15.6	-13.6	0	7.5
Oil Mop ZRV	28.6	2.5	21.3	48.1	18.3	26.3	28.6	2.5	21.3	3.3	6.9	26.3
Marco Belt skimmer				54.5	49.3	43.6				39.6	49.3	40
Fixed Submersion plane	142.4	98		124.3	82.9		142.4	98		124.3	82.9	
DIP 2001		36.3					-74.9	28.6				
Stationary Skimmer - Skim pak	64.8		11.7	40.6		8.3	64.8		11.7	40.6		8.3
Ship Skimmer	71.4		55				-47.4		33.8	0		0
Harbourmate weir skimmer	86.5		15.8	33.7		9.2	-157.8		15.8	22.9		7.9
weir skimmers, Destroil, GT-185	120.3		83.7	61.7		21.3	103.7		69.1	61.7		21.3
Veegam towed weir	87.4	25.7	23.9	67.9	152	4.7	60.5	25.7	23.9	36.6	152	3.5
Transrec		4.1						4.1				

The following points must be made about skimmer test data.

1. The most important point is that most skimmers show unique data and response to current or tow speed. It is difficult to generalize about skimmers without making the point that there are many exceptions. In this report, some generalizations are made but the author is fully aware of the difficulty of doing so.

2. The test data presented in Tables 4 and 6 are summarized from a variety of literature sources. The accuracy of these sources is unknown in every case, although Schulze (1998) is believed to be a highly accurate summary. Several of the literature sources behind this reference were checked and no errors were noted. It should also be recognized that the accuracy and precision of some of the data are questionable. Furthermore, many data points were collected in the 1970s.

3. The variability of the data may no doubt be due to the variability in test conditions and also in the capability to measure the necessary parameters. Some of the data summarized here are actually estimates.

4. It will be noted very readily that the change rate of skimmer effectiveness, particularly ORR, will usually increase with increasing tow speed. Schulze (1998) had noted this. The reason, as Schulze also noted, is no doubt the increased oil encounter rate when tow speed increases. This complicates calculations of the ‘decrease’ in ORR with increasing tow speed.

5. The effect noted in point 4 above also occurs with some increasing wave activity. The same reason is probably pertinent here as well. This also complicates calculations for decline in recovery with wave height, however, as the wave increases, the performance generally falls and one can use these values separately.

6. Some skimmers may show unusually high or low performance in these data. This is largely due to the test conditions. For example, if a skimmer is not tested at a high tow speed or a high wave, its performance may appear to be very good compared to a similar skimmer that is tested under more rigorous conditions. There is no easy way to deal with these variances.

7. The effect of ice on performance is shown in Table 7. The average ORR declines somewhat with increasing ice percentage. Both TE and RE appear, on average, to be unaffected by ice concentration.

8. There are many other factors that influence oil recovery for a skimmer. These include oil viscosity and thickness of oil presented to a skimmer. These factors were kept constant throughout this exercise by taking the same conditions with only the variable of interest, tow speed, or wave height as a variable. The cross correlation matrix for all skimmers in this study is given in Table 8, for the Marco belt skimmer in Table 9, and for the Veegarm system, an advancing weir, in Table 10. These tables show that combining data such as is done in Table 8 results in little, if any, correlation between different factors. The reason for this is that different factors influence different skimmer systems differently. For example, an increasing viscosity positively affects the ORR of the Marco skimmer (as can be seen in Table 9) and negatively affects a disk skimmer. These correlations show that many of the common-sense relationships do hold true as long as individual skimmers or skimming principles are examined.

Table 7 Tests of Skimmer Performance with Changing Ice Conditions

			Ice Performance				**Conditions**							
Skimmer	Reference	Year of Test	Slope of ORR $m^3/h\%$	ORR Slope %/%	Slope of TE %/%	Slope of RE %/%	Ice Conc. %	Oil Type	Oil Viscosity mPa. S	Slick Thick mm	Number of **Tests**	ORR m^3/h	TE %	RE %
Skimming Bow	Abdelnour, 1985	1984					0	medium	460	6 ave	4	1.2	6.8	
Skimming Bow	Abdelnour, 1985	1984	0.01	0.5	-0.1		30	medium	460	10 ave	3	1.03	9	
Skimming Bow	Abdelnour, 1985	1984	0.01	0.8	0		50	light/medium	22/460	6 ave	5	0.7	8	
Skimming Bow	Abdelnour, 1985	1984	0.01	0.9	-0.1		70	light/medium	22/460	8 ave	9	0.46	11	
Rope Mop	Schulze, 1998	1984					0	light	17	4	1	2.9	53	50
Rope Mop	Schulze, 1998	1984	0.02	0.7	-0.6	0.1	25	light	17	3	2	2.4	68	47
Rope Mop	Schulze, 1998	1984	-0.05	-1.8	0.2	-0.6	25	light	17	8	2	4.2	49	66
Rope Mop	Schulze, 1998	1984	0.03	1.1	-0.1	-0.3	50	light	17	3	2	1.3	58	67
Rope Mop	Schulze, 1998	1984	0.04	1.3	0.7	0.7	75	light	17	3	1	0	0	0
Rope Mop	Schulze, 1998	1984					0	light	17	3	2	2.7	59	29
Rope Mop	Schulze, 1998	1984					0	light	17	8	1	4.9	41	50
Rope Mop	Schulze, 1998	1984	-0.03	-1.2	-1.7	-0.2	12.5	light	17	3	1	3.1	80	32
Rope Mop	Schulze, 1998	1984	-0.1	-2.1	-1.2	-0.2	12.5	light	17	8	1	6.2	56	52
Rope Mop	Schulze, 1998	1984	0.01	0.4	-0.5	-0.1	25	light	17	3	4	2.4	72	31
Rope Mop	Schulze, 1998	1984	-0.06	-1.2	-1.2	-0.4	25	light	17	8	3	6.4	70	59
Rope Mop	Schulze, 1998	1984	0.02	0.6	-0.3	0.1	37.5	light	17	3	1	2.1	71	26
Rope Mop	Schulze, 1998	1984	0.03	1.2	0.2	0.3	50	light	17	3	1	1.1	49	15
Rope Mop	Schulze, 1998	1984	0.04	0.7	-0.2	0.2	50	light	17	8	1	3.1	51	41
		average	-0.001	0.14	-0.35	-0.04								

Table 8 **Cross Correlation Matrix for Factors Influencing Performance for All Skimmers in this Study**

	Parameter													
	ORR/curr	**%ORR/curr**	**TE/curr**	**RE/curr**	**ORR/wave**	**%ORR/wave**	**TE/wave**	**RE/wave**	**Oil Visc**	**Slick mm**	**Tow m/s**	**Wave m**	**ORR**	**TE**	**RE**
ORR/curr	1.00	0.61	-0.03	**0.71**	-0.21	-0.11	0.31	-0.35	0.19	-0.26	0.28	0.06	-0.31	-0.13	-0.11
%ORR/curr	0.61	1.00	0.32	0.58	-0.11	0.06	0.31	-0.29	-0.08	0.01	0.15	0.14	-0.28	-0.35	-0.27
TE/curr	-0.03	0.32	1.00	-0.47	-0.41	-0.26	0.59	-0.53	-0.11	-0.08	-0.37	-0.09	-0.14	-0.40	-0.15
RE/curr	**0.71**	0.58	-0.47	1.00	-0.04	0.06	-0.03	0.37	0.06	-0.26	0.34	0.19	-0.44	-0.18	-0.21
ORR/wave	-0.21	-0.11	-0.41	-0.04	1.00	0.39	0.01	0.35	0.02	-0.04	0.19	-0.11	-0.17	-0.11	-0.15
%ORR/wave	-0.11	0.06	-0.26	0.06	0.39	1.00	-0.03	0.38	0.06	0.04	-0.03	0.09	0.07	-0.12	-0.13
TE/wave	0.31	0.31	0.59	-0.03	0.01	-0.03	1.00	-0.03	-0.03	-0.01	-0.13	-0.18	0.00	-0.58	-0.32
RE/wave	-0.35	-0.29	-0.53	0.37	0.35	0.38	-0.03	1.00	0.17	0.26	-0.32	0.05	0.12	0.05	-0.18
Oil Visc	0.19	-0.08	-0.11	0.06	0.02	0.06	-0.03	0.17	1.00	-0.18	-0.02	-0.06	-0.04	0.18	0.11
Slick mm	-0.26	0.01	-0.08	-0.26	-0.04	0.04	-0.01	0.26	-0.18	1.00	-0.27	0.12	0.68	0.11	0.06
Tow m/s	0.28	0.15	-0.37	0.34	0.19	-0.03	-0.13	-0.32	-0.02	-0.27	1.00	0.16	-0.05	-0.16	-0.08
Wave m	0.06	0.14	-0.09	0.19	-0.11	0.09	-0.18	0.05	-0.06	0.12	0.16	1.00	-0.06	-0.26	-0.18
ORR	-0.31	-0.28	-0.14	-0.44	-0.17	0.07	0.00	0.12	-0.04	0.68	-0.05	-0.06	1.00	0.25	0.06
TE	-0.13	-0.35	-0.40	-0.18	-0.11	-0.12	-0.58	0.05	0.18	0.11	-0.16	-0.26	0.25	1.00	0.09
RE	-0.11	-0.27	-0.15	-0.21	-0.15	-0.13	-0.32	-0.18	0.11	0.06	-0.08	-0.18	0.06	0.09	1.00

Values in bold are significant cross-correlation factors

Table 9 Cross Correlation Matrix for Factors Influencing Performance for the Marco Belt Skimmer

	ORR/curr	%ORR/curr	TE/curr	RE/curr	ORR/wave	%ORR/wave	TE/wave	RE/wave	Oil Visc	Slick mm	Tow m/s	Wave m	ORR	TE	RE
ORR/curr	1.00	0.56	0.78	0.63	-1.00	-1.00	-1.00	1.00	0.50	0.13	0.55	0.55	-0.43	-0.74	-0.69
%ORR/curr	0.56	1.00	0.82	0.22	-1.00	-1.00	-1.00	1.00	0.75	0.73	0.85	0.65	0.37	-0.75	-0.72
TE/curr	0.78	0.82	1.00	0.65	1.00	1.00	1.00	-0.19	0.67	0.53	0.53	0.65	-0.12	-0.81	-0.80
RE/curr	0.63	0.22	0.65	1.00	1.00	1.00	0.93	0.29	0.27	0.08	-0.02	0.35	-0.48	-0.44	-0.53
ORR/wave	-1.00	-1.00	1.00	1.00	1.00	0.87	0.54	0.09	0.65	0.75	0.76	-0.40	0.72	-0.16	-0.28
%ORR/wave	-1.00	-1.00	1.00	1.00	0.87	1.00	0.53	0.04	0.46	0.69	0.66	-0.25	0.52	-0.28	-0.25
TE/wave	-1.00	-1.00	1.00	0.93	0.54	0.53	1.00	0.68	-0.31	-0.13	0.56	-0.52	-0.07	-0.72	-0.20
RE/wave	1.00	1.00	-0.19	0.29	0.09	0.04	0.68	1.00	-0.54	-0.47	0.44	-0.24	-0.39	-0.80	-0.55
Oil Visc	0.50	0.75	0.67	0.27	0.65	0.46	-0.31	-0.54	1.00	0.90	0.32	0.37	0.50	0.06	-0.43
Slick mm	0.13	0.73	0.53	0.08	0.75	0.69	-0.13	-0.47	0.90	1.00	0.33	0.25	0.69	0.11	-0.31
Tow m/s	0.55	0.85	0.53	-0.02	0.76	0.66	0.56	0.44	0.32	0.33	1.00	-0.16	0.50	-0.48	-0.13
Wave m	0.55	0.65	0.65	0.35	-0.40	-0.25	-0.52	-0.24	0.37	0.25	-0.16	1.00	-0.39	-0.50	-0.89
ORR	-0.43	0.37	-0.12	-0.48	0.72	0.52	-0.07	-0.39	0.50	0.69	0.50	-0.39	1.00	0.38	0.33
TE	-0.74	-0.75	-0.81	-0.44	-0.16	-0.28	-0.72	-0.80	0.06	0.11	-0.48	-0.50	0.38	1.00	0.70
RE	-0.69	-0.72	-0.80	-0.53	-0.28	-0.25	-0.20	-0.55	-0.43	-0.31	-0.13	-0.89	0.33	0.70	1.00

Values in bold are significant cross-correlation factors

Table 10 Cross Correlation Matrix for Factors Influencing Performance for the Veegarm System

	ORR/curr	%ORR/curr	TE/curr	RE/curr	ORR/wave	%ORR/wave	TE/wave	RE/wave	Oil Visc	Slick mm	Tow m/s	Wave m	ORR	TE	RE
ORR/curr	1.00	0.94	0.48	0.64	-0.12	0.09	0.38	-0.33	0.15	-0.38	0.20	0.23	-0.78	-0.53	-0.66
%ORR/curr	0.94	1.00	0.48	0.64	0.06	0.23	0.31	-0.13	0.20	-0.19	0.17	0.18	-0.71	-0.50	-0.56
TE/curr	0.48	0.48	1.00	0.65	-0.38	-0.23	0.70	-0.51	0.21	-0.10	-0.15	0.04	-0.50	-0.71	-0.45
RE/curr	0.64	0.64	0.65	1.00	-0.32	-0.11	0.42	-0.47	0.61	-0.02	0.08	0.14	-0.53	-0.57	-0.53
ORR/wave	-0.12	0.06	-0.38	-0.32	1.00	0.87	-0.38	0.62	0.17		0.28	-0.05	0.32	0.30	0.54
%ORR/wave	0.09	0.23	-0.23	-0.11	0.87	1.00	-0.37	0.27	0.02		0.08	0.04	-0.04	0.20	0.21
TE/wave	0.38	0.31	0.70	0.42	-0.38	-0.37	1.00	-0.42	-0.11		0.18	-0.31	-0.37	-0.56	-0.47
RE/wave	-0.33	-0.13	-0.51	-0.47	0.62	0.27	-0.42	1.00	0.27		0.33	-0.07	0.69	0.40	0.80
Oil Visc	0.15	0.20	0.21	0.61	0.17	0.02	-0.11	0.27	1.00		-0.11	-0.01	0.74	0.34	0.78
Slick mm	-0.38	-0.19	-0.10	-0.02						1.00	-0.01	-0.17	0.45	0.11	0.71
Tow m/s	0.20	0.17	-0.15	0.08	0.28	0.08	0.18	0.33	-0.11	-0.01	1.00	-0.26	0.29	-0.31	0.28
Wave m	0.23	0.18	0.04	0.14	-0.05	0.04	-0.31	-0.07	-0.01	-0.17	-0.26	1.00	-0.29	-0.40	-0.35
ORR	-0.78	-0.71	-0.50	-0.53	0.32	-0.04	-0.37	0.69	0.74	0.45	0.29	-0.29	1.00	0.44	0.85
TE	-0.53	-0.50	-0.71	-0.57	0.30	0.20	-0.56	0.40	0.34	0.11	-0.31	-0.40	0.44	1.00	0.42
RE	-0.66	-0.56	-0.45	-0.53	0.54	0.21	-0.47	0.80	0.78	0.71	0.28	-0.35	0.85	0.42	1.00

Values in bold are significant cross-correlation factors

Another question that arises is the relationship between the decrease in performance and the parameter that is being examined. As with booms described above, it was found that the general relationship with performance and waves is a square root one. A typical analysis is shown in Figure 8. Models then used to predict the performance of skimmers were based on the square root function and the decreases in performance from empirical data as summarized in Table 4.

Figure 10 shows the oil recovery rate (ORR) change for groups of skimmers and the average of all the skimmer data. This shows that the recovery is significantly decreased by harbour chop more than by regular waves. Figure 11 shows the ORR for a variety of specific skimmers. It can be seen from this figure that ORR changes significantly between specific skimmers. Similarly the change in TE and RE are shown in Figures 12 and 13, respectively. The differences between individual units will again be noted.

The change in the performance indicators with increasing current or tow speed were also examined. As was noted earlier and can be seen in Tables 4 and 6, often the ORR increases with increasing tow speed. This is because the oil encounter rate is increased, at least up to the point that the skimmer can handle the increased velocity. Often skimmers show an increase up to a point and then show a decrease. This was handled in averaging the decrease in performance with current by looking at the positive values (decrease in performance only). The change in ORR with increasing current or tow speed cannot be shown because generally it is an increase. The TE does generally decrease with increasing tow speed as seen in Figure 14. One sees a significant different in the throughput efficiency of the different types of skimmers with the changing speed or current.

In conclusion, the use of the average decrease in performance (ORR, TE, or RE) with increasing current appears to yield a reasonable estimate of performance with increased wave energy.

4.4 Dispersants

The variance of dispersant effectiveness with wind speed is not a simple linear function (Fingas, 2000b). It is known from the literature that effectiveness goes down with decreasing dispersant but goes up with increasing energy. The deposition is known to vary with wind speed (Giamona et al., 1994). The empirical data in Table 11 from various sources, but mainly Giamona et al. (1994), was correlated to observe whether simple relationships could predict the relationship between wind and deposition. Included in the correlation were aircraft speed, head wind, cross wind, measured droplet diameters, and altitude with the deposition percentage. Surprisingly, it was found that altitude had little relation to the deposition percentage, but the others did. Dropping all parameters except wind speed and the particle average volume diameter, it was found that a relatively simple relationship could be established for deposition with wind speed. This relationship is shown in Figure 15. This figure shows the three-way correlation between Volume Mean Diameter (VMD), wind, and the percent deposition. The VMD here is the actual value less the optimal diameter of 300 µm . The correlations had shown that the best deposition was obtained with this VMD and lesser VMD would result in poorer deposition. The correlation achieved was 0.54, which is rather good considering the many variables in deposition, including those mentioned earlier. From this, a simple correlation for deposition with wind relationship was derived:

$$\text{Deposition (\%)} = (80 - 3 \text{ X Wind Speed}) \qquad (6)$$

This was used in subsequent calculations for relative dispersant effectiveness.

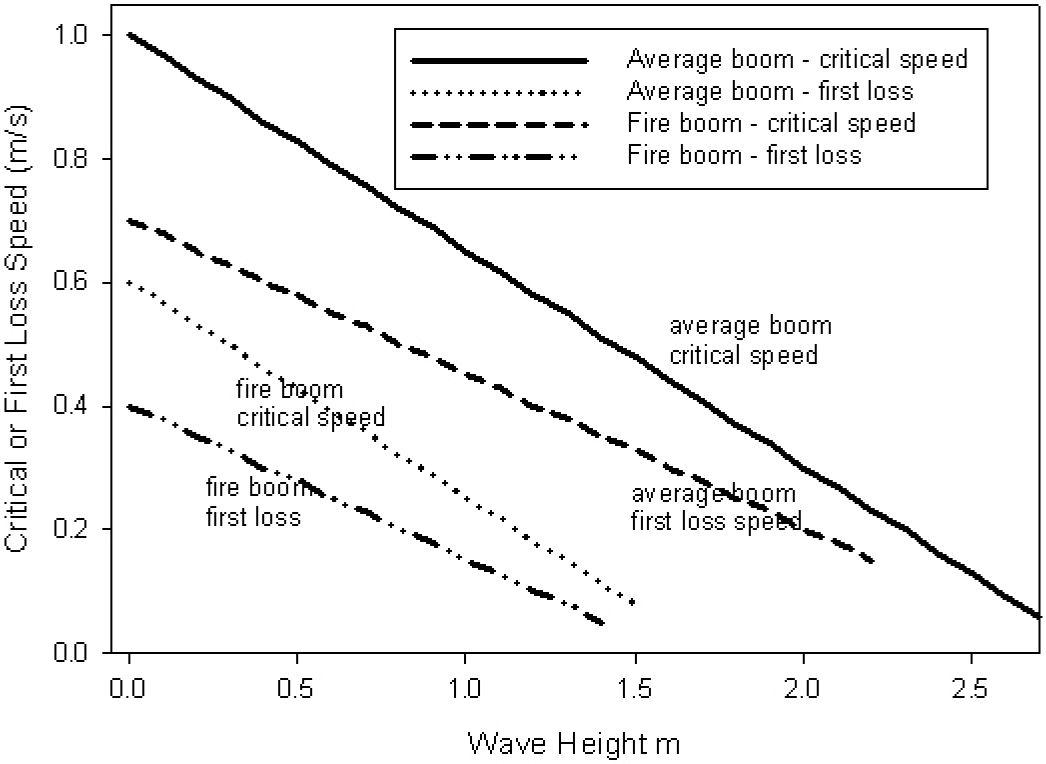


Figure 8 Effect of Waves on Boom Performance

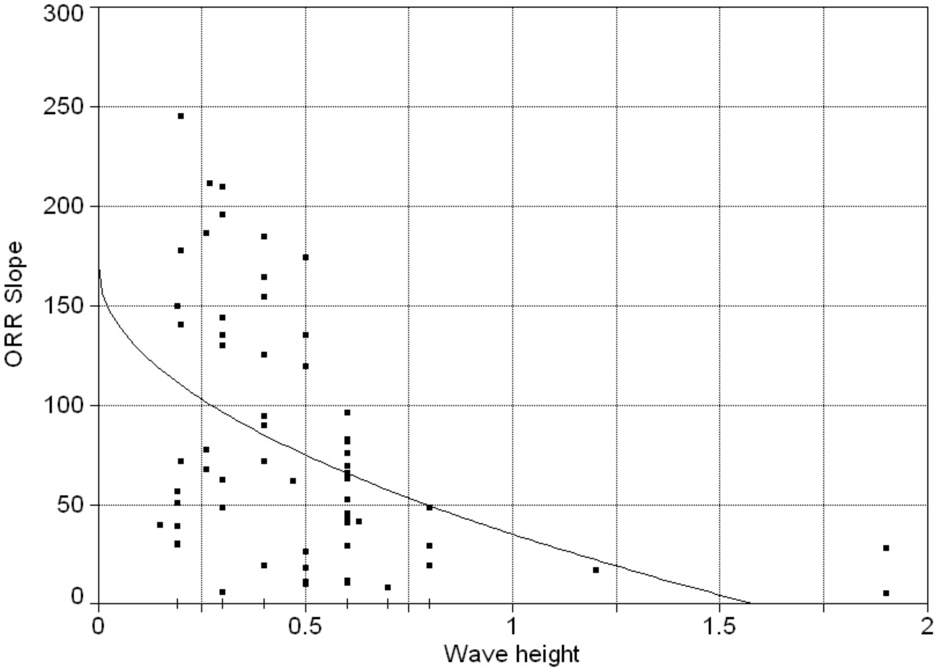


Figure 9 Relationship between ORR (Oil Recovery Rate) and Wave Height (m)

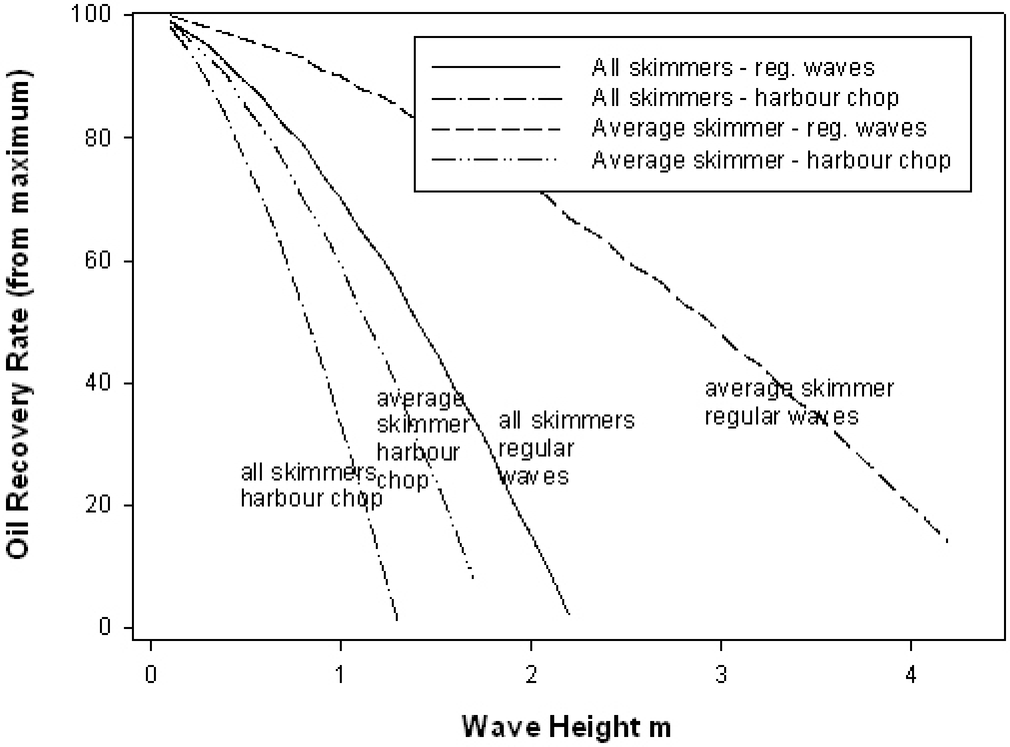


Figure 10 Effect of Waves on Skimmer Performance

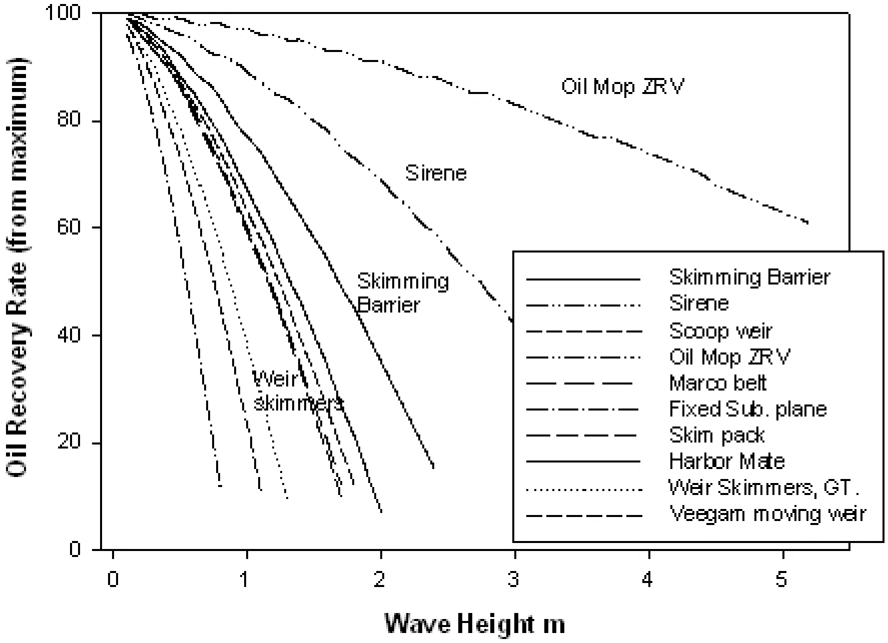


Figure 11 Performance of Specific Skimmers in Waves

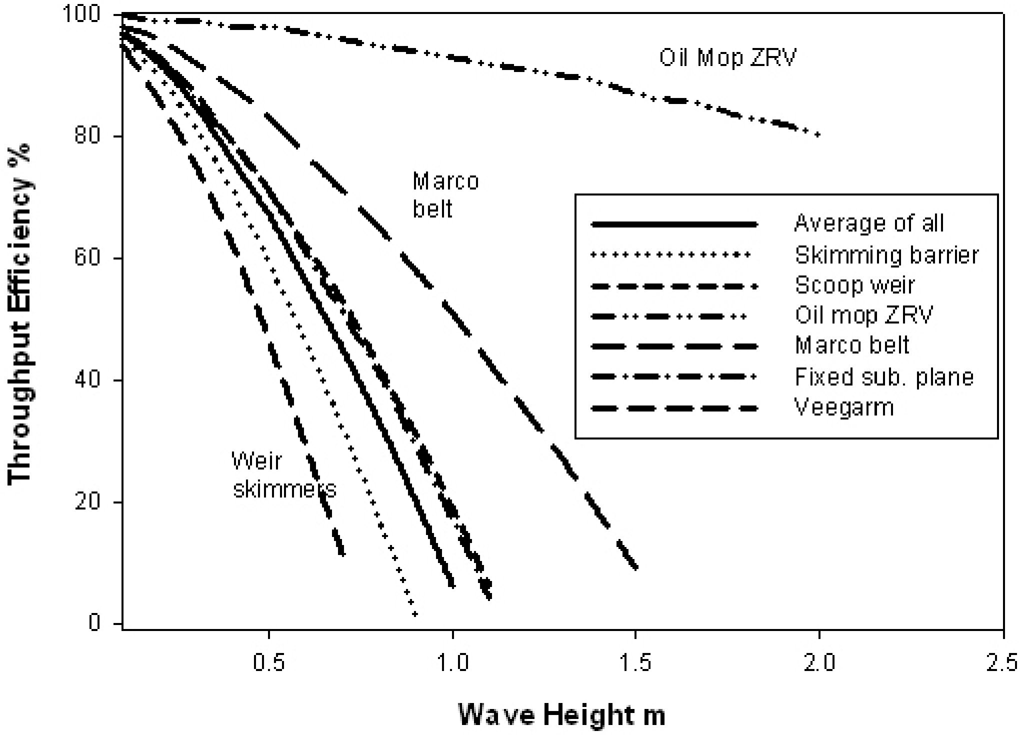


Figure 12 Effect of Waves on Throughput Efficiency (TE)

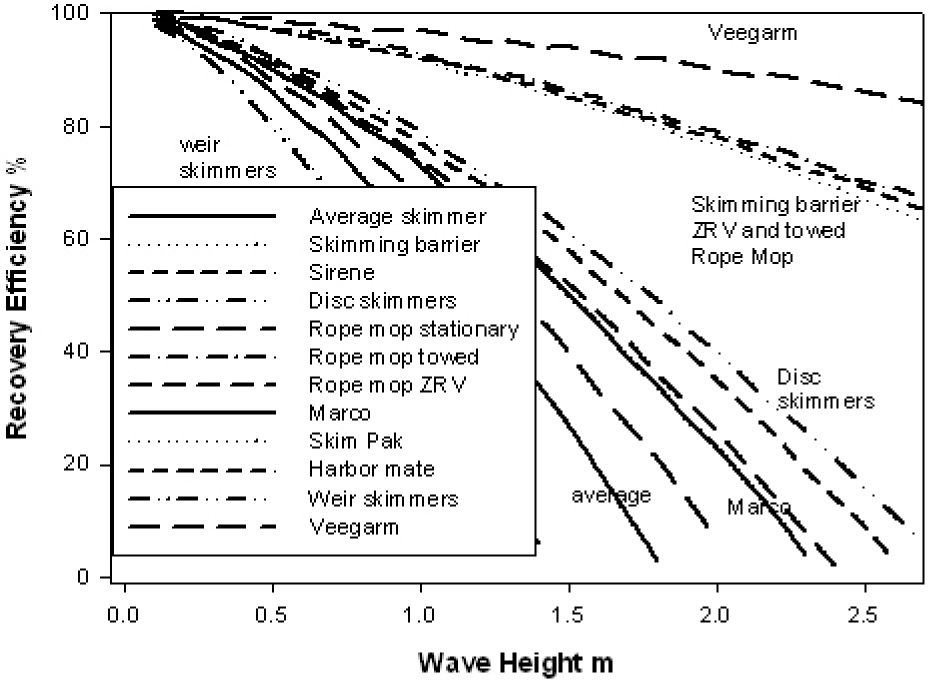


Figure 13 Effect of Waves on Recovery Efficiency (RE)

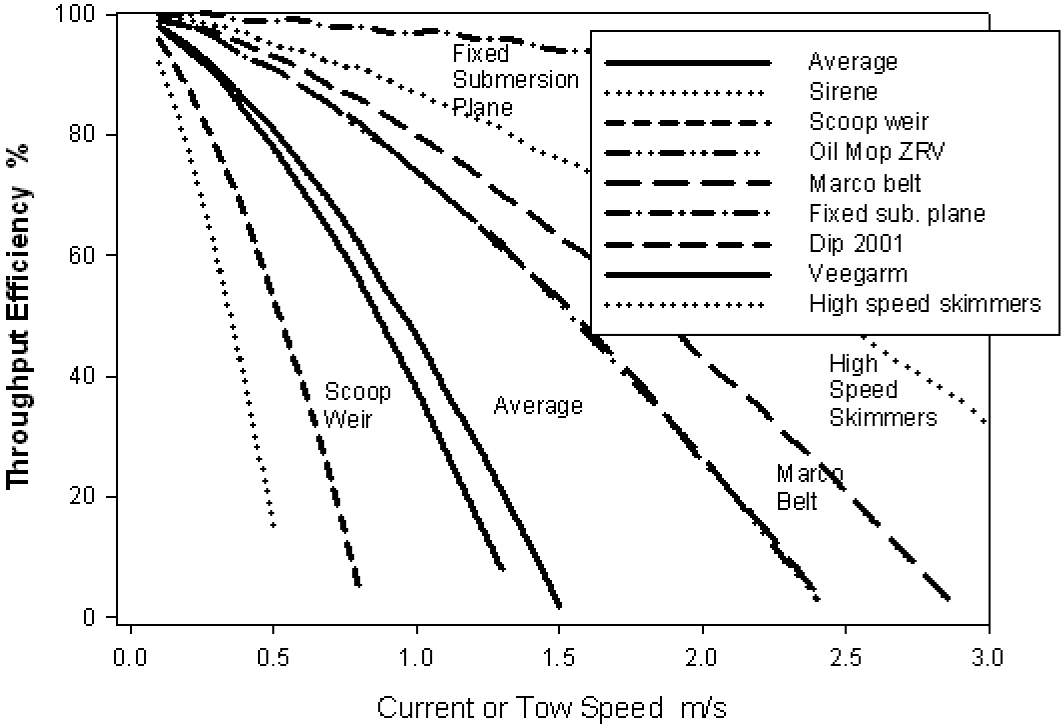


Figure 14 Effect of Current or Tow Speed on Recovery Efficiency (RE)

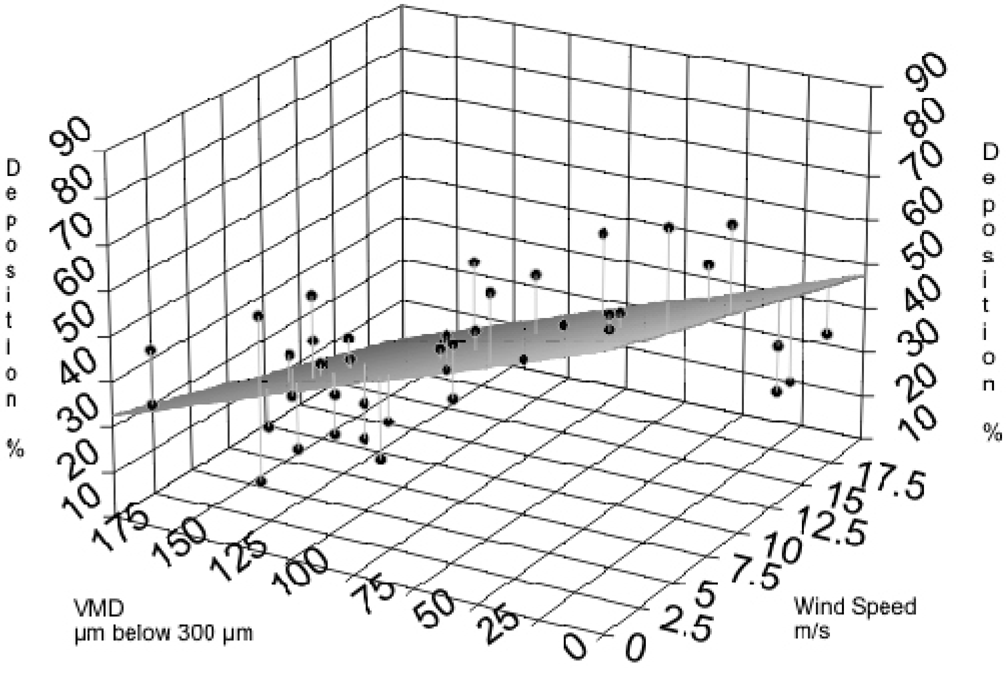


Figure 15 Correlation of Wind, Droplet Size and Deposition The Volume Mean Diameter (VMD) is the particle size smaller than 300 µm, the three dimensional view also shows the fit surface. The circles above and below the fit surface show data scatter.

Table 11 Dispersant Spray Trials at Alpine, TX

Dispersant	Spray System	gallons Sprayed	Litres Sprayed	Ground Speed (kn)	Altitude ft	Wind Speed (kn)	Cross Wind	Deposition %**	Droplet information (µm) average (sm)	maximum	Approximate VMD*
9527	ADDS	45	171	140	50	13	-9	68	104	969	300
9527	ADDS	45	171	140	100	9	-8	15	162	1108	450
9527	ADDS	45	171	140	100	13	-9	59	78	630	300
9527	ADDS	45	171	140	150	17	-12	48	116	758	300
9527	ADDS	45	171	140	120	17	-13	73	120	671	250
9527	ADDS	45	171	140	50	18	-15	66	68	671	200
9527	ADDS	45	171	140	100	14	-12	75	68	888	300
9527	ADDS	45	171	140	150	15	-15	56	93	687	400
9527	ADDS	56	212	140	50	8.5	-2	46	35	544	400
9527	ADDS	45	171	140	100	9.3	1	78	93	630	300
9527	ADDS	60	227	140	150	6	0	38	76	778	450
9527	ADDS	30	114	140	120	10.2	-7	52	137	646	350
9527	ADDS	38	144	140	50	13	-1	50	70	758	400
9527	ADDS	41	155	140	120	9.5	-9	75	96	785	250
9527	ADDS	56	212	140	150	12	-5	33	101	689	400
9527	MASS	116	440	200	100	2		42	87	639	150
9527	MASS	59	224	200	100	2	1	38	61	1018	200
9527	MASS	41	155	200	100			31	76	838	250
9527	MASS	40	152	200	100			29	85	903	150
9527	MASS	40	152	200	100			19	81	656	150
9527	MASS	52	197	200	100	6	4	86	94	809	200
9527	MASS	41	155	200	100	7	-4	40	105	510	200
9527	MASS	36	136	200	100	9.5	1	49	55	879	250
9527	MASS	60	227	200	100	7	1	44	52	506	150
9527	MASS	93	352	200	100	4.5	-1	54	56	796	150
9527	MASS	65	246	200	100	7	2	23	94	810	200
9527	MASS	113	428	200	100	12	5	20	91	832	100
9527	DC-4	32	121	136	50	17	-15	31	60	317	150
9527	DC-4	0	0	136	50			74			
9554	MASS	52	197	200	100	3.5	3	56	67	842	150
9554	MASS	48	182	200	100	3.5	0	44	76	918	150
9527	MASS	71	269	200	100	2.5	1	47	30	348	100
9527	DC-3	37	140	115	50			46	50	594	150
9527	DC-3	33	125	115	50	4.5	-1	53	83	690	300
9527	DC-4	38	144	115	50	6.5	0	20	54	316	200
9527	DC-4	43	163	136	50	5.5	1	22	57	591	150
9527	DC-4	71	269	136	50	5.5	-2	34	57	591	150
9527	DC-4	81	307	136	50	9	-2	13	49	405	150
9527	Air Tr.	0	0	119	15	2.5	-8	40	31	711	100
9527	Air Tr.	0	0	119	15	2.5	-1	35	38	488	200
9527	Air Tr.	0	0	119	30	2.5	-2	1	31	377	150
9527	Air Tr.	0	0	119	30	7	-4		42	405	150

**calculated in this work

*where volume hits 50 percent in middle of distribution

The final model to be achieved should conceptually consist of the deposition times the decrease in dispersion caused by the decrease in deposition, then times the increase in dispersion caused by the increasing wave energy. The next step is to separate natural and chemical dispersion so that the effect of dispersants alone can be estimated. The first step is to calculate the fall off in deposition with wind speed, which was done with the formula illustrated in Figure 15. Then the drop in chemical dispersion effectiveness with decreasing dispersant amount was calculated using the square root function as determined from empirical data as illustrated in Figure 16 (Fingas, 2000b). Then the natural dispersion was calculated using the Delvigne and Mackay natural dispersion approximations in which the natural dispersion varies as the square of the wave height. It is then presumed that a light oil would disperse naturally nearly completely by the wave height of about 25 m or a wind of about 25 m/s as was observed during the *Braer* incident. See Section 3.5 for discussion on this issue.

Figure 17 shows the standard wind-wave conversion (Hunt and Groves, 1976).Using this conversion the total dispersant effectiveness model was created as shown in Figure 18. It is important to stress that what is shown here is relative effectiveness, that is the rationalized effectiveness with the maximum set to 100%. The value typically measured in laboratory tests or other such similar effectiveness tests is absolute effectiveness. Thus, if one wanted to know the effectiveness percent at a particular wind or wave condition, then the relative effectiveness is multiplied by the absolute effectiveness. For example, if a dispersant has a value of 40% in the laboratory, then at a wind speed of about 12 m/s (25 knots), the relative effectiveness is 60% and the effectiveness then becomes the two factors multiplied or 0.4 × 0.6 or 24%.

The dispersion model will be described in greater detail in this section. The natural dispersion follows Delvigne and Mackay approximations, specifically:

$$\text{Natural dispersion} \propto (\text{wave height} + 1.2)^2/5 \qquad (7)$$

Chemical dispersion is modelled using a 4-step process. The first step is to calculate the loss in effectiveness with deposition. The deposition was calculated as above using empirical data as shown in Figure 15.

$$\text{The loss in effectiveness with deposition} \propto \sqrt{(80\text{-}\%\text{dep})} \qquad (8)$$

This value is rationalized then to be a relative number, that is starting from a maximum of 100%.

The next step is to bring in the wave height as well as the wind with a Delvigne-like relationship.

$$\text{Relative dispersion} \propto (\text{loss with wind})^2 * \text{wave height} \qquad (9)$$

The relative dispersion was then averaged over immediate increments to ensure that it went in smoother increments with increasing wind and wave height.

Chemical dispersion is also known to vary with temperature (Fingas, 2000b; Fingas et al., 2003). Table 12 shows the collection of data on some recent temperature and salinity variances (Moles et al., 2001). The graph of the temperature versus effectiveness of these is shown in Figure 19. On average, the effectiveness decreases as the square root of the temperature between 3 and 22°C.

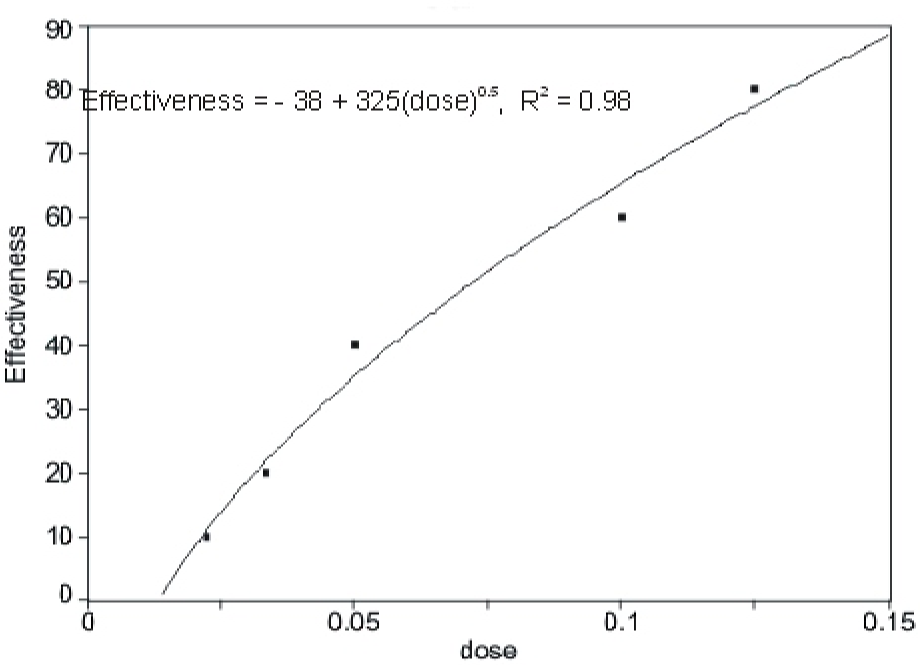


Figure 16 Correlation of Dose (dispersant to oil ratio) and Dispersant Effectiveness

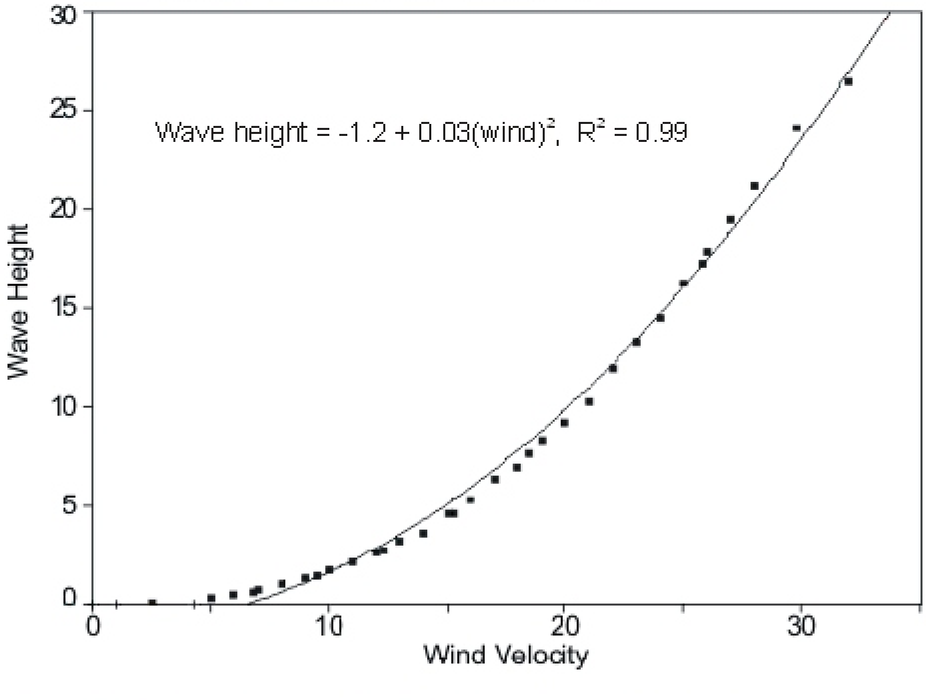


Figure 17 Correlation of Wind Speed and Wave Height

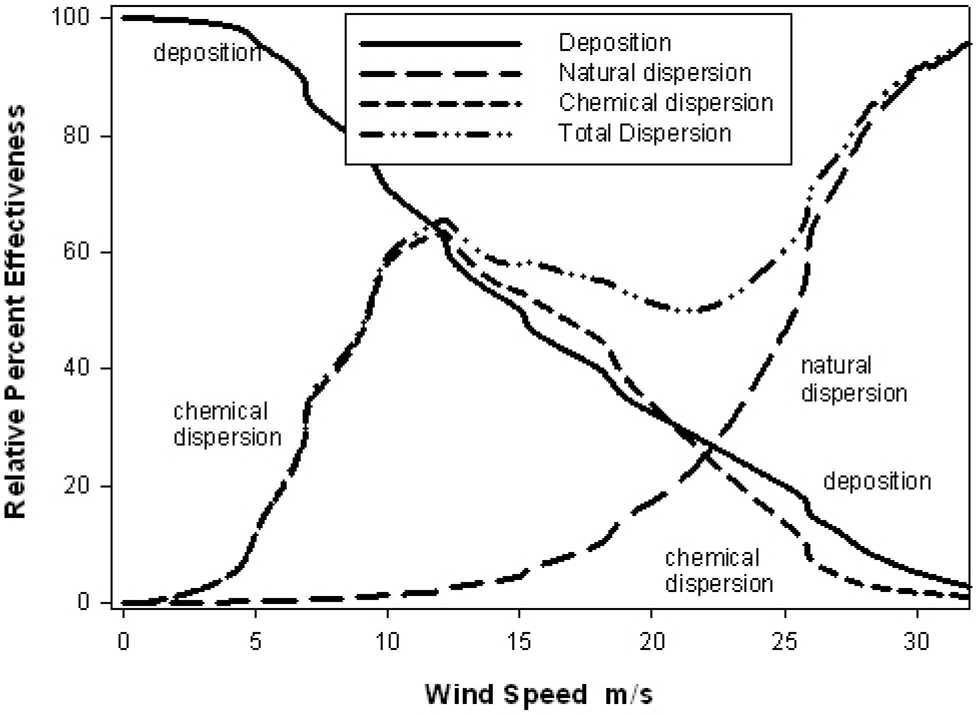


Figure 18 Model of Relative Dispersion with Wind

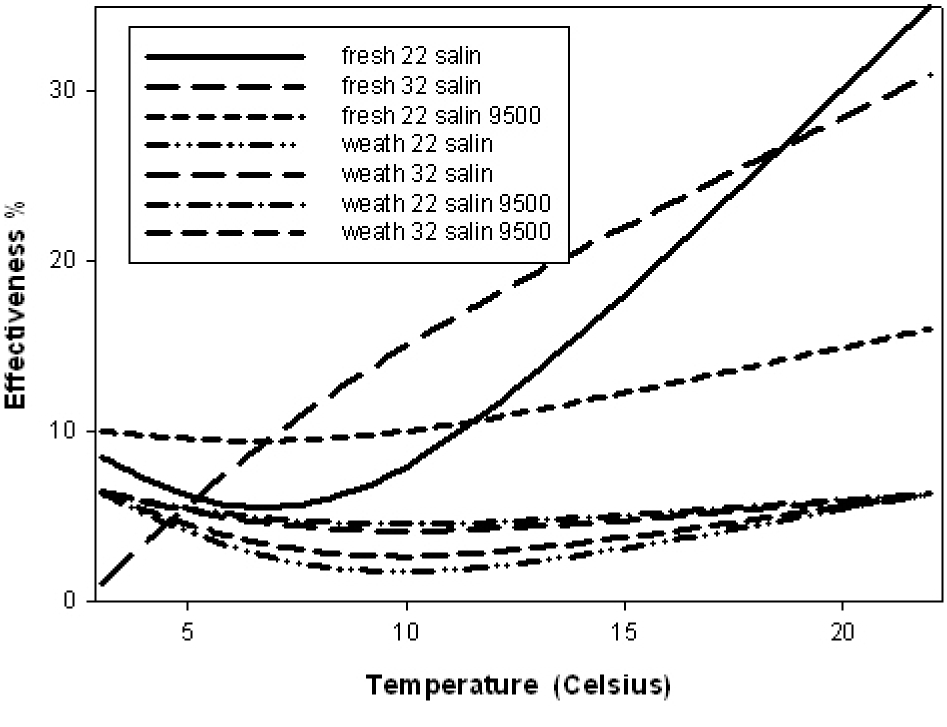


Figure 19 Effect of Temperature on Dispersion (after Moles et. al., 2001)

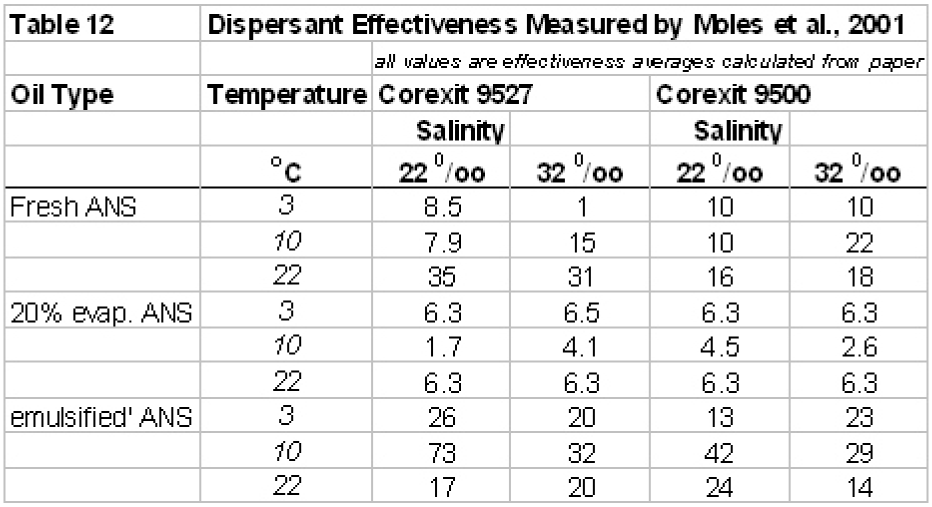


Table 12	Dispersant Effectiveness Measured by Moles et al., 2001				
	all values are effectiveness averages calculated from paper				
Oil Type	**Temperature**	**Corexit 9527**		**Corexit 9500**	
		Salinity		**Salinity**	
	°C	**22 ^{0}/oo**	**32 ^{0}/oo**	**22 ^{0}/oo**	**32 ^{0}/oo**
Fresh ANS	*3*	8.5	1	10	10
	10	7.9	15	10	22
	22	35	31	16	18
20% evap. ANS	*3*	6.3	6.5	6.3	6.3
	10	1.7	4.1	4.5	2.6
	22	6.3	6.3	6.3	6.3
emulsified' ANS	*3*	26	20	13	23
	10	73	32	42	29
	22	17	20	24	14

4.5 In-situ Burning

The relation between burning and weather conditions noted that there were several components. If containment is involved, the limitations are those of the containment boom, already discussed in Section 4.2. The relationships are shown in Figure 8. Whether or not containment is required, there are two factors important to burning: the ability to ignite and the ability to maintain burning in a wind. The latter part of this, the ability to maintain burning in wind, is probably not of concern. The limitation on burning may be the ability to ignite in a wind. As noted in Section 3.6, no specific tests were conducted on ignition limits. However, there are some pieces of information that can be used to make an estimate on igniting using current techniques. It should be noted that techniques which involve some form of sheltering may increase the limits of ignition in wind. Thornborough (1997) noted a success in ignition at 13 m/s (25 knots) winds. Discussions with Guenette and Allen indicated that this burn might have a probability of 0.8 at 13 m/s and that it certainly had a probability of 1 at 10 m/s or about 20 knots. There are no known data on higher velocity winds. If ignition is assigned a probability of 0.8 and 10 m/s is assigned a probability of 1, since this has been performed several times, one can extrapolate a probability of ignition using a linear form as shown in Figure 20.

The burning of oil in ice reduces the efficiency somewhat (Buist et al., 2003). This data can be used to show the decrease in effectiveness. Table 13 shows that on average, Frazil or slush ice slows burning by 0.45 mm/min and brash ice, by 0.8 mm/min.

4.6 Others

Provant (1992) rated the decrease in performance of decanting (gravity separation) with wave height as: wave height up to 0.9 m, 0.8 decanting factor (e.g., 80% effective); waves of 1 to 2 m, 0.8; waves of 2.1 to 2.7 m, 0.7; and over 2.8 m, 0.6. These data result in a simple nomogram as shown in Figure 20.

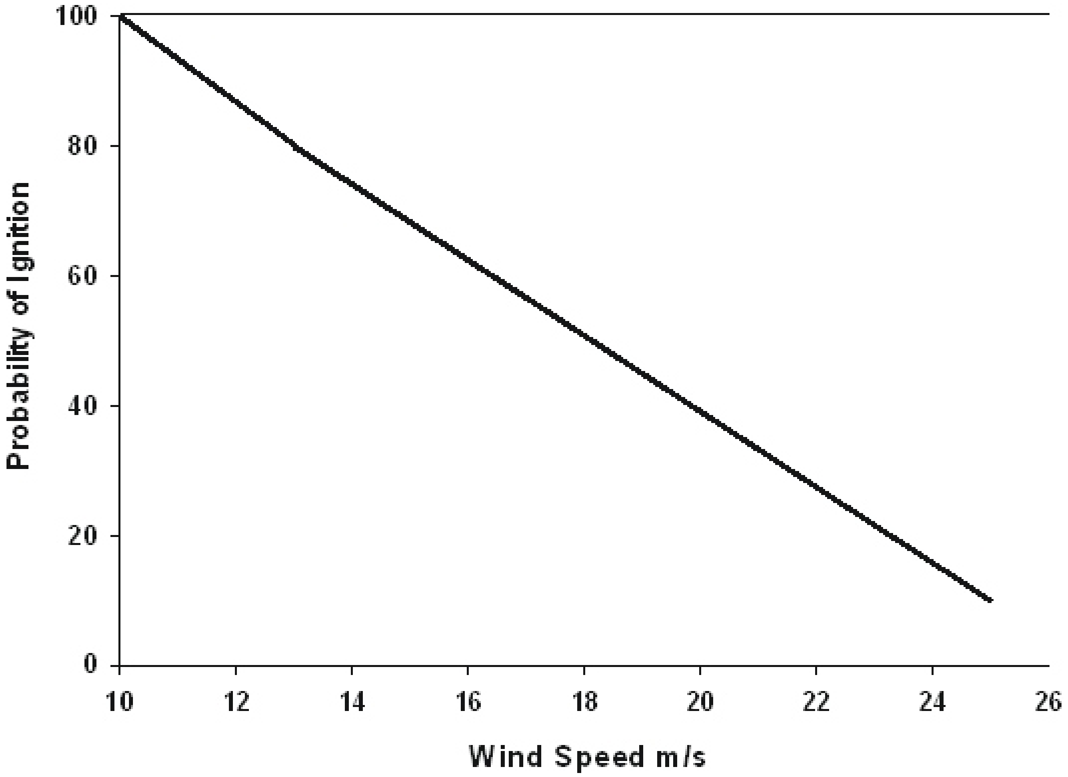


Figure 20 Probability of Ignition with Wind Speed

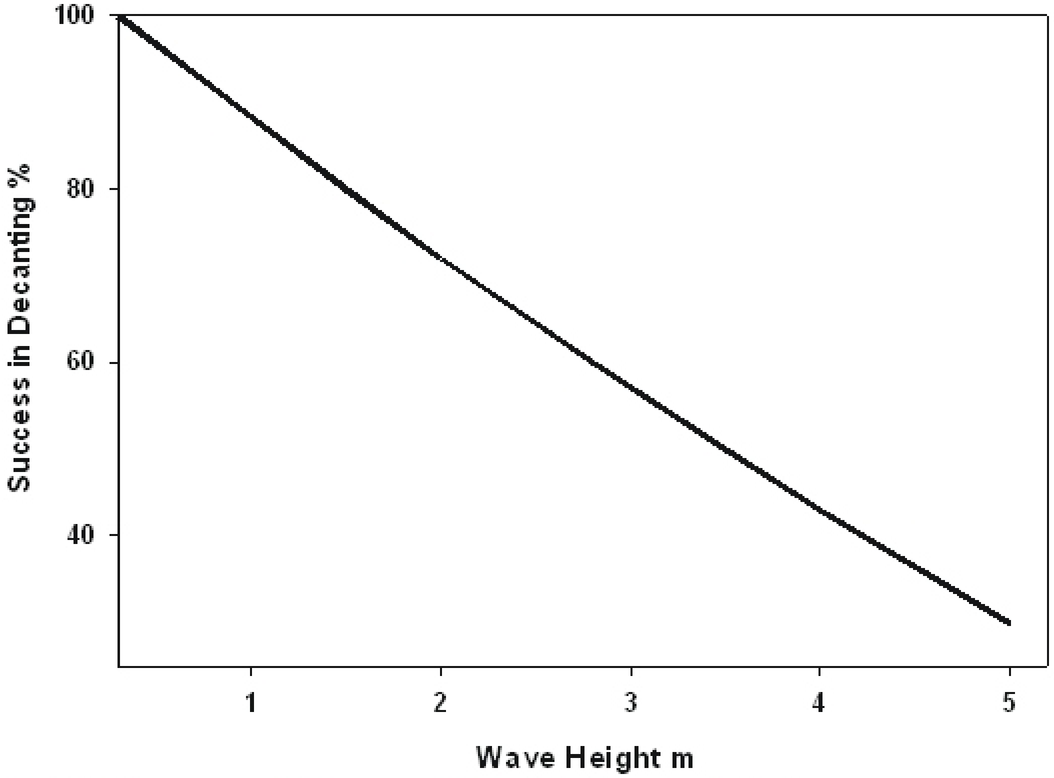


Figure 21 Success of Decanting with Wave Height

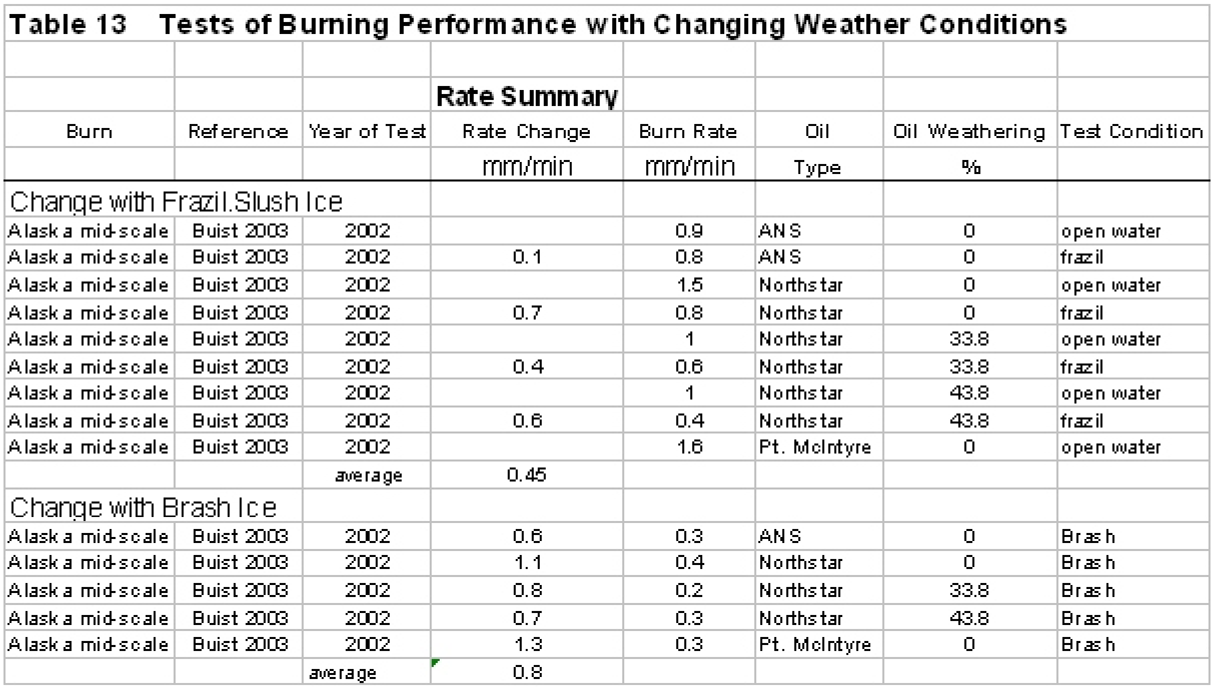


Table 13 Tests of Burning Performance with Changing Weather Conditions

			Rate Summary				
Burn	Reference	Year of Test	Rate Change	Burn Rate	Oil	Oil Weathering	Test Condition
			mm/min	mm/min	Type	%	
Change with Frazil.Slush Ice							
Alaska mid-scale	Buist 2003	2002		0.9	ANS	0	open water
Alaska mid-scale	Buist 2003	2002	0.1	0.8	ANS	0	frazil
Alaska mid-scale	Buist 2003	2002		1.5	Northstar	0	open water
Alaska mid-scale	Buist 2003	2002	0.7	0.8	Northstar	0	frazil
Alaska mid-scale	Buist 2003	2002		1	Northstar	33.8	open water
Alaska mid-scale	Buist 2003	2002	0.4	0.6	Northstar	33.8	frazil
Alaska mid-scale	Buist 2003	2002		1	Northstar	43.8	open water
Alaska mid-scale	Buist 2003	2002	0.6	0.4	Northstar	43.8	frazil
Alaska mid-scale	Buist 2003	2002		1.6	Pt. McIntyre	0	open water
		average	0.45				
Change with Brash Ice							
Alaska mid-scale	Buist 2003	2002	0.6	0.3	ANS	0	Brash
Alaska mid-scale	Buist 2003	2002	1.1	0.4	Northstar	0	Brash
Alaska mid-scale	Buist 2003	2002	0.8	0.2	Northstar	33.8	Brash
Alaska mid-scale	Buist 2003	2002	0.7	0.3	Northstar	43.8	Brash
Alaska mid-scale	Buist 2003	2002	1.3	0.3	Pt. McIntyre	0	Brash
		average	0.8				

5. Overview of Weather Limitations

The changes in the effectiveness of countermeasures with waves are shown in Figure 22. This figure shows the plots of typical skimmers, booms, and the decanting estimation. This shows that there is a wide discrepancy between the capability of various skimmers to deal with wave height but that booms are fixed and have limitations at the lower end of the wave scale.

Figure 23 summarizes the wind speed limitations of several countermeasures. The waves have been equated to wind for this diagram. This shows how booms are limited by wind speed (and the resulting waves), to a low wind speed of about 3 m/s. Harbour skimmers are limited to similar wind/wave regimes. High speed skimmers can deal with great wind/wave systems. Chemical dispersion peaks at winds of about 12 m/s as this is the point at which decreasing deposition is matched by increasing sea energy. The probability of ignition persists throughout the diagram to yield a lower probability at winds of about 25 m/s.

Figure 24 shows the current or tow speed limitations of several countermeasures. The average skimmer and boom is limited to below about 1 m/s, while high speed and zero relative velocity skimmers (ZRV) have potentially much greater potentials. Figure 25 shows an overall view of the effect of wind on several countermeasures.

Temperature does not limit most physical recovery or burning. It does, however, limit dispersion to a certain degree.

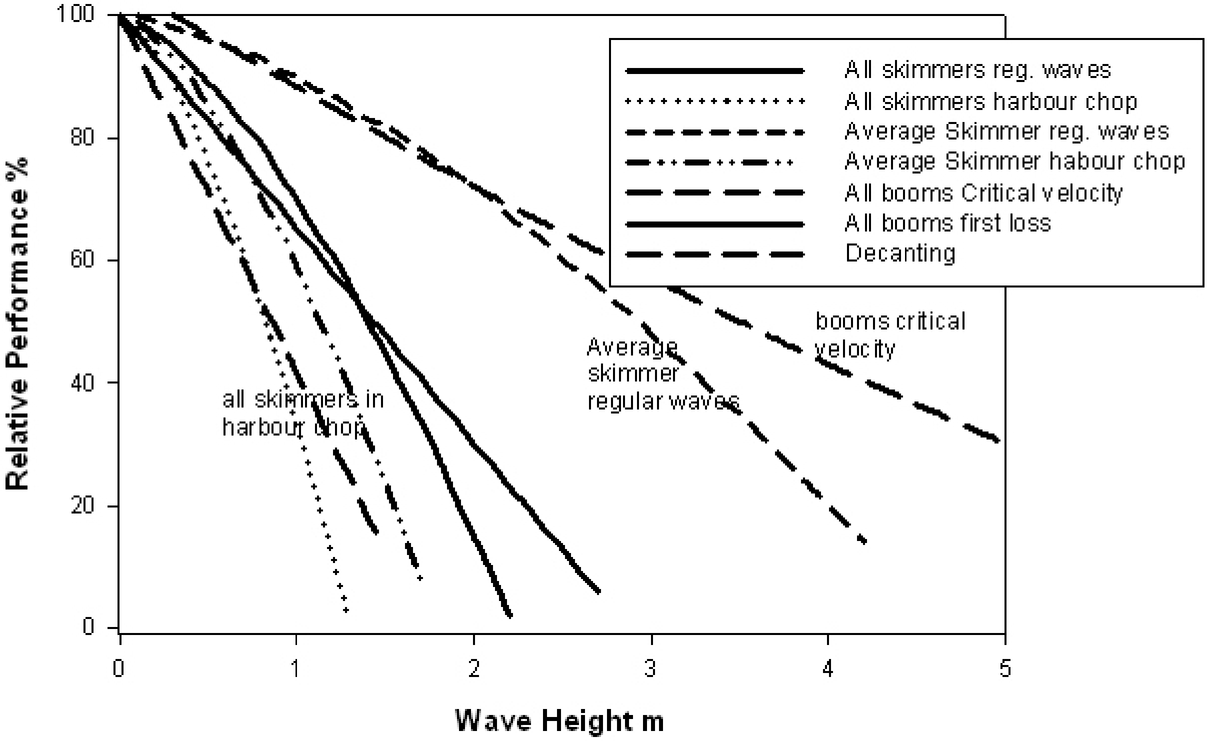


Figure 22 Relative Performance of Countermeasures with Wind Height

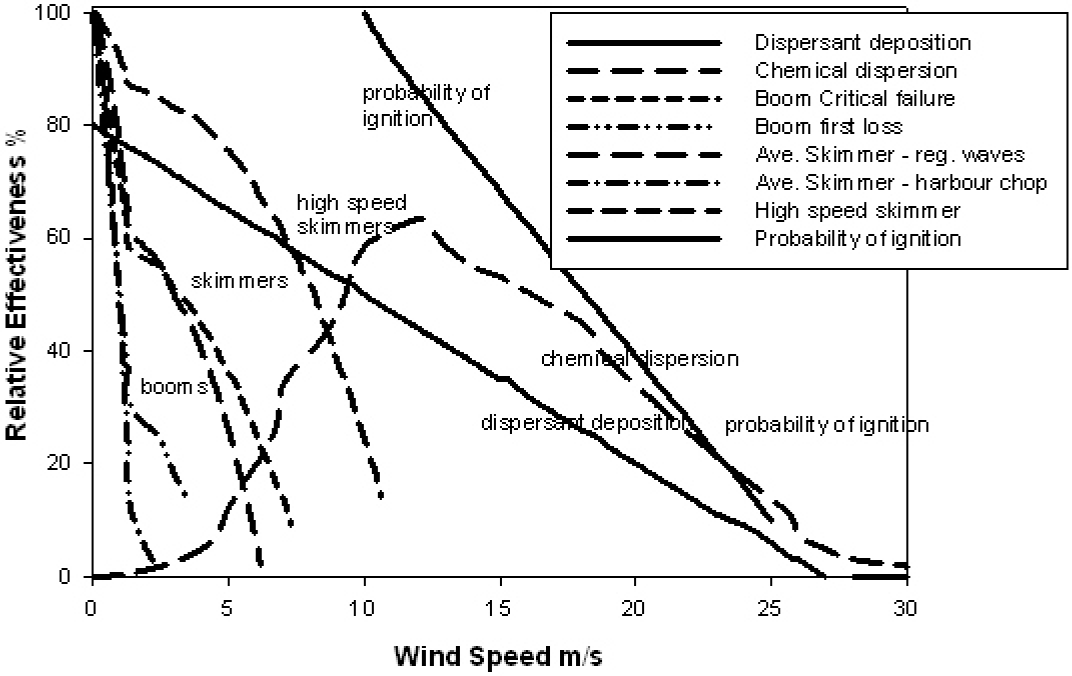


Figure 23 Relative Performance of Countermeasures with Wind Speed

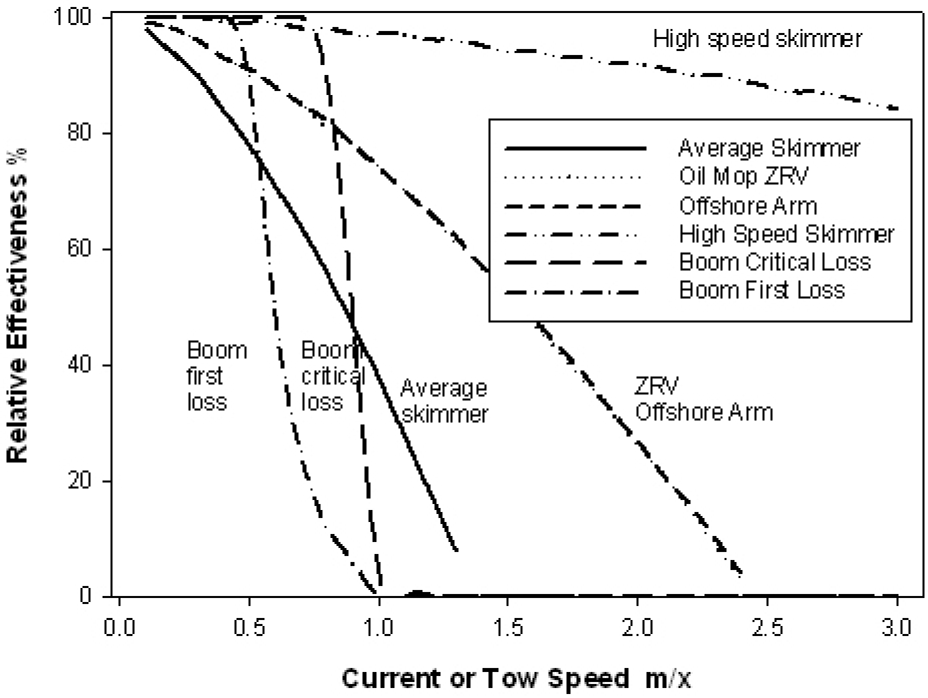


Figure 24 **Relative Performance of Booms and Skimmers with Current or Tow Speed**

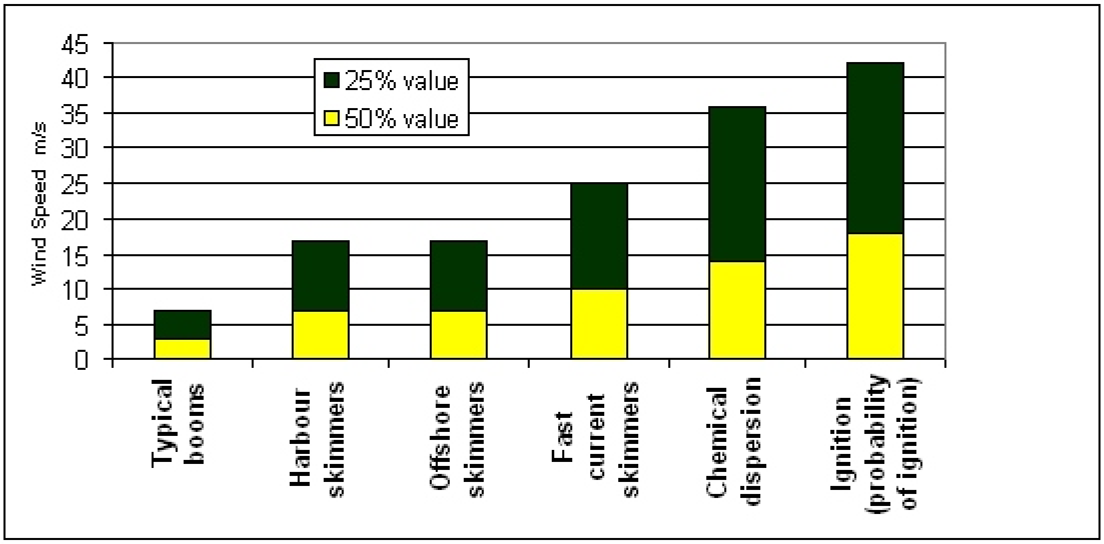


Figure 25 **Relative Performance (points at which 25% and 50% of maximum performance are achieved) of Various Countermeasures with Wind Speed**

6. Summary and Conclusions

Spill countermeasures are affected by weather conditions such that, in some cases, they cannot continue under adverse weather conditions. The literature did not show any quantitative guides for the performance of countermeasures under varying weather conditions, however, many *a priori* estimates are available. These *a priori* guides may not be useful as they lack quantitative backing. Data could be extracted from a large number of papers to enable assessment of changes in the performance of countermeasures related to weather conditions. Many estimates or traditional limits are found in the literature, but these vary considerably and may not be useful. Table 14 summarizes the many limits found in the literature, as well as the numerical findings of this report. Table 14 shows the high scatter of the *a priori* limits around the 25 and 50% performance limits developed in this report.

The most important factors that influence the performance of countermeasures are the wind and wave height. These two factors are related and, given a typical sea, can be inter-converted. These factors must sometimes be considered separately, however, so that specific weather effects can be examined. Other weather conditions affecting countermeasures include currents and temperature. Currents are important in that they become the critical factor for certain countermeasures such as booms. Temperature primarily affects dispersants and has been shown to have only minimal effect on other countermeasures.

Booms are the countermeasures most susceptible to weather conditions. Booms will fail at a current of 0.5 m/s (1 knot) regardless of design or other conditions. This is due to inherent hydrodynamic limitations. There is wave-associated degradation of this value and this is dependent on design. Nomograms for some typical booms are given.

Skimmers show degradation of recovery potential with increasing wave height and also with relative current. Skimmer performance is very individual and a number of skimmer performance curves have been developed for this study. Some skimmers can only function effectively in absolutely calm waters while others have recovered oil in sea states of up to 5 or 6 (wave heights of up to 3 m or 18 feet with corresponding winds of up to 15 m/s or 30 knots). Sufficient data exist to predict performance with waves and currents for over 30 specific skimmers and 10 generic types. Advancing skimmers generally show an increase in oil recovery with increasing current or tow speed because this presents more oil to them or increases the encounter rate.

The weather affects dispersant application and effectiveness in three ways: the amount of dispersant that contacts the target is highly wind-dependent; the amount of oil dispersed on the surface is very dependent on ocean turbulence and other energy; and the amount of oil remaining in the water column is dependent on the same energy. Nomograms for effectiveness have been created. At high sea energies, many lighter oils can disperse naturally.

The weather affects in-situ burning in two ways: the ability to ignite oil in a given wind and the ability to sustain ignition in a given wind. While there are few data on these, estimates of ignition success can be made based on prior experience.

Table 14 Summary of Weather Limits or Functions Noted in this Report

			Variable Limits						A Priori Limits			Other				
Countermeasure			Wind	m/s	Wave	m	Current	m/s	Wind	Wave	Current	Wind	Wave	Current	Notes	Function
	Reference	Type	25%	50%	25%	50%	25%	50%	m/s	m	m/s	m/s	m	m/s		
Booms	This work	first loss												0.5 to .06	measured	
		critical velocity	3	4	1.2	2	0.5	0.7						0.4	typical	
	Yazaki 1983	government specification										10	1	0.25	spec for type C boom	
	Yazaki 1983	government specification										20	1.5	0.5	spec for type D boom	
	Williams and Cooke 1985	bubble barrier critical velocity										8 to 10			oil held several m away	
	Brekne et al. 2003	critical velocity							20	2.5					design for new boom	
	Tedeschi 1999	critical velocity							8 to 9							
	Nash and Hillger	first loss												0.1 to 0.6	measured - calm	
	Nash and Hillger	first loss												0 to 0.6	measured - regular waves	
	Nash and Hillger	first loss												0 to 0.38	measured - harbour chop	
	Van Dyck and Bruno	catenary tow optimal												0.5		
	Marks et al. 1971	total force on boom														varies directly as wave height
	Milgram 1977	fabric tearing strength														one-third power of wave height
	Potter et al. 1999	towing force														varies directly as wave height
	Schulz and Potter 2002	towing force														varies directly as wave height
	Suzuki et al. 1985	critical velocity													increased in ice from 0.4 to 0.5	
	Brown et al. 1993	critical velocity												0.25	if oil was heavy oil	
	Hansen 2001	critical velocity												3	test for JBF 6001	
	Hansen 2001	critical velocity												3.5	test for Current Buster	
	Eryuzlu and Hausser 1977	floating deflector												0.8 to 2.1	successful deflection	
	Folsom and Johnson 1981	critical velocity												3	claim for boom	
	Nash and Johnson	critical velocity												3	test for plunging jet	
	Swift et al. 2000b	critical velocity												1.03	containment for submerged bow plane	
	Meikle 1983	fire resistant boom test												1		
	Buist et al. 1983	fire resistant boom test											4	0.4	in towing mode primarily	
Skimmers	This work	typical harbour	7	10	1.5	2	0.6	1								
		typical offshore	7	10	2.5	5	4	7								
		fast current	2	4	10	15	5	8								

Table 14 ctd. Summary of Weather Limits or Functions Noted in this Report

			Variable Limits						A Priori Limits			Other				
Countermeasure			Wind	m/s	Wave	m	Current	m/s	Wind	Wave	Current	Wind	Wave	Current	Notes	Function
	Reference	Type	25%	50%	25%	50%	25%	50%	m/s	m	m/s	m/s	m	m/s		
Skimmers	Reed 1995	mechanical recovery efficiencies										5			80% efficiency	
	Peigne 1985	successful recovery										10	1 to 2		Sirene and ESCA tests	
	Reed 1995	mechanical recovery efficiencies										10			60% efficiency	
	Wilson 1981	tests										15	3		weir boom tests	
	Nordvik 1995	successful recovery										10 to 13	2.5		successful recovery	
	Leigh 1973	design objectives										10 to 14	1.2		um skimmer and weir basin objectives	
	Koops 1985	successful recovery											2		skimming vessel recovery	
	Brekne et al. 2003	tests											3	0.8	Ocean Buster tests	
	Gates and Gordiano 1985	effect of waves											0.18 to 0.47		no decrease for wave increase	
	Hara et al. 2002	increase in capability											from 1 to 2 or 3		increase in capability by moon pool	
	Allen 1988	mechanical cleanup							6	0.8						
	Dempsey 2002	offshore work generally							12	3						
	Koops and Huisman 2002	skimmers generally							13							
	Decola 2003	Wash./Or. Guide - mechanical cleanup									0.5					
	Koops 1988	skimmers generally								1.5						
	Steen 2002	general limit								1						
	Koops and Huisman 2002	general limit								5						
	Akahoshi et al. 2002	sea recovery limit								2.5						
	Provant 1992	degradation in performance								0.9					80% effective	
	Provant 1992	degradation in performance								1 to 2					70% effective	
	Provant 1992	degradation in performance								2.1 to 2.7					50% effective	
	Provant 1992	degradation in performance								over 2.8					10% effective	
	Nordvik 1995	Transrec performance								1.5					15 to 85% TE	
	Nordvik 1995	Transrec limitations								4					expected limits of operation	
	Tech. Serv. Br. 1984	temperature limitations													temperature no difference	
	Shum and Borst 1985	ice limitations													50% ice caused no difference	
	Hansen 20021	tests												3	Ocean Buster tests	
	Coe 1999	tests												3	USCG high speed skimmer	

Table 14 ctd. Summary of Weather Limits or Functions Noted in this Report

			Variable Limits						A Priori Limits			Other				
Countermeasure			**Wind**	m/s	**Wave**	m	**Current**	m/s	**Wind**	**Wave**	**Current**	**Wind**	**Wave**	**Current**	**Notes**	**Function**
	Reference	**Type**	**25%**	**50%**	**25%**	**50%**	**25%**	**50%**	m/s	m	m/s	m/s	m	m/s		
Chemical	This work	typical rising/falling	0 to 1	22												
Dispersion	Decola 2003	Wash./Or. Guide							1 to 10			3			minimum	
	Koops and Huisman 2002	natural dispersion										5			minimum	
	Allen 1988	general dispersion							12	3						
	Decola 2003	EPA region size guide							13							
	ExxonMobile 2000	application - large aircraft							15 to 18	9 to 12						
	Koops and Huisman 2002	chemical dispersion							2 to 20							
	ExxonMobile 2000	application - workboat							3 to 11	0 to 3						
	ExxonMobile 2000	application - single-engine aircraft							8 to 11	2 to 3						
	ExxonMobile 2000	application - helicopters							9 to 11	2 to 8						
	Daling 1988	dispersion and temperature													20% fall off with lower temperature	
	Lunel and Lewis 1999	lower sea threshold													15% for low sea, 30% for calm	
	Lunel et al. 1995a	classification of energy													0 to 5 m/s = low; 6 to 10 m/s high energy	
	Scholz et al. 1999	lower energy threshold													winds 2.5 to 12 m/s waves 0.1 to 2 m	
	Lunel 1995a	Braer sea energy													16 to 26 m/s waves 6 to 12 m; winds gusts up to 35 m/s	
	Mackay et al. 1980	natural dispersion													directly with square of wind	
	Delvigne and Sweeney 1988	natural dispersion													directly with square of wind	
	Koops 1988	natural dispersion													directly with wave height	
	Moles et al. 2001	temperature effects													effectiveness decreased with lowering temperature	
	Lindblom 1983	aerial application droplet size													directly with wind velocity	
	Lewis 1995	helicopter bucket deposition													speed of 7 m/s caused 30% deposition	
	Lewis 1995	helicopter bucket deposition													wind of 2 to 5 m/s caused 20% loss	
	Payne et al. 19991b	deposition with wind													wind of 7 to 10 m/s caused loss of deposition	
Burning	This work	probability of ignition	18	24												
	Thornborough 1997	actual ignition										10	1.5	0.9	Helitorch	
	Thornborough 1997	actual ignition										10 to 13	1 to 2	0.9	hand held igniter	
	Moffat and Hankins 1997	ignitor test										8 to 10			successful test	
	Allen 1988								11	1.1						
	Nordvik 2002	ignition limit							10 to 12							
	Buist et al. 2003b	ignition limit							1o to 12							

7. Recommendations

The following three recommendations might be considered: further work on techniques that take weather conditions into account; further development of equipment that is appropriate for difficult weather conditions; and improvements in understanding how weather affects situations.

A factor that should be considered is the way in which countermeasures are applied as weather conditions may dictate against that specific countermeasure. It is suggested that more emphasis be placed on 'hit and run' tactics, that is tactics that can be deployed and withdrawn very quickly. This would take advantage of the narrow weather windows that often occur during a spill situation. Examples of this are the use of rapid-deployment side-sweeps which can be deployed within 30 minutes. Most systems require anywhere from hours to days to fix and deploy.

The situation during the *Prestige* spill highlights the utility of this tactic. Several large recovery ships were in the area and recovered a total of 13,000 tons of oil. One Dutch vessel alone recovered 9,000 tons. This vessel had a rapidly deployable sweep arm, which was put on deck when sea conditions dictated and then rapidly deployed back on the sea when recovery was possible. Such successes should be studied and the results widely published. As it stands now, most of the information on this recovery was presented verbally at the last oil spill conference.

The work on 'Windows of Opportunity' as presented in papers by Champ and Nordvik suggests that most of the opportunity lies at the beginning of a spill when the oil is more readily recovered, dispersed or burned. While this is true to a certain extent, more emphasis and studies are necessary on situations in which this is not the case. Furthermore, the 'Windows of Opportunity' approach did not fully consider weather and focussed more on time and the change in oil properties with time. More work needs to be done on considering weather conditions in the context of both tactics and strategies to deal with oil spills.

The second recommendation is that promising technologies should be further pursued. Skimmers that show promise of working in faster currents have been developed and tested at very high speeds. These include zero-relative velocity skimmers, such as the Oil Mop ZRV which shows ability to recover at high speed and was relatively unaffected by small waves. The Veegarm skimmer (predecessor to the skimmer used by the Dutch at the *Prestige* spill) shows a high throughput efficiency under a variety of sea conditions. The skimmer barriers, particularly the one dubbed 'skimming barrier', show great potential for large oil recoveries, up to 75 m^3/h under a variety of sea conditions. The 'Fixed Submerged Plane' showed similar characteristics, but was also never pursued to a commercial stage. The new high-speed skimmers show very good promise at recovering at speeds of up to 3 m/s (6 knots) with waves. The most promising of these are the Ocean Buster, USCG HSS, Steam Stripper, and Nofo units. This work is ongoing, so there may be progress on these.

There will not be great progress in booming, simply because there are hydrodynamic limits. With dispersants, the weather limits are similarly fixed by natural processes. For burning, the development of sheltered ignition devices, similar to one noted in the text, could extend ignition out to very high winds − possibly as high as 30 m/s (60 knots). This technology is simple and a prototype unit has already been developed and tested.

For the third recommendation, some research might be devoted to improving our understanding of how weather affects countermeasures. This is the first comprehensive report on weather effects on countermeasures, despite the fact that it is a serious issue. In particular, the model for predicting dispersant effectiveness as presented here requires improvement and more extensive data-backing. This would involve more extensive work, such as that done by Delvigne, on measuring the effect of waves and sea energy on dispersion to form a quantitative measure. In addition, the effect of windrowing of oil at sea by higher winds needs to be examined. There are many data gaps in the areas of dispersants and weather.

8. References

Abdelnour, R., T. Johnstone, and D. Howard, “Laboratory Testing of an Oil Skimmer Boom in Broken Ice Fields” in *Proceedings of the Eighth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 131-148, 1985.

Akahoshi, S., S. Ono, T. Iwasaki, and E. Kobayashi, “Study of Large Oil Recovery System for Use Under Rough Sea Weather Conditions”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Allen, A.A., “Comparison of Response Options for Offshore Oil Spills”, in *Proceedings of the Eleventh Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 289-306, 1988.

Allen-Jones, J., “Design and Hydrodynamic Testing of an Oil Slick Containment System”, in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 469-497, 1997.

An, C.F., H.M. Brown, R.H. Goodman, and E.J. Clavelle, “Animation of Boom Failure Processes”, in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1181-1185, 1997.

API, *Environmental Considerations for Marine Oil Spill Response*, American Petroleum Institute, Publication Number 4706, Washington, DC, 291 pp., 2001.

Arita, M., M. Yamaguchi, S. Narita, K. Koyama, K. Ueda, and K. Izumiyama, “Countermeasures for Oil Spills in Cold Water - In the Case of Japan”, in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 265-270, 1998.

Aurand, D., “The Application of Ecological Risk Assessment Principles to Dispersant Use Planning”, in *Spill Science and Technology Bulletin*, *Vol. 2*, pp. 241-247, 1995.

Ayers, R.R., J.P. Fraser, and L.J. Kazmierczak, “Developing an Open-Seas Skimmer”, in *Proceedings of the 1975 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 401-408, 1975.

Bayoumi, M. and G. Ghalwash, “Estimating Rates of Oil Spills in the Egyptian Ports and Application of the Technology of ‘Windows-of-Opportunity’”, in *Water Pollution*, Wit Press Southhampton, UK, pp. 538-543, 1999.

Bech, C., P. Sveum, and I. Buist, “The Effect of Wind, Ice and Waves on the In-Situ Burning of Emulsions and Aged Oils”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 735-748, 1993.

Beynon, L.R. “Codes of Practice for Dealing with Oil Spills at Sea and on Shore: A European View”, in *Proceedings of the 1969 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 617-626, 1969.

Bitting, K.R., “NOFI Oil Vee-Sweep and Extension Boom Test at OHMSETT”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 173-187, 1993.

Bitting, K.R. and P.M. Coyne, “Oil Containment Tests of Fire Booms”, in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 735-754, 1997.

Boumeester, R.J.B. and R.B. Wallace, “The Break-up of an Oil Film due to Wind-Wave Action”, in *Proceedings of the Eighth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 14-25, 1985.

Boumeester, R.J.B. and R.B. Wallace, “Oil Entrainment by Breaking Waves”, in *Proceedings of the Ninth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 39-49, 1986.

Brandvik, P.J., P.S. Daling, and K. Aareskjold, *Chemical Dispersability Testing of Fresh and Weathered Oils - An Extended Study With Eight Oil Types*, Report No. 02.0786.00/12/90, IKU SINTEF Group, Norway, (DIWO Rep. 12), 78 p., 1991.

Brandvik, P.J., A. Lewis, P.S. Daling, and T. Strøm-Kristiansen, “On-Land and Offshore Testing of a New Helicopter Bucket for Dispersant Application - Response 3000D”, in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 499-519, 1997.

Brekne, T.M., S. Holmemo, and G.M. Skeie, “Optimizing Offshore Combat of Oil Spills - Development of New Booms and Helicopter-Base Application of Dispersants”, in *Proceedings of the 2003 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 2003.

Brown, H.M. and R.H. Goodman, “Initial Dynamics of Oil on Water”, in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 61-68, 1995.

Brown, H.M. and R.H. Goodman, “Development of Containment Booms for Oil Spills in Fast Flowing Water”, in *Proceedings of the Twenty-second Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 823-823, 1998.

Brown, H.M., R.H. Goodman, and P. Nicholson, “The Containment of Heavy Oil in Flowing Water”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 457-465, 1992.

Brown, H.M., P. Nicholson, R.H. Goodman, B.A. Berry, and B.R. Hughes, “Novel Concepts for the Containment of Oil in Flowing Water”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 485-496, 1993.

Brown, H.M., R.H. Goodman, C.F. An, and J. Bitner, “Boom Failure Mechanisms: Comparison of Channel Experiments with Computer Modeling Results”, in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 457-467, 1997.

Buist, I.A., “Window-of-Opportunity for In Situ Burning”, in *Spill Science & Technology Bulletin, Vol. 6*, pp. 341-346, 2003.

Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy, and I.R. McAllister, “The Development and Testing of a Fireproof Boom”, in *Proceedings of the 1983 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 43-51, 1983.

Buist, I., S. Potter, D. Mackay, and M. Charles, “Laboratory Studies on the Behaviour and Cleanup of Waxy Crude Oil Spills”, in *Proceedings of the 1989 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 105-113, 1989.

Buist, I, J. McCourt, J. Mullin, N. Glover, C. Hutton, and J. McHale, “Mid-Scale Tests of In-Situ Burning in a New Wave Tank at Prudhoe Bay, AK”, in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 399-622, 1998.

Buist, I., L. Majors, K. Linderman, D. Dickins, J. Mullin, and C. Owens, “Tests to Determine the Limits of In-Situ Burning of Thin Oil Slicks in Brash and Frazil Ice”, in *Proceedings of the Twenty-sixth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 629-648, 2003.

Champ, M.A., “The Technology Windows-of-Opportunity Oil Spill Response Strategy”, in *Oil Spills First Principles: Prevention and Best Response*, B.E. Ornitz and M.A. Champ (eds.), Chapter 7, Elsevier Publishing, Amsterdam, Holland, pp. 289-324, 2002.

Champ, M.A., A.B. Nordvik, and J.K. Simmons, “Utilization of Technology Windows of Opportunity in Marine Oil Spill Contingency Planning, Response and Training”, in *Proceedings of the 1997 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 993-994, 1997.

Chen, A., “Development of a High-Current Velocity Oil Containment System”, Unpublished paper, Exxon Production Research Company, Houston, TX, 1998.

Cheng, C-Y., A. Ernest, R. Aguilar, and J. Bonner, “Hydrodynamic Characterization of COSS (Coastal Oil-Spill Simulation System) Wave Tank”, in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 89-98, 1998.

Christodoulou, M.S. and J.T. Turner, “Experimental Study and Improvement of the Rotating Disc Skimmer”, in *Proceedings of the 1987 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 101-108, 1987.

Clauss, G.F. and W.L. Kühnlein, “Efficiency of Selected Oil Skimming Systems in Irregular Seas”, in *Proceedings of the 1991 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp 115-124, 1991.

Clavelle, E.J. and R.D. Rowe, “Numerical Simulation of Oil Boom Failure”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 409-418, 1993.

Coe, T., “Control of Oil Spills in Fast Water Currents - A Technology Assessment”, in *Proceedings of the 1999 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1999.

Cooper, D. and R. Mackay, “Assisted Viscous Oil Pumping”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Cormack, D. and J.A. Nichols, “The Concentrations of Oil in Sea Water Resulting from Natural and Chemically Induced Dispersion of Oil Slicks”, in *Proceedings of the 1977 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 381-385, 1977.

Daling, P.S., “A Study of the Chemical Dispersibility of Fresh and Weathered Crude Oils”, in *Proceedings of the Eleventh Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 481-499, 1988.

Daling, P.S., P.J. Brandvik, and I. Singsaas, “Weathering of Oil and Use of Dispersants: Methods for Assessing Oils’ Properties at Sea and the Feasibility of Oil Spill Dispersants”, in *NOSCA Seminar on Oil Pollution Control*, 7 p., 1995.

D’Atri, B. and T. King, “Flicking Your Bic at Twenty-five Below”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 669-677, 1993.

DeCola, E., *Dispersant Use in Oil Spill Response: A Worldwide Legislative and Practical Update*, Aspen Law and Business, New York, NY, 314 p., 2003.

Delvigne, G.A.L., "Barrier Failure by Critical Accumulation of Viscous Oil", in *Proceedings of the 1989 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 143-148, 1989.

Delvigne, G.A.L. and C.E. Sweeney, "Natural Dispersion of Oil", *Oil and Chemical Pollution, Vol. 4*, pp. 281-310, 1988.

Delvigne, G.A.L. and L.J.M. Hulsen, "Simplified Laboratory Measurement of Oil Dispersion Coefficient - Application in Computations of Natural Oil Dispersion", in *Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 173-187, 1994.

Dempsey, J., "First Response to Oil Spills in the Grand Banks Production Area", in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Devitis, D.S. and L. Hannon, "Resolving the Tow Speed that Causes Boom Oil Loss", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995.

Dicks, B., D.V. Ansell, C.C. Guenette, T.H. Moller, R.S. Santner, and I.C. White, "A Review of the Problems Posed by Spills of Heavy Fuel Oils", in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Dorrler, J.S., R. Ayers, and D.C. Wooten, "High Current Control of Floating Oil", in *Proceedings of the 1975 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 347-353, 1975.

Elliot, A.J. and B. Jones, "The Need for Operational Forecasting during Oil Spill Response", *Marine Pollution Bulletin*, *Vol. 40*, pp. 110-121, 2000.

Environment Canada, "A Winter Evaluation of Oil Skimmers and Booms", Environmental Protection Service, EPS 4-EP-84-1, 109 p., 1984.

Environment Canada, *Field Guide for the Protection and Cleanup of Oiled Shorelines*, Second Edition, Environment Canada, Atlantic Region, Environmental Emergencies Section, Dartmouth, NS, 201 pp., 1998.

Eryuzlu, N.E. and R. Hauser, "Use of Floating Deflectors for Oil Spill Control in Fast Flowing Waters", in *Proceedings of the 1977 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 335-340, 1977.

Etkin, D.S., "Estimating Cleanup Costs for Oil Spills", in *Proceedings of the 1999 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1999.

Etkin, D.S., “Comparative Methodologies for Estimating On-Water Response Costs for Marine Oil Spills”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 1281-1289, 2001.

Etkin, D.S. and P. Tebeau, “Assessing Progress and Benefits of Oil Spill Response Technology Development Since Exxon Valdez”, in *Proceedings of the 2003 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 2003.

ExxonMobil, *Dispersant Guidelines*, Exxon Mobil Corp., Alexandria, VA, 2000.

Fang, J. and K-F. Wong, “Instability of Oil Slicks Contained by a Single Boom”, in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 447-468, 2000.

Fang, J. and K-F. Wong, “Optimization of an Oil Boom Arrangement”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 1367-1374, 2001.

Farlow, J.S. and R.A. Griffiths, “OHMSETT Research Overview, 1979-1980”, in *Proceedings of the 1981 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp.661-666, 1981.

Farmwald, J.W. and W.G. Nelson, “Dispersion Characteristics and Flammability of Oil Under Low Ambient Temperatures Conditions”, in *Proceedings of the Fifth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 217-238, 1982.

Fay, R.R., “Measuring the Aerial Application of Oil Dispersant from Very Large Aircraft at Moderate Altitude”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1057-1063, 1993.

Fingas, M.F., *The Basics of Oil Spill Cleanup: Second Edition*, CRC Press, Boca Raton, FL, 256 p., 2000a.

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

Fingas, M.F. and M. Punt, *In-Situ Burning: A Cleanup Technique for Oil Spills on Water*, Environment Canada, Ottawa, ON, 214 p., 2000.

Fingas, M.F., Z. Wang, M. Landriault, J. Noonan, and R. Mackay, “The Effect of Varying Salinity and Temperature on the Dynamics of Orimulsion in Water”, in *Proceedings of the 2003 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 419-427, 2003.

Fiocco, R.J. and R.R. Lessard, "Demulsifying Dispersant for an Extended Window of Use", in *Proceedings of the 1997 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 1015-1016, 1997.

Fitzmaurice, M.R., "Can Oil Slicks be Contained?", *Proceedings of the 11th Australian Conference*, pp. 683-688, 1993.

Folsom, B.A. and C. Johnson, "Development of a High Current Steamlined Oil Boom/Skimmer for Inland Waterways", in *Proceedings of the 1977 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 323-327, 1977.

Fredriksson, D.W., C.S. Albro, and S.A. Ostrazeski, "Hydrodynamic Calibration of a Meso-Scale Wind-Wave Flume Basin for the Study of Spilled Oil", in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1541-1553, 1996.

Freestone, F.J., R.A Anderson, and N.P. Trentacoste, "United States Environmental Protection Agency Research in High-Speed Devices for the Recovery of Thin-Film Oil Spills", in *Proceedings of the 1975 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 409-414, 1975.

Fuentes, H.R., R. Jaffe, V.A. Tsihrintzis, and D. Boye, "In-water Natural Dispersion", *Water Resources, Vol. I*, pp. 638-642, 1995.

Gates, D.C. and K.M. Corradino, "OHMSETT Tests of the Toscon Weir Skimmer and Gravity Differential Separator", in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 35-40, 1985.

Getman, J.H., "Performance Tests of Three Fast Current Oil Recovery Devices", in *Proceedings of the 1977 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 341-346, 1977.

Giammona, C., K. Binkley, R. Fay, G. Denoux, M. Champ, R. Geyer, F. Bouse, I. Kirk, D. Gardisser, and R. Jamail, *Aerial Dispersant Application: Field Testing Research Program, Alpine, Texas*, MSRC Technical Report Series 94-019, Marine Spill Response Corporation, Washington, DC, 54 p, 1994.

Goodman, R.H., "Limited Data Sets and the Statistical Validity of Oil Spill Response Data", in *Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 895-903, 1994.

Goodman, R.H., H.M. Brown, C.F. An, and R.D. Rowe, "Dynamic Modeling of Oil Boom Failure Using Computational Fluid Dynamics", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 437-455, 1997.

Gregory, G.L., A.A. Allen, and D.H. Dale, "Assessment of Potential Oil Spill Recovery Capabilities", in *Proceedings of the 1999 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 1367-1374, 1999.

Grenon, S., "How to Prioritize Numerous Environmental Issues? Case Study of the Havre-Saint-Pierre Spill", in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 943-951, 2000.

Grilli, S.T., T. Fake, and M. Spaulding, "SlickMap: An Interactive Computer Model of Oil Containment by a Boom", in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 953-986, 2000.

Guenette, C.C. and I.A. Buist, "Testing of the Lori 'Stiff Brush' Skimmer Sweep System", in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 451-476, 1993.

Guenette, C.C. and J. Thornborough, "An Assessment of Two Off-shore Igniter Concepts", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 795-808, 1997.

Guenette, C.C. and R. Wighus, "In-Situ Burning of Crude Oil and Emulsions in Broken Ice", in *Proceedings of the Ninteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 895-906, 1996.

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.

Hann, R.W., "Unit Operations, Unit Processes and Level of Resource Requirements for the Cleanup of the Oil Spill from the Supertanker Amoco Cadiz", in *Proceedings of the 1979 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp.147-161, 1979.

Hansen, K.A., "Equipment Evaluation of Fast-Water Oil Recovery Equipment", in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 367-384, 2000a.

Hansen, K.A., "Second Phase Evaluation of Fire Resistant Booms: Containment Performance", in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 429-445, 2000b.

Hansen, K.A. "Development of a Fast-Water Field Guide", in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 237-273, 2001.

Hansen, K.A. “Fast Water Oil Spill Response ”, in *Proceedings of the Twenty-fifth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 169-179, 2002.

Hara, S., K. Yamakawa, K. Hoshino, K. Yukawa, K. Hikida, H. Kagemoto, T. Kinoshita, and C. Marugame, “Improvement of Performance on Multi-purpose Work Vessel”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Harper, J., A. Godon, and A.A. Allen, “Costs Associated with the Cleanup of Marine Oil Spills”, in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995.

Harris, C., “The Sea Empress Incident: Overview and Response at Sea”, in *Proceedings of the 1997 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 177-184, 1999.

Hvidbak, F. and P.A. Gunter, “Preparation for Recovery of Heavy Oil Spills, with Emphasis on Mechanical Feeder Skimmers”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002a.

Hvidbak, F. and P.A. Gunter, “The Development and Test of Techniques for Emergency Transfer of Extreme Viscosity Oil (Refloated Bitumen)”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002b.

Hunt, L.M and D.G. Groves, *A Glossary of Ocean Science and Undersea Technology Terms*, Compass Publications, Arlington, VA, 1976.

Jeffery, P.G., “Large-Scale Experiments on the Spreading of Oil at Sea and Its Disappearance by Natural Factors”, in *Proceedings of the 1971 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 469-374, 1971.

Jensen, D.S., W. Lindenmuth, R.L. Beach, and D.J. Norton, “Energy Dissipative Devices to Control Oil Slicks in Fast-Current Environments”, in *Proceedings of the 1975 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 355-362, 1975.

Johannessen, B.O. and A. Mjelde, “Certification of Oil Spill Response Equipment”, in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 295-301, 2001.

Johnston, A.J., M.R. Fitzmaurice, and R.G.M. Watt, “Oil Spill Containment: Viscous Oils”, in *Proceedings of the 1993 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 89-94, 1993.

Koops, W., "A Discussion of Limitations on Dispersant Application", *Oil and Chemical Pollution, Vol. 4,* pp. 139-153, 1988.

Koops, W. and S. Huisman, "Let the Oil Wash Ashore - In Case of Heavy Oil Spills", in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Koops, W., F.J. Sanders, and J.M. Gubbens, "The Katina Oil Spill 1982, Combatting Operation at Sea", in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 299-306, 1985.

Kordyban, E., "The Effects of Waves on the Oil Slick Retention at a Retention Boom", *Journal of Energy Resources Technology, Vol. 114*, pp. 31-37, 1992.

Lamp, H.J., "Lake Champlain: A Case History on the Cleanup of #6 Fuel Through Five Feet of Solid Ice at Near-Zero Temperatures", in *Proceedings of the 1971 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 579-582, 1971.

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 also in *Spill Science & Technology Bulletin, Vol. 4*, pp. 257-266, 1997.

Lehr, W., C. Barker, and D. Simecek-Beatty, "New Developments in the Use of Uncertainty in Oil Spill Forecasts", in *Proceedings of the Twenty-second Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 271-284, 1999.

Lehr, W.J. and D. Simecek-Beatty, "The Relation of Langmuir Circulation Processes to the Standard Oil Spill Spreading, Dispersion and Transport Algorithms", *Spill Science & Technology Bulletin, Vol. 6*, pp. 247-253, 2000.

Leigh, J.T., "Oil Recovery on the High Seas", in *Proceedings of the 1973 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 351-360, 1973.

Lewis, A., "Calibration and Use of a Helicopter Bucket to Apply Oil Spill Dispersants", in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 505-517, 1995.

Lewis, A. and D. Aurand, *Putting Dispersants to Work: Overcoming Obstacles*, Technical Report IOSC-004, American Petroleum Institute, Washington, DC, 78 p, 1997.

Lewis, A., P.S. Daling, T.S. Kristiansen, I. Singsaas, R.J. Fiocco, and A.B. Nordvik, "Chemical Dispersion of Oil and Water-in-Oil Emulsions: A Comparison of Bench Scale Test Methods and Dispersant Treatment in Meso-Scale Flume", in *Proceedings of the Seventeenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 979-1010, 1994.

Lewis, A., P.S. Daling, T. Strom-Kristiansen, and P.J. Brandvik, “The Behaviour of Sture Blend Crude Oil Spilled at Sea and Treated With Dispersant”, in *Proceedings of the Eighteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp 453-469, 1995a.

Lewis, A., P.S. Daling, and A.B. Nordvik, “The Effect of Oil Weathering on the Laboratory Determined Effectiveness of Oil Spill Dispersants”, *Marine Spill Response Corporation Workshop*, Marine Spill Response Corporation, Washington, DC, 28 p, 1995b.

Lewis, A., A. Crosbie, L. Davies, and T. Lunel, “Large Scale Field Experiments Into Oil Weathering at Sea and Aerial Application of Dispersants”, in *Proceedings of the Twenty-first Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp 319-344, 1998a.

Lewis, A., A. Crosbie, L. Davies, and T. Lunel, “The AEA ‘97 North Sea Fields Trials on Oil Weathering and Aerial Application of Dispersants”, in *Dispersant Application in Alaska: A Technical Update*, Prince William Sound Oil Spill Recovery Institute (OSRI), Cordova, AK, pp. 78-109, 1998b.

Lichte, H.W., “Skimming Barrier Performance Evaluation: Offshore Version and Harbour Version”, in *Proceedings of the 1979 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp.489-492, 1979.

Lichte, H.W., M.K. Breslin, G.F. Smith, D.J. Graham, and R.W. Urban, *Performance Testing of Four Skimming Systems*, EPA report number EPA-600/2-81-189, Cincinnati, OH, 1981.

Lichtenthaler, R.G. and P.S. Daling, “Dispersion of Chemically Treated Crude Oil in Norwegian Offshore Waters”, in *Proceedings of the 1983 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 7-14, 1983.

Lindblom, G.P. and B.S. Cashion, “Operational Considerations for Optimum Deposition Efficiency in Aerial Application of Dispersants”, in *Proceedings of the 1983 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 53-60, 1983.

Lindstedt-Siva, J., “Advance Planning for Dispersant Use”, in *Proceedings of the 1987 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 329-332, 1987.

Lunel, T., “Dispersion of a Large Experimental Slick by Aerial Application of Dispersant”, in *Proceedings of the Seventeenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 951-977, 1994a.

Lunel, T., “Field Trials to Determine Quantitative Estimates of Dispersant Efficiency at Sea”, in *Proceedings of the Seventeenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1011-1021, 1994b.

Lunel, T., “Dispersant Effectiveness at Sea”, in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 147-155, 1995a.

Lunel, T., “The Braer Spill: Oil Fate Governed by Dispersion”, in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995b.

Lunel, T., “Research Requirements to Determine Dispersant Effectiveness at Sea”, in *Second International Oil Spill Research and Development Forum*, Vol. 1, International Maritime Organization, London, UK, pp. 271-285, 1995c.

Lunel, T., “Understanding the Mechanism of Dispersion through Oil Droplet Size Measurements at Sea”, in *The Use of Chemicals in Oil Spill Response*, STP 1252, American Society for Testing and Materials, Philadelphia, PA, pp. 240-285, 1995d.

Lunel. T., “Sea Empress Spill: Dispersant Operations, Effectiveness and Effectiveness Monitoring”, in *Dispersant Application in Alaska: A Technical Update*, Prince William Sound Oil Spill Recovery Institute (OSRI), Cordova, AK, pp. 59-77, 1998.

Lunel, T., “Dispersant Pre-Approvals: Best Practice”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 441-444, 2001.

Lunel, T. and L. Davies, “Dispersant Effectiveness in the Field on Fresh Oils and Emulsions”, in *Proceedings of the Nineteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1355-1393, 1996.

Lunel, T. and P. Wood, “A Laboratory Dispersant Effectiveness Test which Reflects Dispersant Efficiency in the Field”, in *Proceedings of the Nineteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp 461-480, 1996.

Lunel, T. and A. Lewis, “Optimisation of Oil Spill Dispersant Use”, in *Proceedings of the 1999 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 187-193, 1999.

Lunel, T., G. Baldwin, and F. Merlin, “Comparison of Meso-Scale and Laboratory Dispersant Tests with Dispersant Effectiveness Measured at Sea”, in *Proceedings of the Eighteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 629-651, 1995a.

Lunel, T., L. Davies, and P.J. Brandvik, “Field Trials to Determine Dispersant Effectiveness at Sea”, in *Proceedings of the Eighteenth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp 603-627, 1995b.

Lunel, T., J. Russin, N. Bailey, C. Halliwell, and L. Davies, “A Successful at Sea Response to the Sea Empress Spill”, in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1499-1519, 1996.

Lunel, T., J. Rusin, N. Bailey, C. Halliwell, and L. Davies, "The Net Environmental Benefit of a Successful Dispersant Operation at the Sea Empress Incident", in *Proceedings of the 1997 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 185-194, 1997.

Lystad, M. and E.A. Martinson, "Currents Computed with a Barotropic Ocean Model: Application to Simulation of Oil Slick Movements in Actual Weather Conditions", in *Mechanics of Oil Slicks*, Ancient Editions, Paris, France, pp. 133-148, 1981.

Marks, W., G.R. Geiss, and J. Hirschman, "Theoretical and Experimental Evaluation of Oil Spill Control Devices", in *Proceedings of the 1971 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 393-404, 1971.

Mackay, D., "Effectiveness of Chemical Dispersants Under Breaking Wave Conditions", in *The Use of Chemicals in Oil Spill Response*, STP 1252, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 310-340, 1985.

Mackay, D., I. Buist, R. Mascarenhas, and S. Petersen, "Oil Spill Processes and Models", Manuscript Report EE-8, Environmental Protection Service, Ottawa, ON, 1980.

Martinelli, F.N. and B.W.J. Lynch, *Factors Affecting the Efficiency of Dispersants*, LR 363 (OP), Warren Spring Laboratory, Stevenage, 18 p, 1980.

McCourt, J. and L. Shier, "Interaction between Oil and Suspended Particulate Material in the Yukon River", in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 79-87, 1998.

McCourt, J., I. Buist, B. Pratte, W. Jamieson, and J. Mullin, "Testing Fire Resistant Booms in Waves and Flames", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 823-839, 1997.

McWilliams, J.C. and P.P. Sullivan, "Vertical Mixing by Langmuir Circulations", *Spill Science & Technology Bulletin, Vol. 6*, pp. 225-237, 2000.

Meikel, K.M., "An Effective Low-Cost Fireproof Boom", in *Proceedings of the 1983 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 9-42, 1983.

Milgram, J.H. and R.J. van Houten, "Mechanics of a Restrained Layer of Floating Oil Above a Water Current", *Journal of Hydronautics, Vol. 12*, pp. 93-108, 1978.

Milgram, J.H., "Physical Requirements for Oil Pollution Barriers", in *Proceedings of the 1977 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 375-381, 1977.

Moffatt, C. and P. Hankins, “Results of Experiments with Flare Type Igniters on Diesel Fuel and Crude Oil Emulsions”, in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1197-1214, 1997.

Moles, A., L. Holland, and J. Short, *The Effectiveness of Corexit 9527 and 9500 in Dispersing Fresh, Weathered and Emulsion of Alaska North Slope Crude Oil Under Subarctic Conditions*, Prince William Sound Regional Citizens’ Advisory Council, Anchorage, AK, 24 p., 2001.

Nash, J.H. and M.G. Johnson, “Coherent, Plunging Water Jets for Oil Spill Control”, in *Proceedings of the 1981 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 655-660, 1981.

Nash, J.H. and R.W. Hillger, “Preliminary Results of the Verification of Offshore Oil Spill Containment Boom Performance Evaluation Protocol”, in *Proceedings of the Eleventh Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 267-276, 1988.

Nash, J.H. and D.D. Molsberry, “The Performance of Booms in an Offshore Environment”, in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995.

Neal, R.W., R.A. Bianchi, and E.E. Johanson, “The Design and Demonstration of a Remotely-Controlled High-Seas Oil Recovery System”, in *Proceedings of the 1975 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 395-399, 1975.

Nordvik, A.B., “The Technology Windows-of-Opportunity for Marine Oil Spill Response as Related to Oil Weathering and Operations”, *Spill Science & Technology Bulletin, Vol. 2*, pp. 17-46, 1995.

Nordvik, A.B., “Time Window-of-Opportunity for Oil Spill Planning and Response”, *Pure and Applied Chemistry*, *Vol. 71*, pp. 5-16, 1999a.

Nordvik, A.B., “Summary of Development and Field Testing of the Transrec Oil Recovery System”, *Spill Science & Technology Bulletin, Vol. 5*, pp. 309-322, 1999b.

Nordvik, A.B., S.L. Sloan, J. Stahovec, K. Bitting, and D.F. Pol, “Phase 3: Oil Containment Boom at Sea Performance Tests”, MSRC Technical Report Series 95-003, Marine Spill Response Corporation, Washington, DC, 86 p, 1995a.

Nordvik, A., K. Bitting, P. Hankins, L. Hannon, and R. Urban, “Full Scale Oil Containment Boom Testing at Sea”, in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995b.

Nordvik, A.B., M.A. Champ, and K.R. Bitting, “Review of the Processes for Estimating Time Windows for In-Situ Burning of Spilled Oil at Sea”, in *Oil Spills First Principles: Prevention and*

Best Response, B.E. Ornitz and M.A. Champ (eds.), Elsevier Publishing, Amsterdam, Holland, Appendix V., pp. 573-601, 2002.

Nordvik, A.B., M.A. Champ, and K.R. Bitting, "Estimating Time Windows for Burning Oil at Sea: Processes and Factors", *Spill Science & Technology Bulletin, Vol. 6*, pp. 347-3359, 2003.

O'Brien, M.L., "At-Sea Recovery of Heavy Oils - A Reasonable Response Strategy?", in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Oebius, H.U., "Physical Properties and Process that Influence the Cleanup of Oil Spills in the Marine Environment", *Spill Science & Technology Bulletin, Vol. 5*, pp. 177-289, 1999.

Ouwerkerk, M.R., P.R.H. Verbeek, and T. Schut, "A New Tool for Large-Scale Oil Combat", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995.

Payne, J.R., J.R., Clayton, G.D. McNabb, and B.E. Kirstein, "Exxon Valdez Oil Weathering Fate and Behaviour: Model Predictions and Field Observations", in *Proceedings of the 1991 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 641-654,1991a.

Payne, J.R., J.R., Clayton, C.R. Phillips, J.U. Robinson, D. Kennedy, J. Talbot, G. Petrae, J. Michel, T. Ballou, and S. Onstad, "Dispersant Trials Using the Pac Baroness, A Spill of Opportunity", in *Proceedings of the 1991 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 427-433, 1991b.

Payne, J.R., T.J. Reilly, R.J. Martrano, G.P. Lindblom, M.C. Kennicutt, 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.

Pearson, L.A., "Opinions on the Use of Oil Spill Response Methods in Prince William Sound and Cook Inlet, Alaska", in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 191-202, 2000.

Peigne, G., "Ecumoire II: Evaluation of Three Oil Recovery Devices Offshore", in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 13-18, 1985.

Pope, P., A. Allen, and W.G. Nelson, "Assessment of Three Surface Collecting Agents during Temperature and Arctic Conditions", in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1985.

Potter, S., J. McCourt, and R. Smith, “Estimation of Towing Forces on Oil Spill Containment Booms”, in *Proceedings of the Twenty-second Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 825-832, 1999.

Provant, S.G., “Assessment of the Transrec-350 Mechanical Recovery Capacity of the Oil Spill Response Equipment in Prince William Sound”, in *Proceedings of the Fifteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 219-237, 1992.

Reed, M., O.M. Aamo, and P. Daling, “Quantiative Analysis of Alternate Oil Spill Strategies Using OSCAR”, *Spill Science & Technology Bulletin, Vol. 2*, pp. 67-94, 1995a.

Reed, M., O.M. Aamo, and P.S. Daling , “OSCAR, A Model System for Quantitative Analysis of Alternate Oil Spill Response Strategies”, in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 815-835, 1995b.

Reed, M., C. Turner, and A. Odulo, “The Role of Wind and Emulsification in Modelling Oil Spill and Surface Drifter Trajectories”, *Spill Science & Technology Bulletin, Vol. 2*, pp. 143-157, 1995c.

Salt, D., “Aerial Dispersant Spraying: A Daylight-Only Tool?”, in *Proceedings of the 2001 International Oil Spill Conference,* American Petroleum Institute, Washington, DC, pp. 1223-1225, 2001.

Scholz, D.K., J.H. Kucklick, R. Pond, A.H. Walker, A. Bostrom, and P. Fischbeck, *A Decision-Maker’s Guide to Dispersants: A Review of the Theory and Operational Requirements*, American Petroleum Institute, Publication Number 4692, Washington, DC, 1999.

Schulze, R. *Oil Spill Response Performance Review of Skimmers*, ASTM Manual Series, ASTM, West Conshohocken, PA, 1998.

Schulze, R., *Oil Spill Response Performance Review of Booms*, MMS Internal Report, Washington, DC, 2003.

Schulze, R. and J. Lane, “A Performance Review of Oil Spill Containment Booms”, in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 285-293, 2001.

Schulze, R. and S. Potter, “Estimating Forces on Oil Spill Containment Booms”, *Spill Technology Newsletter, Vol. 27*, pp. 1-10, 2002.

Schwartz, S.H., “Performance Tests of Four Selected Oil Spill Skimmers”, in *Proceedings of the 1979 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 493-496, 1979.

Sebastiao, P. and C.G. Soares, “Modeling the Fate of Oil Spills at Sea”, *Spill Science & Technology Bulletin, Vol. 2*, pp. 121-131, 1995.

Shonting, D., A. Petrillo, and P. Temple, “Wind Wave and Turbulence Observations Related to Oil Mixing Parameters”, in *Proceedings of the Workshop on the Physical Behaviour of Oil in the Marine Environment*, Princeton University, Princeton, NJ, pp. 6.63-6.88, 1979.

Shum, J.S. and M. Borst, “OHMSETT Tests of a Rope-Mop Skimmer in Ice-Infested Waters”, in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 31-33, 1985.

Simecek-Beatty, D. and D. Timmons, “The Use of Real-Time Water Level Measurements in Emergency Operations”, in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 287-295, 1995.

Simecek-Beatty, D. and W.J. Lehr, “NOAA-MMS Joint Langmuir Circulation and Oil Spill Trajectory Models Workshop”, in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 601-610, 2000.

Simecek-Beatty, D., C. O’Connor, and W.J. Lehr, “3-D Modeling of Chemically Dispersed Oil”, in *Proceedings of the Twenty-fifth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 1149-1159, 2002.

Sloan, S.L., K.R. Bitting, and A.B. Nordvik, *Phase 1: Oil Containment Boom at Sea Performance Tests*, MSRC Technical Report Series 94-007, Marine Spill Response Corporation, Washington, DC, 85 p., 1994.

Smedley, J.B., “Assessment of Aerial Application of Oil Spill Dispersants”, in *Proceedings of the 1981 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 253-257, 1981.

Smith, G.F. and H.W. Lichte, *Summary of U.S. Environmental Protection Agency’s OHMSETT Testing, 1974-1979*, EPA report number EPA-600/9-81-007, Cincinnati, OH, 1981.

Smith, J.B.H., C. McLellan, and L.R. Pintler, “Development of an Oil Skimming System to Meet Navy Specifications”, in *Proceedings of the 1989 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 91-94, 1989.

Steen, A. W. Konkel, W. Lerch, D. Lessard, and J. Clark, “Realities of Physical Encounter Rates for Mechanical Response at Sea”, in *Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response*, International Maritime Organization, London, UK, 2002.

Suzuki, I., Y. Tsukino, and M. Yanagisawa, “Simulation Tests of Portable Oil Booms in Broken Ice”, in *Proceedings of the 1985 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 25-30, 1985.

Suzuki, I., R. Tasaki, K. Miki, E. Kajita, and T. Yagi, “Oil Layer Flow Around Skimming Vessels”, in *Proceedings of the 1989 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 167-173, 1989.

Swift, M.R., J. Belanger, B. Celikkol, R.R. Steen, and D. Michelin, “Observations of Conventional Oil Boom Failure” in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 481-482, 2000a.

Swift, M.R., B. Celikkol, R.R. Steen, W. DiProfio, and S.E. Root, “A Flexible Submergence Plane Barrier for Fast Current Applications”, in *Proceedings of the Twenty-third Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 401-414, 2000b.

Tedeschi, E., “Booms”, in *Pure and Applied Chemistry*, Vol. 71, pp 17-25, 1999.

Thalich, P and C. Xizobo, “Accurate Simulation of Oil Slicks”, in *Proceedings of the 2001 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 1133-1137, 2001.

Thomas, D. and T. Lunel, “The Braer Incident: Dispersion in Action”, in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 843-859, 1993.

Thornborough, J., “United Kingdom In-Situ Burn Trials, Lowenstoft, 1996”, in *Proceedings of the 1997 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 131-136, 1997.

Thorpe, S.A., “Langmuir Circulation and the Dispersion of Oil Spills in Shallow Seas”, *Spill Science & Technology Bulletin, Vol. 6*, pp. 213-223, 2000.

Trudel, K., S. Ross, R. Belore, S. Buffington, and G. Rainey, “Technical Assessment of the Use of Dispersants on Spills from Drilling and Production Facilities in the Gulf of Mexico Outer Continental Shelf”, in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 531-549, 2001.

Trudel, K., S. Ross, R. Belore, S. Buffington, G. Rainey, C. Ogawa, and D. Panzer, “Technical Assessment of Using Dispersants on Marine Oil Spills in the U.S. Gulf of Mexico and California”, in *Proceedings of the 2003 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 1-8, 2003.

Tsang, G. and N. Vanderkooy, “Development of a Novel Ice Oil Boom for Flowing Waters”, in *Proceedings of the 1979 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 377-385, 1979.

Ueda, K., H. Yamanouchi, and K. Hikida, “Recovery of Spilled Oil in Waves”, in *Proceedings of the Twenty-fourth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 275-283, 2001.

Van Dyck, *Improving the Performance of Oil Spill Containment Booms in Waves: Part I - Literature Review, Part II - Physical Model Study: Procedure and Results*, Report Number SIT-DL-94-9-2-2700, Stevens Institute of Technology, Hoboken NJ, 20 p., 1994.

Van Dyck, R.L. and M.S. Bruno, "Effect of Waves on Containment Boom Response", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995.

Watkins, R.L., "The Effectiveness of Oil Spill Recovery Systems", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, 1995.

Webb, R., "Sea-Ice Over-Flooding: A Challenge to Oil Spill Countermeasures Planners in the Outer Mackenzie Delta, N.W.T.", in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 671-677, 1995.

Wicks, M., "Fluid Dynamics of Floating Oil Containment by Mechanical Barriers in the Presence of Water Currents", in *Proceedings of the 1969 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 55-101, 1969.

Widawsky, A., "Development of Harbor Oil Spill Removal-Recovery Systems: Phase I", in *Proceedings of the 1975 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 379-386, 1975.

Williams, R.E. and T.S. Cooke, "Feasibility of Using a Bubble Barrier for the Containment/Incineration of Spilled Oil", in *Proceedings of the Eighth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 212-227, 1985.

Wilson, H.B., "Development and Testing of a Weir Boom for Oil Recovery at Sea", in *Proceedings of the 1981 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 643-648, 1981.

Wong, K.-F., and M. Witmer, "Flow Around an Oil Boom System", in *Proceedings of the Eighteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 671-677, 1995.

Wooten, D.C., "Mechanical Control of Oil Spills Utilizing a Streamlined Boom", in *Proceedings of the 1973 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 383-389, 1973.

Yazaki, A., "Research and Development in the Institute of Ocean Environmental Technology", in *Proceedings of the 1983 International Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 95-103, 1983.

Youssef, M. and M.L. Spaulding, "Drift Current Under the Combined Action of Wind and Waves in Shallow Water", in *Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 767-783, 1994.

Zhang, Z., C.F. An, R.M. Brown, H.M Brown, and R.H. Goodman, “Numerical Study on (Porous) Net Boom Systems - Front Net Inclined Angle Effect”, in *Proceedings of the Twenty-second Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 903-919, 1999.

Zhu, S-P. and D. Strunin, “A Numerical Model for the Confinement of Oil Spill with Floating Oil Booms”, *Spill Science & Technology Bulletin, Vol. 7*, pp. 249-255, 2002.