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ESTIMATING FORCES ON OIL SPILL CONTAINMENT BOOMS

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Introduction

There has been a continuing requirement to predict the drag force on a towed containment boom without conducting tank tests. Formulas have been developed, but until recently, they have not been accurate over extended ranges of conditions and boom types. While there has been general agreement that the drag force on a towed boom is proportional to the square of the tow speed, much more is needed to compute this force with any degree of precision.

Until recently, two formulas were commonly used to estimate forces on booms: a relatively simple formula contained in the Technical Information Papers published by the International Tanker Owners Pollution Federation (ITOPF) and a more complicated formula developed by Exxon Production Research Company and published since 1986 in the *World Catalog of Oil Spill Response Products.*

The former is referred to as the ITOPF formula and the latter as the World Catalog formula. Comparing the loads predicted by these formulas with the loads measured in at-sea tests has shown that both methods follow measured results in rather limited areas and in many cases underestimate the actual drag force on booms.

Controlled tests were recently performed specifically to compare the measured drag force with computed force using existing formulas. The tests were also intended to develop a more exact means of computation using the new formulas devised from these measured results. The U.S. Department of the Interior, Minerals Management Service (MMS) 1999 test program was specifically designed to develop a

A note to our readers

This volume of the Spill Technology Newsletter will be the last one produced on paper. We are finally succumbing to the cost savings and convenience of making the newsletter available on our website only. To continue receiving the newsletter in its electronic format, please go to the Environmental Technology Centre website and enter yourself on the mailing list for the newsletter. The address is: www.etc-cte.ec.gc.ca/SpillTechnologyNewsletter.

This article describes the tests performed at OHMSETT that were used to develop new empirical formulas for computing drag force on oil spill containment booms. The formulas commonly used (the ITOPF and World Catalog formulas) are discussed to determine if, based on the test data, they could be improved to more accurately calculate drag force. The results using various computational methods are compared and assessed to determine how well they follow controlled test results and published results in field tests.

The work described in the article was performed under contract to the U.S. Department of the Interior, Minerals Management Service. James Lane and Robert Smith were Project Managers and Joe Mullin was Program Director.

means of computing drag force that follows measured results more exactly (Potter and McCourt, 1999).

The tests were performed at the OHMSETT facility (Oil and Hazardous Materials Simulated Environmental Test Tank) in New Jersey. The tests included:

- measuring forces on seven different booms towed at a range of different speeds;
- comparing the results with loads predicted by the ITOPF and World Catalog formulas; and
- developing a new set of empirical equations in the ITOPF format that match measured results.

Although these tests were an important step in developing a computational method of estimating forces on booms, this work had several limitations. First, the force of the wind was not considered in determining total force. Second, the empirical formulas developed require a separate constant for each type of boom and each of three operating environments. Third, the only wave heights tested were 18.5 cm (7.3 in) and 31.2 cm (12.3 in), or roughly 0.15 m (0.5 ft) and 0.3 m (1 ft). A set of constants for existing equations was proposed for larger waves, but these could not be confirmed with measured results.

Although these recent tests considerably improved the accuracy and credibility of force computations, it appeared that additional work would be required to clear up possible problems and establish a means of computing forces in more severe wave conditions. To this end, MMS commissioned another study (as yet unpublished) to determine how well the new empirical equations (referred to hereafter as the MMS equations) follow measured results and if the ITOPF or World Catalog equations had the potential for producing similar or even better results. This was done by:

- computing drag force in each controlled test using the MMS equations and comparing these results with measured results;
- computing drag force using the World Catalog equations and comparing these results with measured results;
- using measured results to adjust the World Catalog equations so that they produce results that more nearly follow measured values; and
- assessing the performance of these two computation methods to determine which serve the user best and in what circumstances.

Additional computations were not made using the ITOPF equations because it was determined that they are simply a special subset of the MMS empirical equations.

Minerals Management Service Tests at OHMSETT

(Potter and McCourt, 1999)

The U.S. Department of the Interior, Minerals Management Service, sponsored a series of tests that were carried out at OHMSETT from June 24 to July 10, 1998. These tests measured the drag force on towed booms using seven containment booms and a range of gap ratios, wave conditions, and tow speeds. The data from these tests were used to develop equations that predict drag force and required boom tensile strength. A comparison was made between these results and the ITOPF equations, the World Catalog equations, and forces measured in the tests performed at sea by the Marine Spill Response Corporation and U.S. Coast Guard.

Test Description

Booms were deployed in the OHMSETT test tank for full-scale tests. A load cell was mounted on each of the tow points on the towing bridge. The load cells had a capacity of 2000 pounds force with an accuracy of ± 10 pounds force. The load cells were calibrated prior to the tests and checked to confirm their accuracy. Data from the load cells, wave height, and tow speed were recorded by computer every 0.1 seconds. Visual observations recorded boom behavior including submergence, planing, wave conformance, and splashover.

Table 1 MMS Tests of Booms at OHMSETT (Potter and McCourt, 1999)

Boom	Freeboard ft (cm)	Draft ft (cm)	Buoyancy-to-weight ratio*
CCG 18-in curtain boom	0.5 (15)	1.125 (34)	5:1
CCG 18-in fence boom	0.58 (18)	0.92 (28)	3:1
CCG 24-in curtain boom	1.1 (34)	0.92 (28)	14:1
CCG 36-in fence boom	1.0 (31)	2.0 (61)	5:1
USCG 47-in Oil-Stop curtain boom	1.42 (43)	2.5 (76)	20:1
CCG 78.5-in Ro-Boom curtain boom	2.8 (85)	3.7 (110)	20:1
US Navy 52-in curtain boom	1.33 (41)	3.0 (91)	8:1

** Buoyancy-to-weight ratio as reported by the manufacturer.*

Boom Description

The specifications of the booms used for the testing are outlined in Table 1.

Test Variables

The test matrix included four variables: tow speed, wave conditions, boom length, and gap ratio. Most booms were towed at four speeds: 0.3, 0.5, 0.8, and 1 m/s (0.5, 1.0, 1.5, and 2.0 knots). Some of the larger booms were towed at only three speeds. Tests were conducted in calm water, a regular wave with a height of 18.5 cm (7.3 in), and a harbor chop wave with a height of 31.2 cm (12.3 in). There were 358 test runs, with 48 runs per boom in most cases.

Average tension was recorded as half the sum of the tension on each of the two tow points. This is half the drag force computed in the World Catalog formula. The tests showed that the tension experienced by a boom is not constant, particularly when the boom is towed through waves. As the boom follows the crests and troughs of waves, the tension fluctuates, peaking as the boom catches the front of the wave.

Peak and mean tension values were recorded, 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 analysis was on these 95th percentile tension loads.

MMS Formulas for Boom Tension

(Potter and McCourt, 1999)

Measured data for the booms tested were tabulated for the various tow speeds, gap ratios, and wave conditions. These data were then used to develop a set of formulas to compute the tensile force on a boom in terms of the projected area of the submerged portion of the boom and tow speed. Since the force of the wind was determined to be small, it was not included.

The equations developed take the form of the ITOPF equation with a special set of constants developed for each boom and environmental condition. The study notes that the correlation was done using a least-squares fit with all but a few R-squared values of 0.95 or greater.

The original equation had a conversion factor to maintain consistent units. Only the converted equation is considered here, and the constant K is the converted value called 'K' in the report. The basic equation developed for tension is shown by:

$$T = K A V^2$$

where: T = tensile force, pounds (1/2 drag force)*

K = constant with the units $lb_f/(ft^2 \times knots^2)$

A = projected area of the submerged portion of the boom, ft^2

V = tow speed, knots

* to convert to kilograms, multiply by 0.45

Table 2 Values of K for Booms Tested

Boom	Calm Water	Regular Waves	Harbor Chop
CCG 18-in curtain boom	1.7	2.8	3.1
CCG 18-in fence boom	1.7	4.9	5.5
CCG 24-in curtain boom	2.0	2.8	3.5
CCG 36-in fence boom	3.2	5.7	7.0
USCG 47-in Oil-Stop curtain boom	2.0	2.9	2.9
CCG 78.5-in Ro-Boom curtain boom	4.8	6.0	6.6
US Navy 52-in curtain boom	3.4	4.5	4.6
Maximum Values	4.8	6.0	7.0
Average Values	2.7	4.2	4.7

The projected area is defined as either the boom draft times the towing gap or the boom length times the draft times the gap ratio.

This basic equation becomes a whole series of equations by giving values to K that permit the computed values of tension to follow measured values taken at the 95th percentile. The computed values of K to be used in the equation are shown in Table 2.

Discussion of Earlier Empirical Equations

The following is the ITOPF equation, which is perhaps the best known equation for computing forces on booms (ITOPF, 1986).

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

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

Although not specified in some references, the submerged area is clearly what is generally called the "projected area", which is either the boom draft times the towing gap or the boom length times the draft times the gap ratio.

It is difficult to compare the results using the ITOPF formula and other computations because of the units of force. Furthermore, the force computed here is the drag force, not tension (one half of drag force), which is used in the MMS equations. Other computations used here give the result in pounds of force.

After converting units and changing the result to tension rather than drag force, the ITOPF equation was found to be identical to the MMS equation with K = 2.66. Because the ITOPF equation is essentially a subset of the MMS equations, it is not used here to compare computed values of tension.

The World Catalog/Exxon formulas have been published in editions of the World Catalog since 1986 and most recently in 1999 (Exxon, 1982; Schulze, 1999). These formulas are shown by the following:

$$T_a = 0.5\ L\ \tau C_d\ \rho_a\ f\ V_a^2$$

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

$$D = 2\ (T_a + T_w)$$

where: D = total drag force, pounds force*

T_a = tension due to wind, pounds force

T_w = tension due to waves, pounds force

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 the 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

* to convert to kilograms, multiply by 0.45

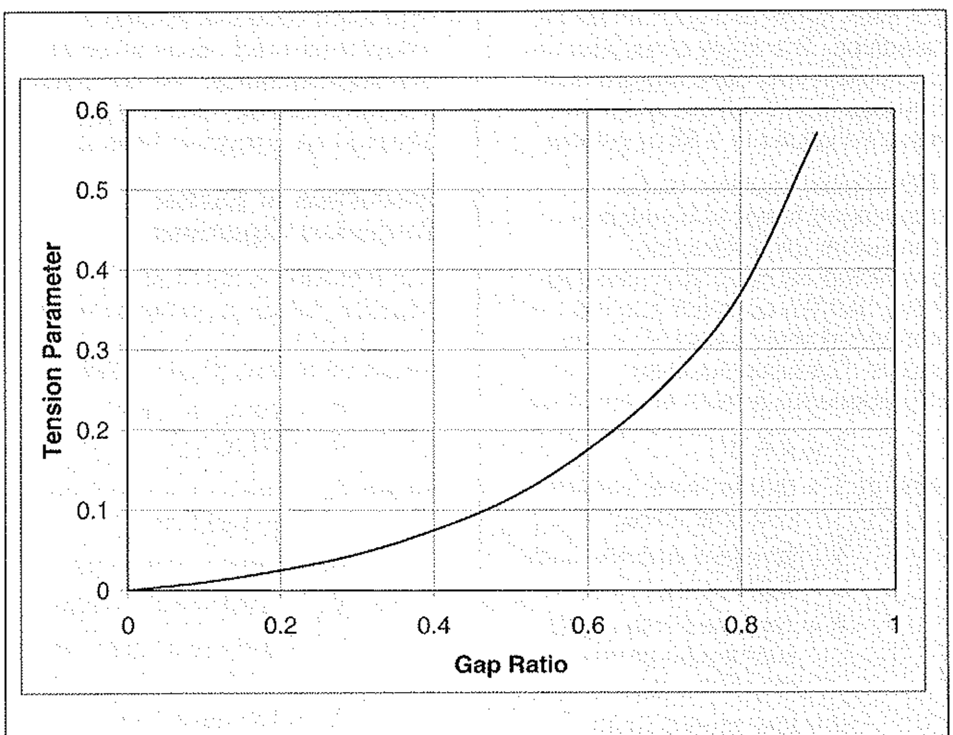


Figure 1 Tension Parameter vs Gap Ratio

Note that, unlike other formulas, all velocities are in feet/second; therefore, most towing velocities must be converted. (1 knot = 1.69 ft/s)

The MMS study notes that the force of wind is generally a very small part of the force on the boom. For example, using the above formulas, for a 0.75-m/s (1.5-knot) current, 10-m/s (20-knot) wind, and a typical draft-to-freeboard ratio of 2:1, the load caused by wind would be only about 10% of that due to the water current. Since winds were light during the OHMSETT force measurement tests, the force of the wind was not considered in the computations.

Tension parameter (τ) in the World Catalog equation is a function of the gap ratio and discrete values can be taken from the curve in Figure 1. Note that in the simple ITOPF formula and in the MMS empirical formulas that are described later, the force is proportional to the projected area of the boom, which means that it is directly proportional to the gap ratio. The curve for tension parameter is not a straight-line function, so the force is increasing exponentially with the gap ratio, which yields a different result.

The source of the "tension parameter" curve is apparently some theoretical work done by Jerry Milgram of MIT under contract to Exxon. The curve assumes that a boom under tow has a catenary shape in a plan view, which helps in calculating loads on booms. Users of the World Catalog equation have long suspected that results of computations could be improved by adjusting the tension parameter curve or drawing a series of curves, based on carefully measured values of boom tension taken from full-scale tests. This had never been done because test data were not available. It has been done now, however, and with considerable success using MMS data. The following describes this procedure in detail.

Adjustment of the World Catalog Equation

The World Catalog equation follows measured values of tension well in some cases but sometimes gives values that are low. Users have suspected that the low values were caused by a flawed curve for tension parameter, which may not have been developed with detailed measured data. MMS commissioned a second study to determine how well the new MMS empirical equations follow measured results and to see if the World Catalog equations could be adjusted to conform to measured data (Schulze, 2001).

Improving the World Catalog equation is justified because it has a term to account for wave height. This is significant because it means that any wave height can be entered. The MMS equations adjust computed values using a separate constant for each wave height, but the wave sizes are small and limited to those that could be generated in the full-scale tank tests. The only wave heights tested were 18.5 cm (7.3 in) and 31.2 cm (12.3 in), or roughly 0.15 m (0.5 ft) and 0.3 m (1 ft).

It is not known how these equations perform with higher waves. Therefore, the task was to adjust the World Catalog equations, which can be used for any wave height, so that they follow the measured test data. This was done by using the MMS 95th percentile measured tension at 0.5 m/s (1 knot) in calm water for each boom tested as a solution to the World Catalog equation and computing a new value of tension parameter for each gap ratio tested. The calm water result was used to determine the new tension parameter curve because the World Catalog equations have an entry for wave height.

A value of 0.5 m/s (1 knot) was selected as the best place to centre data because that is often the upper limit for effective containment. Since all of these equations have a term of velocity squared, using a higher towing speed, such as 1 m/s (2 knots), could tend to increase any errors there may be in the equations.

Using this information, a set of curves was drawn for tension parameter for each boom size, but not for each boom type. These new values of tension parameter were then used to compute a result corresponding to measured values taken during tests. The results of these computations are very encouraging.

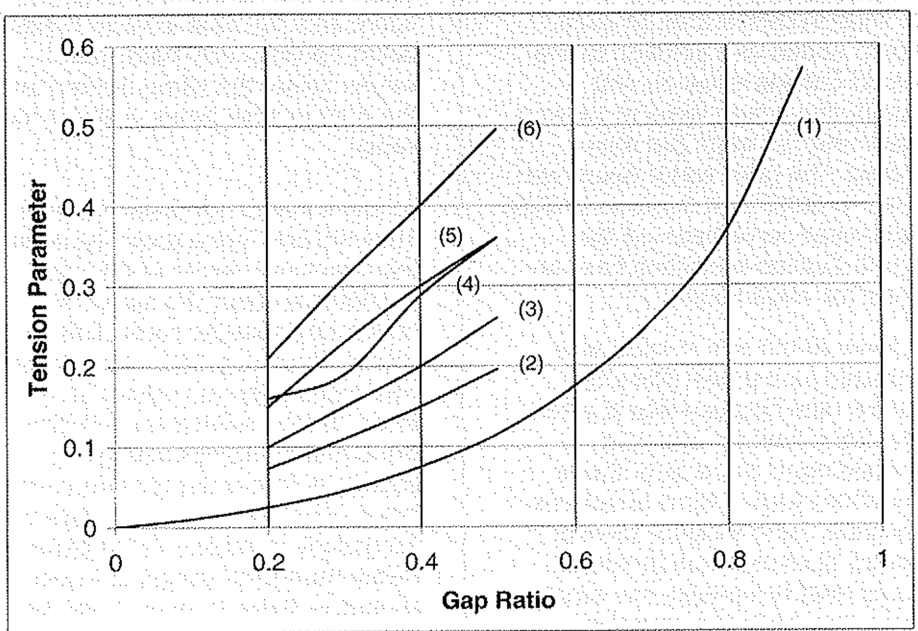
The adjusted World Catalog equations follow measured results as well as the MMS empirical equations and sometimes better. The MMS empirical equations are easier to use, but they are less universal. The constants for these equations only include calm water and waves of 17.8 and 30.4 cm (7 and 12 in), which is rather restrictive in that protected water is defined by waves of up to 0.9 m (3 ft) and open water by waves of up to 1.8 m (6 ft). As the World Catalog equation has a term for wave height, it has potential for use in a far wider range of sea conditions.

The new curves for tension parameter based on the computations described above are shown in Figure 2. The same curve is used for both the Canadian Coast Guard 18-in (46-cm) curtain boom and the 24-in (61-cm) curtain boom because the measured values follow the same pattern and the draft in both cases is about the same.

A new curve is not drawn for the 18-in (46-cm) fence boom because the measured values at 0.5 m/s (1 knot) are about the same. At higher tow speeds, particularly in waves, the fence boom has some very high measured values of force. In fact, neither the MMS nor the adjusted World Catalog equations follow the tension on the fence boom at higher tow speeds, particularly in waves. Attempting to follow measured values at higher speeds is likely to result in values that are much too high at lower speeds, particularly at around 0.5 m/s (1 knot) where most of the towing is likely to be done. This leads to the decision to make the equations fit measured values for fence booms as well as possible up to 0.5 m/s (1 knot) and then allow a larger deviation for higher tow speeds.

It can be seen in Figure 2 that, except for the fence boom, the new curves for tension parameter are nearly straight lines. This suggests that the World Catalog equations could be further simplified. A constant could be developed for each boom type so that the user could use that constant and gap ratio, eliminating the requirement to go to a curve for tension parameter. The new constants that can be used along with gap ratio in modified equations are shown in Table 3.

The new constants (C) shown in Table 3 can be combined with other constants in the existing World Catalog equation to produce a greatly simplified equation for boom tension. Terms combined in a single constant include the following:



1) Original curve
2) 18- and 24-in curtain boom
3) 47-in curtain boom
4) 36-in fence boom
5) 52-in curtain boom
6) 78.5-in curtain boom

Figure 2 New Curves for Tension Parameter vs Gap Ratio Corresponding to Measured Results

Table 3 Special Constants for the World Catalog Equations

Boom Type	Tension Parameter Curve	World Catalog Constant C
18- and 24-in curtain	2	0.38
47-in curtain	3	0.5
36-in fence	4	0.72
52-in curtain	5	0.75
78.5-in curtain	6	1.0

ρ_w = density of water ($1.98\ slugs/ft^3$)

τ = tension parameter, dimensionless

C_d = drag coefficient (assumed to be 1.5), dimensionless

L = length of the boom, ft

d = boom draft, ft

A = projected area, ft^2 (boom length x draft x gap ratio); eliminates the need for L and d.

Thus, from the original equation:

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

Gather original constants ($0.5 \times C_d \times \rho_w = 0.5 \times 1.5 \times 1.98 = 1.5$) and add the new constant C, which takes the place of tension parameter. The new World Catalog equation for tension caused by the force of water then becomes:

$$T_w = 1.5\ CA\ (1.69V_w + 0.5\ \sqrt{H_s})^2$$

where: T_w = tension, pounds force*

C = boom constant shown in Table 3

A = projected area, ft^2 (boom length x draft x gap ratio)

V_w = tow speed, knots

H_s = wave height, feet

* to convert to kilograms, multiply by 0.45

V_w is entered in knots since the conversion factor has been added for feet/second. This a much simpler formula to work with than the original World Catalog formula. The constant C can have one of five values depending on boom size. When working with a single boom and gap ratio, the formula can be reduced to a single constant to be used with tow velocity and wave height.

As the force of the wind was not measured in the MMS tests, there are no new measured values to compare with computed values. In order to eliminate the need for tension parameter entirely, the equation for tension caused by the wind can be adjusted to include the new constant C and the projected area of the boom above the water. The original equation:

$$T_a = 0.5\ L\ \tau\ C_d\ \rho_a\ f\ V_a^2$$

T_a = tension due to wind, pounds force

V_a = wind speed, ft/sec

ρ_a = density of air ($0.00238\ slugs/ft^3$)

L = length of the boom, ft

f = boom freeboard, ft

τ = tension parameter, dimensionless

C_d = drag coefficient (assumed to be 1.5), dimensionless

Gather original constants ($0.5 \times C_d \times \rho_a = 0.5 \times 1.5 \times 0.00238 = 0.001785$)

A = projected area of the boom above the water, ft^2, which is the length x freeboard x gap ratio; this eliminates the need for L and f

C = boom constant from Table 3.

Thus, from the original equation, T_a becomes :

$$T_a = 0.001785CA\ (1.69\ V_a)^2$$

As before, the drag force is given by:

$$D = 2\ (T_a + T_w)$$

where: D = total drag force, pounds force*

T_a = tension due to wind, pounds force

T_w = tension due to waves, pounds force

* to convert to kilograms, multiply by 0.45

Assessment of Performance of Tension Computations for All Booms Tested

Now consider how all of the computed results using the MMS equation and the World Catalog equations compare with the measured results (Schulze, 2001). Although both sets of equations were formulated to follow measured results, neither do so perfectly.

The MMS equations follow measured results by curve fitting. The World Catalog formula does the same thing by fitting the tension parameter curve to each gap ratio of measured values at a base value of 0.5 m/s (1 knot) of tow speed in calm water. This point was selected because 0.5 m/s (1 knot) is perhaps the most typical tow speed and the equation has a term that makes an adjustment for wave conditions, so it is appropriate to base the equation on calm water.

• **CCG 18-in curtain boom** - The MMS and World Catalog equations follow measured values well. The general performance of both sets of equations is about the same, although World Catalog results have a tendency to be somewhat low.

• **CCG 18-in fence boom** - The equations do not follow measured results as well for fence booms, particularly at higher tow speeds. In calm water, both types of equations are good up to 1 m/s (2 knots). In the 0.18 m (0.6 ft) wave, World Catalog is better up to 1 m/s (2 knots) for the longer boom and MMS is better for the shorter boom. The same is true in the 0.30 m (1 ft) wave. In most cases, the World Catalog equations are better than MMS up to and including 0.8 m/s (1.5 knots); at 1 m/s (2 knots) something happens so that neither set of equations represents measured values very well. Note that the World Catalog does not use a new constant for the 18-in (34-cm) fence boom but the MMS equation does.

• **CCG 24-in curtain boom** - Measured and computed data are close throughout. Either computation system is satisfactory for this boom in the described environments.

• **CCG Oil-Stop 47-in curtain boom** - Measured and computed data are close throughout. Either computation system is satisfactory for this boom in the described environments.

• **US Navy 52-in curtain boom** - Computed values for this larger boom are not quite as close to measured results as for the smaller booms, but they are close enough for most purposes. Either system of computation would be satisfactory for this boom in the described environments.

• **CCG 78.5-in Ro-Boom curtain boom** - Measured data on this large boom are much more irregular than on the smaller booms. As a result, equations are also much less likely to follow the measured data. Even though tow speeds were closer together [there were no trials at 1 m/s (2 knots)], measured values were highly variable. In spite of these differences, both equations were able to compute the forces on the booms well enough to be useful in all tests reported.

• **CCG 36-in fence boom** - For reasons that are not well understood, measured tension on fence booms is highly irregular and therefore difficult to simulate with equations. In all environments, both systems of equations do well up to 0.8 m/s (1.5 knots), then they fall well below measured values. Since fence booms are less likely to be towed at 0.8 m/s (1.5 knots) and above, it would seem to be wise to leave the equations as they are. Anyone who needs detailed information on tension on larger fence booms at 0.8 m/s (1.5 knots) and above should develop a special set of constants for that particular application.

The World Catalog equations have a variable for wave height. In Table 5, boom tension for the boom sizes shown in protected water and open water using the MMS equations is compared with the averaged values of K and the World Catalog equations using appropriate wave heights.

Although basin-measured values of tension are not available for 0.9- and 1.8-m (3- and 6-ft) waves, these computed values of tension suggest that the MMS equations underestimate tension in protected water and waves in open water, especially at lower tow speeds.

Overall Assessment of Results

The measured test results assessed here suggest that either the MMS equations or the World Catalog equations could be used for computing forces on booms in most situations. Table 5 suggests that the World Catalog equations

Table 4 Values of the Constant K for Standard Water Body Classifications

Water Body Classification	Average Values of K
Calm Water [Wave height 0 to 0.3 m (1 ft)] 18-in Booms	1.7
Protected Water [Wave height 0 to 0.9 m (3 ft)] 24- and 36-in Booms	4.3
Open Water [Wave height 0 to 1.8 m (6 ft)] 47-, 52-, and 67-in Booms	4.7

may be better in protected water and waves in open water that cannot be generated in a test tank.

The MMS equations may be easier to use since they involve fewer terms. With constants gathered together, however, the adjusted World Catalog equations require little more effort. In addition, those with good computer skills report that they are able to set up the World Catalog equations in a spreadsheet format and the equations are solved in the computer. Based on the analysis of this study, it seems clear that both systems of equations have a secure place as tools to compute tension of towed containment booms.

Comparing Measured Tension in Offshore Tests with Computed Results

In the new MMS study (Schulze, 2001), measured tension from offshore tests is compared with computed results using both the MMS and World Catalog formulas. In some cases, computed values follow measured results very well and in other cases, computed results are much larger than measured results. There are many reasons for this, only some of which are well understood.

The following are some reasons for differences between offshore measurements and computed results.

- Offshore tests generally report average tension whereas equations shown in this article are designed to estimate values at the 95th percentile, or two standard deviations above the mean. Standard deviation has rarely been recorded in offshore tests, but when it has, it is generally large, sometimes much larger than the average value itself (Nordvik et al., 1995). In most cases, computed values of tension for offshore operations are much larger than average measured values, which is good because it shows computed values are predicting numbers that may be within the 95th percentile, which provides a safety factor for boom design and use.

- It is difficult to measure tow speed accurately offshore, particularly at lower speeds. In early tests, speed measurement techniques were crude, sometimes based on timed drift of wood chips. In addition, currents sometimes occur offshore that are not being measured. Since all equations that predict boom tension have a squared term for tow speed, inaccuracies can cause a substantial change in the result.

- Gap ratio has a significant effect on boom tension. It is often difficult to maintain the desired gap ratio in offshore tests which results in a large difference between measured tension and computed tension.

- Computed tension is directly proportional to boom draft. As booms are towed at higher speeds, they sometimes tend to submerge, which may result in increased boom draft. (The bottom tension member of a curtain boom may tend to bow the boom up so that draft may not increase even though freeboard is decreasing.) In any

Table 5 Computed Values of Tension for Typical Booms in Protected Water and in Open Water

Tow Speed (knots)	MMS Computed Tension (lbs)	World Catalog Tension (lbs)
Protected Water - 0.9-m (3-ft) wave; 36-in Boom - Freeboard .30 m (1 ft), Draft .60 m (2 ft), Length 61 m (200 ft); Gap Ratio 0.3; MMS Computation K = 4.3; WC Constant C = 0.72		
0.5	129	377
1.0	516	847
1.5	1161	1500
2.0	2064	2336
Open Water - 1.8-m (6-ft) wave; 52-in Boom - Freeboard 0.4 m (1.3 ft), Draft 0.9 m (3 ft), Length 61 m (200 ft); Gap Ratio 0.3; MMS computation K = 4.7; WC Constant C = 0.75		
0.5	212	868
1.0	846	1720
1.5	1904	2862
2.0	3384	4294

case, an unreported increase in boom draft will make measured tension larger than computed tension.

- Wave action increases tension on booms, but not always in a way that can be predicted by an equation. Wave steepness, measured by wave length-to-height ratio, is likely to be more significant than wave height alone, but this relationship has not been documented and is not recognized in equations for boom tension. It is easy to understand how an extremely long wave will have no effect on boom performance, but short, choppy waves will change performance. Tests suggest that wave length-to-height ratio is the controlling factor and that the crucial point is a length-to-height ratio of about 12 to 15:1. Waves longer than this are not likely to affect boom performance but shorter waves certainly will.
- Some booms fail by planing in offshore tests. The resulting reduction in boom draft causes a decrease in boom tension or boom tension that does not increase with increasing tow speed.

Future boom tests could help to resolve these differences by including the following measurements.

- Report observed values of tension including average and 95th percentile loads.
- Report accurate observations of boom gap ratios, currents, tow speeds, and boom drafts and account for variations during the test.
- Report wave length-to-height ratios as well as wave heights.

Summary

The MMS equation provides good results in calm water and in waves up to 0.3 m (1 ft) high. Use the equation shown below with the appropriate constants. Average constants are provided for higher waves, but computed values may be low. For waves larger than 0.3 m (1 ft), it may be better to use the World Catalog equations, entering the appropriate wave height.

MMS Equation

$$T = K A V^2$$

where: T = tensile force, pounds

K = constant, $lb_f/(ft^2 \times knots^2)$

A = projected area of the submerged portion of the boom, ft^2

V = tow speed, knots

The projected area is defined as either the boom draft times the sweep width or the boom length times the draft times the gap ratio. Use the values of K shown in Table 6. Computed values of tension follow measured values taken at the 95th percentile. Drag force is two times the tension. Suggested values of K for protected water and open water are averages that were not verified with measured test data.

World Catalog Equation

The World Catalog equation provides results that are comparable to the MMS equation and are likely to be better for waves higher than 0.3 m (1 ft).

$$T_w = 1.5\,CA\,(1.69V_w + 0.5\sqrt{H_s})^2$$

where: T_w = tension, pounds force*

C = boom constant shown in Table 7

A = projected area, ft^2 (boom length x draft x gap ratio)

V_w = tow speed, knots

H_s = wave height, feet

* to convert to kilograms, multiply by 0.45

Computed values of tension follow measured values taken at the 95th percentile. Drag force is two times the tension. Appropriate values for the constant C are shown in Table 7.

The World Catalog also has an equation for the force of the wind.

Table 6 Values of K for Booms Tested

Boom	Calm Water	Regular Waves	Harbor Chop	Protected Water	Open Water
CCG 18-in curtain boom	1.7	2.8	3.1		
CCG 18-in fence boom	1.7	4.9	5.5		
CCG 24-in curtain boom	2.0	2.8	3.5	4.3	
CCG 36-in fence boom	3.2	5.7	7.0	4.3	
USCG 47-in Oil-Stop curtain boom	2.0	2.9	2.9		4.7
CCG 78.5-in Ro-Boom curtain boom	4.8	6.0	6.6		4.7
US Navy 52-in curtain boom	3.4	4.5	4.6		4.7
Maximum Values	4.8	6.0	7.0		
Average Values	2.7	4.2	4.7		

Table 7 Special Constants for the World Catalog Equations

Boom Type	World Catalog Constant C
18- and 24-in curtain	0.38
47-in curtain	0.5
36-in fence	0.72
52-in curtain	0.75
78.5-in curtain	1.0

$T_a = 0.001785CA\,(1.69\,V_a)^2$

where: T_a = wind tension, pounds force*

A = projected area of the boom above the water, ft^2, which is the length x freeboard x gap ratio

C = boom constant shown in Table 7

V_a = the velocity of the wind, knots

* to convert to kilograms, multiply by 0.45

Finally, drag force is given by:

$D = 2\,(T_a + T_w)$

where: D = total drag force, pounds force*

T_a = tension due to wind, pounds force

T_w = tension due to waves, pounds force

* to convert to kilograms, multiply by 0.45

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