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OHMSETT SUPPORT OF THE OFFSHORE BOOM AND SKIMMER TRIALS, ST. JOHN'S, NEWFOUNDLAND

by

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FOREWORD

[1-2 paragraphs of Standard EPA Foreword]

This report contains a summary of activities performed and data obtained by Roy F. Weston, Inc., the operating contractor for EPA's OHMSETT test facility, in support of a series of interagency cooperative exercises renown as the 1987 OffShore Boom and Skimmer Trials. These exercises were conducted in Canadian ocean waters near St. John's, Newfoundland in September, 1987, and involved joint sponsorship, planning, and performance by the U.S. Environmental Protection Agency, Environment Canada, the Canadian Coast Guard, the U.S. Minerals Management Service, and numerous other participants. The work performed by the OHMSETT operating contractor constitutes only a small portion of the overall project, and no attempt has been made in this report to describe the complete operations that were conducted or the results that were obtained, except as they impacted OHMSETT support operations. The report focuses on the planning, implementation and data collection activities provided by Roy F. Weston, Inc., and its subcontractors, ICF Technology, Inc. and Enviresponse, Inc., in support of the overall efforts.

ABSTRACT

Following nearly two years of planning and coordination, a joint Canadian - United States oil spill, control, and cleanup exercise was conducted off the shore of Newfoundland in September, 1987. The EPA Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility operating contractor, Roy F. Weston, Inc., supported this exercise by providing an instrumented oil containment boom for evaluation of boom performance methods, oil recovery instrumentation, analysis of the recovered product, and direct support of the offshore operations with ten OHMSETT personnel.

To evaluate relative boom and water motions, pressure transducers and digital data loggers were procured, installed on an available oil containment boom, and calibrated at the OHMSETT test facility. Eight channels of such depth-measuring instrumentation, with one-hour recording capability were provided on the boom that was shipped to St. John's, Newfoundland for the test sequences that occurred during the period of September 20-24, 1987.

Instrumentation to measure flow rates and gross volumes of recovered oil during the skimmer-evaluation phase of the offshore trials was also designed, fabricated, calibrated, and operated by OHMSETT personnel. This system consisted of an in-line venturi flow meter arrangement, tank depth-sounding gauges, and both in-line and stratified-liquid tank sampling devices. Samples collected during the recovery operations were subsequently analyzed by ASTM methods to determine the percent of water in the recovered product.

The offshore tests that were conducted consisted of a practice run, with only simulated oil release, on September 21, and a full-scale exercise with release of oil on September 24. Although operational difficulties were encountered in maintaining an acceptable configuration of the instrumented boom deployed during the offshore tests, fifty-six minutes of data were obtained on all eight channels during the practice run.

Following repair of instrumentation cabling that had been damaged during the practice run, forty-six minutes of data from four channels were recorded during the actual exercise, amid continuing problems related to the seaworthiness of the instrumented boom. In addition, flow rates, recovered volumes, and oil/water ratios were determined for the various skimmers deployed during the oil recovery phase of the operations.

The OHMSETT activities were only a small portion of the overall effort during the offshore tests, and this report focuses on the experimental procedures and findings related to the instrumented boom and the oil recovery measurements. The overall test operations are discussed only as they relate to the portions involving OHMSETT participation.

CONTENTS

EXHIBITS

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

OHMSETT -- Oil and Hazardous Materials Simulated Environmental Test Tank

CCG -- Canadian Coast Guard

SYMBOLS

ACKNOWLEDGMENT

This work was supported by various member agencies of the U.S. EPA's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) Interagency Technical Committee (OITC).

The OITC currently includes the U.S. EPA, U.S. Coast Guard, the Minerals Management Service, the Canadian Conservation and Protection Service and the U.S. Navy.

The support and encouragement of numerous personnel from OITC agencies are acknowledged. In particular, we wish to express appreciation to the following sponsors and clients for their continuing support:

- U.S. Environmental Protection Agency - Robert Hillger, Project Officer, and Richard Griffiths
- U. S. Minerals Management Service - Edward Tennyson
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- Canadian Coast Guard - William Ryan and Wayne Halley

We are grateful for the supreme efforts that the OHMSETT staff provided during the work at the OHMSETT facility and in Canada. Truly, the project was a team effort; the many and varied ideas, comments and extra efforts of the entire staff contributed in no small measure to the success of the program.

SECTION 1

INTRODUCTION

BOOM PERFORMANCE EVALUATION

The OHMSETT Interagency Technical Committee (OITC) has been supporting oil spill research and spill containment procedures development for many years.

Much of this work has been performed at the U.S. EPA's Oil and Hazardous Materials Simulated Test Tank (OHMSETT) in Leonardo, NJ, and by the OHMSETT contractors at other locations. A summary of work performed through 1979 by the OHMSETT contractor has been published.[1] Since 1980, a variety of research programs have been conducted to evaluate the performance of oil containment booms, to determine the environmental and operational factors that affect boom performance, to determine whether boom performance can be quantitatively measured and reliably predicted, and to develop a protocol for evaluating boom performance without the need for spilling oil in open-water tests. A brief summary of the considerable previous work leading to the efforts described in this report is presented below.

The large amount of data acquired at the OHMSETT facility on a broad variety of booms have demonstrated that performance (defined as the ability of a moving boom to contain oil) depends on several operational characteristics, including the following:

- o Speed of the moving boom relative to the surface current
- o Kinematic properties of the water or oil/water medium, including wave height, wave period, wave uniformity, density, and viscosity.
- o Mechanical and kinetic properties of the boom.

The previous work has shown that, whereas a complete analysis of boom design from first principles would be exceedingly difficult or impossible, it may be possible to evaluate boom performance by selected testing under controlled conditions. Specifically, it has been postulated that boom performance can be demonstrated reliably by measuring the relative motions of boom components and the water medium, using the sea state as a forcing function, without the need for spilling oil in open waters.

At the time the current project was initiated, a methodology for conducting boom performance testing and for analyzing the data had been proposed, in the form of a draft Boom Test Protocol.[2] In its purest form, the protocol would allow boom performance to be predicted solely from the seakeeping ability of the boom in open waters, as measured by the motion of the boom relative to the water. If this analysis proved to be intractable, the protocol includes provisions for conducting both in-tank tests (where spilled oil would be controlled) and open ocean tests without the need for releasing oil.

As a result of the previous work, it has been postulated that the seakeeping ability of the boom can be quantified from the relative motions of boom and medium, by measuring the frequency and energy associated with each moving mass. From these motion spectra, the ratios of power densities for the boom and the water at each discrete frequency of oscillation can be derived. The Boom Test Protocol specifies that these ratios, called Response Amplitude Operators (RAOs), as measures of the wave-riding or wave-following ability of the boom, are related directly to the ability of the boom to contain oil.

The boom motion spectra can be obtained from direct accelerometer measurements or from amplitude (depth) records over time, for critical segments of the boom. The motion spectra of the medium can be obtained from similar instrumentation attached to a wave-rider buoy.

The work described in this report stemmed from a recognition that the methodology for evaluating boom performance had not been tested adequately under open-sea conditions. Additional data were needed during boom deployment in sea states typical of those encountered in response actions, and during actual oil containment in open water.

OIL RECOVERY EVALUATIONS

The gross performance of oil recovery equipment is most simply evaluated as the volume of oil recovered per unit time. The two parameters which must be measured for such evaluations are the recovery rate of product (generally an oil-water mixture), and the recovery efficiency, or the relative amounts of oil and water in the recovered product. These parameters can be determined dynamically, from measurements of flow rate and collection of in-line samples for analysis, or statically, from volume measurements and stratified sampling of bulk recovered product. Considering the numerous operational parameters that directly affect recovery methods, significant variation in recovery rate and efficiency is expected over even short periods of time. Therefore, recovery performance is best evaluated by integration of dynamic measurements.

A large body of information on oil recovery evaluations has been generated at the OHMSETT facility and elsewhere. Extensive testing has been performed within test tanks and contained test pools. However, fewer measurements have been made for open-sea spills. The instances in which recovery of any accidental release can be instrumented are rare, and there have been only a limited number of cases where performance of recovery equipment has been documented adequately.

OFFSHORE OPERATIONAL TESTS AND REPORT

For over two years, plans have been under development by OITC member agencies for conducting a series of open-water tests in which various oil containment and recovery equipment could be evaluated. These tests have been designed to allow evaluation of oil containment boom performance and oil recovery equipment and procedures within an operational spill scenario. The overall planned test objectives, procedures and schedule are described in Test

Protocol for Offshore Boom and Skimmer Trials, 3rd Draft, S.L. Ross Environmental Research Limited, May, 1987. The offshore trials were viewed as a realistic opportunity to test the boom performance evaluation methodology developed by OITC-sponsored research over the past several years, as well as to evaluate quantitatively the recovery efficiency of different types of skimmer equipment. Accordingly, the OHMSETT contractor was tasked with providing technical support for the offshore tests in the areas of boom performance and oil recovery instrumentation.

The purpose of this report is to provide a summary of the systems that were developed and deployed, the measurements that were made, and the data and results obtained during the OHMSETT portions of the Offshore Boom and Skimmer Trials. No attempt has been made to describe or document the overall offshore test program, of which the OHMSETT activities were only a small part.

OBJECTIVES

The objectives of the OHMSETT project were to:

1) Design, instrumentation for collection of boom performance data and to prepare and deliver to the Offshore Trial assembly point an operational length of oil boom;

2) Incorporate testing of the instrumented boom for wave-following properties, within the context of the overall Offshore Boom Trial plans;

3) Analyze the boom performance data according to the draft boom test protocol; and

4) Provide instrumentation, methods and personnel for collecting data on the rate of oil recovery during comparative skimmer operations.

AUTHORITIES

This project was authorized by Work Assignment No. 0-87204, Task 2 (dated July 17, 1987), under Contract No. 68-03-3450 from the USEPA to Roy F. Weston, Inc., the operating contractor for the USEPA OHMSETT facility in Leonardo, NJ; and by Contract No. KE144-7-6048/01-SS from the Environment Canada to WESTON. The USEPA project primarily involved preparation of the instrumental systems, and the Canadian portion of the project dealt exclusively with direct technical support to the offshore operations. This report has been prepared to satisfy the requirements of both contracts.

SECTION 2

CONCLUSIONS

OVERALL CONCLUSIONS

The overall conclusions of this project, from the standpoint of OHMSETT involvement in the Offshore Boom and Skimmer Trials, are as follows:

1. The feasibility of instrumenting an oil containment boom, collecting data in an open-water environment, and analyzing the results in accordance with procedures specified in the draft Boom Test Protocol was demonstrated.

2. Off-the-shelf instrumental systems are available for measuring the boom performance parameters required by the Protocol.

3. An alternate methodology is available for analysis of boom performance in the event that data on the sea state are unavailable.

4. Relative recovery rates and recovery efficiencies of oil skimming equipment can be measured, in an operational scenario, by a combination of flow meters and oil/water ratio product analysis.

SPECIFIC CONCLUSIONS

1. First response strain-gauge bridge pressure transducers are appropriate sensors for determination of boom motions under conditions of open-sea deployment.

2. Digital data loggers of appropriate resolution and memory capacity are available for recording of data required by the Boom Test Protocol.

3. The conditions existing during the tests were not ideal for evaluation of oil retention booms according to the proposed protocol. In particular, tow speeds were generally too high, and were not varied through the stages of oil retention, first loss, and gross loss as planned. The selected boom did not perform well under the conditions of high tow speed and high sea state, and difficulties were encountered in maintaining proper boom tension and configuration.

4. Despite the operational difficulties, the general methodology for instrumenting a boom to measure and record wave-following ability was tested successfully. Instrumenting a boom to provide very precise data on immersion and motion characteristics, while withstanding the rigors of extensive testing, was shown to be feasible.

5. The methodology for computing boom performance parameters appears to be valid for actual oil-spill data.

6. The methods chosen to measure oil recovery rates and efficiency appear to be acceptable.

SECTION 3

RECOMMENDATIONS

Although the overall feasibility of instrumenting oil containment and recovery equipment to provide quantitative evaluation of performance measures was shown, during this program, it was also indicated that improvements are possible. Additional work on tension and recovery flow measurements should be accomplished before procedures are fixed or standards are developed.

Sealed pressure transducers with no capillary tube vent are recommended for use in performing boom immersion and motion measurements. The small drift that might be experienced for the closed system will insignificantly affect subsequent data interpretation, and the problems encountered in maintaining a dry transducer element would be avoided.

SECTION 4

METHODS AND MATERIALS

SELECTION OF THE BOOM

Beginning in July, 1987, OHMSETT began preparing and calibrating instrumentation for measuring boom performance during the offshore trials. Although the general requirements both for instrumental design and for specific components was known from previous OHMSETT work, the exact specifications and methods for ruggedizing and mounting of components depended on the exact boom structure that would serve as the instrumental platform during the tests. Thus the initial step was to obtain a typical oil containment boom, for which instrumentation would be procured, installed and tested.

The available and suitable options for booms were reviewed at the onset of the program. This research quickly led to selection of the Globe Oil Fence 48 boom, for several reasons:

(1) A significant length, 152m, of the Oil Fence 48 was on hand at the OHMSETT facility, and an additional length of 90 meters could be supplied immediately by the manufacturer. Thus, the required length of 200-250 meters to realistically simulate a typical deployment was made available at no cost to the program.

(2) The selected boom was expected to be capable of performing the operations denoted within the Offshore Trial Test Protocol. Specifically, it was felt that the boom could be towed at 0.5 to 1 kt (relative to the surface current) and was expected to retain a major portion of the released oil volume (approximately 80 M^3) at the lower end of this speed range.

(3) Booms of this design had undergone extensive testing in the OHMSETT test tank, as described in Section 1. Thus, comparisons between at-sea and tank testing would be possible following the Offshore Trials.

(4) The Globe Oil Fence 48 contains rigid structural ribs upon which the instrumentation and cables could be mounted.

Above all, based on previous OHMSETT testing, it was believed that the boom would be suitable for oil containment under the planned operational conditions (relative speed of 0.5-1 kt during tests, sea state of 2-3, and maximum wind velocity of 15 kt).

Following selection of the Globe Oil Fence 48, work began immediately on preparing the boom for installation of the instrumentation and cables. Work began by replacing broken ribs and floats and patching torn sections of the skirt on the 152-meter length of boom available at the OHMSETT facility. Spare parts and hardware were provided by Globe International, along with three additional 30-meter sections of boom. All sections of the boom (8 sections totalling 244 meters) were present at the OHMSETT facility by August 15, and all outfitting was completed by August 28, 1987.

BOOM INSTRUMENTATION AND WIRING

Measurement of wave-following ability

To determine the wave-following ability of the boom, i.e. to measure the motion of the boom relative to the waves, pressure transducers with reasonable accuracy and a relatively fast response time (compared to the height and period of the waves) were required. Drawing upon experiences gained in previous OHMSETT work, capacitance-bridge transducers were selected for this purpose. These bridge-type transducers provide acceptable response time and accuracy, but require one side of the bridge to be maintained at atmospheric pressure. For transducers to be located on the boom skirt under water, this link would be provided by a capillary tube vented above the water level. If a short tube were used, deployment of the boom and the action of rough seas can result in water entering the capillary, which (at best) provides an erroneous reference level and (at worst) an inoperable transducer if water reaches the sensing element. Thus transducers were ordered with cables long enough to contain an unbroken and intact capillary tube extending from each transducer to the tow boat. Eight Druck Model PTX/160D transducers, two each with cable lengths of 76, 107, 137, and 168 meters, were ordered with direct HERMIT 2000 connectors and sealed end caps.

Eight transducers were mounted near the bottom of the boom skirt, at approximately 30-meter intervals from the center. Two transducers were mounted near the center of the boom (i.e., near the apex of a catenary formed by the boom) to provide useful information from the location where oil is contained and/or lost. A schematic diagram of transducer locations, as they would appear operationally, is shown in Exhibit 1. When the boom is deployed, each transducer is located at a nominal depth of 0.57 meters below a calm water surface. Each half of the boom was wired separately, with cables from the four transducers on each side running back to separate recording systems on each tow boat. The split cabling resulted in reduced lengths of cable runs, reduced bulk of the wiring harness along the boom, and maintenance of mechanical symmetry along the boom. As noted previously, each transducer ordered was specified with the required length of cable, hermetically sealed by the manufacturer, completely from the transducer to the required connector for the recording system on each tow boat.

To record the output of the pressure sensors in the desired digital format, Hermit 2000 (TM) data recorders were used. Two of these units were custom modified by In-Situ, Inc., and provided with the Druck pressure transducers described above as a complete unit with all matching cables and connector assemblies. Each of the two HERMIT recorders was modified by In-Situ to allow four-channel recording at a constant interval of 0.25 seconds. The internal memory in each HERMIT allowed storage of four channels of 16,384 12-bit words. Thus, two units provided a full hour of recording capability for eight channels with the desired resolution.

Mounting Of The Transducers on the Skirt

The body of each pressure transducer was attached to a boom structural rib at the desired location near the bottom of the skirt using two clamps and the bolts which originally attached the rib to the boom skirt. Additional physical protection of the transducer and cable attachment point was provided by surrounding the transducer with a short length of heavy-walled aluminum conduit, which was mounted to the structural rib using U-bolts. Holes were drilled in the conduit to allow free passage of water to the sensing element. Tests were performed in the OHMSETT test tank to verify that the protective casing had no observable effect on pressure-time measurements for wave motion. A close-up view of the pressure transducer mount with surrounding conduit and attached cables is shown in Exhibit 2.

The cables from transducers on each half of the boom were harnessed together and the bundle of one to four cables (depending on position along the boom) was covered with split automotive heater hose, wrapped with plastic electrical tape, and secured with plastic wire ties. A photograph of this operation is given in Exhibit 3. The cabling was attached to each structural rib 1.22 meters along the boom, allowing sufficient slack between attachment points for stretching and folding of the boom. The cable assembly was attached loosely along the tow line, and the excess cable (approximately 30 meters) was bundled into a tight coil. The completed assembly afforded considerable protection for the cable runs, both between transducers and from the boom to the tow boats.

Although each cable connector was supplied by In-Situ, Inc., with an o-ring-sealed protective cap, additional protection was provided by inserting each connector in a plastic bottle, using a tight-fitting split rubber stopper, and completing the seal by covering with moldable 3M self-vulcanizing rubber tape. This seal was shown to be leakproof at 7-foot depth in the OHMSETT Test Tank for a period of 12 hours.

Boom Tension Instrumentation

A tow line of 31.8-mm diameter twisted-braid Nylon, 15.24 meters long, was attached to each end of the boom through a 4.5-m steel cable choker. The tow line ends terminated in shackles attached through strain links to the towing bit of each boat. The strain links were Metrox Model No. TL101-10K load cells providing a full-scale tension range of 10,000 lb. The load cells were ordered with 9.15 meters of custom-sealed cable and connectors. The 4-20 ma output of each load cell was amplified by a Metrox Model 2060-00 Signal Conditioner/Amplifier, which also provided power to the strain-gauge bridge within each load cell.

The output of one load cell was recorded directly on a strip chart recorder with a 5-volt range. The recorder response for a calibrated tension input of 9,500 lb. was found to be 3.8 volts. The other load cell was connected to a TELOG Model 2107 0-5 volt data logger, operated at 5-second timing internals with 10-bit resolution and 1,628-word memory. Programming was input to, and data was dumped from the TELOG data using a Zenith Z181 portable computer with floppy diskette storage.

A photograph of the load cell within the tow line is given in Exhibit 4.

DYNAMIC OIL RECOVERY INSTRUMENTATION

To provide a quantitative measure of the performance of various skimmers, in-line flow measurements were made during recovery operations. The systems and instrumentation deployed for these measurements were as follows:

- A custom-made venturi tube with 10.2-cm diameter inlet and outlet tubes and a throat diameter of 8.0-cm was used to measure flow from the skimmers. The pressure differential across the throat was measured using a Rosemount Model 1151 Differential Pressure transmitter, providing a 4-20 ma output over a preset pressure range of 0-254 mm of water (flow rate of 0-45 m^3/hr). The output of the Rosemount unit was monitored by a Telog Model 2101 current data logger, operated at 5-second sampling intervals and controlled by an IBM PC/XT microcomputer. The reading on the faceplate of the Rosemount gauge also was monitored during the tests. A photograph of the venturi arrangement is shown in Exhibit 5.

- A Rosemount Model 1151 transmitter with one side open to the atmosphere was connected at the inlet end of the venturi tube to measure the discharge pressure of the skimmer pump. The output of this Rosemount unit, adjusted for 50 psig full-scale output, was monitored by a Telog Model 2107 0-5 volt data logger. The Telog was programmed by an IBM PC/XT microcomputer, which served for storage of data files on floppy disk. The reading on the faceplate of this Rosemount gauge also was monitored during the tests.

- Samples of recovered product were obtained periodically through a stopcock located downstream from the outlet end of the venturi tube. Approximately 100-mL samples (in duplicate whenever flow rate permitted) were collected in 125-mL polyethylene bottles for subsequent determination of percent water in the product.

STATIC RECOVERED-PRODUCT MEASUREMENTS

The depth of product within the recovery tanks was measured using a 3-meter marked pole designed for measuring the contents of gasoline service station tanks. Samples of the stratified product in the recovery tanks were collected by custom-made "Johnson" samplers, a 3-meter long chambered sampling tube. Chambers were formed by o-rings at 15.2-cm intervals along the plunger rod. The volume of each chamber, approximately 30-mL, was be separately collected as the plunger was removed. The samples allowed a determination of percent water in each 15-cm layer in the recovery tanks.

PHOTO/VIDEO INSTRUMENTATION

Pretest, test, and post-test operations conducted by OHMSETT personnel were documented using still photography and video tape. The equipment used during these exercises included Nikon F3 and FE cameras for color print and slide photography, and two Sony Model CCD-V110 8-mm color cameras for video coverage.

LABORATORY EQUIPMENT AND MATERIALS

The percent water in recovered product, both for in-line samples and samples of the stratified recovery tank contents, was determined by ASTM Method No. 1796 using a Damon/IEC Model HN-S centrifuge with 125-mL graduated tubes. Make-up solvent used for samples of insufficient volume was ACS reagent-grade toluene. Viscosity and specific gravity of initial and recovered materials were determined using ASTM Methods 2983 (Brookfield Model LVT Viscometer) and by ASTM Method D1298 (glass hydrometers). Viscosity standards used during the laboratory work, obtained from Brookfield, were 100 cps (lot No. 111585) and 975 cps (lot No. 100385) fluids.

OTHER EQUIPMENT AND MATERIALS

The distances between tow boats and between each boat and various targets on the boom were monitored during the tests using Ranging, Inc. Model 1200 and Model 620 optical rangefinders. The rangefinders were calibrated and expected uncertainties were determined using targets at fixed distances prior to the sea trials.

The relative speed between each tow boat and the surface water was measured using floating wood chips. Distances of 6.1 and 9.15 meters were measured and marked along the rail of the tow boats. Wooden blocks, measuring 1.25cm x 5.0cm x 7.6cm and painted fluorescent orange, were dropped at one mark and the time required to traverse the distance between marks was measured by a stopwatch. The distance traversed was divided by the time of traverse to determine tow boat speed.

SECTION 5

EXPERIMENTAL PROCEDURES

BOOM IMMERSION MEASUREMENTS

Calibrations

Although each pressure transducer was received with a recent manufacturer's calibration certification (in the form of a "scale factor" to be used in programming the recording system), static linearity calibration checks at known depths were performed, and dynamic records of wave spectra in the OHMSETT test tank were obtained. The calibration and response were measured over a depth range of zero to 1.2 meters and for a representative wave period of about 3 seconds. Because the HERMIT 2000 data loggers are continuous-recording devices with slow data dump capability, the calibrations were performed at various depths of immersion while operating the recorders continuously.

The pressure transducer calibrations were checked in two groups of four on separate days. The transducers were clamped to a crosspiece attached to a 3 meter long pipe with markings at 25.4 mm intervals. The pipe was lowered to immerse the sensors to a given depth in the test tank for 15 seconds, providing 60 data points at the rate of 4 per second. During this period, the

Hermit 2000 digitized and recorded the output of the transducers. The assembly was then lowered to the next designated level. The procedure was repeated until the transmitters had traversed the operating range anticipated in the offshore trials. In this calibration series, measurements were made at 15 depths between zero and 1.22 meters of immersion.

The data stored in the Hermit were dumped to an IBM PC/AT computer using the RS232C interface, and the output was written to a floppy disk. The data in the file were imported to a Lotus 123 spreadsheet and edited to remove transient data, i.e. data points recorded at intermediate levels between the designated depths. An example of data records prior to the editing is shown in Exhibit 6. The average datum at each immersion level was calculated. Because the change in immersion is the parameter of interest, the data were tared to the first average, which forced the first value to be zero. A least-squares regression analysis was made of additional measured immersion and the known added immersion. The regression results are shown with plots of the data for the eight transducers in Exhibits 7 through 14.

The calibrations were performed in the open Test Tank. The wind-induced surface chop was estimated at about 6mm (1/4 inch) during the calibration procedure. The wavelet action undoubtedly affected the accuracy of the "known" added immersion, the effect being more pronounced at small depths. The wavelets also affected the precision of the shallow measurements, defined as the coefficient of variation. However, the regression analysis showed that the transducer outputs are linear with depth and that added immersion is measured accurately by the transmitters. The lowest value calculated for the coefficient of correlation is greater than 0.999, indicating that, at worst, approximately 0.05% of the scatter in the edited data is not explained by the changing level of immersion.

No measurable difference in the data was found during experiments in which the sensors were being raised or being lowered. The data obtained with a given sensor while raising the sensor was equivalent to that obtained while lowering the sensors.

Tank Tests

Several tests were performed using the wavemaking capabilities of the OHMSETT test tank to evaluate the performance of the pressure transducers. In the first test series, the dynamic response of the transducers as wave-measuring devices was documented. A group of four transducers were mounted on the calibration rod which was affixed to the moveable bridge spanning the tank, with the depths set at a nominal value of 0.6 meters. The test tank wave generator was operated at 20 RPM with an 11.4-cm stroke to generate waves with an amplitude of about 0.3 meters and a period of about 3 seconds. After about 6 minutes, the bridge began moving forward into the waves at a speed of 15 m/min. (0.55 knots). A plot of approximately 4000 data points from one of the transducers is given in Exhibit 16, over a time period including the time prior to initiation of waves, during waves with the bridge motionless, and following the initiation of bridge motion. The transducer data were fast-Fourier transformed using the Basic program PROTO5 (see Appendix B), to obtain the magnitude/frequency spectra for a stationary transducer (Exhibit 17) and for a moving transducer (Exhibit 18). All eight transducers produced very similar results in two sets of such measurements.

The single major peak in the magnitude spectrum of Exhibit 17, with very little fine structure (harmonics), corresponds to the output expected for tank waves (i.e. monochromatic waves with a fundamental frequency of 0.33 Hz (20 rpm)). Because the transducers were at rest, the frequencies of principal and reflected waves were identical. With the transducer in motion (Exhibit 18), there is a positive Doppler shift in the fundamental frequency of the principal wave, and a corresponding negative shift for the reflected wave. Because the end of the tank contains a simulated beach to dampen reflections, the reflected wave is much lower in magnitude than the principal wave. For a sensor (bridge) velocity of 15m/min (0.25 m/sec) and the observed wave velocity of 5.23 m/sec, the expected Doppler frequencies are:

$$f_d = fo/(1 +/- 0.25/5.23) = 0.33/(1 +/- 0.047)$$

$$fd\ (forward) = 0.346\ Hz$$

$$fd\ (reflection) = 0.315\ Hz$$

The Doppler frequencies correspond very closely to the frequency of the peaks shown in Exhibit 18, i.e., 0.35 and 0.31 Hz.

After completion of the tests described above, one of the transducers was encased in the aluminum conduit sheath that had been designed to provide protection when mounted on the boom. The test with waves and bridge motion was repeated. There was no observable difference in the resulting wave or frequency spectrum occasioned by the presence of the protective sheath.

Following installation of four transducers on each 122-meter length of boom, the units were placed in the test tank and arrayed linearly along the long (North-South) dimension. The booms were tied to a moveable bridge at the south end of the tank, and the other ends were fastened with lengths of tow line through strain gauge load links at the north end of the tank. A photograph of the arrangement, is shown in Exhibit 19. The moveable bridge was used to apply several hundred pounds of tension to the boom, waves were generated, and the wave spectra for the four transducers were recorded. A representative wave record and corresponding magnitude spectrum are shown in Exhibits 20 and 21.

Several characteristics of the spectra produced by the boom motions in the test tank are of interest. First, there is a decided fine structure present, as noted in the magnitude-frequency spectrum shown in Exhibit 21, when compared to the spectrum obtained for waves using fixed transducers. (Exhibit 17). At least four harmonics were noted in each of the magnitude spectra, indicating that boom motions were somewhat more complex than simple wave motions. However, the major component of energy (which is proportional to the area under the magnitude-frequency curves) remains at the fundamental frequency of the waves, (the measured wave frequency for this test was 0.303 Hz).

An additional point to be made regarding the spectra is that there are components at very low frequencies, on the order of 0.01-0.04 Hz This feature may relate to the resonant frequency of the tank. The tank is 203 meters in length and 2.4 meters deep, and a seiche wave would have a fundamental frequency of about 0.012 Hz. The low-frequency component may also be due to a vibrational mode of the stretched boom. This explanation is supported by the observation that the low-frequency modes are more prominent in the boom spectra than in the fixed-sensor spectra. In either case, the amount of energy represented by frequencies other than the fundamental is very small.

A final series of tank tests was performed prior to removal of the boom sections from the tank for packing and transport to St. John's, Newfoundland. In this sequence, a test was performed over a period of time approximating the duration of testing planned during the offshore tests (one hour).

Approximately 14,000 data points were recorded over 55.5 minutes for each of four sensors on the East boom section, which was placed under 3,100 Newtons (700 pounds) of tension. These data were analyzed separately for each of 13 segments of 1024 data points.

Practice Run

The instrumented boom was deployed during the practice run conducted off the coast of Newfoundland near Torbay Point on September 21, 1987. Data were recorded for 55 minutes on all eight transducers during the practice run. The boom was maintained in a catenary configuration that was roughly symmetrical, although the gap of the catenary varied considerably. The opening of the boom varied between 50 and 180 meters, because of the difficulty the tow boats encountered in maintaining course and spacing. For most of the test duration, the gap was roughly twice the desired distance of 84 +/- 15 meters, and the boom gap ratio was much greater than desired. In addition, the speed of the boom through the water generally appeared to be too great for retention of oil.

Offshore Test

Following repair of the cables on one half of the boom, which had been severed by tow boat propellers during the practice run, the boom was deployed as part of the actual offshore oil-release exercise on September 24, 1987. Forty-six minutes of data were recorded during the offshore test. Two of the transducers on which repairs had been attempted became inoperable throughout and provided no useable results. Of the six remaining sensors, four provided a full 46 minutes of data; transducers 1 and 3 on the Port side and transducers 3 and 4 on the starboard side. The remaining two transducers on the port side recorded useful data only for about 5 minutes, after which a twist in the boom placed both sensors out of the water for the remainder of the test.

BOOM TENSION MEASUREMENTS

Calibration

The Metrox Model TL-1010K strain links were received from the manufacturer with calibration data which was used directly in establishing output ranges of the instrumentation. Calibration data are as follows:

- S/N 2668 (Tow boat CG212)
  sensitivity = 1.744 mv/v, shunt calibration
  = 42,072 Newtons (9,458 lb.)

- S/N 2667 (Tow boat CG206/214);
  sensitivity = 1.744 mv/v, shunt calibration
  = 42,393 Newtons (9,530 lb.)

The gain # of each amplifier was adjusted to provide an output corresponding to 11,128 Newtons/volt (2,500 lb/volt), by use of the shunt calibration function and a digital voltmeter. Thus, a full-scale tension of 44,484 Newtons produced an output signal which was 80% of the 5-volt range used for the strip chart recorder and the TELOG data logger.

<u>Practice Run.</u>

No records of tension on the boom were obtained from the load cell connected to the strip chart recorder during the practice run. Apparently, the strain gauge amplifier was overloaded by radio-frequency interference from the boat's generator, resulting in full scale deflection of the recorder at all times.

Records obtained from the Telog recorder show that the measured tension oscillated considerably even over the 5-second sampling interval that was used. A plot of the data, averaged over 25-second intervals, is shown in Exhibit 22. Throughout the practice run, the tension was never within the range expected for a towed boom of this size and length. A static tension level on the order of 9,000-11,000 Newtons was expected, whereas the data shows a variable tension between 900 and 4,500 Newtons.

Offshore Tests.

Essentially no data were obtained from the load links on either side of the boom during the offshore tests. It is possible that the twists in the tow and shackle arrangement that occurred during the tests may have loosened the cable connection at the strain link. During the test, it was observed that there was often slack in the tow lines as the tow boats jockeyed to maintain proper direction and speed.

FLOW AND RECOVERY MEASUREMENTS

Calibration

The 4-inch Venturi tube and associated Rosemount pressure gauges were calibrated at OHMSETT prior to shipment to St. John's. The Rosemount transmitters were calibrated by adjusting the full-scale output to correspond to an applied pressure head, by means of a water-filled manometer tube. The faceplate readings at several values of applied pressure were obtained to demonstrate that the expected square-root relationship between readings and applied pressure was valid, see Exhibit 23. It was determined that the Rosemount signal was proportional to the square root of the differential pressure and, therefore, should be directly proportional to flow through the Venturi tube.

The linear relation between flow and Rosemount gauge readings was tested by pumping salt water through the Venturi at various pumping rates and measuring the output of the pressure transmitter. The results using the face-plate scale of the Rosemount are summarized in Exhibit 24 for two sets of tests at a full-scale output of 0.50 meters of water.

The Telog data recorder was used during the calibration series to evaluate this selection for recording the Venturi data. The Telog unit collected data over a programmable time interval, providing the maximum and minimum values of data collected each second and the average over the interval, and was programmed to provide tabular flow rate data directly in gallons per minute. An example of the output is provided in Exhibit 25 exactly as the data were output from the microcomputer controller. The right side of the data display in the Exhibit 25 provides a rough plot of the data.

The Rosemount transmitter used to measure the pressure of the skimmer pump discharge line was calibrated directly in pressure units, so that a full scale reading corresponded to 3.45×10^5 Newtons/m^2.

The depth of fluid in the recovery tanks was measured by a 3 meter (10-ft) pole with 6.4 mm markings. No attempt was made to calibrate either the measuring device or the volume-depth relationship of the recovery tanks. Rather, the geometry of the cylindrical tanks (6.4 meters in length and 2.13 meters in diameter) was used to calculate the volume using the following relation:

$$\text{Volume} = LR^2 \left((Q/57.3) - \sin Q \cos Q\right.$$

$$\text{Cos } Q = 1 - (H/R)$$

where H is the height of liquid in the tank of length L and radius R, and the angle Q is computed in degrees.

Practice Run.

No measurements of flow rate or recovered product were made during the practice run on September 21, 1987.

Offshore Tests.

Flow and total recovery measurements of oil collected by various skimmers were made during the offshore tests. No flow, discharge pressure, or tank accumulation was observed during attempts to operate the Heavy Oil Skimmer.

During the 23-minute period of operation of the Framo skimmer, the venturi flow rates were recorded by the Telog data recorders using 5-second averaging, the discharge pressure was recorded manually at approximately 10-minute intervals, and the depth of recovered product in the storage tank was measured at approximately 5-minute intervals.

Similar measurements were made during the 29 minutes that a Terling GT185 skimmer was operated.

LABORATORY MEASUREMENTS

Duplicate in-line samples were collected every 5-10 minutes during operation of the Framo skimmer, and single samples were collected over approximately 10-minute intervals during operation of the Terling GT185 skimmer. These samples were subsequently analyzed by ASTM methods to determine the percent of water in the recovered materials.

OTHER MEASUREMENTS

Tow Speed was measured using wood chips, and distance between tow boats and to various points on the boom were measured by optical rangefinders during the offshore tests. The tow speed was measured by timing a given distance traveled by floating wood chips dropped over the side of each tow boat. Fixed distances were marked along the rail of each tow boat. To determine the precision and accuracy of this method, several series of tests were performed using the technique on the moving bridge of the OHMSETT test tank. These results are showed that a set of measurements would be expected to obtain values within +/- 20% of the mean and the true speed.

The Rangefinders used to determine distance were calibrated by adjustment to provide the best image at a known distance of 100 meters. Several sets of measurements were made using the rangefinders to determine marked distances from 10 meters to 200 meters. It was determined that an accuracy or a precision of +/- 20% could be expected.

SECTION 6

RESULTS AND DISCUSSION

BOOM MOTION MEASUREMENTS

Practice Run

Typical boom wave records over short and longer periods are given in Exhibits 26 and 27. The increased complexity of the boom motions on the ocean surface, compared to that obtained for monochromatic waves in the test tank, is noted.

The 55 minutes of data allowed 13 segments, each containing 1048 data points, to be analyzed for each of the eight sensors. A typical magnitude-frequency spectrum obtained by processing the boom wave data is given in Exhibit 28. It is noted that most of the energy from the boom motion is contained within a band of frequencies from 0.1 to 0.7 Hz. Although there is some activity over higher frequencies (i.e., above 1 Hz), the magnitude is at or near the noise level and individual harmonics are less than 0.01 meters. Some of the spectra exhibited significant very-low-frequency activity, in the range of zero to 0.1 Hz. which may be related to the erratic variations in tow speed and catenary conformation that occurred during the test.

The spectra from the various transducers along the boom were remarkably similar for any given time segment, exhibiting similar variations to those observed between different time segments at the same transducer. The one-third significant wave height, calculated as 2.83 times the square root of the area under the magnitude spectrum, was found to be within the range of 0.06 to 0.09 meters at all boom locations. These results indicate that the motion of the boom is sufficiently similar throughout its length, and over time, that statistical analysis is possible.

Offshore Test

A typical boom wave record obtained during the test is presented in Exhibit 29. The magnitude-frequency spectrum for the same 1048 data point segment is given in Exhibit 30.

The spectra obtained during the offshore tests are similar, basically, to those obtained during the practice run. Most of the energy is contained in the range of zero to 1.0 Hz, with considerable noise but no discrete significant peaks at higher frequencies. There is considerable energy in the very low frequency band.

The magnitude of the boom spectrum at any given frequency is considerably greater than that obtained during the practice run, as would be expected for the greater sea state that was present. There was a decrease in magnitude at the significant frequencies (0-1 Hz) as the test progressed, indicating a somewhat diminishing swell during the time when data were being recorded. The one-third significant wave height throughout the spectra are consistently between 0.14 and 0.17 feet. A table of H (1/3) obtained during both the practice run and the offshore tests is given in Exhibit 31.

OIL RECOVERY MEASUREMENTS

Offshore Test

Recovery information for the Framo skimmer is summarized in Exhibit 32. As evident from the plot, the product recovery rate of the Framo skimmer was approximately 0.75 m/min (200 gpm) over a significant portion of the time it was deployed. The results obtained by measurement of the tank volumes (see Exhibit 33) are in close agreement to those obtained from the venturi flow rates, and indicate an average overall flow rate of 0.72 m/min. (192 gallons per minute). The total height of product in the tank was 1.079 meters (42.5 inches), corresponding to 11.58 cubic meters (3070 gallons). The height of remaining product, following draining of free-standing water, was 0.705 meters, corresponding to 6.60 cubic meters (1750 gallons). Of the product remaining in the tank, the subsequent analysis of stratified samples (see Section D) showed that about 40% was emulsified water. Therefore, the Framo skimmer was found to recover 3.77 +/- 0.75 m^3 (1000 +/- 200 gallons) of oil at an overall rate of 0.17 m^3 (45 gallons) of oil per minute and a recovery efficiency of 32%.

A summary of the flow data obtained for the GT185 skimmer is given in

Exhibit 34. The Venturi data indicated an average flow rate of near 0.38 m^3/min. (100 gpm) after an initial startup period, and the tank sounding data (Exhibit 35) showed an overall average recovery rate of about 0.32 m^3/min. (85 gpm). The final depth of product in the tank was 0.914 meters, corresponding to a volume of 9.35 cubic meters (2,480 gallons). No free-standing water was observed in the recovered material, but subsequent analysis showed that the product contained an average of 54% of emulsified water. Thus, the GT185 skimmer was found to recover 4.15 +/- 0.38 cubic meters (1100 +/- 100 gallons) of oil at an overall rate of 0.14 m^3 (38 gallons) of oil per minute and a recovery efficiency of about 44%.

LABORATORY MEASUREMENTS

The results obtained by analysis of in-line samples for percent water are given in Exhibit 36. There was considerable difficulty in obtaining these samples and, because of the large volume of discharge lines, an uncertainty regarding which skimmer produced the sampled product at any given time. The data do not provide conclusive evidence of skimmer performance. The data from samples of the Framo skimmer (which are less uncertain) generally agree with the conclusion that approximately 34% of the product was oil.

Stratified samples of the recovered product in the storage tanks were also collected, following stripping of free-standing water.

The samples collected within depth intervals in the recovery tanks also were analyzed. The data obtained from analysis of these samples from the

Framo skimmer and the GT185 skimmer are provided in Exhibit 37. It is noted that the samples from the GT185 contain significantly more emulsified water (averaging 55%) than the samples from the Framo skimmer (averaging 37%). Also, all of the water found in the product recovered by the GT185 was emulsified water.

The data for the GT185 skimmer shows the correct number (6) of six-inch samples to correspond to the observed 36-inch depth of fluid in the tank. However, the number of six-inch samples (5) from the Framo skimmer does not correlate with the measured depth of fluid in the tank, 27.5 inches. Also, the volumes found in the individual compartments varied considerably from the expected 30 mL. It is possible that (1) the sampler leaked between compartments prior to sample collection; (2) the samples were collected at a slant rather than vertically, a likely occurrence since they were taken atop the tank on a rolling, pitching deck; (3) exact separations between compartments were not obtained during the sample collection; and/or (4) the sampler was closed at the deep end of the tank during a pitch motion of the ship. Each of these factors will affect the results derived from the laboratory data, generally by lowering the calculated recovery efficiency of the skimmer.

OTHER MEASUREMENTS

Practice Run

The sparse data obtained for compass reading (heading), distances between boats and to various points on the boom, and through-the-water speed during the practice run are provided in Exhibit 38. Because of the difficulty encountered in maintaining orientation and tow speed, most measurements were variable and erratic. Activities necessary to maintain a proper boom configuration took precedence over the distance and speed data collection efforts.

The small amount of speed and orientation data obtained during the offshore test is provided in Exhibit 39. Because major activity focused on keeping the tow lines clear of the boat props and maintaining observation to detect boom twist and roll, only a limited number of measurements were made. Attempts to measure boat heading were forsaken entirely, because the boom direction changed often, and rapidly, as needed to maintain the boom location with respect to the oil slick. These changes in boat conformation made woodchip measurements erratic, and most attempts resulted in obtaining no data. Some of the reportable results indicated that the boom was being towed within the range of 0.5 to 1 knot. However, most observations denoted more rapid movement of the boom.

REFERENCES

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2. Borst, M.J., and Nash, J.H. Oil Containment Boom Test Protocol (In preparation). U.S. Environmental Protection Agency, Cincinnati, Ohio, 1988.

GLOSSARY

BOOM PERFORMANCE - The ability of an oil containment device to contain an oil slide during deployment.

RECOVERY EFFICIENCY - The volume of oil recovered by a skimmer device, divided by the total volume of recovered product, within a given time interval.