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Evaluation of Four Oil Spill Recovery Systems in Fast Water Conditions at Ohmsett

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16. Abstract (MAXIMUM 200 WORDS)

Even though 70 percent of the oils transported on U.S. waterways are in currents that routinely exceed one knot, very little research and product development has been conducted on new technologies and strategies to respond to oil spills occurring in currents over one knot. Oil spills in fast moving water (one to five knots) are hard to control and recover due to the ease at which oil mixes with water and entrains under booms and skimmers. Fast currents also make it difficult to deploy equipment and maneuver on the water. A lack of effective fast water containment and recovery systems, anchoring problems, and limited training and experience in these difficult and dangerous response conditions have hampered response efforts in currents on rivers and coastal areas. The Coast Guard R&D Center is executing the project, "Innovative Response Techniques (Fast Water Containment)." The goal of this effort is to improve the United States Coast Guard's (USCG) fast-water containment and recovery capabilities by identifying and testing the most promising equipment.

The goal of this part of the project was to measure the performance of oil spill recovery systems that would potentially be effective in fast moving water conditions of one to five knots. The specific objectives of this test series were to develop a testing protocol for fast water equipment evaluation, define the operational capabilities of four recovery systems, and aid in improving the performance of the systems. Four systems that were identified in a previous report (Coe and Gurr, 1999) were evaluated in both calm and harbor chop wave conditions while encountering both light and heavy viscosity oils. Each system was operated as specified by the manufacturer or their representative. Two of these systems can recover oil efficiently in calm water up to three knots and in harbor chop waves up to two knots. The other systems performed well up to three knots in calm water. This equipment should improve the recovery of oil in fast currents and can also be utilized to increase recovery rates for advancing vessels in open waters. The results can also be used to develop better methods and techniques in fast current areas.

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EXECUTIVE SUMMARY

Oil spills on fast-moving water are difficult to contain and recover. A previous study (Coe and Gurr, 1999) revealed that about 70 percent of oil is transported in waterways that routinely have currents that exceed one knot. In addition, between 1992-1997, 58 percent of all oil spills over 100 gallons occurred in fast current areas. This was a total of 4,519,749 gallons. Existing containment recovery systems are not effective in high current areas. This performance gap has prompted the Coast Guard to identify and evaluate promising systems in an effort to respond to oil spills in currents ranging from one to five knots. The goal of this effort was to improve the fast-water containment and recovery capabilities in all United States Coast Guard (USCG) areas of operation by identifying and testing the most promising equipment. The Coe and Gurr study also identified several pieces of equipment that have the potential of performing well in fast-water areas. The goal of this test series was to quantify the performance of these systems and provide the manufacturers the opportunity to improve their equipment. Four recovery systems were evaluated:

- DIP600: manufactured by JBF Environmental, a division of Slickbar Products Corporation. This system is owned by the U.S. Coast Guard and is known as the High Speed Skimmer (HSS).
- FasFlo Skimmer: manufactured by Vikoma International Ltd. of Great Britain.
- Blomberg High Speed Circus: developed by Erling Blomberg and licensed to Foilex in Sweden.
- Current Buster™ System, manufactured by NOFI TROMSØ AS of Norway.

The four recovery systems differ in type and design. Each was rigged for testing and operated as specified by the manufacturer to achieve optimum performance. The measurement of effectiveness for these tests is the throughput efficiency (TE), which is the ratio of the amount of oil recovered to the amount of oil encountered.

The JBF DIP600 and the Vikoma FasFlo Skimmer each use deflection booms to direct encountered oil to the skimmer. Each accumulates oil into a collection well from which an offload pump transfers the recovered product to storage. The JBF skimmer was at least 70 percent effective when recovering both light and viscous oils in calm and wave conditions at two knots. Its average performance at three knots was over 55 percent. The FASFLO could not collect oil in waves, but was over 60 percent effective at two knots for both types of oils.

The High Speed Circus Skimmer is a shipside-mounted system that uses sweeping arms to divert surface oil to the collector. Oil accumulates in the collector from which offloading is accomplished with the use of a floating weir-type skimmer. This system was unable to collect oil in waves. The intermediate-sized model used for this test was over 75 percent effective at two knots in calm water.

The NOFI Current Buster System is an inflatable boom system that is designed for encountering and containing spilled oil at tow speeds over three knots. A floating skimmer and pump is employed within the boom “separator tank” for offloading. This system performed better than the other systems, recovering over 90 percent of the distributed oil in calm water up to three knots.

The results of these tests indicate that oil can be efficiently recovered at speeds over three knots in calm water and two knots in harbor chop waves. These speeds are higher than the capabilities of most existing systems.

This series of tests has advanced the knowledge of oil spill containment and response in fast currents. A protocol has been developed that has established a benchmark for future improvements to these systems or for other potential systems. Oil spill response planners and regulators can utilize the outcome of these tests to increase their equipment capabilities that could result in better responses. A smaller impact on the environment would be a beneficial consequence.

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1.0 Introduction

1.1 Background

Oil spills in fast moving water above one knot are difficult to control and recover due to the ease at which oil mixes with water and entrains under booms and skimmers. Fast currents also make deploying equipment and maneuvering on the water very difficult and dangerous due to the high forces exerted on boats and recovery equipment. A lack of effective fast water containment and recovery systems, mooring problems, and limited training and experience in these difficult and dangerous response conditions have hampered response efforts in currents on rivers and coastal areas. Even though 70 percent of the oils transported on U.S. waterways are in currents that routinely exceed one knot, very little research and product development has been conducted on new technologies and strategies to respond to oil spills occurring in currents from one to five knots.

The Coast Guard R&D Center is executing the project Innovative Response Techniques (Fast Water Containment). The goal of this effort is to improve the fast-water containment and recovery capabilities in all United States Coast Guard (USCG) areas of operation by identifying and testing the most promising equipment. Four skimming systems were evaluated and tested at Ohmsett, the National Oil Spill Response Test Facility. These systems were identified in a report that assessed the state-of-the-art in fast water response, (Coe and Gurr, 1999).

The Ohmsett Facility is the only large-scale test tank in North America where full-scale oil recovery equipment and techniques can be tested in water with spilled oil. Almost all performance data on oil spill equipment in the USA is based on tests performed at Ohmsett. The Department of the Interior (DOI) Minerals Management Service (MMS) operates this facility for the use of other government agencies and commercial concerns (see Appendix A).

1.2 Test Objectives

The objectives of this series of tests were to develop a testing protocol for fast water equipment evaluation, define the operational capabilities of four recovery systems, and aid in improving the performance of the systems. A series of preliminary Protocol Verification tests were performed to quantify the accuracy of the test results. This was accomplished by performing repeated tests with fixed independent variables. The preliminary testing ensured that the test methods employed during evaluation of the recovery systems would be unbiased and would provide accurate and repeatable performance data in fast-water environments.

Performance values for each recovery system were obtained for varying surface conditions and current speeds while recovering medium and high viscosity oils. Testing was conducted in accordance with ASTM F 631-93, “Standard Guide for Collecting Skimmer Performance Data in Controlled Environments.” During the evaluation, adjustments and modifications to the systems were encouraged in an effort to improve performance. The manufacturers and USCG representatives agreed upon the modifications prior to making any adjustments. System performance was quantified primarily in terms of Throughput Efficiency (TE), a percentage measurement which quantifies the volume of oil collected versus the volume encountered. This factor is the most independent from operator capabilities and represents the best measurement for given test conditions. Recovery Efficiencies (RE), the amount of oil recovered with respect to

the volume of fluid recovered, and Recovery Rates (RR), the amount of oil recovered in a specific time period, were obtained as secondary performance measurements. Calculations of TE, RE and RR are described in Appendix B

1.3 Testing-General

A skimming system evaluation includes qualitative as well as quantitative information. This study focuses on data typically measured during full-scale testing. Operational concerns identified during testing that would apply in the field were also noted. These resulting performance values are considered the results of a measurement system in which there are many sources of variation or error. Critical measurements include the amount of oil distributed during a test, the total volume of recovered fluid, the volume of oil recovered after free water is decanted, and the laboratory analysis of recovered fluid samples.

1.3.1 Test Setup-General

The general test basin setup used for the fast water system evaluation is shown in Figure 1. The recovery systems were rigged within the Test Basin between the Main and Auxiliary Bridges. Each skimmer was deployed in accordance with the manufacturer's directions. Illustrations of each skimming system test setup and procedures specific to each system are presented in the corresponding test sections of this report.

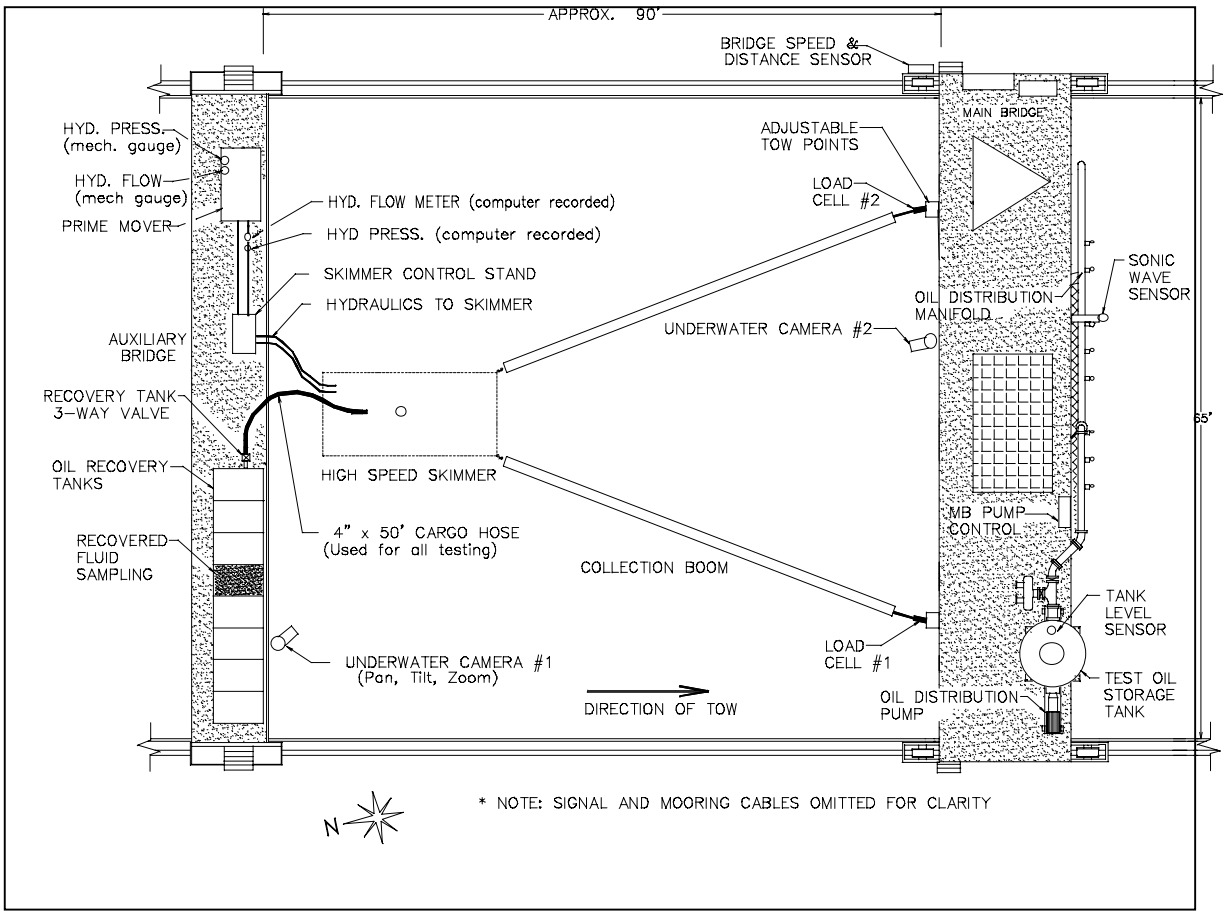

Figure 1. Setup for Fast Water Equipment Performance Tests.

Each system was towed from adjustable tow points located on the North side of the Main Bridge. During wave-generated surface conditions, the skimmers were towed into the waves. The Auxiliary Bridge served as a platform for a Deutz 80 horsepower (hp) hydraulic power supply and a hydraulic control stand, at which, the skimmer operator was stationed. Standard fifty-foot lengths of hydraulic hose were used between the prime mover, the control stand, and the skimmers. A cargo line was routed from the offload pump to the calibrated recovery tanks, also located on the Auxiliary Bridge. Test oil storage and distribution, instrumentation connections, video monitors, recorders and testing operations were controlled from the Main Bridge. Variations to this setup are described in the appropriate sections describing each system.

Prior to testing, the test oil was loaded into the 1500 gallon Ohmsett Main Bridge storage tank. From this tank, the distribution pump delivers oil through pneumatically operated valves located along a manifold near the water surface. Each valve was equipped with fanning nozzles to aid in spreading the oil into a slick.

1.3.2 Method-General

All tests were performed using the following basic procedure, except where noted otherwise:
With all test personnel in their assigned positions, the data collection computer and video cameras were started. The Main Bridge distribution pump was started and set for the predetermined pump rate in the circulate mode. If the skimming system had powered components (belts, discs, etc.), they were started at this time. If off loading pumps were used, the start time coincided with the first oil encountered and ended when the last oil was encountered. The bridges and skimming system were then accelerated to the test tow speed. Once at speed, the oil distribution manifold was opened, creating an oil slick. The recovered fluid was pumped directly to the Auxiliary Bridge recovery tanks. Collection of the recovered fluids was segmented into two independent collection tanks. The first collection period began when the skimmer first encountered the oil slick. Near the end of the Test Basin after the distribution manifold was shut off, the recovery system was operated until the last of the distributed oil had been encountered. The elapsed time that the oil was encountered was documented as the “recovery time.” The bridges and skimming system were then decelerated to a stop. The second collection then occurred in which the skimmer and cargo hose were purged and all collected oil recovered for measurement. The system was then returned to the North end of the Test Basin and prepared for the next test.

Fluid depth measurements were taken in the recovery tanks to obtain the total volume of oil recovered during the test runs. The recovery tanks were then decanted of free water, a second depth measurement taken, and the fluid sampled using either a stratified sampling thief or a grab sampler. The sampled fluid was analyzed in the Ohmsett laboratory to determine the percent water in oil. The depth measurements and sample numbers were then recorded on an oil recovery log.

1.3.3 Test Schedule

The systems were tested under calm conditions and harbor chop and with two oil types. Testing began with a 2-knot tow speed for each set of conditions. The tow speeds were increased by 1-

knot increments up to 5 knots. Tests that resulted in acceptable performance were repeated in accordance with the fast-water protocol described in Section 1.4.

1.3.4 Test Fluids

The oils selected for this test were Hydrocal 300 and Sundex 8600T, which are standard test oils used at the Ohmsett facility. Typical properties for these oils are listed in Appendix C, Tables C-1 and C-2. Viscosities versus temperature curves are shown in Appendix C, Figure C-1. The anticipated test oil viscosities ranged from 200 to 300 cPs for Hydrocal 300 and 14,000 to 20,000 cPs for Sundex 8600T and was dependent on ambient temperatures.

1.3.5 Testing of Oil Properties

The oils used for testing were characterized from samples taken each time the Main Bridge storage tank was filled. A test oil distribution log was generated and indicated test oil type, sample number, temperature, test date, and the test for which it was used. The following tests were run on oils at the Ohmsett Oil Analysis Laboratory: viscosity, bottom solids and water, specific gravity, surface and interfacial tension. Brief descriptions of these tests and physical data appear in Appendix C.

1.3.6 Test Basin Water Properties

Periodic samples of the test basin water were taken during the test program to monitor the effectiveness of the filtration system and to document the physical properties of the water. The sampling frequency is dependent on filter operation requirements. The following tests were run: oil and grease in water, pH, turbidity, and salinity. A complete description of these test methods and the results can be found in Appendix C.

1.3.7 Wave Conditions

Two surface conditions were employed during this test series, calm and harbor chop waves. The same harbor chop wave condition was generated during each recovery system test. Harbor chop waves were created with the wave generator located at the South end of the test basin. A wave analysis was performed for each test and is reported by test number in Appendix D. The average wave height, defined as the average height of the highest one-third of the waves ($H^1/_3$), for the harbor chop generated throughout the test series was about 11 inches.

1.3.8 Data Collection and Instrumentation

Data were collected electronically and manually recorded during each test. Appendix E provides general information on the typical electronically collected data during testing, the collection method, location of instrumentation, and instrumentation specifications. Manually collected data were recorded on log sheets with the corresponding test numbers. Analytical data were generated from sampling of the recovered test fluids and the results used in performance calculations.

1.3.9 Quality Analysis

General instrumentation checks were performed to insure that the Test Plan's instructions were followed and that records, logs, and notes obtained during the test were complete and accurate. Appendix F provides information on the various elements as they relate to the accuracy, precision, and validity of the test data presented.

1.4 Test Protocol Verification

Testing equipment at speeds greater than two knots is difficult at Ohmsett. Measurement errors can be magnified during the short duration of the runs down the tank. The limitations of the oil distribution and collection system can also add to the errors. Significant measurements that can be affected are the amount of oil distributed during a test, the total volume of recovered fluid, the volume of oil recovered after free water is decanted, and the laboratory analysis of recovered fluid samples. Inherent error in each measurement affects the precision of the final calculations. An example of the influence of the measurement on the results is given in Appendix G. Finally, the amount of oil distributed during a run and how the encounter time is measured can also influence the final results. The Test Protocol Verification will determine the procedures for obtaining repeatable quality data.

1.4.1 Protocol Verification Objectives

The primary objective of the Protocol Verification was to determine the effects on precision when performing multiple pass tests. When performing tests at 2 knot speeds or greater, the steady-state operation time is reduced. The Test Basin length limits the two to five knot runs to actual encounter times from 2 minutes to 45 seconds, respectively. The volume of oil distributed and recovered is less than tests performed at slower speeds. Longer test duration increase the total volume of oil distributed and recovered, therefore minimizing inherent measurement error. A recent concept adopted at the Ohmsett Facility is “multiple pass” testing in which a particular test and the parameters are constant for multiple passes down the tank. The volume of oil distributed and recovered then accumulates, resulting in larger volumes from which to obtain measurements.

Once the protocol evaluation was complete, a determination was made as to the number of “passes” to be used per test during the Fast Water Equipment tests. The benefits of multiple pass tests were quantified using TE values and deviations from the mean data set using the JBF DIP600 skimming system. The JBF DIP600 skimmer is currently included in the USCG spill response equipment inventory, after having been tested at Ohmsett in 1997. (DeVitis, 1997)

1.4.2 Protocol Verification Procedure

The number of “passes” down the tank was varied to effectively determine inherent error in the measurement system. Three single pass tests, three double pass tests and two triple pass tests were performed. All other parameters remained constant throughout the test series. The quantity of oil distributed and recovered were the primary measurements used to determine skimming system throughput efficiency . The offload pump was not operated during the protocol tests to eliminate variation in performance due to operator inconsistency. The TE value was obtained for each of the single, double and triple pass tests. All tests were performed using the following set of test parameters that were selected based on the previous tests in 1997:

- Tow Speed = 2 knots
- Oil Type = Hydrocal 300
- Oil Distribution Rate = 150 gpm
- DIP Belt Speed = Zero relative velocity
- Basin surface condition = calm

1.4.3 Protocol Verification Results

All data were analyzed to determine the mean of the data at the conclusion of the "Protocol Verification." Table 1 shows TE values obtained for each single, double, and triple pass tests, as well as the entire data set statistics.

Table 1. Throughput Efficiency Data

	Single pass	Double pass	Triple pass	Complete Data Set
TE Values (%)	76, 70, 82	69, 71, 75	72, 74	69,70,71,72,74,75, 76,82
Mean (%)	76	71.7	73	73.6
Mean Difference Compared to Complete data set (%)	2.4	1.6	0.6	---

1.4.4 Discussion of Results

When compared to the average of the complete data set, the mean difference decreased as the number of passes per test increased. This trend towards a tighter data set confirmed that multiple pass testing did increase the accuracy and precision of reported values. The data spread was also markedly reduced during these runs as compared to the previous testing of the JBF 600. Consideration was also given to the time and fluid volumes necessary to achieve the higher accuracy that was required to make a final decision regarding single, double, or triple pass tests. Double pass tests were selected based on the allotted testing period for each system and the significant improvement in data quality.

The other two issues for the protocol is the amount of oil that is distributed during a run and the length of time that the skimmer encounters oil. Larger amounts of oil during a run also minimize measurement errors. After evaluating the distribution system on the main bridge, it was determined that a slick thickness of five millimeters at the mouth of the skimmer is the maximum that could be created at five knots. This thickness was then used to calculate distribution rates for the other tow speeds to maintain the same slick thickness. The equation needed to determine the oil distribution rate for various speeds and widths is given in Appendix G. The oil encounter time, that is especially important during the recovery rate runs, is slightly different for each type of skimmer. The start time for all skimmers was chosen to be the moment that the distributed oil encounters the skimmer. The recovery time ends when the last of the oil reaches the off-load pump. For the JBF 600, ten seconds was used to account for the time for the oil to travel down the belt and get to the collection well where the pump is located.

2.0 Testing of the JBF DIP 600 Skimmer

2.1 Skimmer Description

The DIP 600 was designed as a high speed incline skimmer employing the Dynamic Incline Plane (DIP) principle. This system was selected as the Coast Guard's High Speed Skimmer (HSS) and six have been bought. The original patents on the DIP technology have expired. However, an application patent, which reserves the exclusive right "to manufacture DIP oil collection modules ....", was awarded to JBF Scientific in 1995.

The skimmer measures 20 feet (6.1 meters) in length by 8 feet (2.4 m) in width, with an overall height of 6 feet 10 inches (2.08 m) and a draft of 4 feet 6 inches (1.4 meters). The complete skimmer dry weight is 7500 pounds (3400 kilograms). Lifting eyes are provided to accommodate a four-point sling. The skimmer is constructed primarily of marine grade aluminum and utilizes stainless steel hardware. Floatation is provided by four air inflatable urethane pontoons that attach to the hull with strapping. The pontoons are inflatable to 2 psi (.14 Bar) and are also equipped with fender cushions where side abrasion is likely. Figure 2 shows the pontoons, stern vents and the DIP Hydraulic drive motor.

Figure 2. JBF Skimmer being lowered into test tank.

The incline plane assembly, which is 48 inches (1.22 meters) wide and approximately 16 feet (4.9 meters) long, consists of a chain-driven rotating polyvinyl chloride belt. The incline plane is orientated with the leading edge above the water surface and angled down below the vessel. As the system moves through the water, the oil is forced to follow the belt to the collection well underneath the surface, as shown in Figure 3. The belt is typically operated at zero relative velocity (ZRV), which is defined as the belt rotational speed equal to the velocity of the fluid passing through the skimmer. When oil reaches the belt's end, buoyant forces cause the oil to surface into the collection well. The collection well provides a region for oil to rise to the surface, which is where the Desmi DOP-250 offload pump is located. Free water entering the skimmer is allowed to escape through vent holes located at the bottom stern. Offloading operations begin when a sufficient volume of oil is recovered into the collection well. The hydraulic input power required to operate the belt chain drive is 5-7 gpm (19-26.5 liters/min). The Desmi DOP-250 offload pump requires 42 gpm (159 l/min) at 2500 psi (170 Bar) for maximum pumping rates.

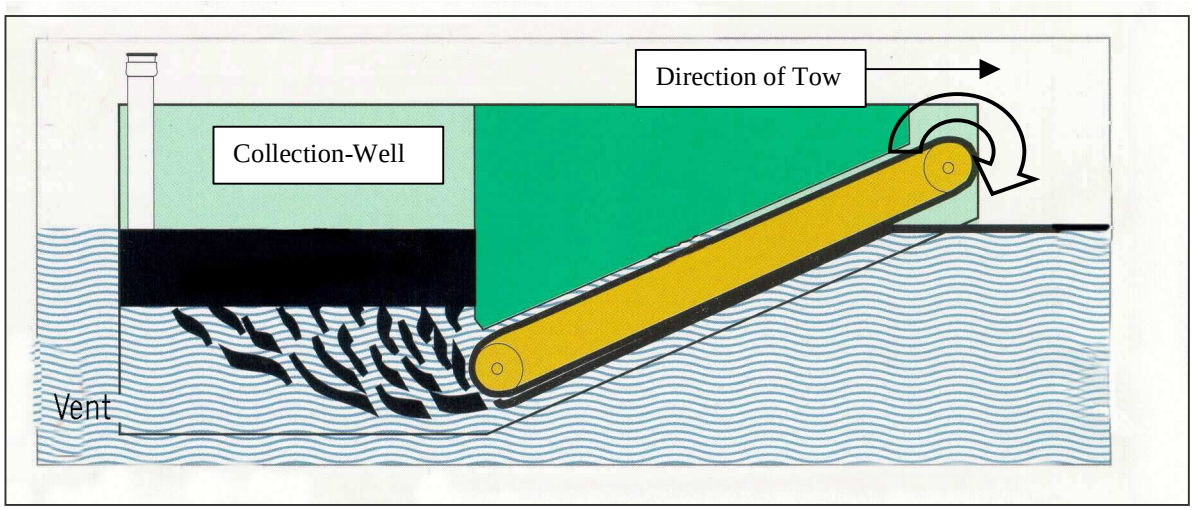

Figure 3. Schematic of Dynamic Incline Plane (DIP) principle.

2.2 Test Setup, JBF DIP 600

The JBF DIP 600 skimming system was positioned between the Ohmsett Main Bridge and the Auxiliary Bridge. For test numbers 1 through 47 the JBF Skimmer was configured using an Applied Fabrics Globe Boom (See Figure 4). The globe boom section lengths were 25 feet (7.6 meters) long, had an overall height of 24 inches (.61 meters), and a freeboard and draft of 12 inches (.3 meters). Two 4000-pound (17793 Newtons) load cells were installed at the Main Bridge tow points to monitor the towing forces. Two underwater cameras were used during testing to document the events both in and around the skimmer.

Figure 4. JBF Skimmer Test Setup with Applied Fabrics Globe Boom.

The sweeping boom mouth opening was 28 feet (8.5 m) wide, angled outward 17.5 degrees from the skimmer inlet to form a sweeping vee-shape. Hydraulic power for the DIP belt and offload pump was provided from a Deutz prime mover capable of 42 gpm (159 l/m) at 3000 psi (207 Bar). The prime mover and a JBF skimmer control stand were operated from the Auxiliary Bridge. A 4-inch (10 cm) by 50-foot (15.25 meters) flat hose was used as the cargo line routed from the Desmi DOP-250 pump discharge to the fluid recovery tanks, also located on the Auxiliary Bridge. There were eight individual cells within the recovery tank to segregate collection periods.

For test numbers 48 through 82, the JBF Skimmer was configured using a prototype Canflex High Current Boom, as shown in Figure 5. The prototype boom sections were 40 feet (12.2 m) long and were equipped with upper and lower cross bridles to maintain a tapered vee-shape. This arrangement resulted in a mouth width 32 feet (9.75 m) and maintained a sweep angle of 17.5 degrees. The Canflex boom's overall height is 36 inches (.92 m), with a 14-inch (36 cm) draft and a 22-inch (56 cm) freeboard. The boom is designed to facilitate higher speed recovery without entrainment or drainage losses.

Figure 5. JBF Skimmer with Canflex High Current Boom.

2.3 Detailed Test Description and Results

A total of 82 passes in the Test Basin resulted in 44 individual provided TE values under various test conditions and parameters. The skimmer was exposed to both light and heavy viscosity oils both in calm and harbor chop waves, for speeds ranging from 2 to 5 knots. Values for TE obtained during the core test schedule served as a datum in which to gage effects of operating the skimmer at non-optimum belt speeds and offload pump rates. A number of other tests were

executed to quantify the effects on performance when operating the skimmer at other than optimum belt speeds and offload pump rates. Tests were also performed to determine the collection well oil capacity. The TE performance data and corresponding test parameters are presented for each tow speed in the tables below.

Results from tests 1 through 15 (2 knot repeat tests) provided data which illustrate an increased accuracy for TE values when performing multiple pass tests, as discussed in Section 1.4.3. All subsequent tests were double pass tests unless otherwise noted. Two low speed recovery tests were performed at 1 and 1.5 knots for which TE values were determined. These were single pass tests in which the belt was operating at ZRV, the oil being recovered was Hydrocal, there were calm surface conditions, and the offload pump was not operating. At one knot, the TE was 71 percent and for 1.5 knots the TE was 88 percent.

During the 2-knot tests, the DIP belt was operated at ZRV and the offload pump was not operated. It was determined from volume calculations that the collection well capacity was ample to collect the volumes encountered. Therefore, collected oil was recoverable at the conclusion of each test without risk of overloading the well capacity. Not operating the offload pump also nullified possible operator inconsistencies. For the first 3 tests shown in Table 2, the JBF Skimmer encountered 150 gpm of oil. This is equivalent to a slick thickness of 7.5 millimeters at the skimmer mouth. A distribution rate of 100 gpm was used for the second three tests. The values in Table 2 show that the results were consistent.

Table 2. JBF DIP 600 TE values at 2 knots

Test Number	Oil Type	Lead Boom	Surface Condition	TE (%)
3-4	Hydrocal	Globe boom	Calm	72
5-6	Hydrocal	Globe boom	Calm	71
10-11	Hydrocal	Globe boom	Calm	75
55-56	Sundex	High Current	Calm	98
69-70	Sundex	High Current	Harbor Chop	89
75-76	Hydrocal	High Current	Harbor Chop	70

The TE performance for three, four and five knots are shown in Tables 3 and 4. The oil distribution rate was adjusted to maintain an equivalent slick thickness (5 mm) as experienced in two-knot tests. Therefore, except for tow speed, the set of test parameters for the remaining tests were constant. The high current lead boom was used for all tests at 4 and 5 knots. The results indicate that the skimmer recovers the higher viscosity oil more efficiently. The performance at four knots was about half of that at three knots. Performance at 5 knots was about one-third of that at three knots.

Table 3. JBF DIP 600 TE values at 3 knots

Test Number	Oil Type	Lead Boom	Surface Condition	TE (%)
40-41	Hydrocal	Globe boom	Calm	45
50-51	Hydrocal	High Current	Calm	47
77-78	Hydrocal	High Current	Harbor Chop	36
57-58	Sundex	High Current	Calm	93
59-60	Sundex	High Current	Harbor Chop	61

Table 4. JBF DIP 600 TE values at 4 and 5 Knots.

Test Number	Tow Speed (knots)	Oil Type	Surface Condition	TE (%)
48-49	4	Hydrocal	Calm	24
79-80	4	Hydrocal	Harbor Chop	19
61-62	4	Sundex	Calm	48
63-64	4	Sundex	Harbor Chop	40
52-53-54	5	Hydrocal	Calm	6
81-82	5	Hydrocal	Harbor Chop	19
65-66[1]	5	Sundex	Calm	16
67-68[1]	5	Sundex	Harbor Chop	29

Note: 1) DIP belt was not operating properly, belt rotational speed was varying

The JBF DIP 600 collection well oil capacity, defined as the volume of oil retained within the collection well while underway, was determined during tests 19 through 22. The collection well was preloaded with 600 gallons (2640 liters) of oil. The skimmer was then towed in calm water at two knots with the belt operating at ZRV. Figure 6 illustrates oil loss from the collection well's lower stern drain vents directly below the collection well and from the belt drive motor port through the hull. The skimmer was towed at 2 knots for two more passes until oil losses from the collection well stopped. The skimmer was then towed at three-knots during which oil was lost only during a disturbance (i.e. such as a bump). This indicated that the oil retained in the collection well was in equilibrium when experiencing two and three knot relative current speeds. A total of 550 gallons (2420 l) of oil was offloaded from the collection well.

Figure 6. Oil Loss during collection well capacity test.

TE was measured at various offloading pump rates to determine the effect on efficiency. The results are shown in Table 5. All tests were performed in calm surface conditions with the DIP belt operating at ZRV while recovering Hydrocal test oil. The maximum pumping rate of the offload pump was 440 gpm (1936 l/m). The corresponding Recovery Efficiency (RE) values do not indicate a strong trend distinguishing higher or lower RE when operating the offload pump. This supports the operational concept of offloading intermittently when the collection well has accumulated a sufficient volume. Another benefit of offloading intermittently is that the collected oil will have a residence time during which gravity separation can take place, resulting in a higher RE.

Table 5. JBF DIP 600 RE values at 2 knots

Test Number	Encounter Rates (gpm)	Offload Pumping Rate-Actual (gpm)	Recovery Efficiency (%)	Throughput Efficiency (%)
38	150	41	55	76
36	150	93	69	74
32	150	143	49	74
44	150	146	68	65
46	150	235	46	60

A change in the collection well fluid elevation (while in tow) was identified during these tests due to the dynamic pressure increase in the collection well. The static water line within the collection well was measured at 5½ inches (14 cm) above the offload pump inlet. Prior to Test 32, this level was observed to increase with tow speeds. During 2-knot tows, the elevation level of the fluid increased 6 more inches (15 cm). The change in fluid level during the tests, plus the initial 5½ inches of fluid above the pump inlet when static, resulted in 11½ inches (29 cm) of product above the pump inlet while in tow. After offloading, approximately 75 gallons (330 l) of oil remained in the collection well after all tests. This was due to the 5½ inches (14 cm) of fluid space above the pump inlet. Based on the physical measurements of the collection well, it was determined that an additional 125 gallons (550 l) would be required to provide a sufficient oil preload in the collection well for the oil/water interface to correspond to its pump inlet while in tow. For an operator to efficiently utilize storage space, a high percentage of oil is desired when offloading. A minimum of 200 gallons (880 l) would have to be recovered before offloaded fluid would contain oil. Therefore, the RE data obtained were for conditions in which an operator did not optimally offload. Test number 32 and beyond were performed as double passes in which the preload oil/water interface elevation discrepancy relative to the pump inlet was considered.

The effects of a broken belt drive assembly and in cases where the DIP belt operates too slow or faster than ZRV were also investigated. These tests were performed with the following independent variables as constants:

- Tow speed-2 knots
- Offload pump is off
- Oil Distribution Rate at 150 gpm
- Calm surface conditions

The TE data are presented in Table 6 for various belt speeds. The skimmer was still able to recover oil without the belt operating.

Table 6. JBF DIP 600 TE data for various belt speeds

Test Number	Tow Speed (knots)	Belt Speed (% of ZRV)	Oil Type	Throughput Efficiency
42-43	2	0	Hydrocal	56
26-27	2	50	Hydrocal	67
28-29	2	150	Hydrocal	88
71-72	2	50	Sundex	97
73-74	2	150	Sundex	96

Tow forces were continually monitored during the test series to provide operational information to the manufacturers and users. The average tow force values in each boom leg obtained for tow speeds of 2 to 5.0 knots in calm and harbor chop wave conditions are presented in Table 7. The reported values are averaged from a 20-second data set taken during steady towing conditions.

Table 7. JBF DIP 600 Tow Force Values.

Tow Speed (knots)	Surface Condition	Average Tow Force per Boom Leg (lbf)
2	Calm	270
3	Calm	560
4	Calm	1012
5	Calm	1530
2	Harbor Chop	311
3	Harbor Chop	603
4	Harbor Chop	1073
5	Harbor Chop	1606

2.4 Discussion of Results

During the 2-knot recovery tests with Hydrocal, the average TE value achieved was 72 percent for all double pass tests in calm surface conditions (including data obtained during the "protocol testing). A TE value of 70 percent was obtained while experiencing harbor chop waves, indicating an insignificant effect on performance. The highest TE values were obtained while recovering Sundex, the TE values were 98 percent and 89 percent for calm and harbor chop waves, respectively.

Given the same test parameters at 3-knot tow speeds with Hydrocal, the TE values dropped by 36 percent for calm water tests and 46 percent in harbor chop. The lost oil was observed escaping from the bottom stern vents, the end of the DIP belt and the belt drive motor location. While recovering Sundex, the increase from 2 to 3 knots in calm surface conditions resulted in a slight downgrade in TE from 98 percent to 93 percent, or a 5 percent decrease. Recovering Sundex in waves at 3 knots resulted in a TE of 61 percent or 31 percent less than the 2-knot tow speed. The TE values obtained during 4 and 5-knot tests were below 50 percent. Figure 7 graphically illustrates the effects of increasing relative currents (tow speed) versus TE performance. It should be noted that the TE values were consistently higher when recovering Sundex then when recovering Hydrocal. Not shown is the highest TE value obtained while recovering Hydrocal, 88 percent at 1.5 knots.

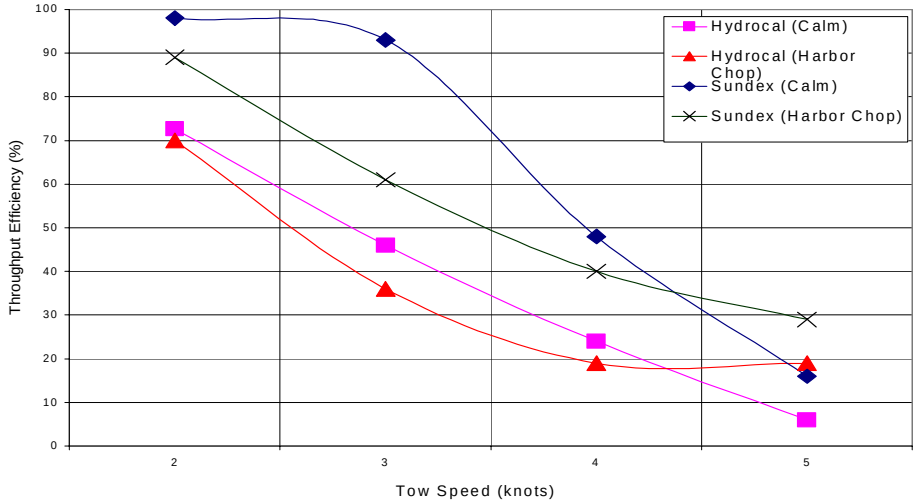

Figure 7. Throughput Efficiency versus Tow Speed.

The results of varying the DIP belt speed indicated a decrease in TE values for slower than ZRV, and an increase in TE with the belt operating faster than ZRV. Figure 8 graphically illustrates this trend for Hydrocal. The effects on TE values when varying the DIP belt speed was only notable when recovering Hydrocal test oil. When recovering Sundex at 50 percent and 150 percent of ZRV belt speed, the TE values were 97 percent and 96 percent, respectively, compared to a 98 percent TE when recovering at ZRV. TE data for recovering Sundex without the belt moving were not obtained. Therefore, improved TE performance can be achieved while recovering lighter oils by increasing the incline belt rotational speed. Recovery operations of light oil with a failed belt system would degrade performance but would not render the skimmer useless. The increase of TE with Hydrocal with faster belt speeds raises the issue of the actual water current that the belt is encountering. The data suggests that the channeling of the water from the 28-foot width at the leading edge of the booms to the four-foot width at the mouth of the skimmer, may actually increase the current flowing into the skimmer. More work needs to be done to verify this issue so that users can optimize belt speed and performance.

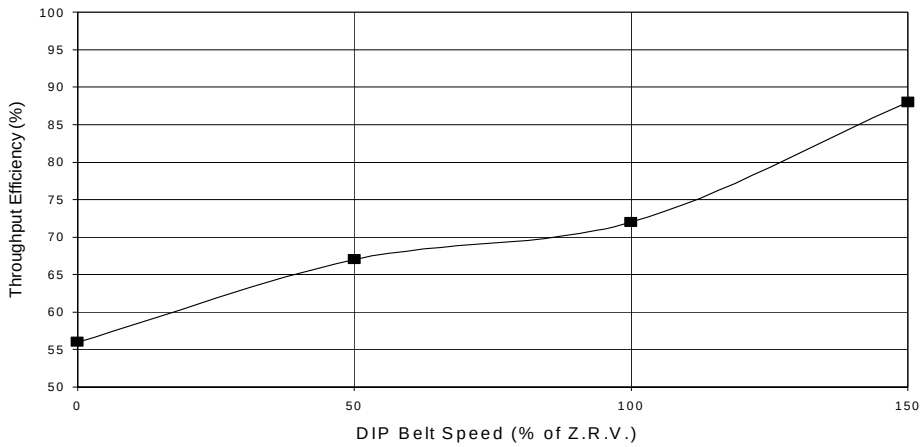

Figure 8. Throughput Efficiency versus DIP Belt Speed for Hydrocal.

Throughput Efficiency (TE) was evaluated in a series of tests to quantify the short-term results for offload pumping rates greater than, less than and equal to the encounter rate. This performance parameter is most dependent upon an operator's ability to identify when offloading should take place. Figure 9 illustrates actual TE values obtained at 2 knots while recovering Hydrocal test oil in calm surface conditions. As expected, lower offload pump rates allowed for collected oil to accumulate, resulting in higher TE values.

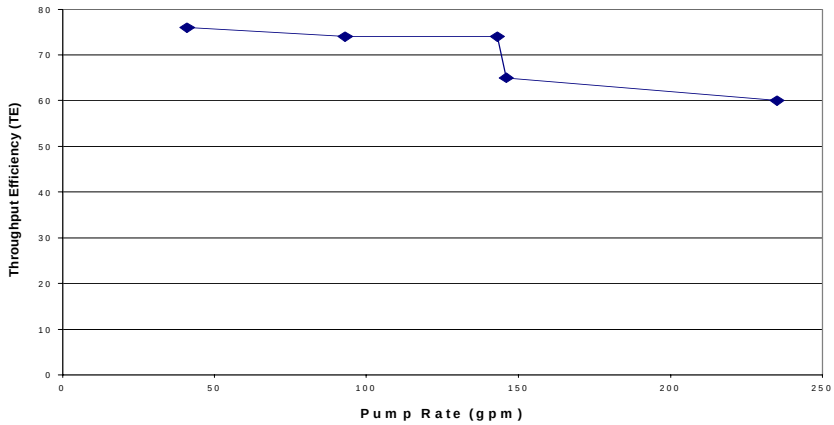

Figure 9. TE versus Pump Rate for JBF Skimmer

The TE values accurately represent offloading operations at various pump rates without allowing a reserve of collected oil to accumulate. The minimum volume necessary for efficient offloading was determined to be 200 gallons. This is the volume of fluid that remains in the collection well above the pump inlet while operating. The maximum volume contained within the collection well, before an overloaded or loss condition occurs, is 550 gallons. Maximum RE values will be obtained when the collection well capacity is maintained in the 200-gallon to 550-gallon range. Optimum RE values would be achievable if the operator was aware when approximately 550 gallons was collected, and offloaded at that time. This would give the recovered fluid the maximum residence time in the collection well, allowing separation to occur.

2.5 Historic Data Comparison

The JBF DIP600 was evaluated during the project, *USCG High Speed Skimmer Performance Tests at Ohmsett*, January 1997. [Devitis, 1997] During this study, two different lead booms were tested with the JBF skimmer. Setup Number 1 used a USCG Fast Sweep boom which was 61.7 feet (18.8 m) long with a mouth opening of 41 feet (12.5 m). The Fast Sweep was also equipped with netting located at the bottom of the boom skirt. The purpose of this netting is to restrict the boom legs from forming a catenary thereby maintaining the V-sweep shape, and to reduce the relative current velocity at the skimmer mouth. Setup Number 2 utilized a pair of plain inflatable boom sections 40 feet long, resulting in a mouth opening of 28 feet. Cross bridles were installed at three locations to aid in maintaining a funnel shape. The funnel angle for both setups was constant. Setup Number 2 was used only during tests recovering Hydrocal 300 test oil.

The average TE values from the January 1997 test and the data generated during this study are shown in Table 8 below. The TE values obtained during this study were obtained while using the Canflex prototype boom. Both studies employed multiple pass testing, but the results are not consistent.

Table 8. Historic Data Comparison

TEST PARAMETERS			AVERAGE TE VALUES (%) [Range in Brackets]		
Tow Speed (Knots)	**Oil Type**	**Surface Condition**	**Jan 1997 [1,2] Setup #1 (netting)**	**Jan 1997 [1,2] Setup #2 (w/o netting)**	**Jul 1999 [2]**
3	Hydrocal	Calm	41 [34-48][3]	47 [33-66][3]	46
3	Hydrocal	Harbor Chop	54	46	36
4	Hydrocal	Calm	38	34	24
4	Hydrocal	Harbor Chop	39.6	26	19
5	Hydrocal	Calm	---	---	6
5	Hydrocal	Harbor Chop	---	---	19
3	Sundex	Calm	68.3 [51-88][3]	---	93
3	Sundex	Harbor Chop	82.5 [64-100][3]	---	61
4	Sundex	Calm	78.3	---	48
4	Sundex	Harbor Chop	87.7	---	40

Notes: 1) from Devitis, et.al. 1997
2) Average wave height for harbor chop was 11-14 inches for 1997 test, 10.9 inches for 1999 test.
3) Range of data collected

There were multiple differences between the first set of tests in 1997 and those performed in 1999. The differences include the off-load pumping technique, the amount of oil distributed, the viscosity of the oil, the belt speed, the lead-in booms and the number of runs. The differences for each of these issues are:

Off-Load Pumping - For the trials in 1997, an operator controlled the pump so oil was removed from the collection well when he thought that enough was present. If the operator runs the pump frequently, he is assured of recovering all of the oil but the RE will be reduced as water will also be recovered. The pumping for the 1999 tests occurred at the end of the run. This method assumes that the collection well has the capacity to capture and hold all of the oil that surfaces. Theoretically, the second method should provide the maximum TE. In addition, two pumps were present in the collection well for the first set of tests. These reduced the overall volume of the well but not by a significant amount.

Amount of Oil - The encounter rate for the first set of tests was about twice that for those in 1999. Continual off-load pumping had to be performed because the collection well could not contain the amount of oil distributed. It is not clear if the higher concentrations of oil can affect the performance of the belt.

Oil Viscosity - The viscosity of the second set of tests was higher than the viscosity measured in the first tests because the test was in the spring rather than the fall. It is not clear if the differences actually influenced the results.

Belt Speed - Belt speeds for the first test was set at ZRV by using the flow gauge mounted on the hydraulic prime mover. For the second tests, personnel determined the revolutions of the belt by timing the belt seam from the Main Bridge. These two methods

need to be correlated and verified. The actual speed of the water within the skimmer also needs to be quantified. (see discussion below)

Lead-in Booms - Three sets of lead-in booms were used. The first test used the V-sweep and two plain inflatable booms. The V-Sweep has been shown to reduce entrainment losses in previous boom tests. New Canflex booms were used for the second tests. The Canflex Boom creates a complex wave regime in front of the skimmer due to its seams. This may have caused mixing that entrained additional oil that missed the skimmer opening.

Number of Runs - Only a single double-pass run was performed for each of the systems at 4 knots in 1997. Review of the data at 3 knots indicates a wide range for the January 1997 test results that generally overlaps the data collected in 1999. It is not clear why there is such a wide range of performance in 1997.

If there is an opportunity in the future, additional tests should be performed that can isolate each of the differences discussed above to verify the best combination for use in Coast Guard buoy tenders.

3.0 Testing of the VIKOMA FasFlo Skimmer

3.1 Skimmer Description

The FasFlo is an advancing weir type skimmer designed to encounter spills at speeds up to 6 knots. Outboard pontoon style floats filled with closed-cell foam provide buoyancy. The skimmer body and pontoons are constructed of marine grade aluminum, as shown in Figure 10. The vessel length is 13 feet-2 inches (4 m), with a width of 7 feet-11 inches (2.4 m), and a draft of 2 feet (.61 m). Patents were taken out in the UK at the time of design conception.

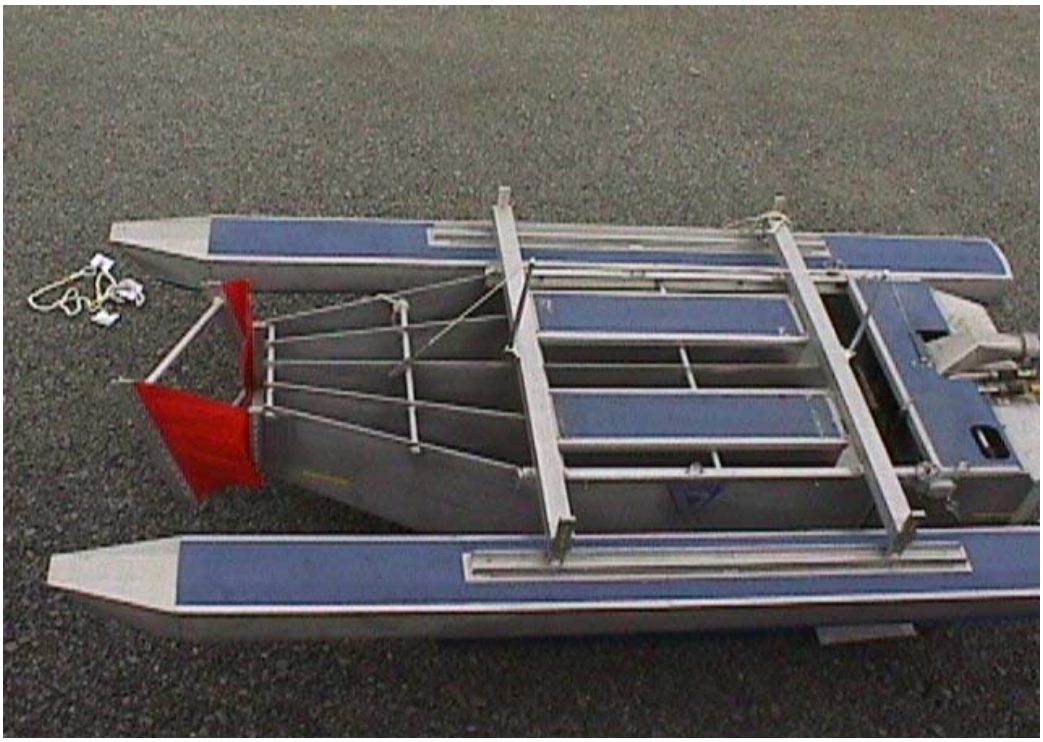

Figure 10. FasFlo Skimmer prior to entering Ohmsett test tank.

The oil/water enters the skimmer mouth at high speeds and then, by design, expands laterally and downward once in the expansion zone, thereby reducing the internal flow velocity, as illustrated in Figure 11. The entry guide vanes, shown in Figure 12, create a hydraulic jump facilitating oil/water separation at the surface. The encountered oil remains on the surface and is collected over a self-adjusting weir into a sump area. An offload pump, located in the sump, transfers the collected oil to storage. The offload pump is a rotary lobe pump, hydraulically powered and operated remotely from the power source. The hydraulic input power required to operate the offload pump is 21 gpm (92 l/m) at 2300 psi (160 bar). Offloading operations begin when a sufficient volume of oil has been collected. The manufacturer's claim of recovery equals the claimed offload pump rate of 300 gpm (1140 l) at zero head (water). For the system to operate properly, the water level within the hull must be at a height that permits the self-adjusting weir to work correctly. There are multiple methods to adjust the system. The pontoons are adjustable vertically, as well as laterally. The skimmer is equipped with two canvas drogues that increase tension in the towing booms, enabling the system to maintain a straighter boom profile to the skimmer entrance. A hydroplane, located near the water discharge, provides adjustment to optimize the water level in the skimmer for a given relative current speed. The flexible connection between diversion boom and the skimmer, shown in Figure 13, allows the buoyancy of each to operate independently.

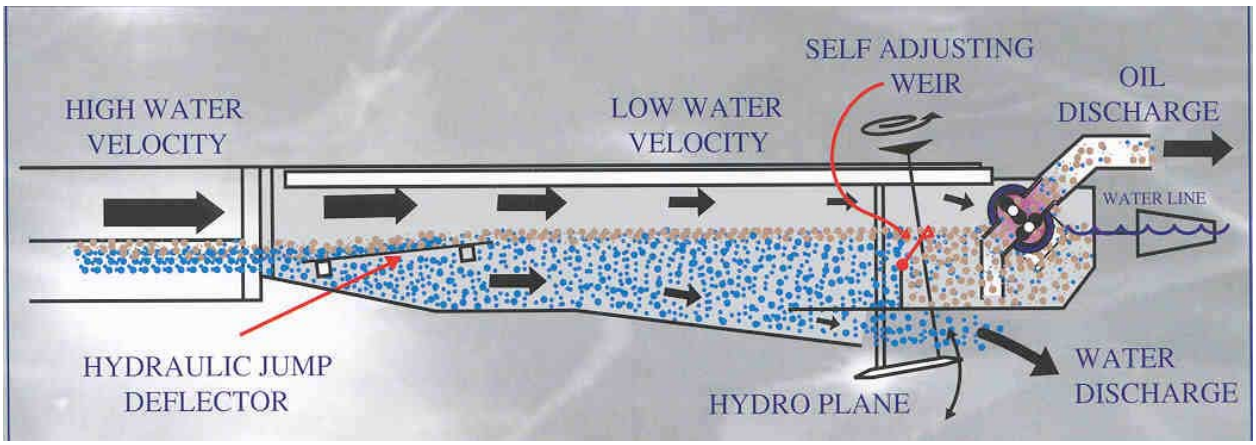

Figure 11. FasFlo Skimmer diagram.

Figure 12. Entry Guide Vanes.

Figure 13. Expansion Zone to produce Laminar Flow.

3.2 Test Setup

The FasFlo skimming system consisted of the Vikoma "FasFlo Skimmer" and two sections of inflatable sweep boom provided by the manufacturer. Each boom section was 33 feet (10 m) long with 20 inches (51 cm) of freeboard and $14^1/_2$ inches (35 cm) measured draft. The FasFlo skimmer arrived packaged in a crate, and supported by a special support stand, as shown in Figure 14. A four-point sling was attached for removal of the skimmer from the crate. Skimmer assembly was complete after installing the pontoons (four bolt connections) and attaching two drogues.

Figure 14. FasFlo Skimmer in Support Stand.

Pontoon adjustments were initially located vertically at the third hole (out of seven) from the bottom, and laterally centered in the center of the five holes provided. The adjustable Hydroplane was initially positioned at a 4° negative angle. The boom sweeping width was 20 feet (6.1 m), equivalent to a 15° angle from the direction of tow.

3.3 Detailed Test Description and Results

Prior to testing with oil, dry runs were performed to confirm proper operations of the skimming system and to identify tow speed limitations. With the drogues deployed, the maximum tow speed was 4.5 knots, at which, the sweeping boom arms and the skimmer lost freeboard. Without the drogues deployed, the sweeping arms formed a larger catenary shape and freeboard was lost at 4 knots, as seen in Figure 15.

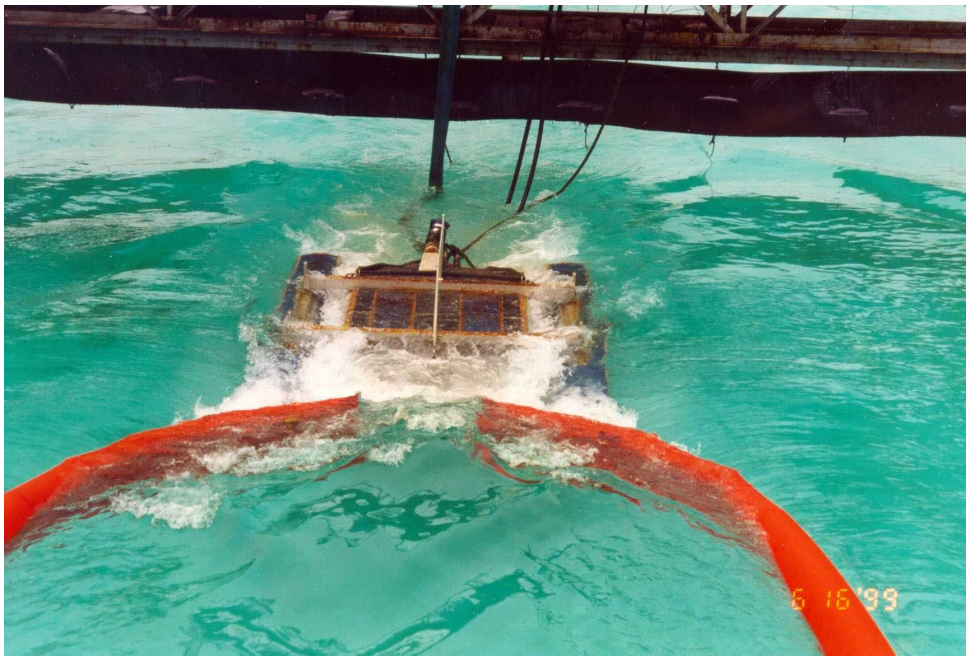

Figure 15. Maximum Tow Speed of FasFlo Skimmer, Freeboard Lost at 4 knots.

During the standard TE recovery tests, the offload pump was started when oil reached the skimmer mouth and was stopped approximately 10 seconds after the last of the distributed oil was encountered. Table 9 presents the 2-knot TE performance results. Configuration changes of the skimmer were made in an attempt to increase performance. Changes included the lengthening of the drogue towline, changing the foil angle, adjusting the pontoon's draft and adjusting the approach angle of the boom. Variation in TE results may be due to some of these changes.

Table 9. FasFlo TE values at 2 knots

Test Number	Oil Type	Surface Condition	TE (%)
84-85	Sundex	Calm	94
88-89	Sundex	Calm	84
98-99	Sundex	Calm	85
100-101	Hydrocal	Calm	79
108-109	Hydrocal	Calm	81
110-111	Hydrocal	Calm	87
112-113	Hydrocal	Calm	64
104	Hydrocal	Harbor Chop	3
92-93	Sundex	Harbor Chop	0

As shown above, the TE values while recovering Sundex at 2 knots in calm surface conditions (test number 84-86, 88-89, and 98-99) averaged 88 percent. Figures 16A and 16B illustrate the FasFlo skimmer recovering Hydrocal (left) and Sundex (right) at 2 knots in calm surface conditions. Note the slick differences between Hydrocal (nominal viscosity 200 cPs) and Sundex (nominal viscosity 20,000 cPs). The pictures show how each oil responded to the flow patterns created by the sweep booms. The variation in slick width is typical for these types of oils. For both oils, one hundred percent encounter of the slick was confirmed for all tests.

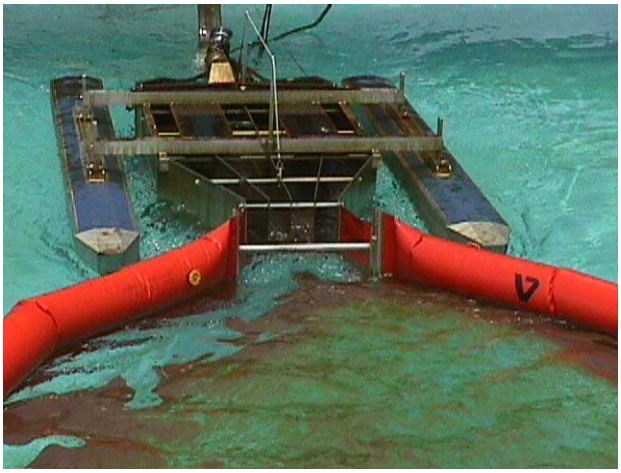

Figure 16A. Skimmer recovering Hydrocal.

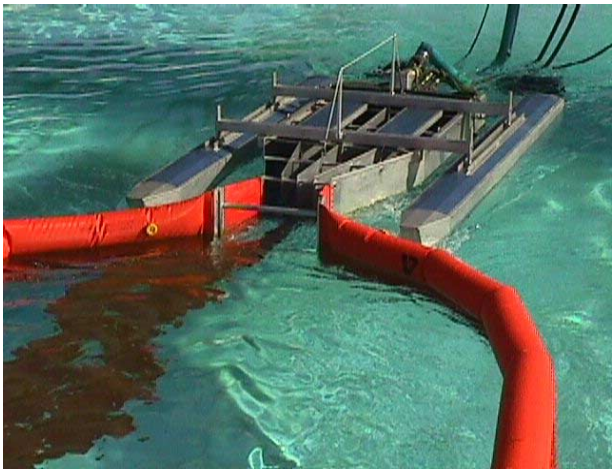

Figure 16B. Skimmer recovering Sundex.

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During testing, the flow pattern of oil through the expansion zone (the four flow chambers) was observed to flow predominately into the outermost channels. After test numbers 88-89, the sweeping boom angle was changed from 15° to 12° resulting in a mouth width of 16.5 feet (5 m). The change appeared to balance the surface oil flow through the expansion zone to the self-adjusting weir for the two-knot runs.

The average TE while recovering Hydrocal (tests number 100-101, 108-109, and 110-111) was 82 percent. Test 112-113 was considered a unique data point due to a lower offload pump rate that may have overloaded the collection well. While experiencing harbor chop wave conditions during tests 92-93 and 104, the TE values were near zero for both oil types. The FasFlo skimmer in harbor chop waves creates severe mixing action at the skimmer mouth and oil was lost behind the skimmer. (see Figure 17) It was observed that the test oil that reached the weir was a small percentage of the recovered fluid due to the mixing.

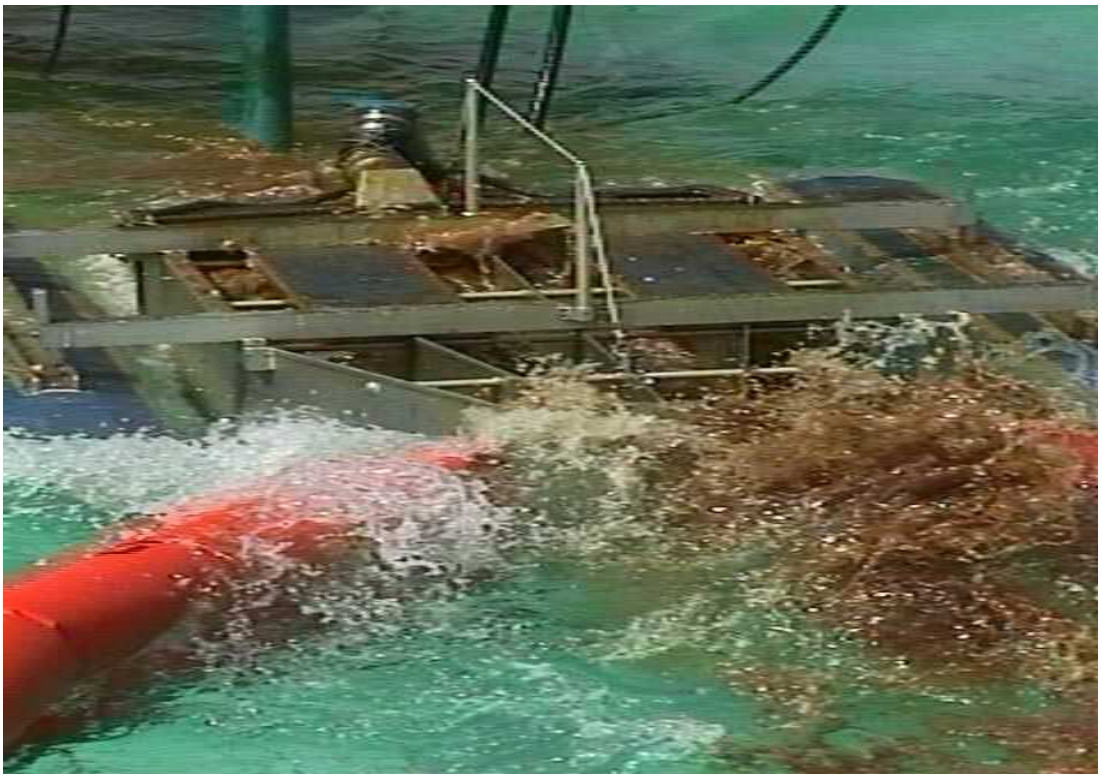


Figure 17. FasFlo Skimmer in Harbor Chop Waves.

The TE performance results at three knots are shown in Table 10. Tests 86-87, 90-91, and 96-97 were performed with all independent test parameters as constants. The sweeping boom width was changed prior to test 90-91 from 20 feet (6.1m) to 16.5 feet (5 m). This change was made to reduce the overall volume of fluid entering the skimmer, to increase the tow speed before loss of freeboard, and to aid in balancing surface oil flow through the expansion chamber to the internal weir. Although tests 90-91 and 96-97 resulted in higher TE values, the surface oil appeared to stagnate in the two center channels but continued to flow well in the outboard ones.

Table 10. FasFlo TE values at 3 knots.

Test Number	Oil Type	Surface Condition	TE (%)
86-87	Sundex	Calm	11
90-91[1]	Sundex	Calm	39
96-97	Sundex	Calm	22
102-103	Hydrocal	Calm	13
114-115[2]	Hydrocal	Calm	0
116[3]	Hydrocal	Calm	0

*Notes: 1) Change in sweeping boom angle is 15° to 12°
2) Sweeping boom mouth opening changed to 7 feet (2.1 m)
3) Hydrofoil was adjusted from 2° negative to 6° negative

Test 102-103 resulted in a TE of 13 percent. The change in oil type, from Sundex (heavy) to Hydrocal (light), was the only parameter change from the previous. In an effort to increase TE performance, the sweep boom mouth opening was reduced to seven feet between the tow points.

Two experimental runs were performed during which no measurable amount of oil was collected (Test number 114-115). Prior to test 116, the hydrofoil was adjusted from 2° negative to 6° negative, with no measurable amount of oil recovered. According to the manufacturer's representative, the optimum position of the hydraulic jump deflector plate (mesh) relative to the water line is to have 1-2 inches exposed. To achieve the proper deflection plate position relative to the water line at 3 knots, the pontoons were adjusted vertically. The final adjustment change raised the skimmer by two inches at the stern, and one inch at the bow.

The 4-knot oil recovery performance results are shown in Table 11. For the 4-knot tests, the sweeping boom mouth width for test 94-95 was 20 feet (6.1 m), for test 106-107 the width was 16.5 feet (5 m), and for test 128-129 the boom width was 7 feet (2.1 m). Prior to test 128-129, four dry runs were performed at 4-knot tow speeds during which, adjustments were made to the hydrofoil. The weir appeared to function properly at four knots with the Hydrofoil at 0 °, although the horizontal plate inside the skimmer was not below the waterline. Table 12 summarizes the tow speed and average tow force per boom leg.

Table 11. FasFlo TE values at 4 knots

Test Number	Oil Type	Surface Condition	TE (%)
94-95	Sundex	Calm	5
106-107	Hydrocal	Calm	3
128-129	Hydrocal	Calm	0

Table 12. FasFlo Tow Force Values

Tow Speed (knots)	Surface Condition	Average Tow Force per Boom Leg (lbf)
2	Calm	173
3	Calm	349
4	Calm	605
2	Harbor Chop	166

3.4 Discussion of Results

At two knots, the FasFlo skimmer was effective at recovering high percentages of the oil it encountered. At three-knot tow speeds and higher, the internal flow velocity was high which caused entrainment of the surface oil. This oil exited with the water discharged from the bottom of the skimmer.

Above two knots, a stagnation condition occurred forward of the collection well. Flow was assisted over the weir only by the induction created by the offload pump. Monitoring the fluid level within the skimmer hull was essential to achieve proper operation of the self-adjusting weir. For optimum oil recovery using the FasFlo skimmer, multiple adjustments were required to achieve the proper internal flow rate, as well as oil/water elevation in the skimmer. This would make it difficult to operate during an actual spill if conditions changed.

4.0 Testing of the High Speed Circus

4.1 Skimmer Description

The High Speed Circus is composed of the collector (shown in Figure 18), inboard and outboard sweeping arms, guide and control lines, and a Foilex Mini Well Skimmer. The Circus collector dimensions are 5.5 feet (1.7 m) long by 4 feet (1.2 m) wide, and 3.25 feet (1 m) high, and weighs approximately 290 pounds (130 kg). The collector was constructed of aluminum including the floatation chambers located on the outer perimeter. The sweeping arms are aluminum tube frames with internal floatation panels built into the barrier fabric. Three models of the Circus skimmer are available from the manufacturer. The model that was used during this evaluation is recommended for harbors, sheltered waters and rivers.

The Circus collects oil by using the sweeping arms to direct the surface water with the oil into the collector. The oil stays on the surface and is recovered by a built-in skimmer head. The excess water continues around the collector and out the bottom below the sweep arm. The Foilex Mini Well Skimmer was equipped with a floating weir head, which was self-adjusting and operational for a 6-inch (15.25 cm) vertical range. Cargo discharge was through a 3 inch (7.6 cm) by 25-foot (7.6 m) soft hose. Two pumps were used during the study. Initial offload pumping was accomplished using an Ohmsett provided peristaltic pump. During later testing, a Desmi DOP-250 pump with a higher pumping capacity was utilized.

Figure 18. Circus Collector.

4.2 Test Setup

The Circus was configured in the test basin to simulate recovery operations along a side of a vessel. A rigid wall was constructed and installed from the Main Bridge to the Auxiliary Bridge that simulated the starboard side of a ship, as shown in Figure 19. The Circus collector was orientated as recommended by the manufacturer with the bumpers against the wall with the inlet facing away from the side of the wall. The collector was using a total of six control lines; four lines tied to the collector functioned as attaching mechanisms and a means of adjusting the pitch, roll and vertical orientation and two lines to control the inboard and outboard sweeping arms. All control lines were routed to the Ohmsett bridges so that they could be easily adjusted. The sweeping arms attached to the collector with a slide and pin connection, which allowed for vertical adjustment. Suspending the inboard end sweeping arm from the top rail of the collector controlled each sweeping arm elevation, relative to the water line. Lines were used initially, but were later changed to quick connect links and shackles for easier adjustments.

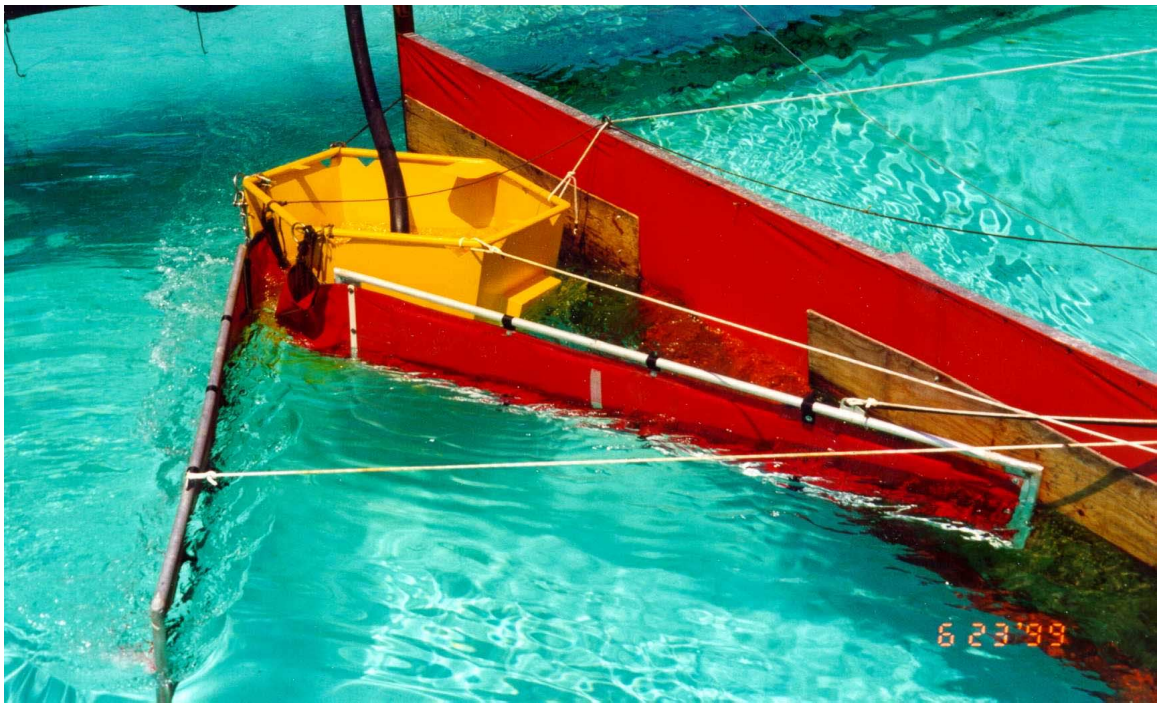


Figure 19. Circus Test Setup.

4.3 Detailed Test Description and Results

Recovery tests were performed using the same technique as discussed in Section 1.3.2. The distribution rate was equivalent to the pumping capabilities of the offload pump. The offload pump was started approximately ten seconds after encountering the spilled oil and ran continuously until the last of the oil encountered the skimmer Tows without oil were performed at the intended test speed to adjust the Circus skimmer collector and sweeping arms.

The first two tests were performed at 1 and 1.5 knots in calm surface conditions. The oil recovery performance results in terms of TE were 90 percent at one knot and 65 percent at 1.5

knots. At 2 knots, the fluid level within the collector raised above the floating weir head. Raising the sweeping arms two inches provided the adjustment necessary to attain the proper internal operational fluid level with respect to the Foilex skimmer. This reduced the draft, therefore resulting in a reduction of the flow into the collector.

A total of eight 2-knot tests were performed and the results are given in Table 13. Tests 134-135 and 136-137 were performed with all independent variables the same except for the offload pump rate which was reduced by 50 percent (from 35 to $17^1/_2$ gpm). This resulted in a 10 percent reduction in TE. Tests 134-135 and 140-141 were repeat tests with respect to independent variables. After test 147, the offload pump was switched to a DOP-250 pump, which is capable of significantly higher pump rates. Test 148-149 was performed at 2 knots with calm surface conditions and the DOP pump was operating at 70 gpm, which is 200 percent of the distribution rate. The result was a maximum TE of 90 percent. Test 157-158 was performed using the same parameters as in Test 148-149, except that the DOP-250 was operated at 50 gpm. The result was a TE of 80 percent, a reduction of 10 percent.

Table 13. Circus TE values at 2 knots

Test Number	Oil Type	Surface Condition	TE (%)
134-135	Hydrocal	Calm	84
136-137	Hydrocal	Calm	76
139	Hydrocal	Harbor Chop	0
140-141	Hydrocal	Calm	89
148-149[1]	Hydrocal	Calm	90
157-158[1]	Hydrocal	Calm	80

Note: 1) Offload Pump was Desmi DOP-250

Test 139 was performed in harbor chop waves during which no oil was recovered; see Figure 20. The $H^1/_3$ significant wave height for this particular test was about 11.7 inches (29.7 cm). No further tests were performed with waves due to mixing action, overloading of the collector and submergence of the weir head.

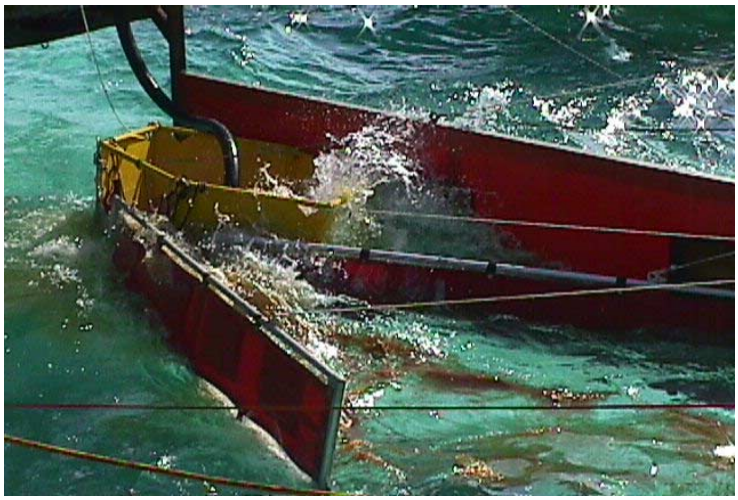


Figure 20. Circus in Harbor Chop Waves.

The Circus achieved a TE of 32 percent for test 142-143 at 3 knots with Hydrocal oil in calm surface conditions using the peristaltic offload pump as shown in Table 14. During tests 151-152 and 153-154 the Circus did not adjust to the proper floating level, resulting in a non-operational position of the skimmer weir head. No setup changes were made between passes. For data purposes, these were not considered valid tests. Under the same conditions but increasing the DOP-250 pump rate to 90 gpm (actual), the highest TE obtained was 50 percent during test 155-156. The sensitivity of proper rigging was noted according to observations.

Table 14. Circus TE values at 3 knots.

Test Number	Oil Type	Surface Condition	TE (%)
142-143	Hydrocal	Calm	32
151-152	Hydrocal	Calm	0
153-154	Hydrocal	Calm	14
155-156	Hydrocal	Calm	50

4.4 Discussion of Results

The recovery tests performed ranged from one knot to three knots. A maximum TE of 90 percent was obtained at one and two knot tow speeds in calm surface conditions. At three knots, a maximum TE of 50 percent was attained with a corresponding RE value of 11 percent. In order for the Circus to operate effectively, the water/oil level within the skimmer must be within the operational range of the floating weir. When changing skimming speeds, system adjustments were necessary to obtain an operational fluid level in the collector. The elevation of the sweeping arms provided a rough adjustment of water level at a given tow speed and adjusting the mouth opening provided a fine adjustment. Alternatively, with the sweeping arms too high, the water level in the hull was low, rendering the weir ineffective and allowing larger volumes of oil to entrain. The sweeping arms were adjusted and secured to the Circus hull by using quick connects which were easily installed and removed. At 1 knot and 1.5 knots, operational water level was obtained when the top of the sweeping arms were positioned approximately 12” (30 cm) from the top of the Circus hull, as shown in Figure 21.

Figure 21. Circus Skimmer with Sweeping Arms Positioned 12” from the Top of Hull.

At 2 knots, the proper fluid level in the collector was obtained by raising the sweeping arms 4" (10 cm). At 3-knot tow speeds, the sweeping arms were positioned near the top of the Circus hull, as shown in Figure 22.

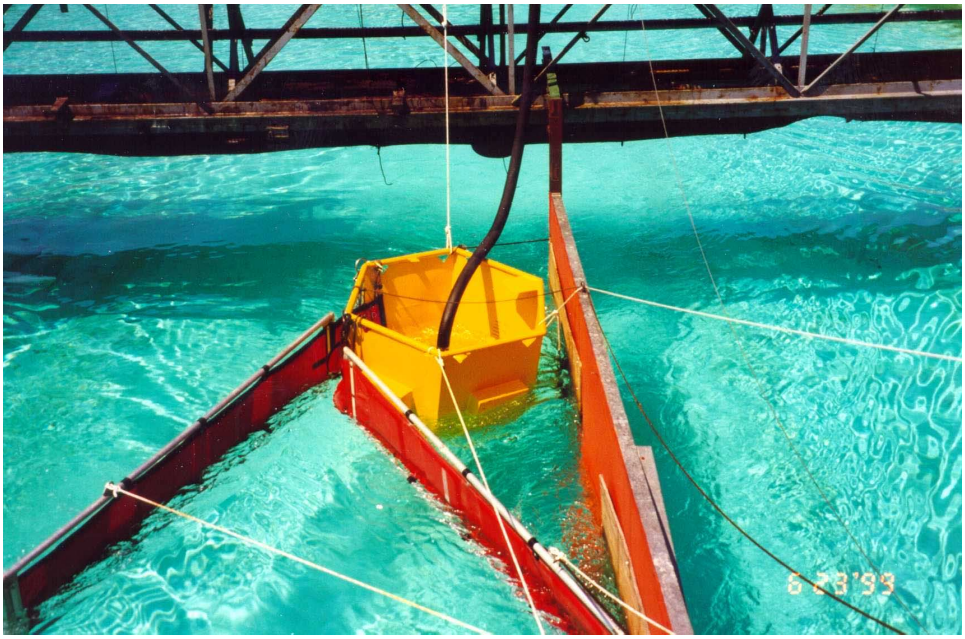


Figure 22. Circus Hull with Sweeping Arms Positioned near the Top of Hull.

When operated properly, a vortex formed in the hull, which aided in funneling surface oil towards the weir as shown in Figure 23.

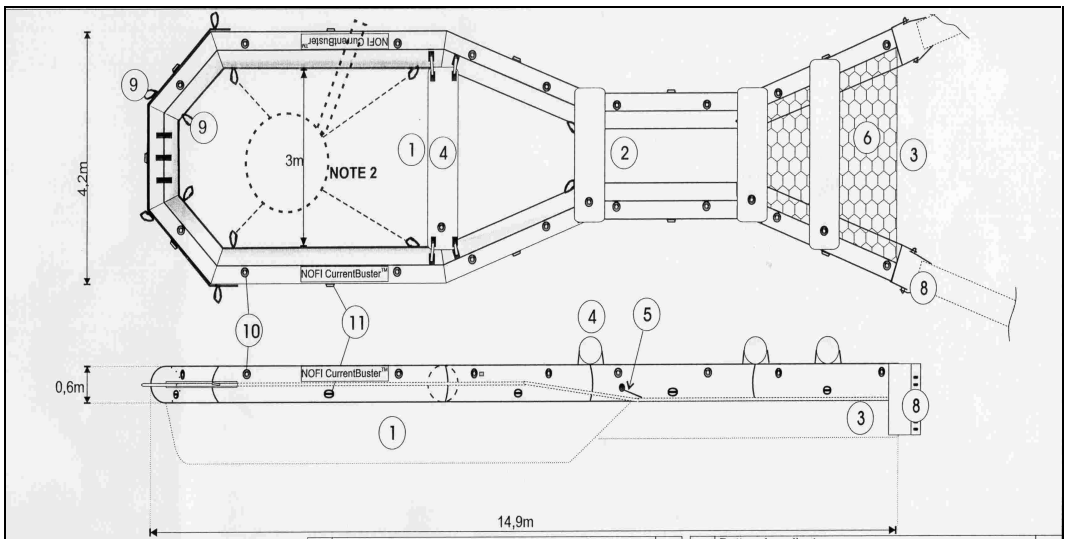
Figure 23. Vortex in Circus Hull.

One of the problems identified during this test was the fluid mixing inside of the hull. This mixing resulted in some of the oil leaking out from under the lead booms and also did not permit the surface skimmer to remove the oil. It appeared to be caused by the flow into the side of the device that impacted on the far side, perpendicular to the flow. Water moved up this surface several inches, creating a head that resulted in a downward flow.

5.0 Testing of the NOFI Current Buster™ High Speed Oil Containment System

5.1 Skimmer Description

The NOFI Current Buster™ Skimmer consists of a sweep with netting (collector) with an open apex, a tapered channel (a skimming device) and a separator (see Figures 24 and 25). The dimensions are 50 feet (15 m) across the sweep mouth, with an overall length of 91 feet (28 m), and a draft of 40 inches (1 m). The sweep collector and collector guide the spilled oil into the tapered channel and then into the separator. The separator tank has a draft of approximately 4 feet 6 inches and has a gross capacity of approximately 6000 gallons. Water is allowed to flow out through an outlet in the bottom of the separator. The Current Buster system can be disassembled into more manageable sized components and packaged on one pallet. It can also be deployed easily from a reel. It is equipped with numerous eyelet type connectors through which coated wire cable is threaded to secure each connection. The separator is equipped with heavy-duty loops around the inside perimeter for securing and mooring a pump or skimmer.



Pos	Description	No. Ant.
12		
11	Handholds	11
10	Inflation valves	22
9	Heavy Duty Fastening Loops (mooring, towing, pump/skimmer fastening etc.)	10
8	DRC Dynamic Response Connector for connection to 450, 600 or 800 sweep	2
7	deleted	1

Pos	Description	No. Ant.
6	Bottom in collector	1
5	Flip	1
4	Transverse bladder	4
3	Collector	1
2	Tapored Channel Skimming Device	1
1	Separator	1

NOTES
1 All measurements in meters
2. An external floating pump or skimmer may be used (not part of the supply)

Figure 24. Current Buster™ General Arrangement.

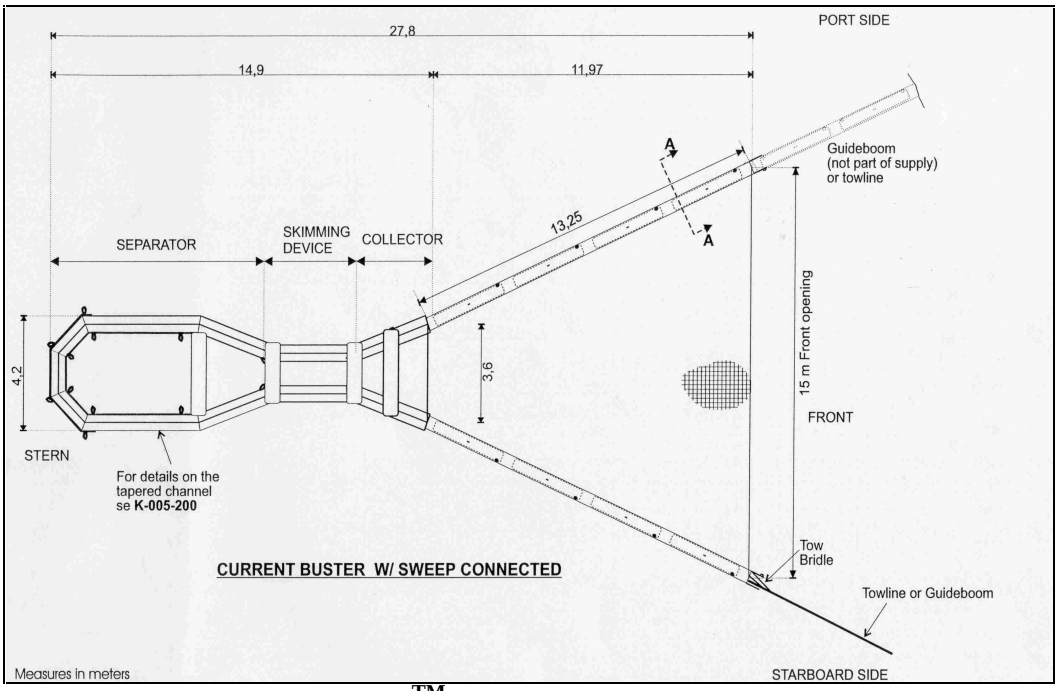


Figure 25. Current Buster ™ Skimmer with Sweep Boom Connected.

5.2 Test Setup

The Current Buster recovery system was rigged between the Ohmsett Main Bridge and the Auxiliary Bridge. Figure 26 shows full deployment of the sweeping boom and the Current Buster system. Tow points were separated 50 feet (15.25 m) to accommodate the sweep mouth. Offloading the recovered oil was accomplished using a Desmi Terminator weir skimmer. The skimmer was powered through a control stand and prime mover, located on the Auxiliary Bridge. This raised concerns as to possible tank bottom effects during testing.

Figure 26. Current Buster Skimmer Setup.

5.3 Detailed Test Description and Results

Prior to testing with oil, dry runs were performed to observe proper operation of the recovery system. When towed at 4 knots, the sweep lost freeboard. To reduce the influx of water into the sweep boom, the tow point separation was adjusted from 50 (15.25 m) to 35 feet (10.7 m) across. The on-site engineer identified that the separator tank did not reach its "full" status as when towed for a longer duration or at steady state conditions. To aid in maintaining the separation tank shape, a supplemental supply of water was continually pumped in. It was also concluded that the separation tank shape would not affect collection performance.

During the oil recovery tests, the system encountered a slick equivalent to a 5-mm slick at the throat of the entrance to the tapered channel-skimming device. The TE values were determined by quantifying the lost oil versus the volume encountered. Table 15 shows the 2-knot TE results.

Table 15. Current Buster TE values at 2 knots

Test Number	Oil Type	Surface Condition	TE (%)
159-160-161	Hydrocal	Calm	91
171-172	Hydrocal	Harbor Chop	61
175-176	Sundex	Calm	98
182-183	Sundex	Harbor Chop	94
188-189	Hydrocal	Harbor Chop	90
199	Hydrocal	Harbor Chop #2	78

During the first 2 knot test (test 159-161), oil losses were observed from the water drain located in the Tapered Channel Skimming Device section forward of the flip valve, although 91 percent of the encountered oil was recovered. With harbor chop wave conditions (test 171-172), the Current Buster collected 61 percent of the encountered oil. After test 171-172, the manufacturer representative identified a flow restriction into the collection tank due to the flip valve so the flip valve was removed. All subsequent tests were performed without the flip valve in place. The purpose of the flip valve was to retain collected oil in the separator. This was not a problem while the system was advancing. Test 171-172 was repeated as test 188-189, where a 90 percent TE was achieved. The significant improvement was attributed to the removal of the flip valve. At 2 knots in calm and harbor chop waves, the Current Buster recovered 98 percent and 94 percent, respectively, when recovering Sundex.

Table 16 shows the performance data for the 3-knot runs. Test 162-163-164 was performed prior to removing the flip valve, resulting in a TE of 88 percent. Once the flip valve was removed (test 194-195), the TE improved to 95 percent. Testing with Sundex and Hydrocal during harbor chop wave conditions resulted in TE values of 60 and 69 percent, respectively. Harbor chop wave type number 2 did not have a significant effect on the TE. Harbor chop wave #2 had an $H^1/_3$ significant wave height of 13.7 inches compared to an averaged 10.9 inches for the standard harbor chop wave. The volume of oil lost includes minor losses due to splashover.

Table 16. Current Buster TE values at 3 knots

Test Number	Oil Type	Surface Condition	TE (%)
162.163,164	Hydrocal	Calm	88
194-195	Hydrocal	Calm	95
196-197	Hydrocal	Harbor Chop	69
198	Hydrocal	Harbor Chop #2	62
177-178	Sundex	Calm	98
184-185	Sundex	Harbor Chop	60

At 3.5 knot tow speeds, the TE values were 91 percent for both oil types in calm surface conditions. (see Table 17) The increase in tow speed from 3 to 3.5 knots did not affect TE performance. During five tests at 3 and 3.5 knots conducted in harbor chop waves while recovering both test oils, all TE values were between 60 percent and 70 percent.

Table 17. Current Buster TE values at 3.5 knots

Test Number	Oil Type	Surface Condition	TE (%)
169-170	Hydrocal	Calm	91
190-191	Hydrocal	Harbor Chop	65
180-181	Sundex	Calm	91
186-187	Sundex	Harbor Chop	70

A test was performed to quantify the volume of oil which can be collected in the separation tank before entrainment of oil and losses would be notable from the separation tank discharge. Approximately twenty-five hundred gallons of Hydrocal test oil was pumped into the separation tank while stationary. Retaining the oil within the separation tank was accomplished by the use of water cannons producing a current forward of the collector. The Current Buster was then accelerated to 2 knots, at which time, losses were observed from the separation tank discharge.

5.4 Discussion of Results

The NOFI Current Buster™ High Speed Oil Containment System tested well overall, but it is not clear if its full capability was reached. When in steady-state recovery conditions, the system is designed to allow out-flow of encountered water through the separator discharge located at the bottom of the separator tank. This hydrodynamic equilibrium was not achievable during 4 knots runs within the length of the test basin. Attempts to test at speeds of 4 knots resulted in an overfull separation tank and loss of freeboard. The freeboard of the sweep boom and netting left approximately 6 feet of clearance between boom and tank bottom, which was sufficient to rule out tank effects at the leading edge of the collector. The separation tank's operational shape may have been affected. If so, this would not have affected the recovery performance, which physically occurs at the tapered channel-skimming device.

The quantity of recoverable oil into the separation tank before losses would occur was not determined, but a range was identified. During the capacity test, losses did occur at 2 knots with twenty-five hundred gallons in the separation tank. During the series of TE tests performed, the recovered oil was allowed to accumulate. A volume of twelve hundred gallons was measured

when offloaded from the separation tank. No oil losses were observed during previous tests at 2 and 3 knots. Therefore, the quantity of oil retained before losses will occur was determined to be between twelve hundred and twenty-five hundred gallons although it is most likely closer to the higher number.

The Current Buster™ collects oil at the highest TE than any other system ever evaluated at speeds over 3 knots. The values for TE were 65 percent for harbor chop and 91 percent in calm water at 3.5 knots.

6.0 Conclusions and Recommendations

Four fast water systems utilizing several approaches to oil spill recovery have been evaluated at speeds up to 5 knots. Both calm water and harbor chop waves were used. A standard protocol was also developed to ensure quality of the data collected at speeds over 3 knots at Ohmsett. This series of tests was not a contest or a contractual obligation. Rather it was an opportunity for manufacturers to find the limits of their systems and attempt to improve their performance. Manufacturers usually do not get this type of opportunity.

The two systems that worked the best at the higher speeds were the NOFI Current Buster™ and the JBF 600 skimmer. Both of these systems have had extensive time and money devoted to their development. The Norwegian government helped to fund the development of the Current Buster™ starting about 5 years ago. The JBF 600 was selected as the Coast Guard's High Speed Skimmer (HSS) after a round of competition in 1996 and further design and evaluation in 1997. These are examples of the magnitude of an effort needed to bring a product to market successfully. The High Speed Circus is just getting some exposure in the United States after being evaluated in Scandinavia and used for cleanup in Vietnam. This is the first time that the Circus, the Fasflo and the Current Buster™ were tested at high speeds with oil. All of the systems are small enough to be deployed from vessels, although some heavy lifting and rigging may be required. They also appear to be robust enough to handle the forces encountered in fast currents, but may not be useful in shallow areas where rocks and debris may puncture the booms.

The tests indicate that all of the systems can efficiently collect oil in calm water with two knots of current. This performance is better than most other systems of similar size. The two larger systems, the JBF 600 and the Current Buster™, can work effectively up to 3 knots and 3.5 knots, respectively. The JBF 600 was able to recover some oil up to five knots although some issues were raised with the results. Further investigations into the issues raised, such as belt speed and lead-in booms, is needed to ensure that this is an effective system for the Coast Guard. Although the size of the Current Buster™ did not permit tow speeds over 3.5 knots, the trends indicate that it will be very efficient at higher speeds. It also performed well in wave conditions, which occur in many oil spill situations. The efforts at Alyeska Pipeline, who owns this equipment, to use this system should be followed to determine if it would work with the CG Spilled Oil Recovery System (SORS) System. The compact storage size of the Current Buster™ could be helpful given to lack of storage on CG buoytenders. The two smaller systems may be useful in some situations but it is not clear that they provide more capability than correctly utilized deflection boom currently provide.

The effect of lead-in booms was documented in these tests. If a wide sweep width is required, conventional boom without netting or cross bridles may form a catenary resulting in a typical boom oil loss scenario. All of the systems encountered this problem at higher speeds when the opening width was set for two knots. Previous tests (DeVitis, 1996 and Goodwin, 1993) showed that underwater netting decreases the oil lost from under the booms by delaying the failure mechanisms. This test confirmed the use of netting to reduce oil losses at speeds over 1 knot. The use of cross bridles on the Canflex High Current Boom also improved the boom's performance but may not be a good substitute for netting.

The other issue with respect to the lead-in booms is their influence on the flow into the skimmer. First, while a wider sweep width increases the area that can be skimmed, it also increases the amount of flow introduced into the skimmer. The large amount of water can influence the skimmer's operation, especially if the opening for the water to escape is small. This was especially apparent in testing the High Speed Circus and Vikoma Fasflo, but was true for the other systems as well. In addition, most conventional booms are not smooth, having seams and connectors along their length. These create complex wave and flow patterns that can affect the movement of the oil. All of the skimmers in this test had problems with complex flows, especially the Fasflo because of it's narrow opening. To reduce water intake and wavemaking, in calm conditions, the lead-in booms should be seamless, semi-rigid and have a shallow draft and high freeboard. Some flexibility should be designed into booms for wave conditions. A redesign of the Canflex boom is needed to meet these criteria. The redesign should be evaluated and compared to the current Vee-sweep system.

There is still a lot to learn about containing and recovering oil in fast currents. Not only does the equipment have to be designed correctly, but it has to be used correctly. In addition, most manufacturers do not have the ability to perform fast water tests with oil. Use of rice hulls and pine bark are not always adequate to evaluate system performance. The tests documented here also show that performance for 3-5 knots cannot be extrapolated from data at 1-2 knots. To increase industry's and the Coast Guard's capabilities, more research needs to be done by performing full-scale testing of equipment to verify manufacturer's specifications.

Finally, the commercial regulations for the Oil Spill Response Organizations (OSRO) and the Coast Guard's own response capability should be evaluated with respect to the data supplied here. It would be useful to correlate the reduction in capability that is currently in the regulation with actual data. This project will continue to evaluate fast water systems at Ohmsett and in the field over the next year and will provide that information to the decision-makers. The result should provide recommendations for methods and techniques that can safely contain oil in fast currents.

7.0 References

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Appendix A. Facility Description

Ohmsett, the National Oil Spill Response Test Facility, has the ability to test full-scale oil spill response equipment; conduct research to improve spill response technology; and hold training sessions with oil in a simulated marine environment under controlled conditions. The Ohmsett facility is located in Leonardo, New Jersey approximately one hour south of New York City.

Ohmsett has been operated and maintained by MAR Incorporated under contract to the U.S. Department of the Interior, Minerals Management Service (MMS) since 1992. Ohmsett is used by both the public and private sectors for evaluation of oil spill response equipment such as booms, skimmers, and temporary storage devices. Ohmsett is also used for research in remote sensing techniques for oil spills, oil behavior and characteristics, and for the evaluation of the fire resistance of containment boom.

The facility's outdoor, above ground, concrete tank is 203 meters (667 feet) long and 20 meters (65 feet) wide, with a water depth of 2.4 meters (8 feet). The tank is filled with 9.84 million liters (2.6 million gallons) of brackish water (maintained at 15-20 parts per thousand) drawn from nearby Sandy Hook Bay. Conditions simulating ocean conditions are created with a wave generating system and a wave dampening artificial beach. Moveable bridges tow equipment at speeds up to 12.6 meters/sec (6.5 knots). Tests can be viewed from travelling bridges, the control tower, or underwater viewing windows on the side of the tank. The data collection and video systems record test results both above and below the water's surface.

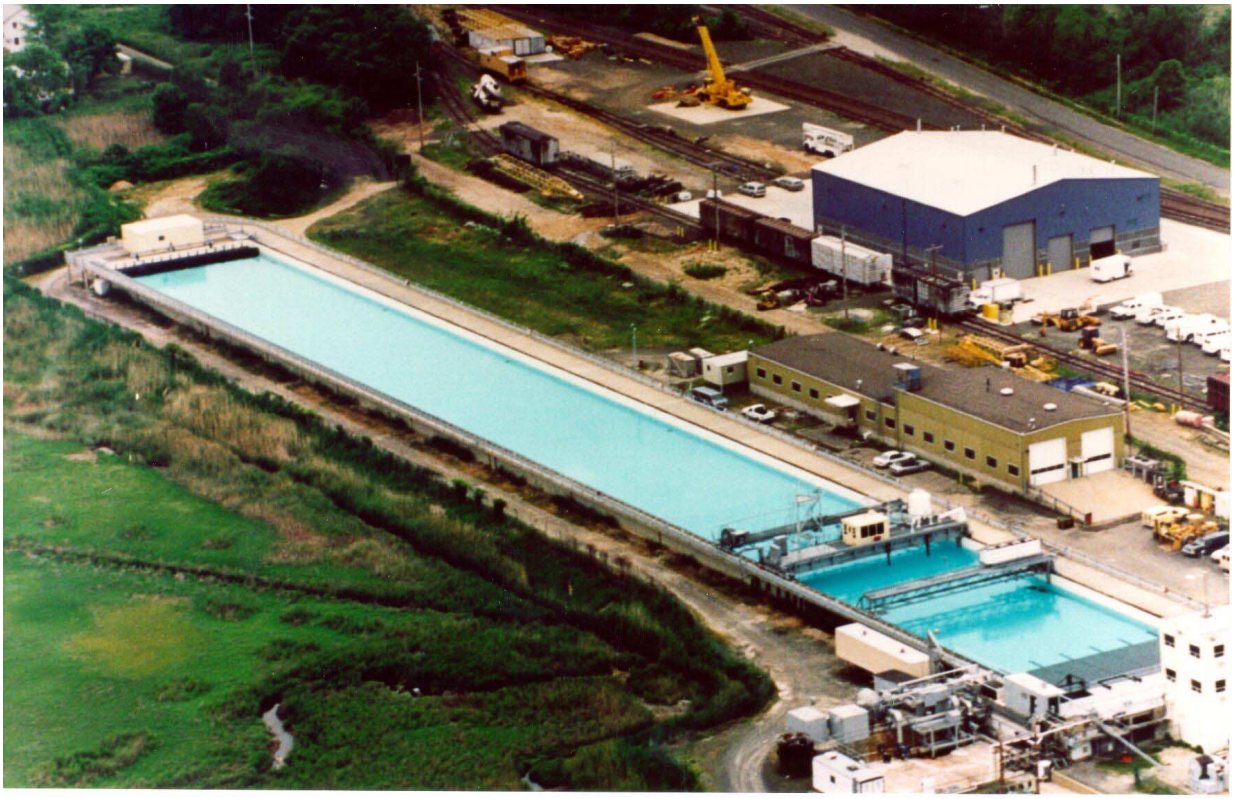

Figure A-1. Ohmsett test tank.

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Appendix B. Method of Calculation for Skimmer System Performance Data

Skimmer performance is typically quantified in terms of Throughput Efficiency (TE), Recovery Efficiency (RE), and Recovery Rate (RR). These volume, rate and time measurements are obtained while operating the skimmer in various pre-determined conditions. These measurements become the basis from which the skimmer performance data was calculated. The measurements include volume of oil encountered, total volume of fluid recovered, volume of oil recovered, and oil Recovery Time. The method of obtaining each is described below:

(1) Volume of oil encountered is equal to the total volume distributed during the test assuming that the skimmer encounters 100 percent of the oil. This value is calculated based on initial and final measurements using the Ohmsett Main Bridge sonic level sensor located on the storage tank. The storage tank level sensor output is in percentage, 100 percent is full, and 0 percent is empty. The percentage is converted to gallons using a table of percent vs. gallons. Using the Ohmsett computerized data collection system, the initial tank level, the change in level during a test, and the final tank level are recorded. As a back-up data source, the Fluid Transfer Technician will manually record tank level readings by test number on the oil distribution log.

(2) Total volume of fluid recovered by the skimmer is calculated from values of fluid depth measurements in the recovery tanks. The skimmer cargo line is connected to the recovery tank manifold where valves are used to direct recovered fluid to specific compartments. There are eight (8) compartments totaling a capacity of 2000 gallons. The depth measurement is multiplied by a factor converting inches to gallons. Each compartment is calibrated and has a specific multiplier factor (**K**) for the conversion. The test numbers, depth measurements and compartment numbers are recorded on the "Auxiliary Bridge Recovery Log."

(3) Volume of oil recovered is calculated from the depth value of the oil after the free water is removed from the compartment. The free water is removed by opening under-drain valves in each compartment and closely observing the decanting process. At the first sign of oil flowing from the under drain, the valve is closed and the second depth measurement is obtained. A sample of the remaining oil is obtained using a grab sampler or a stratified sample thief, depending on the fluid level. The samples are labeled by test number, compartment number and sample method before being sent to the Ohmsett Laboratory for bottom solids and water (BS&W) analysis. Water and Sediment in Petroleum Analysis is described in Appendix C and is reported as a percent based on volume. The percent oil is 100 percent minus the percent BS&W.

The equation used to calculated the volume of oil in a recovery tank compartment is:

Volume of Oil = **K** * depth * (percent oil)

K = multiplier to convert from depth (inches) to volume (gallons)

(4) Oil recovery time is the time in minutes that the skimmer system is operating and encountering distributed oil. At the moment the distributed slick is encountered by the skimmer, the oil recovery time begins. The start and finish time is recorded in the form of a voltage spike, which is recorded on a data channel on the data collection computer. Flow from the skimmer through the Ohmsett recovery tank three-way main valve is directed to predetermined recovery

tank compartments. Once the skimmer encounters the entire slick, the recovery time ends. At test end, the remaining fluid in the skimmer collection well is pumped to a separate compartment of the recovery tanks. Pumping to the recovery tank continues until the skimmer sump is clear of oil. This "remaining oil volume" is included in the total volume recovered for use in the calculation of RR and TE only. Total volume recovered for the RE calculation is determined from the volume of fluid recovered during the actual test runs.

(5) Definitions

$$\text{Recovery Efficiency } (\mathbf{RE}) = \frac{\text{Volume of Oil Recovered}}{\text{Volume of Fluid Recovered}} * 100$$

$$\text{Throughput Efficiency } (\mathbf{TE}) = \frac{\text{Volume of Oil Recovered}}{\text{Volume of Oil Encountered}} * 100$$

$$\text{Recovery Rate } (\mathbf{RR}) = \frac{\text{Volume of Oil Recovered}}{\text{Oil Recovery Time}}$$

Appendix C. Fluids Testing

The oils selected for the skimmer evaluations are stable and have properties that do not vary during a test run. The test oils are refined products and do not have the volatile organic compounds associated with crude oils, however, this does not preclude the test facility from using crude oils if required. Current standard test oils are Hydrocal 300, Calsol 8240, and a heavy Sundex 8600T. Test oils are typically deployed at ambient temperatures, which allow for closer tracking of viscosities during the tests. Table C-1 contains a list of the typical oil properties. Each of the test oils is characterized in the Ohmsett laboratory using applicable ASTM standards. The measurements include surface and interfacial tension, viscosity, specific gravity, and bottom solids and water. A description of these ASTM test methods is described below. The measurements made in the chemistry laboratory at the Ohmsett Facility are as follows:

Table C-1. Standard Test Tank Oil Properties

Test Oils Types	Oil Properties at 25 ^{o} C				
	Viscosity (cPs)	Specific Gravity	Interfacial Tension (dyne/cm)	Surface Tension (dynes/cm)	Bottom solids and H_20
Hydrocal 300	150	0.90	26.7	32.8	< 2%
Calsol 8240	1,400	0.93	31.0	36.2	< 2%
Sundex 8600T	14,000	0.96	32.1	35.5	< 2%

1. Viscosity - ASTM D2983-87 Standard Test Method for Low-Temperature Viscosity of Automotive Fluid Lubricants Measured by Brookfield Viscometer

Viscosity is measured using a Brookfield Engineering Model LV Viscometer. The samples are collected in 600 ml beakers, the contents are cooled to 10 °C (50 °F), then the temperature is raised to 60 °C (140 °F) using a Brookfield Constant Temperature Bath. Viscosity measurements are made every 10 °C (50 °F), yielding a Temperature versus Viscosity curve for each sample collected. This is done to find the viscosity at variable test temperatures and is done for the oil in the test tank.

2. Surface & Interfacial Tension - ASTM D971-91 Standard Test Method for Interfacial Tension of Oil Against Water by the Ring Method

Surface and interfacial tensions are measured with a Fisher Scientific Tensiomat. Approximately 50 millimeters of oil is needed to determine both surface and interfacial tensions. Measurements are made under standardized nonequilibrium conditions in which the measurement is completed one minute after formation of the interface.

3. Specific Gravity - ASTM D1298-85 (1990)e Standard Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method

This analysis is performed using the hydrometer method. The oil sample is transferred to a 500-ml cylinder and the appropriate hydrometer is lowered into the sample and allowed to settle. The hydrometer scale is read and the temperature is recorded.

4. Water and Sediment - ASTM D 1796-97 Standard Test Method for Water and Sediment in Fuel Oils by the Centrifuge Method (Laboratory Procedure)

A recovered oil sample of approximately 100 mls is mixed with an appropriate solvent (toluene), heated to 60 °C (140 °F) if necessary to assure sample uniformity, and rotated at 2,000 rpm in a centrifuge for 15 minutes. The amount of water and sediment is measured and the percentages calculated from the amount of sample used.

5. Oil And Grease - ASTM 3921-96 Standard Test Method for Oil and Grease and Petroleum Hydrocarbons in Water

A 500 - 1000 ml water/oil sample is acidified to a pH less than 2.0 and the oil is extracted with carbon tetrachloride. The oil and grease concentration is determined by comparison of the infrared absorbance of the sample extract with a known-oil reference standard, using a Shimadzu IR-435 Spectrophotometer.

Table C-2. Typical Physical Characteristics of Hydrocal 300 and Sundex 8600T

Characteristic @ 25°C	Hydrocal 300	Sundex 8600T
Specific Gravity	0.88	0.95
Surface Tension	29-32 dynescm	30-36 dynes/cm
Interfacial Tension	26-28 dynes/cm	27-32 dynes/cm
Viscosity @ 25°C	200 cPs	10,000 cPs

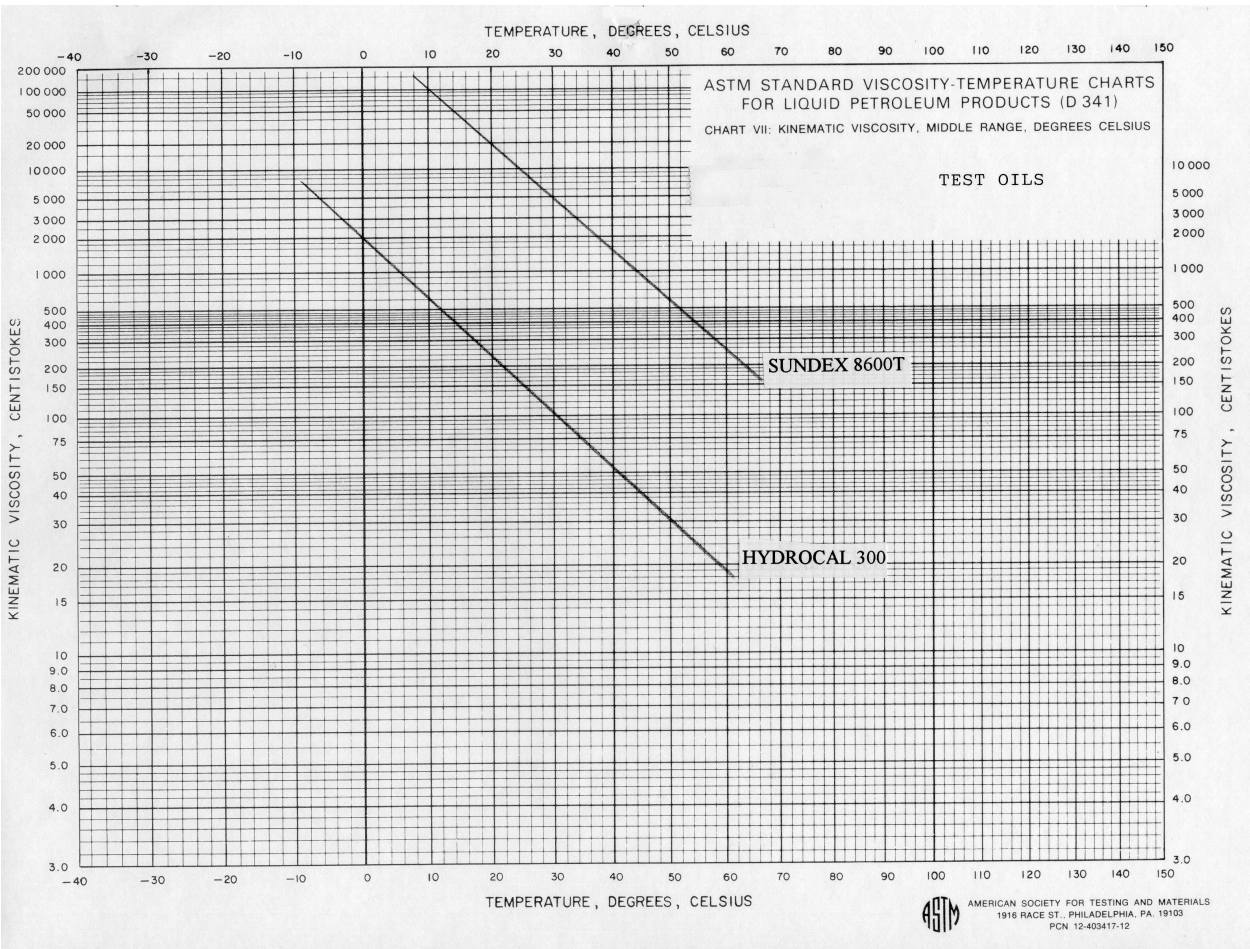

Figure C-1. Oil Viscosity versus Temperature Graph of Hydrocal 300 and Sundex 8600T.

Table C-3. Fast Water Systems Basin Water Analysis Log

Sample ID	Test Date	Temperature °C	Salinity (ppt)	pH	Turbidity (ntu)
5-12-0900	05/12/99	20.5	14.8	7.52	0.54
5-20-0900	5/20/99	21.0	14.5	7.35	0.64
6-17-0900	6/17/99	19.2	14.0	7.60	0.80
6-22-0900	6/22/99	27.0	14.0	7.25	0.50
7-14-0900	7/14/99	27.0	12.0	7.92	1.50

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Appendix D. Wave Analysis

Table D–1. Wave Analysis

Skimmer Type	Test Number	$H^1/_3$ Significant Wave Height (in)
JBF DIP600	59 - 60	11.7
	63 - 64	11.2
	67 - 68	11.5
	69 - 70	10.6
	75 - 76	10.4
	77 - 78	11.5
	79	9.1
	81 - 82	9.0
Vikoma FasFlo	92 - 93	10.9
	104 - 105	12.8
Circus	139	11.7
NOFI Current Buster	171 - 172	11.6
	182 - 183	11.3
	184 - 185	9.5
	186 - 187	9.7
	188 - 189	10.5
	190 - 191	10.0
	192 - 193	10.2
	196 - 197	10.9
	198 – 199*	13.7

Note: All waves in analysis are Harbor Chop created with a 3” stroke at 35 cycles / minute.
* Tests 198 and 199 use Harbor Chop waves created with a 4.5” stroke at 35 cycles / minute.

Table D–2. Averaged Wave Data

$H^1/_3$, Significant Wave Height (in)
10.9

Note: Averaged data includes 3” stroke only.

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Appendix E. Data Collection and Instrumentation

Data obtained during each test includes electronically collected data and manually collected data. The electronically collected data is recorded at the computer console located on the third floor of the Control Tower. Some electronically collected data is monitored at locations other than the data collection computer in order to control test conditions. Instrumentation output signals are directed to the computer and stored by sequential file numbers. A data collection rate of 10 Hertz (Hz) is standard but may be changed for specific data collection needs. There are Bridge speed readouts at the control console and on a panel meter in the Bridge House. The Bridge speed is also displayed on the underwater camera monitor and recorded on the video. The distribution pump rate and test fluid volume are monitored on the Main Bridge, as well as recorded on the data collection computer.

Manually collected data are measured and recorded by assigned technicians. Oil and water properties' data are based on fluid samples obtained during the test period. Data to be collected during tests are listed in Table E-1 along with the method of collection, instrument physical locations and specifications. Computer collected data and manually collected data are randomly checked by the Quality Assurance (QA) Engineer for completeness and accuracy.

Table E-1. Typical Data Collected During Tests

Instrumentation	Location	Data Collected	Make/Model	Instrumentation Specifications
Sonic Level Sensor	Main Bridge oil storage tank	Storage tank level	Milltronics Pl-372 s/n 5827	resolution: ±14inch accuracy: ±0.4% f.s.
Sonic Wave Probe	Main Bridge	Wave profile	Datasonics PSA 900-03	± 1.0 inch
5K Load Cells (2)	Tow points	Tow force	Metrox Model RGAE2052-5K	calib. error<±.25% f.s. ± 12.5 lbs.
Hydraulic Flow Meter	Hyd. supply line betw. control stand & skimmer	Hydraulic flow rate xmitter	Lake Monitor R5S-7HN-75	8-75 gpm, scale acc. ±4% f.s. (36 gpm)
Hydraulic Pressure Sensor	Hyd. supply line betw. control stand & Prime Mover	Hydraulic pressure	Omega PX605	accuracy: ±0.4% f.s. repeatability: ±0.07% f.s. (range 0-3000psi)
Magnetic Pickup Sensor	Main Bridge	Bridge speed	Airpax Model 70087-3040-012	± 0.1 knot
Wind Monitor	West deck	Wind speed Wind direction	R.M. Young Model 05103	speed: ± 0.4 mph direction: ±3.0 degrees
Temperature Probe	West deck	Air temp.	R.M. Young Model 41350	± 1EF
Temperature Probe	NE deck corner	Water temp.	Omega RTD probe Model PR-11-2-100-¼-6E	± 1E F

1. Bridge Speed and Distance

The Main Bridge is powered by a cable drum system and travels along rails that parallel each tank wall. The bridge system is capable of traveling from 0.1 knots to 6.5 knots (.052 meters/sec to 3.34 meters/sec) in increments of 0.1 knots (.052 meters/sec). A pulse-type tachometer sensor monitoring the rotational motion of a wheel on the Main Bridge measures bridge speed. The sensor is an Airpax Magnetic Pickup for Bridge Speed, Model # 70087-3040-012S. The output is recorded and displayed by the data collection system during tests in the Main Bridge house and at the data collection console on the third floor of the Control Tower. The speed is recorded at 10 Hz and displayed in knots.

2. Wind Speed, Wind Direction, and Air Temperature

These meteorological instruments are located on the West side of the Ohmsett Test Basin, at approximately mid-length. The instruments are located on a tower approximately 3 meters (10 feet) above the Test Basin deck. The output of all three instruments is available to the data collection system for recording before, during, and after tests, and is also displayed on a panel at the data collection console in the Control Tower.

The temperature sensor is a Model 41350 manufactured by R.M. Young, Inc. It is located in a Gill Multi-Plate radiation shield for protection and ventilation to prevent direct sunlight from hitting the thermal sensor and giving a false temperature reading.

The wind speed and direction sensor is a Model 5103, also manufactured by R.M. Young, Inc. It is an outdoor, high performance, rugged, four-blade, helicoid propeller wind speed sensor.

The signals from the wind and temperature feed a wind and temperature translator, Model 26302, manufactured by R.M. Young, Inc. A wind and temperature translation unit in the data collection console feed data to the data collection system during tests.

3. Basin Water Temperature

The water temperature is monitored continuously by a temperature dependent resistor probe. An Omega RTD Probe, Model # PR-11-2-100-1/4-6E, is used. The output is displayed as degrees Fahrenheit on a meter at the data collection console, and recorded during tests by the data collection system.

4. Wave Height Meter

The wave height meter is a Datasonics Sonar Air Altimeter, 27 kHz, Model PSA 900-A, S/N 335. An acoustic altimeter specifically designed for use in air measures the wave profile. It is mounted on a support structure extending from the South side of the Main Bridge at a nominal height of 121 inches (3.05 meters) above the mean Basin water surface level. The output of the sensor is available to the data collection system during tests and is also displayed during test runs on the data collection system screen. The output readout is in inches.

5. Oil Tank Level

An ultrasonic level sensor located at the top of the Main Bridge oil storage tank measures the oil tank level. The tank level, in percent, is available during tests at the Main Bridge pump control panel and is recorded during tests, in inches, on the data collection system. The percent and inch values are converted to gallons using calculated tables. "The (sonic) Probe" is manufactured by Milltronics, Model PL-396, S/N 005827.

6. Tension Load Links

Tension load cells rated at 2000, 5000, and 10,000 pounds are used during tow tests and are selected based on boom size and sensitivity required. Their outputs are conditioned and provide a 4-20 milli-amperes (ma) loop output to the data collection system in the Control Tower. The load cells are typically placed in series with the boom towing bridles to measure forces obtained during towing tests. See Figure 1 in the main body of this report for the location of these load cells.

7. Remote Marker Button

This is a portable button that is used to mark events during test runs. The output provided by the pressing of the button, sends a pulse DC voltage that is identifiable within a data channel of the test file. The event mark typically identifies a specific event or the beginning and end time of a steady state test condition.

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Appendix F Assessment of Test Quality

General

The testing was performed as described in this report and in accordance with Ohmsett "General Quality and Procedures and Documentation Plan" Manual, December 1996; and the "Operating Manual for Ohmsett Laboratory Including Laboratory Procedures," January 1997. The following is a description of the various elements as they relate to the accuracy, precision and validity of the test data presented.

Initial Calibration Data

The Ohmsett Quality Control (QC) Engineer verifies all instrumentation utilized during testing to be within the acceptable calibration limits for the test period.

Pre- and Post-Checks and Conditions

Prior to testing, the instrumentation used to collect data for the automated data collection system was checked by the Ohmsett Instrumentation Technician to assure proper operation. Similarly, this instrumentation was also checked upon completion of testing. Both pre- and post-checks were made each test day to provide assurance that the instrumentation was functioning normally during the test period. Weather was observed and recorded continuously during testing by the automated data collection system. This instrumentation was also included in the pre- and post-checks performed by the Ohmsett Instrument Technician.

In addition to the above, independent, random observations were made and recorded by the Ohmsett QC Engineer on the Quality Checklists for pre- and post-test conditions. These observations of pre- and post-test conditions are randomly compared to other data to assure data accuracy.

Test Checks and Conditions

Test data is continuously recorded by the automatic data collection system and by manual methods during testing. Random over-checks are used to observe and record data independently of both the automated data collection system and manual methods. The Ohmsett QC Engineer records this data on the Quality Checklist. During the test program, more than eight hundred over-checks were performed.

Sampling

Sampling is checked for compliance with the instructions in the Test Plan and the "Operating Manual for Ohmsett Laboratory Including Laboratory Procedures." Samples included Basin water analysis, test oil analysis, and recovered fluid analysis. The Test Plan requirement for a minimum of 10 percent duplicate sampling for this analysis was met or exceeded.

Significant Occurrences/Variations

Any significant occurrences/variations that may have affected any of the test results are reported and discussed in the appropriate sections of the test report.

It should be noted that in other than the protocol verification portion of this report, adjustments and modifications were made during testing. This is consistent with the test objectives described in Section 1.2. The changes made and the results are described in the appropriate sections for each of the four recovery systems evaluated.

Data Reduction and Validation

All data reduction and validation are performed in accordance with approved and accepted methods. When non-standard methods were utilized, they are included in the test/data report and sufficiently described so that they can be used by independent sources to duplicate the results.

Data Precision and Accuracy

Data precision is accomplished by measuring variances between and among redundant sampling and repetitive testing. Review of the data indicated that the sampling results were within the prescribed requirements of the test program.

Data accuracy is achieved through the use of calibrated and verified instrumentation and through crosschecks between collected data (both automated and manual) and the independent observations made and recorded on the Quality Checklists.

Basin Water Analysis

Basin water analysis performed during the testing is reported in Appendix C. Review and analysis of the data confirmed that the results were within the precision requirements of the test program.

Test Oil Analysis

The analysis of test oils used during the test program was reviewed for overall variations and for variations between original and duplicate samples. Review of the data indicated that the sampling results were within the prescribed requirements of the test program.

Recovered Fluid Analysis

The recovered fluid analytical techniques described in Appendix C were used to determine the physical makeup of the fluid.. In order to assess the validity/reliability of the data, recovered fluid analyses were reviewed and analyzed for variations for both within-test samples (where more than one sample was analyzed per test) and between original and duplicate samples. Review of the data indicated that the sampling results were within the prescribed requirements of the test program.

Repetitive Test Runs

The objective of the test program was to develop a quantitative measurement of the accuracy and the precision of the test results while defining the operational capability of each of the four recovery systems within the prescribed testing period. Adjustments and modifications were made in order to provide quantifiable performance of each system. With the exception of the protocol verification, repetitive tests, as such, were not performed. The evaluation of each of the four recovery systems are considered to be comparable to the protocol quantitative results within the limits established as described in Section 1.4.2. Details of test parameters and results may be found in the appropriate section for each recovery system.

Documentation of Tests

All analytical laboratory testing results, calibration data, pre and post checks, test checks and conditions, quality checklist, test run data, automated and manually recorded data, as well as above-water and below-water visual documentation used to prepare this Test Report, are on file at the Ohmsett Facility.

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Appendix G Protocol Verification

Protocol Verification

At 2 knot speeds or greater, the steady-state operation time is reduced during a run down the tank. Fast water testing (2 to 5 knots) limits actual encounter time from 2 minutes to 45 seconds, respectively. The volume of oil distributed and recovered is less than that of tests performed at slower speeds. Longer test durations increase the total volume of oil distributed and recovered, therefore minimizing inherent measurement error. Multiple pass testing is used in which a particular test and the parameters are held constant for multiple passes down the tank. The volume of oil distributed and recovered then accumulates, resulting in larger volumes from which to obtain measurements.

One possible scenario demonstrating the benefits of multiple pass testing is explained as follows:

The Ohmsett recover tanks (8 total) are capable of holding 250 gallons each, equating to 5.5 gallons/inch. During a typical high speed recovery test, 100 gallons of oil may be distributed. For this scenario, the skimmer recovers 22 gallons of oil. Measured accurately, this would equal 4 inches of fluid depth and would also result in a TE of 22%. If, by chance, the technician and on-site Quality Assurance personnel both misread the measuring stick by ¼ inch in either direction, the corresponding TE would be 23.4% or 20.6 %, as compared to the actual TE of 22%. This would give an error of 6.4%. For a double, "multiple pass" test, the total volume collected would be 8 inches, or 44 gallons of oil. The corresponding error of ¼ inch, due to the same misreading by the technician and on-site Quality Assurance personnel, is now .97%..

Calculation for Oil Distribution

To simulate a 5 millimeter slick thickness at the skimmer's opening, a flow equation is used:

$$\mathbf{Q = V * W * 0.0164 * 757.97}$$

Where: Q - is the flow rate required in gallons per minute
V - is the velocity in knots
W - is the width of the skimmer opening in feet
0.0164 is 5 millimeters in feet
757.97 is the conversion factor to convert all dimensions to gallons/minute.

For Example: The JBF 600 skimmer has a belt width of 4 feet. At two knots the calculation is:
Q = 2 knots* 4 feet * **0.0164 * 757.97 =** 99.44 or about 100 gallons per minute