Estimation of Towing Forces on Oil Spill Containment Booms

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1. Introduction

Effective use of skimmers or *in situ* burning for an oil spill generally requires that the spill first be contained using booms. Typically, a containment boom would be towed in a "U" configuration or held stationary against a current in order to contain and thicken oil for recovery or burning. In either case, it is important to know the likely forces imposed on a boom so that appropriately sized tow vessels and towing gear are specified for the operation, and more important, so that boom with sufficient tensile strength is selected. Guidance for selecting appropriate tensile strength is provided in *U.S. Coast Guard 33 CFR Part 155, Vessel Response Plans Final Rule* (USCG 1996), and in *ASTM F1523: Selection of booms in accordance with water body classifications* (American Society of Testing and Materials 1996).

Presently, boom towing forces are estimated using several well-known formulae such as those published in the *World catalog of oil spill response products* (Schulze 1995), *Exxon oil spill field manuals* (Exxon 1982), and *International Tanker Owner's Pollution Federation (ITOPF) field manuals* (ITOPF 1986). These formulae estimate the theoretical loads on a boom based on its dimensions, water current or tow speed, wave height, and wind, and include constants to account for boom profile and gap ratio. Recent field testing carried out for the Marine Spills Response Corporation (MSRC) and the U.S. Coast Guard (USCG) (Nordvik et al. 1995a) has shown that these formulae may severely underestimate drag forces. As a result, commonly accepted values for the minimum required tensile forces in a boom may be well below the actual required values.

A series of tests was carried out at the Ohmsett test facility to measure the towing forces on a number of booms using a range of gap ratios, wave conditions, and tow speeds. The data from these experiments was used to develop a simple relationship to predict the tow force and required tensile strength for the various boom and tow parameters. A comparison was also made between the tow forces as measured in the Ohmsett test tank against those measured in the MSRC / USCG field testing.

2. Objectives

The objective of the study was to determine the loads developed on a containment boom when towed in a typical operational configuration. The work was conducted in four phases:

- a test protocol was prepared and circulated for comment among the project participants;
- equipment for testing was identified and assembled at Ohmsett;
- the tow tests were carried out at Ohmsett in July 1998;
- the results were analyzed and the following report prepared to document the study; and,
- the results were presented to the ASTM F20 Committee and at the Arctic and Marine Oilspill Program (AMOP) Technical Seminar 1999.

3. Previous Work

The first phase of the work was a brief review of recent boom testing that included the determination of towing forces. The goal was to establish the theoretical validity of existing formulae given modification to the constants used for boom shape and gap ratio.

3.1 Existing Formulae for Estimating Tow Forces

The formulae currently used for predicting tow loads on containment boom include the following.

The Schulze formula is known as such as it is published in the *World Catalog of oil spill response products* (Schulze 1995). It was originally published in an Exxon spill manual (Exxon 1982), and is based on a theoretical consideration of the wind and current forces acting on a boom. The formula is as follows:

$$T_a = 0.5\ L\ \tau\ C_d\ \rho_a\ f\ V_a^2$$
$$T_w = 0.5\ L\ \tau\ C_d\ \rho_w\ d\ (V_w + 0.5\sqrt{H_s})^2$$
$$D = 2\ (T_a + T_w)$$

where: D = total drag force, lb_f
T_a = tension due to wind, lb_f
T_w = tension due to waves and current, lb_f
V_a = wind speed, ft/s
V_w = current/tow speed, ft/s
ρ_a = density of air (0.00238 slugs/ft^3)
ρ_w = density of water (1.98 slugs/ft^3)
L = length of boom, ft
τ = tension parameter, dimensionless
C_d = drag coefficient [assumed to be 1.5], dimensionless
f = boom freeboard, ft
d = boom draft, ft
H_s = significant wave height, ft

It is interesting to compare the effects of wind and water currents on the total load imposed on a boom. For example, using this formula, and assuming that the freeboard dimension is half the draft (which is typical of containment boom), and assuming a 20 knot wind and 1 knot water current (which are typical containment limits), the load produced by the wind is only 25% of that produced by the current. For that reason the effect of wind is often ignored when estimating forces on a boom.

The tension parameter, "τ", is a function of the gap ratio, and must be read off a graph or from a table (see Figure 1, with selected values for "τ" given in Table 1). This, coupled with the large number of coefficients, can make using the Schulze calculation cumbersome.

Table 1: Tension parameter (τ) for selected gap ratios

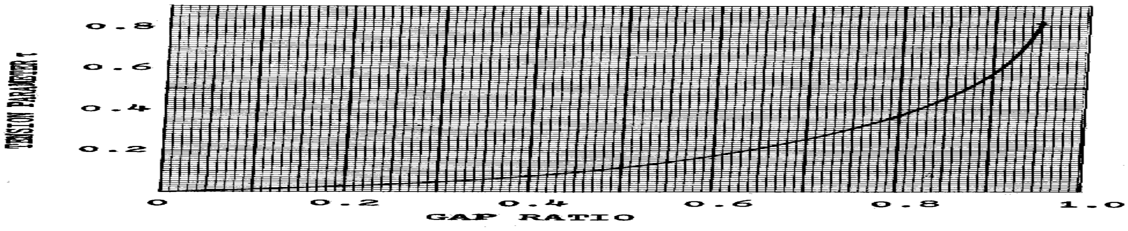
Gap Ratio	Tension parameter (τ), dimensionless
0.2	0.025
0.3	0.045
0.4	0.075
0.5	0.115

A similar formula for estimating the expected tow loads on booms is used by ITOPF in their field manuals (ITOPF 1986). While similar to the Exxon equation it is much simpler, using only a constant, the projected area of the boom, and the wind or current velocity as inputs. Note that the ITOPF formula estimates a total force on the boom, in kilograms-force. (It is assumed that this is simply a conversion from units of pounds-force.) As with the Schulze formula, the estimated force due to wind is much less than that due to currents; using the 20 knot wind and 1 knot water current as in the previous example results in a wind induced force that is only 12.5% of the current induced force.

$$F_w = 26 \, A_w \, (V_w / 40)^2$$

$$F_c = 26 \; A_c \; V_c^2$$

where: F_w = force on a boom due to wind, kg
A_w = freeboard area, m^2
V_w = wind velocity, knots
F_c = force on a boom due to waves and current, kg
A_c = submerged area, m^2
V_c = current/tow velocity, knots


TENSION PARAMETER τ
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
GAP RATIO

3.2 MSRC / USCG Testing of Containment Booms

The impetus for the work reported here was a recent field study (Nordvik et al. 1995a) in which tow forces and other boom performance parameters were measured for a number of offshore containment booms. The objective of the work was to collect quantitative data on containment boom performance including tow forces, skirt draft, and boom freeboard as a function of tow speed. Four booms were tested: the 3M Fire boom, the Norlense Barrier boom, the USCG / Oil Stop boom, and the U.S. Navy USS-42 boom.

The measured tow forces were compared with those predicted by the Schulze and ITOPF formulae and it was found that the predictions significantly underestimated the towing loads experienced in the field. In general, for three of the four booms the tow loads predicted by both the Schulze formula and the ITOPF formula were as little as 25 to 50% of the mean loads measured in the at-sea testing. With only one boom - the 3M Fireboom - did the formulae produce an estimate that was similar to that measured in the field tests.

The authors suggested that there were two main reasons for the discrepancy between measured and predicted tow forces: first, that the formulae failed to account for variation in speed between two tow vessels, as would commonly occur in a towing operation at sea; and second, that the formulae failed to account for variation in the gap distance between the two tow vessels, again a problem that would be typical of an actual containment operation. The authors concluded that additional safety factors would have to be applied to any prediction formula to deal with these dynamic effects that would typically be experienced at sea.

Although the predicted forces were much lower than the measured tow forces, the authors did note that the shapes of the force vs. tow speed curves were similar, indicating that a good correlation should be possible with this type of equation using different constants.

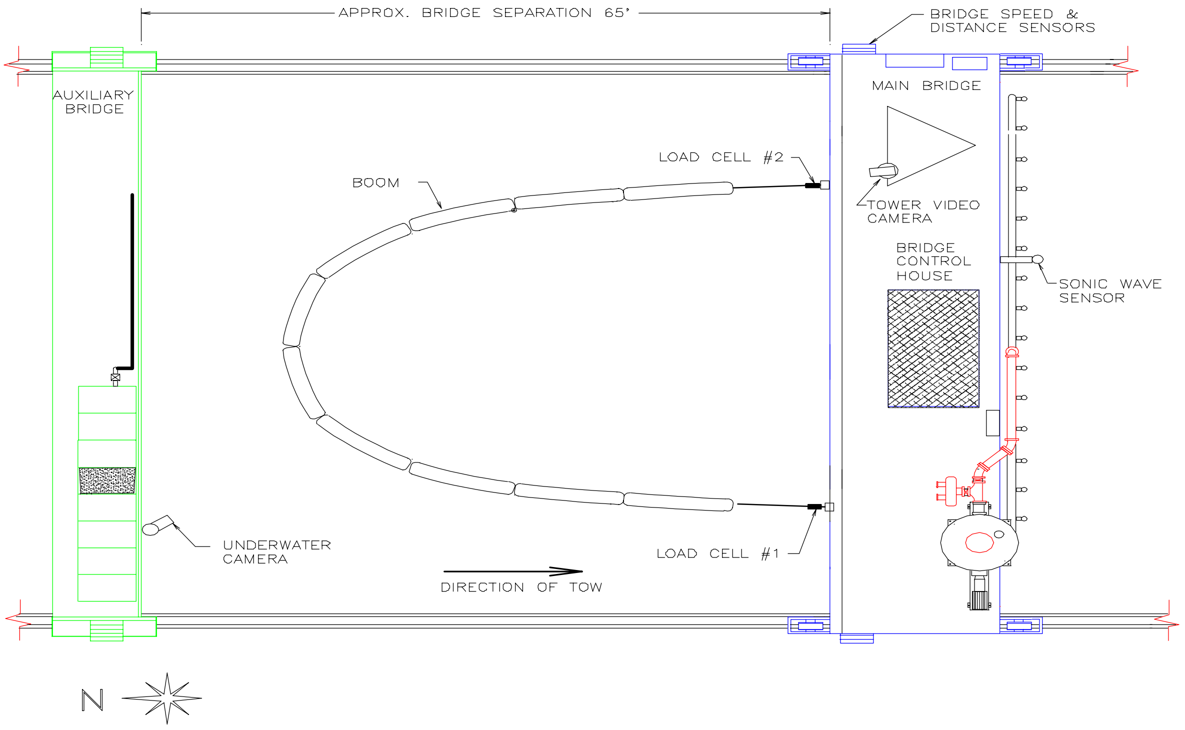
4. Test Methodology

4.1 Test Facility and Equipment

The tow tests were carried out at the Ohmsett, the National Oil Spill Response Test Facility test tank in Leonardo, NJ. Performing the tow tests in the Ohmsett tank allowed the use of full-scale containment boom and very good control and measurement over the key parameters of tow speed, gap distance (and hence gap ratio), and tow forces.

The Ohmsett test tank is 667 feet long by 65 feet wide by 8 feet deep. (Figure 2 shows the layout of the tank, the key equipment, and a boom in position for a tow test.) A towing bridge that spans the tank is capable of speeds of up to 6.5 knots. 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 wave similar to a harbor chop. Different wave heights and lengths can be created by adjusting the stroke and frequency of the paddle. Additional information on Ohmsett is available on the internet at http://www.ohmsett.com.

A load cell was mounted on each of the tow points on the towing bridge. The load cells used had a capacity of 2000 lb_f, with a stated accuracy of ±10 lb_f. (Specifications for the load cells are provided in Appendix A.) The load cells were calibrated prior to the tests and checked afterwards to confirm their accuracy. Data from the load cells, as well as data on wave height and tow speed, were recorded by a computer every 0.1 seconds. Visual observations by test personnel as well as video footage were collected during the test runs to document the behavior of the boom, including submergence, planing, wave conformance, and splashover.


APPROX. BRIDGE SEPARATION 65'
BRIDGE SPEED &
DISTANCE SENSORS
MAIN BRIDGE
AUXILIARY
BRIDGE
LOAD CELL #2
BOOM
TOWER VIDEO
CAMERA
BRIDGE
CONTROL
HOUSE
SONIC WAVE
SENSOR
UNDERWATER
CAMERA
LOAD CELL #1
DIRECTION OF TOW
N

4.2 Containment Booms Tested

In selecting booms for the tests, the goal was to cover a range of commonly-used types and sizes of containment boom. The range of boom types was to include both fence- and curtain-type booms; boom drafts ranging from 12 to 40 inches; and buoyancy-to-weight ratios ranging from 5:1 to 20:1.

Based on these criteria, six containment booms were selected for testing. The key properties for each of these booms are summarized in Table 2. The two sizes of Sanivan curtain-type boom and the two sizes of Flexy fence-type boom are used extensively for containment in nearshore and protected waters. These products use permanent foam floatation, and steel chain as a ballast and tension member. The Ro-boom 2000, the USCG Oil Stop, and the U.S. Navy USS-42 are larger, more rugged booms suited to use in offshore conditions. Each of these booms use individual floatation chambers filled with pressurized air to provide buoyancy, and chain along their bottom edge for ballast and tensile strength. For each boom, an appropriate number of sections was obtained to allow testing of boom lengths of approximately 100 to 150 feet with gap ratios of 0.2 to 0.5.

Table 2: Summary of containment booms tested

Boom	Type	Height, in. (cm)	Draft, in. (cm)	B:W Ratio	Section Length, ft (m)
Sanivan	curtain	18 (46)	11 (28)	5:1	50 (15.2)
Flexy	fence	18 (46)	11 (28)	3:1	50 (15.2)
Sanivan	curtain	24 (61)	13.5 (34)	14:1	50 (15.2)
Flexy	fence	36 (91)	24 (61)	5:1	50 (15.2)
Ro-boom 2000	curtain	67 (170)	43 (110)	20:1	98 (30)
USCG Oil Stop	curtain	47 (119)	30 (76)	20:1	55 (17)

USN USS-42	curtain	52 (132)	36 (91)	8:1	82 (25)

4.2 Test Variables

The test matrix included four independent test variables: tow speed, wave condition, boom length, and gap ratio. In general, the booms were towed at four speeds (0.5 to 2.0 knots) under three wave conditions (calm, regular, harbor chop, conditions listed in Table 3) and with four boom configurations (gap ratios from 0.2 to 0.5). This led to each boom undergoing up to 48 test runs lasting approximately one minute each. In all, 358 test runs were carried out over a period of 12 days from June 24 to July 10, 1998.

Table 3: Summary of wave conditions used

Wave type	Significant wave height, in. (cm)	Average Period, s
calm	0	–
regular wave	7.3 (19)	2.1
harbor chop	12.3 (31)	1.7

Within each one-minute test run, ten seconds were allotted at the beginning of the tow to allow the booms to achieve a steady state configuration. The final 50 seconds of data (a total of 500 readings) were extracted from the computer record and analyzed.

With one load cell on each of the two tow points, the tension acting on the boom at a given point in time was calculated according to:

$$T_{ave} = \tfrac{1}{2} \left(\text{Load cell}_1 + \text{Load cell}_2 \right)$$

The tension experienced by a boom is not constant, particularly when towed through waves. As the boom follows the crests and troughs of the waves the tension fluctuates, peaking when the apex of the boom catches the front of a wave. Peak and mean tension values were determined, with the peak loads defined as the 95th percentile of the tension readings recorded for each run. Because a boom must be designed to be able to withstand these peak tensions, the focus of the subsequent analysis was on these 95th percentile tension readings.

Wind speeds through the test program averaged 6.0 knots, with only one daily average exceeding 8 knots (The average wind speed was 10.8 knots during the first day of testing the US Navy boom). At these low wind speeds, the wind load on the boom would be a minor component of the total load on the boom, and was therefore not considered in the analysis (see section 3.1 for a discussion of the relative effect of wind vs. current).

5. Results

The data for each test run was tabulated with the mean and peak tow force vs. the tow speed for a given length of boom, gap ratio, and wave condition. The data were compared with the Schulze and ITOPF formula predictions, and with the MSRC field tests for the USS-42 and USCG Oil Stop booms. The data were then analyzed to produce a correlation between tow speed, boom dimensions, and the resulting tow forces.

5.1 Comparison of Results with Formula Predictions

An example of the tow force data is given in Figures 3 and 4, which also show a comparison of the measured tow force data vs. that predicted by the Schulze and ITOPF formulae. For the tests shown in Figure 3, in calm conditions, the Schulze formula greatly underestimates the actual tow loads in all cases, while the ITOPF formula significantly overestimates the tow loads for three of the four booms shown. For the tests shown in Figure 4, in regular waves, both the Schulze formula and the ITOPF formula greatly underestimate the actual tow loads in all cases.

5.2 Comparison of Results with Field Testing

Two booms from this study were also tested in the 1995 field testing sponsored by MSRC and USCG (Nordvik 1995a). The results from the field tests were compared with the data collected in this study. Data on the field tests is taken from Sloan et al. 1994, and Nordvik et al. 1995b.

Table 4 below summarizes the data from the field tests involving the U.S. Navy USS-42 and the USCG Oil Stop booms (also see Figure 5). The average tow force vs. tow speed is listed for each of those two booms, as is a “scaled-down” tow force that accounts for the decreased length of boom used in the tank tests described in this report. In the case of the USS-42 boom, a gap of 300 feet was used: compared with the 55.5-foot gap used in the tank tests means that the tow force is reduced by a factor of 5.4 (i.e., 300 ÷ 55.5) for a valid comparison. Similarly, the results for the USCG boom

Figure 3: Tow force data, calm conditions, comparing measured values with formula predictions

Figure 4: Tow force data, regular waves, comparing measured values with formula predictions

Figure 5: Comparison of MSRC field test data with test tank data

are reduced by a factor of 7.3 to account for the difference between the 300-foot swath width of boom used in the ocean testing and the 41-foot gap used in these tank tests (300 ÷ 41 = 7.3).

Table 4: Comparison of data with MSRC tests

Boom	Tow Speed, knots	Mean Tow Force, lb_f			Difference, %
		Tank Tests	MSRC	MSRC (scaled down)	
USS-42	0.5	127	507	94	-26
	1.0	499	1974	365	-27
	1.3	690	--	--	--
	1.5	978	3779	699	-29
USCG	0.5	66	513	70	+6
	1.0	232	1059	145	-38
	1.5	468	1970	269	-42
	2.0	744	2768	378	-49

For all but one of the comparable test runs, the scaled-down tow forces from the in-ocean testing were consistently less than the forces measured in the test tank, averaging 27% less for the USS-42 boom, and averaging 31% less for the USCG boom. On one hand, the consistent difference between the two of 30% or more indicates that there may be some fundamental difference between the two test protocols. The authors of the MSRC study did note that they had concerns over the lack of control over tow speed and gap width, both of which would affect the tow force but it is unlikely that this would completely explain a 30% difference in measured force. On the other hand, it is encouraging to find that the test tank data and field data are at least roughly comparable and that the difference between the two is at least consistent. While a 30% difference may seem to be larger than one would like, it is certainly within typical safety factors that would be used in selecting containment equipment and towing gear. Noting that a doubling of tow speed would result in a quadrupling of boom tension, a safety factor of 300% or more is not unreasonable.

5.3 Correlation of Results

The data for all the booms was then tabulated for the various tow speeds, gap ratios, and wave conditions. A summary page for each boom is shown in Appendix B, and graphs showing the tow force vs. tow speed for each boom are shown in Appendix C. An attempt was then made to correlate the data against a simple formula that included the tensile force developed in the boom, the projected area of the submerged portion of the boom, and the tow speed:

$$T = 1.4\ K\ A\ V^2$$

where: T = tensile force, lb_f
K = constant, dimensionless
A = projected area of the submerged portion of the boom, ft^2
V = tow speed, knots

(Note the inclusion of a conversion factor of 1.4 $lb_f /(ft^2 \cdot knots^2)$ to maintain consistent units: later, for simplicity, this conversion factor will be included in the constant, K'.)

Correlation was done using a least-squares fit. In general the correlation was very good, with all but a few R-squared values 0.95 or greater. (Correlation coefficients for each of the test runs are shown with the graphs in Appendix C.) The value of the constant K, is listed in Table 5 for the various booms types. It can be seen that the value of K varied from as low as 1.2 to an average of 1.9 for the calm condition, increasing significantly to an average of 3.0 and 3.4 for the regular wave and harbor chop, respectively.

Table 5: Value of constant K, for various booms

Boom	Calm condition	Regular Waves	Harbor Chop

Sanivan 18" curtain	1.2	2.0	2.2
Flexy 18" fence	1.2	3.5	3.9
Sanivan 24" curtain	1.4	2.0	2.5
Flexy 36" fence	2.3	4.1	5.0
USCG Oil Stop	1.4	2.1	2.1
Ro-boom 2000	3.4	4.3	4.7
USN USS-42	2.4	3.2	3.3
maximum	3.4	4.3	5.0
average	1.9	3.0	3.4

In order to simplify the formula, one can combine the conversion factor of 1.4 $\text{lb}_f/(\text{ft}^2 \cdot \text{knots}^2)$ with the constant K, which would produce a constant K' (Table 6), to be used as follows:

$$T = K' \ A \ V^2$$

where: T = tensile force, lb_f
K' = constant, $\text{lb}_f/(\text{ft}^2 \cdot \text{knots}^2)$
A = projected area of the submerged portion of the boom, ft^2
V = tow speed, knots

Table 6: Value of constant K', for various booms

Boom	Calm condition	Regular Waves	Harbor Chop
Sanivan 18" curtain	1.7	2.8	3.1
Flexy 18" fence	1.7	4.9	5.5
Sanivan 24" curtain	2.0	2.8	3.5

Flexy 36" fence	3.2	5.7	7.0
USCG Oil Stop	2.0	2.9	2.9
Ro-boom 2000	4.8	6.0	6.6
USN USS-42	3.4	4.5	4.6
maximum	4.8	6.0	7.0
average	2.7	4.2	4.7

This can be compared with the ITOPF formula, described previously, which predicts total load on a boom for a given submerged boom profile and tow speed. Using a range of the above values for K' of 3.4 to 4.7, and correcting for unit conversions and the fact that the ITOPF formula is for total load (i.e., twice the tensile force) leads to a constant for the ITOPF formula of 26 to 46, as compared with the value of 26 that is assumed.

5.4 Grouping of Results by Boom Size and Type

Among the smaller booms, there is a considerable difference between the fence-type and curtain-type booms: the values of the constant K' averages 2.5 under calm conditions and 6.3 under harbor chop for the fence booms, as compared with 1.9 and 3.3 for the curtain booms. This is probably a reflection of the less streamlined shape of the fence-type booms, coupled with their lower buoyancy and concomitant tendency to submerge at tow speeds in excess of 1.5 to 2 knots.

Overall, there is a considerable range in the values of the constant K'. However, there is a trend of increasing value of the constant with boom size. It would be useful to group the results according to boom size, using the size ranges for boom provided by ASTM F1523: *Selection of booms in accordance with water body classifications* (ASTM 1996), as shown in Table 7.

Table 7: Recommended size of boom per water body

Water Body Classification	Wave Height Range*, ft.	Boom height, in.
calm	0 to 1	6 to 24
protected	0 to 3	18 to 42
open water	0 to 6	> 36
* From ASTM F625 *Classifying Water Bodies for Spill Control Systems*		

Grouping the results according to this table, and using the calm water values for the "calm" classification, regular wave values for "protected water", and the harbor chop values for "open water", results in the following values for the constant K' (Table 8).

Table 8: Values of constant K' for booms grouped according to water body classification

Water Body Classification	Average Value of Constant K'
Calm Water (18" booms)	1.7
Protected Water (24" and 36" booms)	4.3
Open Water (47", 52", and 67" booms)	4.7

6. Conclusions

A series of towing tests was carried out at the Ohmsett tow tank to measure the loads imposed on a containment boom while under tow. The tests included a range of boom types and sizes, a range of boom lengths and gap ratios, and a range of wave conditions.

Two of the booms tested in this study had undergone tow testing in a recent field study allowing the comparison of results. The tow forces measured in the in-ocean field testing were found to be approximately 30% less than the forces measured in this study.

Based on the tests in this study, a simple relationship was developed correlating the tensile force developed in a boom vs. the projected area of the submerged portion of the boom and the tow speed:

$$T = K' \, A \, V^2$$

where: T = tensile force, lb_f
K' = constant, $lb_f /(ft^2 \cdot knots^2)$
A = projected area of the submerged portion of the boom, ft^2
V = tow speed, knots

The value of the constant, K', varied from a minimum of 1.7, observed under calm conditions, to a maximum of 7.0 observed under the harbor chop condition.

The results were grouped according to water body classifications of calm water, protected water, and open water, with the following results. The value of the constant, K', averaged: 1.7 for calm water booms under calm conditions; 4.3 for protected water booms in regular waves; and 4.7 for open water booms under the harbor chop wave condition.

7. Recommendations

The results of the towing tests described in this study were used to develop a simple relationship correlating the tensile force developed in a boom vs. the projected area of the submerged portion of the boom and the tow speed. The value of the constant used in that relationship is significantly higher than that used in other similar tow load formulae. A range of constants is recommended for use in the formula, depending on the size of the boom and the intended application (i.e., calm, protected, or open water).

ASTM standard F1523, *Selection of booms in accordance with water body classifications,* specifies minimum physical dimensions and other properties for oil spill containment boom. Of interest here is that the minimum tensile strength requirements in F1523 are based on a formula that has been found to significantly underestimate the tow loads and thus the required tensile strength. The results of this study should be used to revise these minimum tensile strength requirements accordingly. A summary of this study will be presented to the ASTM subcommittee on booms for consideration.

Given the variation in the value of the formula constant for different boom types and shapes, it would be desirable to determine the tow loads for a greater range of boom sizes and shapes. Therefore it is recommended that the measurement of tow loads be included in boom test protocols for field or tank testing.

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Appendix A:

Specifications and Calibration Curves of Load Cells

Appendix B:

Summary of Recorded Tow Force Values per Boom

Appendix C:

Tow Force vs. Tow Speed Curves per Boom