# THE EFFECT OF BUOYANCY-TO-WEIGHT RATIO ON OIL SPILL CONTAINMENT BOOM PERFORMANCE

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## Acknowledgments

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# 1. Introduction

The purpose of this research project was to investigate, through a series of experiments performed at the Ohmsett facility in Leonardo, NJ, the relationship between an oil spill containment boom's buoyancy-to-weight ratio and its performance.

## *1.1 Background*

In a research project funded by the Minerals Management Service, a total of 31 containment boom tests were reviewed dating from 1975 and 1999 (Schulze 2001). Much of the testing was performed at Ohmsett, but some tests were done at other simulation facilities and others were performed in offshore conditions. The purpose of the research project was to summarize boom performance from this broad record of testing and to make generalizations based on the boom's physical characteristics, particularly the buoyancy-to-weight ratio and the draft. One of the main conclusions of the study was that better boom performance might be achieved with increased buoyancy of the boom. An exact relationship was not determined but was identified as an area that required further research.

The Schulze study also suggested that the boom performance as measured by oil loss rate could be related to boom draft. Oil loss rate was at one time part of the standard boom test protocol at Ohmsett. However, in updating the testing protocol several years ago and having it adopted as an American Society of Testing and Materials (ASTM) standard test protocol, it was agreed by the ASTM subcommittee on booms that loss rate could not be properly measured and would not be a valid indicator of boom performance. As such, the measurement of loss rate is no longer recognized as a performance measure in the ASTM test standard for containment booms. Based on this, the focus of this study became performance as measured by first and gross loss speeds, and the effect on this of a boom's buoyancy.

The implication for establishing a relationship between buoyancy and boom performance is that the standards for boom design and selection could be improved. The minimum required values for a boom's buoyancy to weight ratio have long been a concern within the spill response community, in particular, with the relatively low values allowed under United States Coast Guard response regulations as well as the minimum values specified under the ASTM boom selection standard. The subject was especially contentious during the development of the ASTM boom selection standard, which was approved with the note that,

> "*Buoyancy to weight ratios greater than those listed in the table may result in improved boom performance under certain conditions, however further research is required before minimum values greater than those shown in the table can be established*."

For reference, the minimum required buoyancy to weight ratios, as defined by ASTM, are listed below in Table 1. The table also lists the range of applicable wave heights for the three classifications of calm, protected, and open water.

**Table 1: Wave height and required buoyancy of applicable containment boom**

| Location classification | Wave height, feet | Minimum gross buoyancy to weight ratio |
|---|---|---|
| Calm water | 0 to 1 | 3:1 |
| Protected water | 0 to 3 | 4:1 |
| Open water | 0 to 6 | 8:1 |
| Wave height values from ASTM standard F625, *Standard practice for classifying water bodies for spill control systems*; buoyancy values from ASTM F1523, *Standard guide for selection of booms in accordance with water body classifications*. | | |

Based on the above, a series of experiments was designed and performed to define the relationship between the key physical characteristics of a boom and its performance. Ohmsett was the ideal facility for such tests, offering excellent control over the parameters to be measured and allowing a large number of test runs to be accomplished in an economic manner.

## *1.2 Objective*

The objective of the research project was to determine the effects of buoyancy-to-weight (B/W) ratio on boom performance as measured by first loss and gross loss speeds.

## *1.3 Goals*

The objective of the research project was met by achieving the following goals:

- Design and construction of fence-type and curtain-type containment booms, with the ability to vary draft and buoyancy without significantly changing the boom's profile.

- Design and execution of a test plan that included a range of buoyancies through the range of concern, specifically from 4:1 to 10:1.

# 2. Methodology

## 2.1 Specification and Construction of Boom for Testing

The main criteria for the boom to be used in the test were that it be adaptable to provide different buoyancy to weight ratios and drafts without significantly changing its profile. Selection and development of booms for the tank testing were based on the following desired criteria:

- include commonly-used boom types, both fence-type and curtain-type;
- two boom drafts, ranging up to 12 inches, respecting the maximum draft of 1:8 of the tank depth; and
- buoyancy-to-weight ranging from 4:1 to 10:1 or greater.

The maximum boom draft of 12 inches is likely in the lower range of that used in the field, however it is in the upper end of the range that can be used at Ohmsett for comparative testing: as described in Appendix X1 of ASTM standard 2084, the boom draft to water depth ratio should not exceed 1:8 without some concern over test bias.

The buoyancy range of 2:1 to 10:1 represents the range of most concern with regard to the ASTM and USCG selection criteria. At the lower end, the ratio is what could be regarded as the minimum value for effective containment in calm or protected waters, and the upper end represents double the value recommended by these boom selection criteria.

Aside from the effects of buoyancy, Schulze (2001) also concluded that there were changes in performance as a result of shape and vortex effects. These effects are mostly a result of varying boom profile, but could also be influenced by the length of the boom, its deployment mode (i.e., U-, V-, or J-configuration), and gap ratio. To remove this as a concern, all booms in this test were of the same length (namely, 100 feet) and deployed in a U-configuration with a gap ratio of 1:3.

In order to provide a range of B:W ratios, several curtain-type booms of the same overall height were produced but with different diameters of the rolled-foam buoyancy element. A similar curtain-type boom of lesser height but similar buoyancy was also provided to examine the differences with boom height. As well, ballast chains ranging from 1/4-inch to ½-inch were provided to allow some flexibility in providing not only the desired B:W value, but also to provide a boom with adequate roll resistance and good towing characteristics.

For the fence-type boom, a single boom was produced, but with the capability of varying the position and number of floats. Varying the position of the floats was done to provide variation in draft. The number of floats could also be changed to provide variation in buoyancy.

Based on this, the following booms were selected for testing:

**Table 2: Booms selected for testing**

| Boom | Type | Draft, in. | Chain, in. | Estimated B:W Ratio |
|---|---|---|---|---|
| GlobeBoom ED-24 (additional floats, in lower position) | fence | 8 | 5/16 | 5.5 |
| GlobeBoom ED-24 (floats in lower position) | fence | 8 | 1/2 | 3.4 |
| GlobeBoom ED-24 (additional floats, in upper position) | fence | 12 | 5/16 | 5.5 |
| GlobeBoom ED-24 (floats in upper position) | fence | 12 | 1/2 | 3.4 |
| CS-18 | curtain | 9 | 1/4 | 8.3 |
| CS-18 | curtain | 9 | 1/2 | 4.5 |
| CS-24 | curtain | 12 | 5/16 | 7.5 |
| CS-24L | curtain | 12 | 5/16 | 3.4 |
| CS-24O | curtain | 12 | 5/16 | 13.4 |
| B:W ratios calculated from volume and weight of component parts. | | | | |

Applied Fabric Technologies Inc. (AFTI) assisted in the design and selection of booms, and was then contracted to construct the selected booms in preparation for testing.

The GlobeBoom (manufactured by AFTI) is a fence-type boom consisting of a plastic-coated fabric membrane with plastic, foam-filled floats bolted on to the membrane to provide buoyancy (Figure 1). As indicated in the table, floats could be bolted on at an “upper” or “lower” position to vary the boom’s draft. Additional floats were also used to provide added buoyancy for certain tests.

The curtain-type boom listed in the table is representative of lightweight boom used in nearshore and protected waters, and is designated in the table as CS. For this boom the buoyancy consists of a rolled, polyethylene foam log (Figure 2).

For each of the booms, ballast is provided by a chain at the bottom of the boom. Generally this chain would be bolted on to the bottom of the boom or contained within a chain pocket that is integral to the boom membrane. For this test, to allow for flexibility in which chain would be used for a given test, the chains were held within a fold at the bottom of the boom, and secured with a removable bolt and wing nut (Figure 3).

**Figure 1: Fence-type boom used in study**


**Figure 2: Curtain-type boom used in study**

**Figure 3: Curtain boom showing chain pocket along bottom edge**

## 2.2 Test Procedures

The experiments were designed to closely follow the procedures listed in ASTM standard F2084 (ASTM 2003), a copy of which is reproduced in the Appendix. This standard was based primarily on existing test protocols from Ohmsett. Ohmsett staff led in the development and adoption of the ASTM standard.

The following was the sequence of tests for each of the booms:

1. The boom was rigged and otherwise prepared for deployment and connected to the tow bridge establishing the desired gap ratio.

2. Prior to testing with oil, a "dry run" tow was performed to confirm the basic seakeeping of the boom under tow.

3. In calm water, the standard test series was performed, comprising: pre-load determination, testing to first loss, and testing to gross loss.

4. Using the same pre-load volume, the standard test series was repeated for each of the selected wave conditions.

As noted previously, the primary indicators of boom performance in the test standard are the first and gross loss tow speeds. The definitions for these performance indicators are:

*First loss tow / current velocity* - the minimum tow / current velocity normal to the membrane at which oil continually escapes past the boom. This applies to the boom in the catenary position.

*Gross loss tow / current velocity* - the minimum speed at which massive continual oil loss is observed escaping past the boom.

An underwater video camera, mounted on the undercarriage of the auxiliary bridge, was aimed at the apex of the boom. The camera could be controlled from the main bridge, allowing observers to pan along the leading arms of the boom, focus on the apex, or zoom in or out as desired. Output from the camera was recorded, and was monitored to provide real-time observations of when first and gross loss occurred. The recorded video was consulted after a test run when there was uncertainty over when first or gross loss had occurred.

The test matrix included testing in calm water and up to four wave conditions including regular (sinusoidal) waves and irregular waves (referred to at Ohmsett as harbor chop). The wave conditions used were in the range of up to 1 foot in height, appropriate for the size of booms being tested, and were selected in consultation with Ohmsett staff.

## *2.3 Measurement of Boom Physical Characteristics*

Boom length and height was measured with the boom laid out on the deck beside the tank. Prior to measuring, the boom was straightened along its length to remove any kinks. A tape measure was then used to measure the length of the boom, from one end connector to the other. The total height of the boom was also measured with the boom on the deck of the tank.

Once the boom was deployed in the water, freeboard was measured at a minimum of three locations, with the measurements averaged and deducted from the previously measured height measurement to produce an estimate of draft.

## *2.4 Measurement of Buoyancy and Weight*

Over the last few years, the ASTM subcommittee on booms has initiated an attempt to develop a standardized methodology for measuring a boom's buoyancy. During that process, boom manufacturers were surveyed informally of their approach to this. It was found that buoyancy-to-weight ratio has generally not been measured with any rigor. The general approach has been to calculate an estimated buoyancy based on volumes of materials used (and hence the displacement of the boom when submerged) and based on unit weights of materials used in the boom construction. As part of this study, an attempt was made to use materials and equipment at hand at the Ohmsett facility to provide a reasonable estimation of the buoyancy-to-weight of a boom.

The basic approach was to determine the dry weight of the assembled boom, and then to determine the volume of fresh water displaced from a container, external to the test tank, in which the boom was immersed.

The various booms, chains, and spare floats were weighed by placing them on a pallet, then lifting the pallet with a sling that included a 4000-lb load cell. Each lift was repeated at least a second time, or more if the results varied significantly.

Gross buoyancy of a boom is defined as, "the weight of fresh water displaced by the boom totally submerged" according to the ASTM standard terminology on booms (ASTM 2003). As such, the most direct method of measuring buoyancy is to submerge the boom in a container of water and measure the difference in water volume when the boom is immersed. Figure 4 shows the tank that was used for measuring the boom displacement. At each end of the tank, a measuring stick was clamped in place to indicate both the starting height of water, and the height of water when the boom was immersed. A second similar tank was used as a water reservoir so that the amount of water pumped into the "displacement" tank could be measured. In each case, the calculation was: displacement volume = difference between starting and ending height of water times the surface area of the tank.

To hold the boom under water required considerable force. This was accomplished by placing several wooden planks on the top surface of the boom, and then clamping a number of pieces of lumber to the tank edges, with the lumber bearing on the planks, all of this done prior to filling the tank with water. Once the tank was filled and the boom submerged, the planks were also submerged in their entirety, as were portions of the lumber restraining the planks (Figure 5), so their volume had to be measured and considered in the displacement calculation.

**Figure 4: Tank used for measuring boom displacement**

**Figure 5: Planks and lumber used to hold boom underwater**

There is a concern over misrepresenting the buoyancy when dealing with booms that use solid floatation elements that are enclosed within the boom membrane. This style of construction is typical of curtain-type booms. With this style of boom, the membrane generally does not fit snugly around the float log, which results in an air space at each end of the float. This air space would add to the buoyancy of the boom initially. However, once the boom had been used, it is very likely that abrasion of the membrane would allow water to leak into this air space and this added buoyancy would be lost. Such abrasion would not be considered to be damage but rather normal wear-and-tear, and could result from as little use as dragging the boom along a concrete surface or deploying it over the edge of a pier. Based on this, the air that is trapped at each end of a floatation element should not be considered as part of the buoyancy of the boom. To simulate the wear-and-tear that would be expected in normal operations, a small hole was punched top and bottom at each end of each floatation element to allow water to enter the space. (Figure 6, photo DCP2475) This was done prior to testing and prior to the measurement of buoyancy.

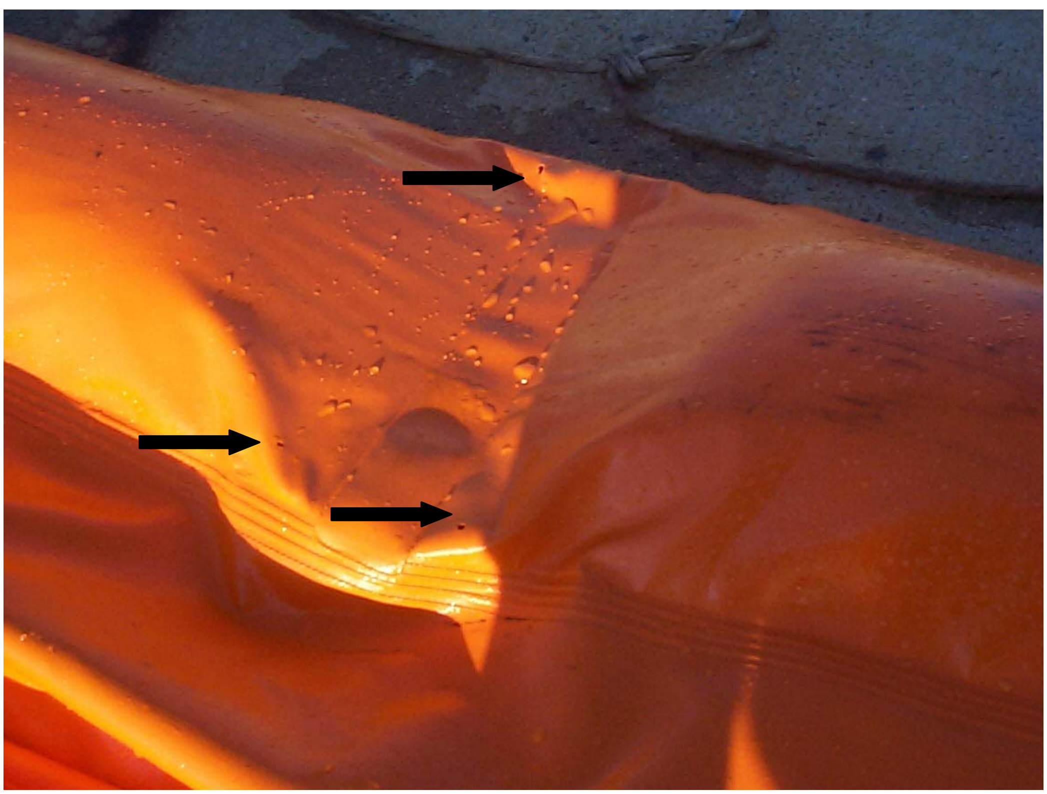

**Figure 6: Small holes punched in boom membrane to simulate normal wear-and-tear**

# 3. Results

## *3.1 Buoyancy measurements*

Buoyancy to weight ratios were estimated, by the boom manufacturer, for each of the booms based on the unit weights and dimensions of component parts of the booms. As part of the test program at Ohmsett, a direct measurement of buoyancy and weight was performed using available equipment. The results of the measured buoyancy are shown in Table 3 with the calculated estimates shown for comparison.

**Table 3: Comparison of calculated and measured buoyancy-to-weight ratios**

| Boom | Chain, in. | Estimated B:W Ratio | Measured B:W Ratio | Difference, % |
|---|---|---|---|---|
| GlobeBoom ED-24 (additional floats, lesser chain) | 5/16 | 5.5 | 4.0 | -27 |
| GlobeBoom ED-24 (lesser floats, larger chain) | 1/2 | 3.4 | 3.0 | -12 |
| CS-18 | 1/4 | 8.3 | 8.1 | -2.4 |
| CS-24 | 5/16 | 7.5 | 8.0 | +6.7 |
| CS-24L | 5/16 | 3.4 | 3.8 | +12 |
| CS-24O | 5/16 | 13.4 | 10.4 | -22 |
| Average difference, % (absolute values) | | | | 14 |

The difference between measured and calculated ranged from a low of 2.4% to a high of 27%. Potential sources of error are as follows:

<u>Potential Sources of Error in Measuring Technique</u>

In holding the boom within the measuring tank, it is possible that air could be trapped within folds of the boom membrane. Care was taken to avoid this potential problem when placing the boom within the tank, and during filling of the tank, and it is unlikely to represent a large error.

As discussed previously, holes were punched at the ends of each floatation element to simulate normal wear-and-tear, and to measure the boom's buoyancy during normal usage. It is possible that, in filling the measuring tank, that these areas were not completely flooded. During the filling of the tank, and again once the tank was filled, attempts were made to agitate the boom to release air from any trapped areas, but this proved difficult with the larger booms due to the large buoyancy forces involved.

There was an inherent source of error in measuring the displaced volume of water. Assuming an accuracy of measuring the water depth of +/- 1/16$^{th}$ of an inch leads to a potential error of less than +/- 10 pounds of buoyancy, or less than a few percent for the booms measured here. To limit the potential magnitude of this error, it is important to use a tank that's dimensions can be measured accurately, and that is no larger than necessary to hold the boom being measured. It is also useful to perform the tests indoors or under calm wind conditions to improve the accuracy of the water depth measurements.

Finally, planks and pieces of lumber were used to hold the boom under water as the tank was being filled. Their submerged volume was measured and accounted for in the calculation of displacement, but their shape and cross-section were somewhat irregular, making a very accurate measure impossible. A standardized submersion apparatus would eliminate or greatly reduce this error.

In total, the likely potential error inherent to the techniques and equipment used was within +/- 10%.

## *3.2 Wave analysis*

The test plan called for tests in both regular (sinusoidal) and irregular (harbor chop) wave conditions. It was intended to use two different wave heights of each of the regular and harbor chop wave conditions. This was done to increase the likelihood that a performance difference would be apparent and measurable.

A wave generator at one end of the tank produces waves, and at the opposite end an artificial beach can be raised to absorb wave energy (resulting in a regular wave) or lowered to produce an irregular waves. Wave amplitude and period is varied at Ohmsett by changing the stroke and speed of the wave generator. To aid in selecting an appropriate wave height and period, Ohmsett has a record that shows the expected wave conditions for various wave generator settings. Based on this, the following conditions were selected (Table 4).

**Table 4: Predicted characteristics for selected wave conditions**

| Wave | Type | Wave generator settings | | Wave height, inches | Wave period, seconds |
|---|---|---|---|---|---|
| | | Stroke, in. | Speed, cpm | | |
| 1 | Regular | 1.5 | 38 | 4 | 1.8 |
| 2 | Regular | 1.5 | 45 | 6 | 1.7 |
| 3 | Harbor chop | 1.5 | 33 | 6 | 1.9 |
| 4 | Harbor chop | 1.5 | 40 | 8.25 | 1.6 |

A computerized data collection system measures and records the distance from the water surface to a meter mounted on the towing bridge. Readings are taken every 0.1 seconds. The data is then analyzed by filtering out spurious readings, graphing it to identify a representative portion, and then measuring the peak-to-trough distances for each wave. For the significant wave height, the upper one-third of the wave heights is averaged. The results of this analysis is shown in Table 5, with the expected conditions also listed for comparison.

**Table 5: Actual vs. predicted characteristics for selected wave conditions**

| Wave | Number of Tests | Type | Predicted significant wave height, inches | Measured significant wave height, inches | | |
|---|---|---|---|---|---|---|
| | | | | Maximum | Minimum | Average* |
| 1 | 10 | Regular | 4 | 6.62 | 4.12 | 5.25 |
| 2 | 8 | Regular | 6 | 5.36 | 3.41 | 4.24 |
| 3 | 12 | Harbor chop | 6 | 8.87 | 5.33 | 6.93 |
| 4 | 7 | Harbor chop | 8.25 | 5.95 | 4.15 | 5.36 |
| * Average refers to average measured for all tests done with that wave height. | | | | | | |

The above comparison of actual vs. predicted wave heights was surprising in that the measured wave height is less for wave #2 vs. #1, and for wave #4 vs. wave #3, contrary to the expected result based on the Ohmsett record of wave heights for various wavemaker settings. For a given wave type and given wave generator stroke setting, increasing the cycle speed of the wave generator should increase the wave height but this is contradicted by the above results. The data was reviewed to confirm that the discrepancy was not due to analytical error but no reasonable explanation was found.

Ohmsett staff were also consulted and asked to review the wave data. The results of their analysis is shown in Appendix B. It compares well with the summary of wave characteristics shown in Table 5: the disparity between their analysis and that shown here (comparing average significant wave height) ranges from +1% for wave #1, -6.7% for wave #2, +5.8% for wave #3, and –12.5% for wave #4. As with the data shown in Table 5, the wave height unaccountably is less for wave #2 vs. #1, and for wave #4 vs. wave #3 despite the higher speed of the wave generator in both cases.

In discussing this issue with Ohmsett staff, it was noted that the record of predicted wave conditions was derived from a ten-minute data set obtained from a single point within the tank. Reflected wave energies and harmonics travel through the wave trains and may have mitigating or amplifying effects on the nominal propagated wave. Therefore, relatively small data sets obtained at different locations may not be representative of overall actual conditions present in the test tank, and may not correspond to the record of wave conditions for that single point.

## *3.3 Boom performance results*

The performance results for the seven booms tested is shown in Table 6, which lists the tow speeds at which first and gross loss occurred for the five wave conditions (calm, two regular waves, and two harbor chop conditions). The buoyancy-to-weight ratio listed in the table is that measured during the course of this project.

**Table 6: Summary of boom performance results**

| Boom | B:W Ratio | First Loss Tow Speed | | | | | Gross Loss Tow Speed | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Calm | R Wave1 (wave #1) | R Wave 2 (wave #2) | HC 1 (wave #3) | HC 2 (wave #4) | Calm | R Wave1 (wave #1) | R Wave 2 (wave #2) | HC 1 (wave #3) | HC 2 (wave #4) |
| Curtain Boom | | | | | | | | | | | |
| CS – O | 10.4 | 0.85 | 0.85 | 0.85 | 0.75 | 0.80 | 1.00 | 0.95 | 0.90 | 0.95 | 0.95 |
| CS – R | 8.0 | 0.85 | 0.70 | 0.60 | 0.75 | 0.75 | 1.00 | 1.00 | 0.80 | 1.05 | 0.92 |
| CS18 – R | 8.1 | 0.87 | 0.90 | 0.80 | 0.85 | -- | 1.10 | 1.00 | 1.05 | 1.00 | -- |
| CS – L | 3.8 | 0.85 | 0.50 | 0.30 | 0.80 | 0.45 | 1.10 | 0.60 | 0.60 | 0.96 | 0.5 |
| Fence Boom<br>*12-inch draft* | | | | | | | | | | | |
| ED24 – HB | 4.0 | 0.83 | 0.85 | 0.85 | 0.85 | 0.70 | 1.00 | 0.95 | 0.95 | 1.05 | 0.95 |
| ED24 – LB | 3.0 | 0.90 | 0.60 | 0.60 | 0.90 | 0.70 | 1.15 | 0.80 | 0.80 | 1.15 | 0.95 |
| *8-inch draft* | | | | | | | | | | | |
| ED24 – HB | 4.0 | 0.85 | -- | 0.80 | 0.75 | 0.75 | 0.95 | -- | 0.92 | 0.97 | 0.97 |
| ED24 - LB | 3.0 | 0.82 | -- | 0.80 | 0.70 | 0.55 | 0.92 | -- | 0.90 | 0.85 | 0.85 |

### 3.3.1 Performance of Fence Boom

Unfortunately, there was less difference than planned between the buoyancy values for the different fence boom configurations. As a result, there was little apparent performance difference between the two booms. In calm water, referring to Table 6, first loss occurred in the range of 0.82 to 0.90 knots, and gross loss occurred in the range of 0.92 to 1.15 knots, with no defined trend related to buoyancy. The results were similar in wave conditions, with some degradation in performance but with no apparent trend related to buoyancy.

### 3.3.2 Performance of Curtain Boom in Various Wave Conditions

Figure 7 shows the first and gross loss tow speeds for the curtain boom in calm water. There is no appreciable difference in the boom performance as a function of buoyancy: first loss speeds are almost constant at 0.85 knots for the four booms tested, and gross loss speeds vary only slightly from 1.0 to 1.1 knots. (As noted above, results for the fence boom were similar.) The lack of difference in performance is perhaps not surprising in that the calm water is a relatively benign environment in which differences in buoyancy would have little apparent effect.

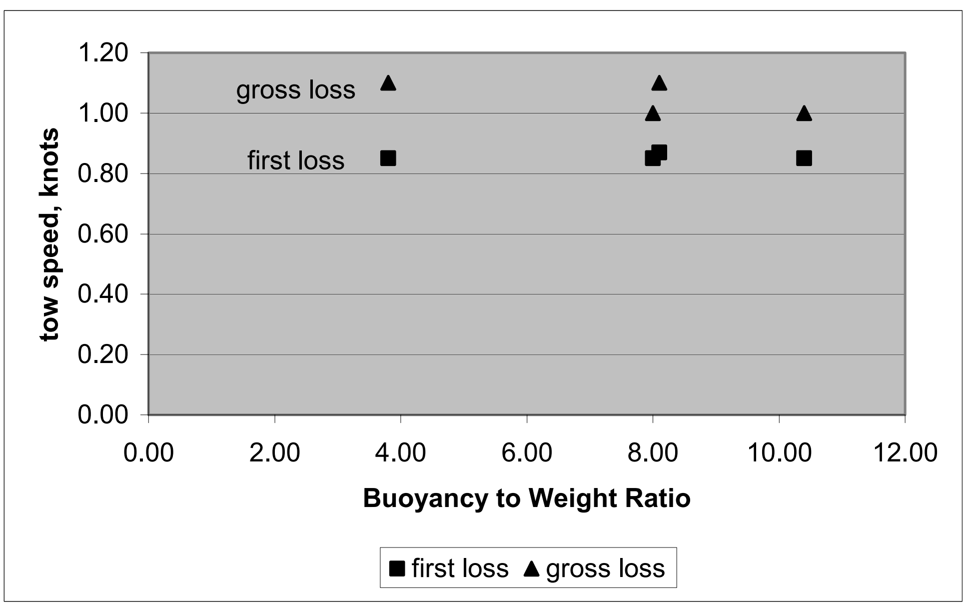


**Figure 7: First and gross loss tow speeds, curtain boom, calm water**

In regular waves, as shown in Figure 8, there is an identifiable trend in boom performance related to buoyancy. First losses occur at 0.85 knots for the most buoyant boom, which is the same first loss speed as for calm water. There is a slight decline to the range of 0.60 to 0.80 knots for the two booms with buoyancies of 8.0 and 8.1, and then a significant decline to the range of 0.3 to 0.5 knots for the least buoyant boom. Similarly, gross loss speeds decline from approximately 1.00 knots for the most buoyant boom to 0.60 knots for the least buoyant.

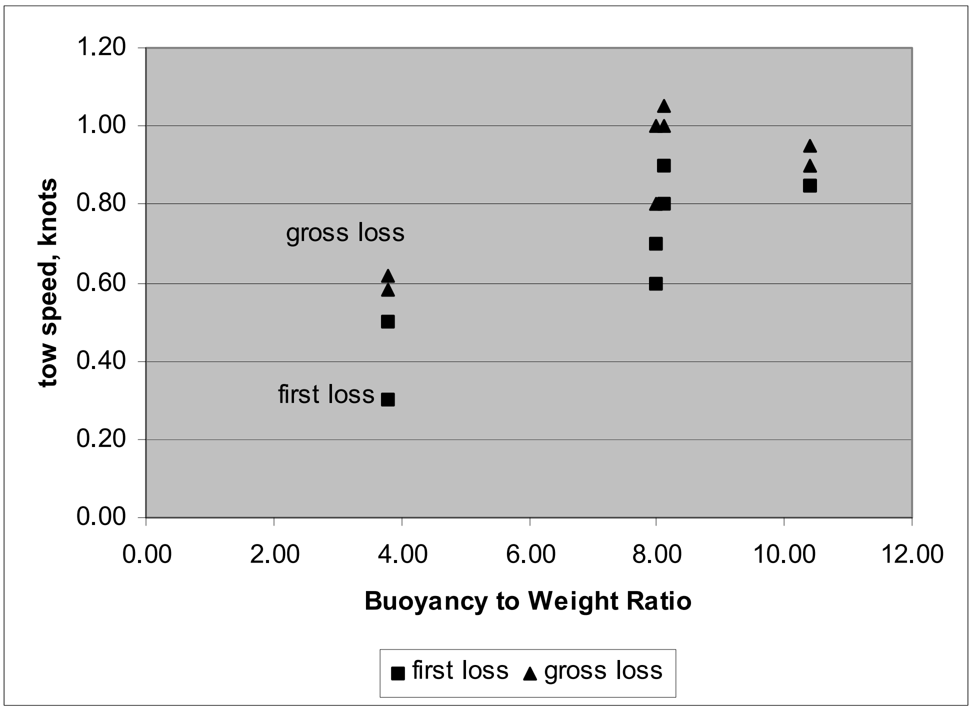


**Figure 8: First and gross loss two speeds, curtain boom, regular waves**

In the harbor chop waves (Figure 9), there is a less defined trend with considerable scatter among the data. Nonetheless, for the booms with buoyancy of 8 to 10, first loss speeds are all in the range of 0.75 to 0.85 knots, and gross loss speeds in the range of 0.9 to 1.05 knots. For the least buoyant boom first loss speeds are 0.45 and 0.80 knots, and gross loss speeds are 0.5 and 0.96 knots.

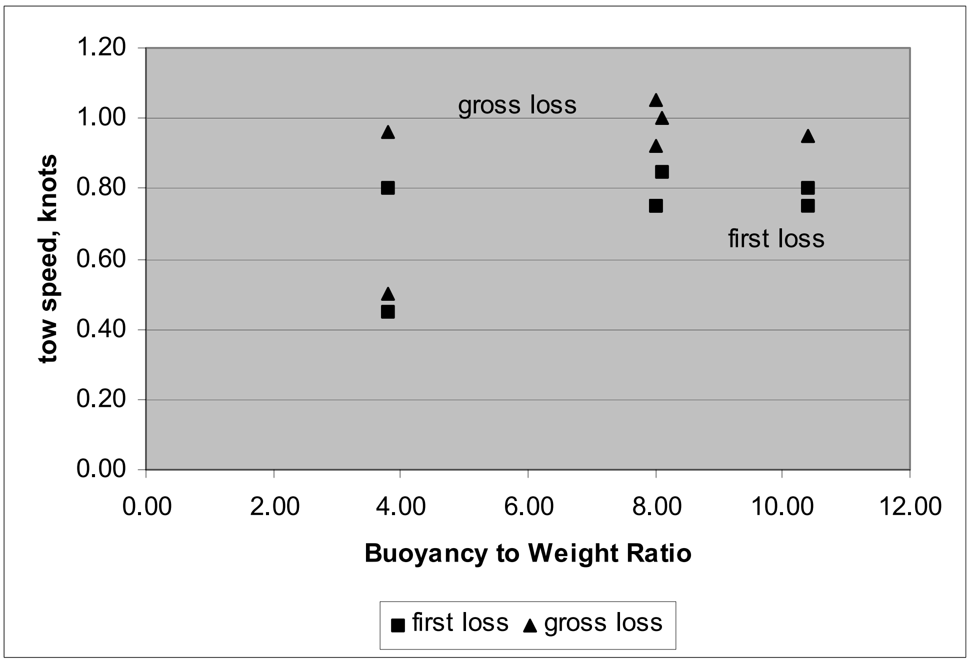


**Figure 9: First and gross loss tow speeds, curtain boom, harbor chop**

The decline in performance is more apparent in Figures 10 and 11, which show the variation in first and gross loss tow speeds for each of three booms (the results for the boom with a buoyancy of 8.1 are not shown for clarity). For the two most buoyant booms there is little change in performance whether the water is calm or when waves are introduced. For the least buoyant boom, there is a significant decline in performance in wave conditions in terms of both first and gross loss tow speeds.

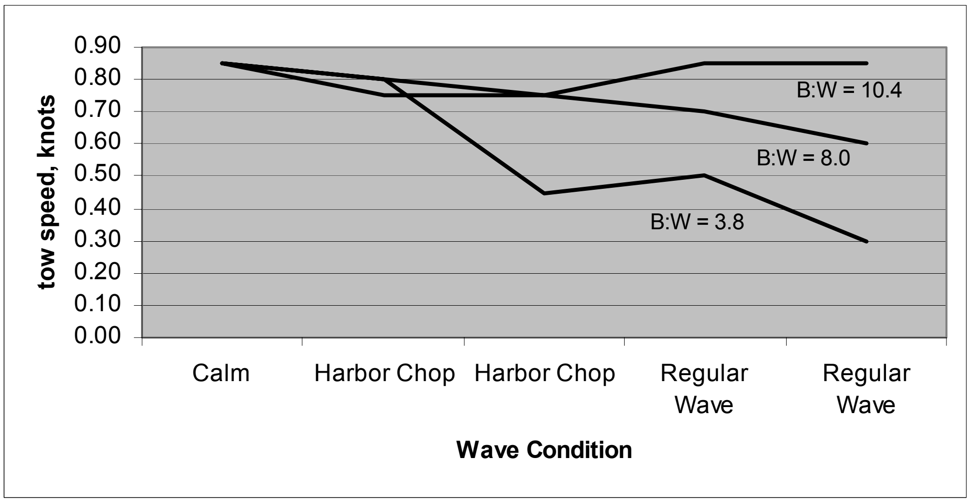


**Figure 10: Change in first loss tow speed with varying wave conditions**

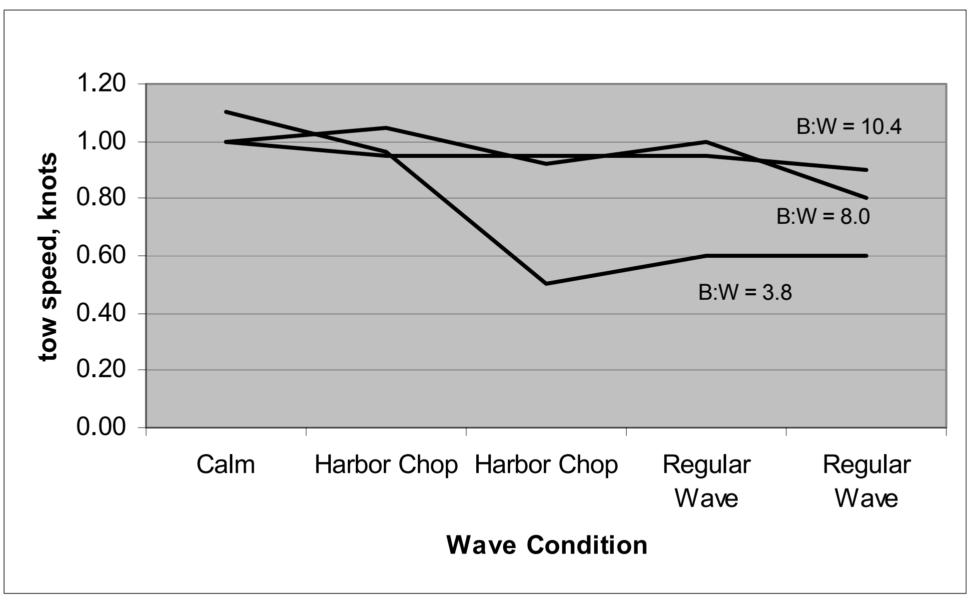


**Figure 11: Change in gross loss tow speed with varying wave conditions**

# 4. Conclusions

Using materials and equipment that were readily available at Ohmsett, the buoyancy to weight ratio was measured for six booms. Compared with the manufacturer's estimate of buoyancy, the measured values differed from a low of 2.4% to a high of 27%. The average difference between estimated and measured was 14%. Several potential sources of error inherent to the techniques and equipment used were considered but were not felt to be a significant contribution to the measured differences. A significant improvement in measuring buoyancy could be made by making a purpose-built submersion apparatus rather than using rough-cut lumber to hold the boom under water, as was done here. The methodology and equipment used is not likely to be applicable to booms larger than those used here, meaning that most offshore booms could not be measured as such.

A fence-type boom was prepared with the ability to vary its floatation and weight elements. However, only a minor variation in buoyancy was achieved with the result that little variation in boom performance was observed.

With the curtain-type boom, buoyancies ranged from 3.8 to 10.4, which covers the range of interest for booms to be used in nearshore and protected waters. There was a significant decline in performance, as measured by first and gross loss tow speeds, with the less buoyant booms. All booms had essentially the same performance when operated in calm conditions; first loss speeds of approximately 0.85 knots and gross loss speeds of 1.0 to 1.1 knots were observed. When operated in regular and harbor chop waves, the first loss tow speed was in the order of 0.5 knots and the gross loss speed was in the order of 0.6 knots for the less buoyant boom, while the values for the more buoyant booms declined only slightly.

# 5. Recommendations

The methodology and equipment used to measure buoyancy was appropriate for the booms used in this study, and the methodology should be codified in a standard for consideration by ASTM. A similar methodology should be developed for larger offshore booms.

Existing protocols for selecting booms suggest that buoyancies as low as 3:1 and 4:1 are appropriate for Calm and Protected waters, defined as having waves of up to 1 foot and 3 feet respectively. These values should be reconsidered in light of the clearly better performance of booms with buoyancies in the range of 8:1 to 10:1.

The test conditions did not include offshore boom, buoyancy-to-weight ratios typical of offshore boom, or offshore wave conditions. As such, no recommendation can be made regarding the minimum buoyancy for offshore boom.

Waves for the tests were selected based on Ohmsett's record of wave conditions. This record documents the wave height and period for a wide range of wavemaker stroke and speed settings. The waves used in this study were found to vary significantly from the recorded wave conditions. This record should be checked to confirm that conditions have not changed since it was produced, and to ensure that users of the facility can easily obtain a desired wave condition.

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# Appendix A:
# ASTM Standard F 2084 – 01
# Standard Guide for
# Collecting Containment Boom Performance Data
# In Controlled Environments

**Designation: F 2084 – 01**

# Standard Guide for Collecting Containment Boom Performance Data in Controlled Environments[1]

This standard is issued under the fixed designation F 2084; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This standard provides a guide for evaluating the effectiveness of full-scale oil spill containment booms in a controlled test facility.

1.2 This guide involves the use of specific test oils that may be considered hazardous materials. It is the responsibility of the user of this guide to procure and abide by the necessary permits for disposal of the used test oil.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*

D 97 Test Method for Pour Point of Petroleum Oils[2]

D 445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (the Calculation of Dynamic Viscosity)[2]

D 971 Test Method for Interfacial Tension of Oil Against Water by the Ring Method[3]

D 1298 Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method[2]

D 1796 Test Method for Water and Sediment in Fuel Oils by the Centrifuge Method (Laboratory Procedure)[2]

D 2983 Test Method for Low-Temperature Viscosity of Automotive Fluid Lubricants Measured by Brookfield Viscometer[4]

D 4007 Test Method for Water and Sediment in Crude Oil by Centrifuge Method (Laboratory Procedures)[4]

D 4092 Test Method for Density and Relative Density of liquids by Digital Density Meter[5]

F 631 Guide for Collecting Skimmer Performance Data in Controlled Environments[6]

F 818 Terminology Relating to Spill Response Barriers[6]

## 3. Terminology

3.1 *Boom Performance Data Terminology*—Terms associated with boom performance tests conducted in controlled environments:

3.1.1 *boom submergence (aka submarining)*—containment failure due to loss of freeboard.

3.1.2 *first-loss tow/current velocity*—minimum tow/current velocity normal to the membrane at which oil continually escapes past a boom This applies to the boom in the catenary position.

3.1.3 *gross loss tow/current velocity*—the minimum speed at which massive continual oil loss is observed escaping past the boom.

3.1.4 *harbor chop*—a condition of the water surface produced by an irregular pattern of waves.

3.1.5 *preload*—during testing, the quantity of test fluid distributed in front of and contained by the boom prior to the onset of a test.

3.1.6 *tow speed*—the relative speed difference between a boom and the water in which the boom is floating. In this standard guide relative current speed is equivalent.

3.1.7 *wave height*—(significant wave height) the average height, measured crest to trough, of the one-third highest waves, considering only short-period waves (i.e., period less than 10 s).

3.1.8 *wave period*—(significant wave period) the average period of the one-third highest waves, measured as the elapsed time between crests of succeeding waves.

## 4. Significance and Use

4.1 This guide defines a series of test methods to determine the oil containment effectiveness of containment booms when they are subjected to a variety of towing and wave conditions. The test methods measure the tow speed at which the boom first loses oil (both in calm water and in various wave conditions), the tow speed at which the boom reaches a gross oil loss condition (both in calm water and in various wave conditions), boom conformance to the surface wave conditions

[1] This guide is under the jurisdiction of ASTM Committee F20 on Hazardous Substances and Oil Spill Responseand is the direct responsibility of Subcommittee F20.11 on Control.

Current edition approved Mar. 10, 2001. Published April 2001.

[2] *Annual Book of ASTM Standards*, Vol 05.01.

[3] *Annual Book of ASTM Standards*, Vol 10.03.

[4] *Annual Book of ASTM Standards*, Vol 05.02.

[5] *Annual Book of ASTM Standards*, Vol 08.02.

[6] *Annual Book of ASTM Standards*, Vol 11.04.

for various wave heights, wavelengths and frequencies, (qualitatively), resulting tow forces when encountering various speeds and wave conditions, identifies towing ability at high speeds in calm water and waves, boom sea-worthiness relative to its hardware (i.e., connectors, ballast members), and general durability.

4.2 User's of this guide are cautioned that the ratio of boom draft to tank depth can affect test results, in particular the tow loads (see Appendix X1 discussion).

4.3 Other variables such as ease of repair and deployment, required operator training, operator fatigue, and transportability also affect performance in an actual spill but are not measured in this guide. These variables should be considered along with the test data when making comparisons or evaluations of containment booms.

## 5. Summary of Guide

5.1 This guide provides standardized procedures for evaluating any boom system and provides an evaluation of a particular boom's attributes in different environmental conditions and the ability to compare test results of a particular boom type with others having undergone these standard tests.

5.2 The maximum wave and tow speeds at which any boom can effectively gather and contain oil are known as boundary conditions. Booms that cannot maintain their design draft, freeboard, profile, and buoyancy at these conditions may be less effective. The boundary conditions depend on the characteristics of oil viscosity, oil/water interfacial tension and oil/water density gradient.

## 6. Test Facilities

6.1 Several types of test facilities can be used to conduct the tests outlined in this guide:

6.1.1 *Wave/Tow Tank*—A wave/tow tank has a movable bridge or other mechanism for towing the test device through water for the length of the facility. A wave generator may be installed on one end, or on the side of the facility, or both.

6.1.2 *Current Tank*—A current tank is a water-filled tank equipped with a pump or other propulsion system for moving the water through a test section where the test device is mounted. A wave generator may be installed on this type of test facility.

6.1.3 Other facilities, such as private ponds or flumes, may also be used, provided the test parameters can be suitably controlled.

6.2 Ancillary systems for facilities include, but are not limited to a distribution system for accurately delivering test fluids to the water surface, skimming systems to assist in cleaning the facility between tests, and adequate tankage for storing the test fluids.

## 7. Test Configuration and Instrumentation

7.1 The boom should be rigged in a catenary configuration, with the gap equal to 33 % of the length; or boom gap-to-length ratio of 1:3. Towing bridles are generally provided by the manufacturer for both ends of the boom which provide attachment points for towing (Fig. 1). At each end of the boom, the towing apparatus shall be joined to the tow bridle or tow lead by a single point only. Boom towing force should be measured with in-line load cells positioned between the boom towing bridles and tow points.

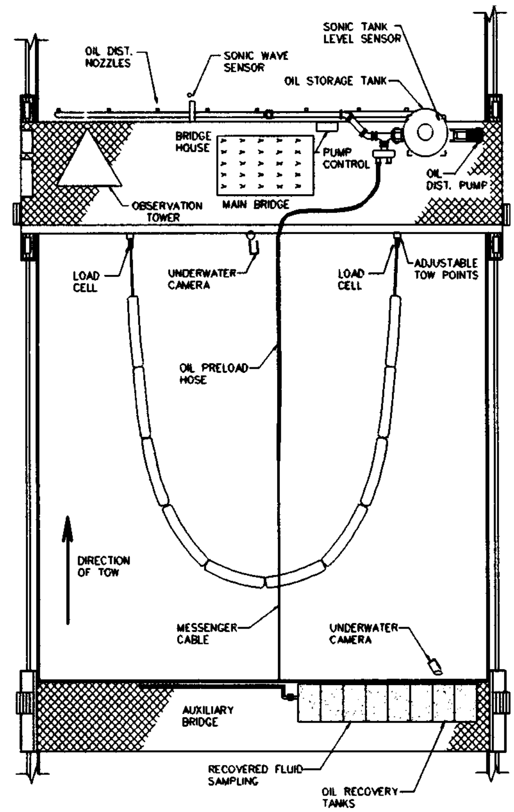


**FIG. 1 Typical Boom Test Setup in Tank**

7.2 Preload oil should be pumped directly into the boom apex.

7.3 Data obtained during each test should include electronically collected data and manually collected data. Oil and water property data should be based on fluid samples obtained during the test period. Recommended data to be collected during testing, along with the method of collection, is listed in Table 1.

## 8. Test Fluids

8.1 Test fluids may be crude, refined, or simulated, but should be stable and have properties that do not vary during a test run. Test oils for use with this guide should be selected to fall within the range of typical oil properties as defined in Appendix X2 of this guide.

8.2 Test fluids should be discharged at ambient water temperatures to reduce variation in fluid properties through a test run.

## 9. Safety Precautions

9.1 Test operation shall conform to established safety (and regulatory) requirements for both test facility operations and oil handling. Particular caution must be exercised when handling flammable or toxic test fluids.

## 10. Test Variables

10.1 At the onset of the test the independent or controlled test parameters should be selected. The test evaluator should

**TABLE 1 Typical Data Collected During Tests**

| Data | Typical Instrumentation | Collection Method |
|---|---|---|
| Wind Speed, Direction | Wind Monitor | Computer/Data Logger, Manual Readings |
| Air and Water Temperature | Resistance Temperature Detector (RTD), Themocouples, Mercury Thermometer | Computer/Data Logger, Manual Readings |
| Tow Speed/Relative Current | Pulse Counter and Digital Input Tachometer, Current Meter | Computer, Control Console, Local Display |
| Wave Data | Distance Sensor, Capacitance probe, Pressure Sensor | Computer/Data logger |
| Tow Force, Average (Maximum during Wave Conditions) | Load Cell | Computer/Data logger |
| Test Fluid (Volume Distributed) | Storage Tank Level Soundings, or Distance Sensor and capacity vs. Volume Conversions | Computer/Data Logger, Manual Readings |
| Distribution Rate | Positive Displacement Pump with Speed Indicator, Volume Distributed Divided by Time | Pump Control Panel, Computer/Data Logger, Manual Readings |

include a discussion of the procedures that were used to establish calibration and standardization. These procedures typically include initial calibrations, pre-test and post-test checks, sampling requirements and documentation of significant occurrences/variations, and data precision and accuracy.

10.2 Data should be expressed with an indication of variability. Table 2 contains a list of typical measurements showing attainable precision and accuracy values.

10.3 Varying surface conditions should be employed during testing. Conditions should be measurable and repeatable. Examples of achievable surface conditions in controlled test environments are:

10.3.1 *Calm*—No waves generated.

10.3.2 *Wave #1*—sinusoidal wave with an $H_{1/3}$ of .30 metres (12.0 inches), wavelength of 4.27 metres (14.0 feet), and an average period of t=1.7 seconds. (Wave dampening beaches are employed during the generation of this wave condition).

**TABLE 2 Measurement Precision and Accuracy**

| Measurement | Accuracy (±) | Precision (±) |
|---|---|---|
| Bottom solids and Water | To be determined (ASTM) | To be determined (ASTM) |
| Oil Distribution | 0.3 $m^3$/HR | 0.05 $m^3$/HR |
| Salinity | .01‰ | .01‰ |
| Specific Gravity, Density | .001 g/$cm^3$ | 0.0001 g/$cm^3$ |
| Surface Tension | 0.1 Dyne/cm | 0.04 Dyne/cm |
| Temperature | 0.2°C | 0.2°C |
| Tow, Current Speeds (Tank/Open water) | 0.051 m/se. (.1 kt)/ 0.255 m/sec (.5 kt) | 0.0255 m/sec (.05kt)/ 0.102 m/sec (.2 kt) |
| Tow Force | 0.25 % of full scale | 2.5 lbs/1000 lbs |
| Viscosity | 2.0 % | 1.0 % |
| Wave Meter, (Tank/Open Water) | 6 mm/10 mm | 1.44 mm/10 mm |
| Wind Direction | 3° | 3° |
| Wind Speed | 0.3 m/s (0.6 mph) | 0.3 m/s (0.6 mph) |

10.3.3 *Wave #2*—Sinusoidal wave with an $H_{1/3}$ of .42 metres (16.5 inches), wavelength of 12.8 metres (42.0 feet), and an average period of t=2.9 seconds. (Wave dampening beaches are employed during the generation of this wave condition).

10.3.4 *Wave #3*—A harbor chop condition with an average $H_{1/3}$ of .38 metres (15.0 inches). This is also defined as a confused sea condition where reflective waves are allowed to develop. No wavelength is calculated for this condition.

where:

$H_{1/3}$ = significant wave height = the average of the highest ⅓ of measured waves,

$L$ = wavelength = the distance on a sine wave from trough to trough (or peak to peak), and

$T$ = wave period = the time it takes to travel one wavelength.

## 11. Procedures

11.1 Prior to the test, select the operating parameters, then prepare the facility and containment boom for the test run. Measure the experimental conditions.

11.1.1 The conventional boom under test should be a full-scale representative section. The boom section's basic physical properties should be measured in accordance with ASTM definitions. Table 3 contains a list of typical measurements and additional specification data.

11.2 Measure or note immediately prior to each test the following parameters:

11.2.1 Wind speed, direction.

11.2.2 Air and water temperature.

11.2.3 General weather conditions, for example, rain, overcast, sunny, etc.

11.2.4 The test fluid used for testing should be characterized from samples taken each time the storage tank is filled. As a minimum, the test fluid should be analyzed for viscosity, surface and interfacial tension, specific gravity and bottom solids and water. The results of each analysis as presented in Table 2 will be reported.

11.2.5 Periodic samples of the test basin water should be taken to monitor the water properties to include oil and grease, salinity, pH, and turbidity.

**TABLE 3 Typical Basic Physical Properties**

| Measurement | Specification Data: As reported by Manufacturer | Specification Data: As measured by Tester |
|---|---|---|
| Boom Type | Fence, curtain, fire containment, other | |
| Length m (ft) | Standard section length, total rigged section | |
| Height mm (in) | Standard section height | |
| Freeboard mm (in) | Distance above water line | |
| Draft mm (in) | Distance below water line | |
| Weight of Section kg/m (lb/ft) | Boom Fabric Type (freeboard and skirt material) and Tensile Strength Characteristics | |
| Ballast Length m (ft) | Ballast Bottom Tension Member Type/Break Strength and Length[A] | |
| Ballast Weight kg/m (lb/ft) | Chain, cable or weights | |
| Gross Buoyancy | Flotation/Buoyancy Type (Air inflatable/foam) | |
| Buoyancy to Weight Ratio | Calculated/Measured (Method shall be documented) | |
| Accessories | Anchor points, lights, tow lines, bridles, etc. | |
| End Connector Type | ASTM Standard, other | |
| Number of tension members and Location | Top, bottom, middle, other | |

[A] All measurements should be taken when member is tensioned to the load expected at a 1 knot tow speed.

11.3 Place the containment boom in the test basin (Fig. 1). Confirm that rigging has been in accordance with manufacturer specifications. Document set-up conditions, for example, tow bridle elevation, boom gap opening, and/or general rigging. Start the oil distribution system, tow mechanism or water flow (if necessary) to begin the test run. The following test parameters will be performed as outlined in Table 4.

11.3.1 The test starts with a Dry Run to confirm the equipment has been properly rigged and all data collection instrumentation is functioning.

11.3.2 The Dry Run is followed by Preload test runs. Preload tests determine the minimum volume of test fluid necessary for a containment boom to display loss by entrainment, and simultaneously determine the volume of test fluid a boom holds until the addition of fluid has a "minimal" effect on the first loss tow speed. As preload volumes are increased, there is a volume at which the addition of test fluid will not change the first loss tow speed (test fluid/water interface entrainment speed). This test is performed in calm water conditions and establishes a baseline preload fluid volume. This baseline containment performance serves as a datum from which improved or diminished containment performance can be measured when encountering other test conditions.

11.3.2.1 The preload volume is determined by performing a series of first loss tests. Beginning with a nominal preload volume, the first loss tow speed is identified. Underwater visibility is essential when identifying loss speeds. The preload volume is increased and the first loss tow speed obtained again. This process is repeated with increasing preload volumes until the addition of the test fluid to the preload has minimal or no effect on the first loss speed. A graph of first loss speed versus preload volume should be created to visually determine the optimum preload volume necessary for the subsequent tests, (first and gross loss in wave conditions, loss and loss rate tests). The graph produced should be a curve of boom capacity versus tow speed. For example, Fig. 2 shows data from a typical boom section. An initial preload volume of 227 litres (60 gallons) was pumped into the boom and the first oil loss speed determined. The second preload volume was 454 litres (120 gallons) and the first loss tow speed was again determined. As shown, when preload volumes are increased the first loss occurs at lower tow speeds. This process is continued until the sensitivity of first loss tow speed becomes minimally dependent on preload volume. For this example, the volume of test fluid at which the addition of more fluid does not affect the first loss tow speed is 450 gallons.

**TABLE 4 Typical Test Schedule**

| Test No. | Test Type | Tow Speed (kts) | Wave Conditions | Preload Volume (gallons) |
|---|---|---|---|---|
| 1 | Dry Run | 1 | calm | N/A |
| 2 | Preload | variable | calm | 60 |
| 3 | Preload | variable | calm | 120 |
| 4 | Preload | variable | calm | 180 |
| 5 | Preload | variable | calm | 240 |
| 6 | Preload | variable | calm | 300 |
| 7 | Preload | variable | calm | 360 |
| 8 | Preload | variable | calm | 420 |
| 9 | Gross Loss | variable | calm | determined during Preload test |
| 10 | 1st & Gross Loss Speeds | variable | calm | determined during Preload test |
| 11 | 1st & Gross Loss Speeds | variable | Wave #1 | determined during Preload test |
| 12 | 1st & Gross Loss Speeds | variable | Wave #1 | determined during Preload test |
| 13 | 1st & Gross Loss Speeds | variable | Wave #2 | determined during Preload test |
| 14 | 1st & Gross Loss Speeds | variable | Wave #2 | determined during Preload test |
| 15 | 1st & Gross Loss Speeds | variable | Wave #3 | determined during Preload test |
| 16 | 1st & Gross Loss Speeds | variable | Wave #3 | determined during Preload test |
| 17 | Critical Tow Speed | variable | calm | none |
| 18 | Critical Tow Speed | variable | calm | none |

11.3.3 The Preload determination should be followed by the Gross Loss, and 1st and Gross Loss Speed tests with waves.

11.3.3.1 First Loss Tow Speed is the lowest speed at which droplets of the test fluid shed (continuously) from the boom. Minor, non-continuous losses are not considered to be first losses. First Loss Tow Speed tests should be carried out in both calm water and various wave conditions. In wave conditions, the test fluid loss may occur in a surging motion. First Loss Tow speed tests are also used to determine the boom preload volume threshold.

The test is performed with the boom configured as illustrated in Fig. 1. The preload volume is pumped from the storage tank into the boom apex. The boom should then be accelerated to a tow speed of 0.5 knots and held there to allow the boom and test fluid to stabilize. The tow speed should then be increased by 0.1 knots in ten second intervals until the continual first loss mode is observed. Fig. 3 shows a typical first failure mode in calm water.

11.3.3.2 Gross Loss Tow Speed is the speed at which massive continual test fluid loss is observed escaping past the boom. The speed increments should be continued beyond first loss until a gross loss failure mode is observed. Fig. 4 shows a typical gross loss failure mode.

11.3.4 The Critical Tow Speed tests demonstrate boom behavior at speeds in excess of normal containment limits. The

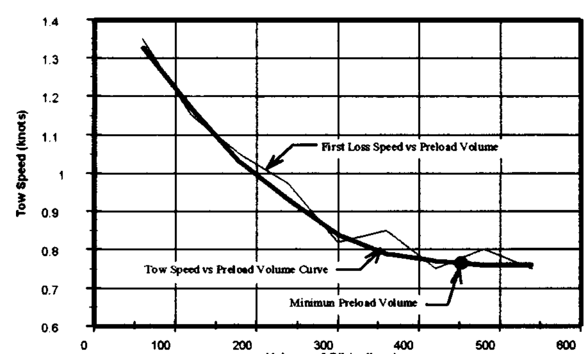


**FIG. 2 Boom Preload Determination Test, First Loss Speed versus Preload Volume**

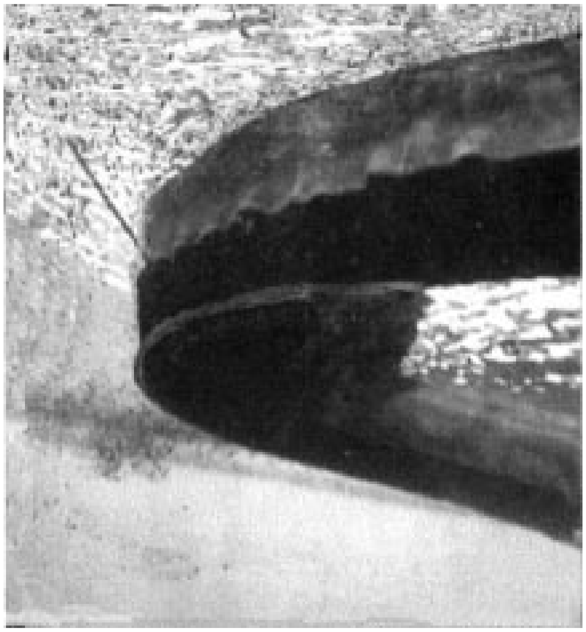

FIG. 3 First Loss

FIG. 5 Critical Tow Speed in Calm Water

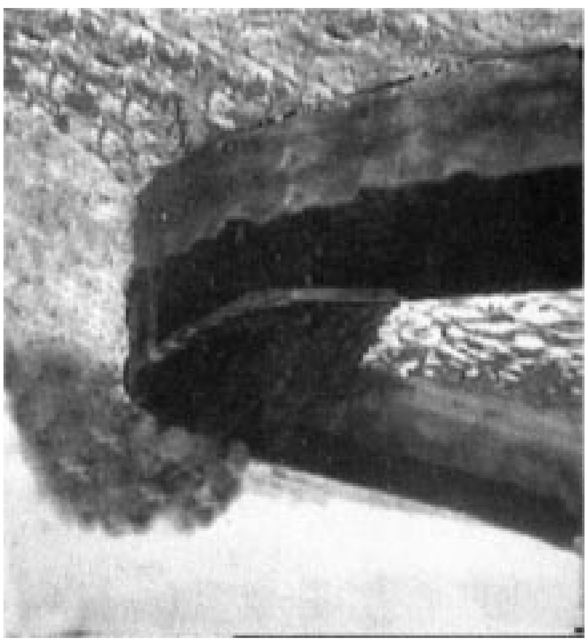

FIG. 4 Gross Loss

test involves towing the boom, without test fluid, at increasing tow speeds. The Critical Tow Speed is met when the boom exhibits one mode of failure, i.e., loses all freeboard (submerges), planes, or mechanically fails and/or has been tested at three times the measured gross loss tow speed. Fig. 5 shows Critical Tow Speed of an oil boom in calm water and illustrates loss of freeboard. Critical tow speed is significant in defining the safe operating limit for the boom, recognizing that normal containment tow speeds may be occasionally exceeded in practice.

11.3.5 Tow the boom in a straight line measuring straight-line tow forces. This test is significant in that it provides useful operational information to manufacturers and potential users when in open-water deployment.

## 12. Report

12.1 The test report shall provide a description of the test set-up, test methods, and significant observations or concerns noted by the test personnel. The report will contain tables, graphs, charts, etc. that accurately describe boom containment and recovery performance based on data collected under specific towing conditions.

12.1.1 Prepare a schematic diagram of the layout for the test series.

12.1.2 Describe the containment boom and basic physical properties.

12.1.3 Prepare a table of results for the test runs, containing information as outlined in Table 4.

12.1.4 Report Ambient conditions, including air temperature, surface water temperature, wind speed, wind direction, and brief statement of weather conditions during the test run. Report tow force measurements and corresponding independent test parameters.

12.1.5 Report tank test fluid properties.

12.1.6 Describe Test instrumentation.

12.1.7 Report Wave conditions.

12.2 Record analytical testing results, automated and manual data, as well as above-water and below-water video documentation (digital camera pictures) should be included and used to prepare the test report/data summaries. Testing results include test run data (test logs), raw computer data files, oil recovery and distribution logs, oil analyses test reports, calibration data, pre and post test checks, and QA checklists.

12.2.1 Graph and table data shall be grouped by test characteristics, the test fluid type, wave type and tow speed. The reports shall include a complete data table containing test numbers, independent variables, and all significant variations and occurrences.

# APPENDIXES

### (Nonmandatory Information)

## X1. RATIO OF BOOM DRAFT TO WATER DEPTH DISCUSSION

X1.1 It is known that if the distance between the bottom of a boom in a test tank and the bottom of the tank decreases below some minimum the tow forces on the boom can be affected. Larrabee and Brown determined that, for such tests, the ratio of boom draft to water depth could not be less than 1:8 **(6)**[7].

X1.2 For oil containment testing, it is generally recommended that the ratio of the boom draft to the water depth in the test tank is greater than some minimum value. Unfortunately, there appears to be no universally-accepted minimum ratio.

X1.3 Values in the literature range from 1:4 **(1)**, to 1:6 **(2)**, to 1:10 used in a number in flume tanks **(3, 4)**, to 1:12 **(5)**.

X1.4 If the draft-to-depth ratio is near the lower end of, or below, the ranges given above, users should confirm that their results are not biased as a consequence.

[7] The **boldface** numbers in parentheses refer to the list of references at the end of this standard.

## X2. STANDARD TEST OILS[8]

X2.1 Values in Table X2.1 refer to test fluid properties at test temperatures. Test methods for fluid properties are specified as follows: viscosity, Test Methods D 445 and D 2983 (report shear rate for viscosity measurement, should be in the range of 1 to 10 $s^{-1}$); density, Test Method D 1298 and D 4092; interfacial tension, Test Method D 971; pour point, Test Method D 97. For all test oils (with the exception of emulsions), maximum sediment and water (BSW) of 0.1 %, Test Method D 4007 and D 1796.

X2.2 Of the five viscosity ranges, numbers I, II, and IV are especially recommended as being indicative, respectively, of lightly weathered, moderately weathered, and significantly weathered crude oils.

X2.3 The following lists examples of hydrocarbon oils that could be used to fall within the specified ranges. This list is intended for guidance only; it should be noted that viscosities of all oils will vary greatly with both temperature and the specific product. Selected oils may be crude, refined, or simulated. In the case of crudes and light refined products, it is acceptable and may be desirable to pre-weather the oil in order to produce a desired viscosity, increase the oil's flash point to a safe level, and produce a more stable test fluid.

[8] This Appendix has been adapted from F 631-93, Standard Guide for Collecting Skimmer Performance Data in Controlled Environments, to make it applicable to the testing at the Ohmsett Facility (located at the Navy Weapon Station Earle, in Leonardo, New Jersey). For comparison purposes, testing at Ohmsett has been completed with standard test oils Hydrocal 300, Calsol 8240, and Sundex 8600 which fall into categories I, II, and III, respectively.

**TABLE X2.1 Candidate Test Oils**

NOTE 1—Test Oils should be selected to fall within these five categories.

| Category | Viscosity, $mm^2/s$ | Density, g/mL | Oil-Air Interfacial Tension, mN/m | Oil-Water Interfacial Tension, mN/m | Pour Point °C |
|---|---|---|---|---|---|
| I[A] | 150-250 | 0.90 to 0.93 | 28 to 34 | 20 to 30 | < -3 |
| II[B] | 1500-2500 | 0.92 to 0.95 | 30 to 40 | 20 to 30 | < -3 |
| III[C] | 17 000 to 23 000 | 0.95 to 0.98 | 20 to 40 | 20 to 40 | < 10 |
| IV[D] | 50 000 to 70 000 | 0.96 to 0.99 | 20 to 40 | 20 to 40 | . . . |
| V[E] | 130 000 to 170 000 | 0.96 to 0.99 | 20 to 40 | 20 to 40 | . . . |

[A] *1*) Alaska North Slope crude oil, 10 to 15 % weathered by volume.
*2*) Fuel oil No. 4 (heavy); can be prepared by blending 40 % fuel oil No. 2 and 60 % fuel oil No. 6.
[B] Fuel oil No. 5 can be prepared by blending 20 to 25 % fuel oil No. 2 with 75 to 80 % fuel oil No. 6.
[C] Residual fuel oil (that is, fuel oil No. 6 prepared to above criteria).
[D] Residual fuel oil (that is, heavy cut of fuel oil No. 6).
[E] Emulsified crude oil, 50 to 80 % water content. The oil may be emulsified by blowing compressed air through water on which the oil is floating.

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# Appendix B:
# Characteristics of selected wave conditions:
# comparison of Ohmsett analysis with SL Ross analysis

**Appendix B:**
**Characteristics of selected wave conditions,**
**comparison of Ohmsett analysis with SLRoss analysis**

SL Ross analysis of wave data

| Wave | Number of Tests | Type | Predicted wave height, inches | Measured significant wave height, inches | | |
|---|---|---|---|---|---|---|
| | | | | Maximum | Minimum | Average* |
| 1 | 10 | Regular | 4 | 6.62 | 4.12 | 5.25 |
| 2 | 8 | Regular | 6 | 5.36 | 3.41 | 4.24 |
| 3 | 12 | Harbor chop | 6 | 8.87 | 5.33 | 6.93 |
| 4 | 7 | Harbor chop | 8.25 | 5.95 | 4.15 | 5.36 |
| * Average refers to average measured for all tests done with that wave height. | | | | | | |

Ohmsett analysis of wave data

| Wave | Number of Tests | Type | Predicted wave height, inches | Measured significant wave height, inches | | |
|---|---|---|---|---|---|---|
| | | | | Maximum | Minimum | Average* |
| 1 | 10 | Regular | 4 | 7.0 | 4.0 | 5.2 |
| 2 | 8 | Regular | 6 | 5.4 | 3.7 | 4.5 |
| 3 | 12 | Harbor chop | 6 | 9.8 | 2.6 | 6.5 |
| 4 | 7 | Harbor chop | 8.25 | 7.4 | 5.4 | 6.0 |
| * Average refers to average measured for all tests done with that wave height. | | | | | | |

Difference between Ohmsett and SLRoss analysis

| Wave | Difference, Ohmsett / SLRoss data | | |
|---|---|---|---|
| | Maximum | Minimum | Average* |
| 1 | +5.7% | -2.9% | -1.0% |
| 2 | +0.7% | +8.5% | +6.7% |
| 3 | +10.5% | -51.2% | -5.8% |
| 4 | +24.4% | +30.1% | +12.5% |
| * Average refers to average measured for all tests done with that wave height | | | |