EVALUATING A PROTOCOL FOR TESTING FIRE-RESISTANT OIL-SPILL CONTAINMENT BOOM

by

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Evaluating a Protocol for Testing Fire-Resistant Oil-Spill Containment Boom*

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Abstract

Most response plans for *in situ* burning of oil at sea call for the use of a fire-resistant boom to contain the oil during a burn. Presently, there is no standard method for the user of fire-resistant boom to evaluate the anticipated performance of different booms. The ASTM F-20 Committee has developed a draft Standard Guide for *In Situ* Burning of Oil Spills On Water: Fire-Resistant Containment Boom; however, the draft provides only general guidelines and does not specify the details of the test procedure. Utilizing the guidelines in the draft standard, a series of experiments was conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves. A wave tank capable of assessing the capabilities of a 15 m section of boom by subjecting it to a 5 m diameter fire with 0.15 m high waves was designed and constructed at the U.S. Coast Guard Fire and Safety Test Detachment in Alabama. A draft test protocol was evaluated using five typical fire-resistant oil-spill containment booms. The results of this evaluation are presented. The strengths and weaknesses of the protocol are discussed along with areas for possible improvement.

1.0 Introduction

In situ burning of spilled oil has distinct advantages over other counter-measures. It offers the potential to convert large quantities of oil into its primary combustion products, carbon dioxide and water, with a small percentage of smoke particulate and other unburned and residue byproducts. *In situ* burning requires minimal equipment and less labor than other techniques. It can be applied in areas

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where many other methods cannot be used due to lack of a response infrastructure and/or lack of alternatives. Because the oil is mainly converted to airborne products of combustion by burning, the need for physical collection, storage, and transport of recovered fluids is reduced to the few percent of the original spill volume that remains as residue after burning.

Oil spills on water naturally spread to a thickness where the oil cannot be ignited or burning sustained. It has been found that an oil thickness of 1 mm to 5 mm is required for ignition depending on the nature of the oil (Buist, *et al.*,1994). As a result, the scenarios which have been developed for *in situ* burning of oil on water include some means for corralling the oil. The use of fire-resistant containment boom is the method most often proposed for maintaining adequate oil thickness to support burning. In that scenario, oil is collected from the spill in a horseshoe or catenary shaped boom towed by two vessels. Once an adequate quantity of oil has been collected from the spill, the oil is ignited and burned while being towed in the boom. The oil is maintained at a sufficient thickness in the apex of the boom to support burning until nearly all of the oil is consumed. The process of collecting and burning can then be repeated. For this scenario to be successful, the boom must be capable of withstanding repeated fire exposures while containing the oil.

Oil-spill planners and responders need to know the expected performance of fire-resistant oil-spill containment boom. The ASTM F-20 Committee has developed a draft Standard Guide for *In Situ* Burning of Oil Spills On Water: Fire-Resistant Containment Boom. The draft standard could be considered a guideline since it does not provide all of the specific details necessary to conduct an evaluation of fire-resistant boom. It does however provide some general performance requirements related to the collection and burning of oil. Since it is a draft document under development, the standard continues to be revised. The draft dated February 14, 1997 was used to develop the test protocol. The principal burn related feature of the draft calls for a burn exposure, cool down cycle consisting of one hour of burning followed by one hour with no burning, followed by one hour of burning and one hour of no burning followed by one hour of burning. This is a total of 3 one hour burn periods and 2 one hour cool down periods. The wave characteristics to which the boom would be exposed during burning and cooling were not specified. The boom should maintain adequate floatation during the exposure and contain a layer of oil 10 mm to 20 mm in thickness without loss.

2.0 Design of Test Procedure

Under the sponsorship of the United States Coast Guard and the United States Minerals Management Service, the National Institute of Standards and Technology conducted a project to develop and evaluate a procedure for testing fire-resistant oil-spill containment boom. This project focused only on fire performance and not the oil-collection performance. Methods for evaluating the oil-collection performance have been reported previously (Bitting and Coyne, 1997).

Five fire-resistant oil-spill containment booms selected by the project sponsors were used in the evaluation of the test procedure. Since the purpose of the project was to evaluate the test procedure and the ASTM used to develop the test protocol is a draft, the booms were not subjected to an accepted standardized test. While the overall performance of the booms was noted, the booms were not evaluated based on a pass-fail criterion.

The philosophy in developing the test procedure was to subject a boom to conditions which could be used to evaluate the performance of the boom when used for *in situ* burning during a spill response. The ASTM draft standard served as guidelines in developing the procedure but there were also environmental, engineering and economic constraints.

Ideally, a test method should provide a measure of performance of the item being tested. The measure should be related in one or more ways to the anticipated use of the item. One method is a test which replicates as closely as possible use conditions. This method is perhaps the easiest to understand and most commonly considered but lacks flexibility. Unless there is a single use condition, a number of test conditions may be required to replicate all possible uses. A second method is a test which measures properties of the item. If the relationship between the properties and the use conditions are known, the performance under a variety of conditions could be predicted.

Two important aspects of a test method are repeatability and reproducibility. Repeatability is the ability to obtain acceptably similar test results for the same item at a given location. Reproducibility is the ability to obtain acceptably similar test results for a given item at different test locations. Items which affect repeatability and reproducibility are control of test parameters and operator bias. Repeatability and reproducibility are often analyzed using statistical methods with a number of tests using multiple items and several test locations.

At the present time, there is not an adequate understanding to develop a test which would relate boom component properties to the performance of a boom in actual use. Further, a component property test method would have to be compared with the performance of a complete boom to determine its ability to predict performance. This leads to the choice of a test which replicates the conditions to which a fire-resistant oil-spill containment boom would be exposed during the oil burning phase of its deployment.

One candidate test method would be to deploy a boom at sea under prescribed conditions, corral a specified quantity of oil, burn the oil and observe the performance of the boom. While this procedure would most closely replicate actual use conditions, it would be very expensive and require environmental permits which are difficult to obtain in United States waters. Temporary oil containment areas in thick ice have been used in some countries to conduct oil-spill research, but the permits required in the United States appear to the same as those for open waters. A related possibility would be to use actual oil spills or so called "spills of opportunity." Fortunately, oil spills are fairly rare occurrences and the opportunity to conduct standardized tests, with a number of booms during a spill, would be an even rarer event.

This leaves a land-based containment tank as the best choice for the evaluation of the fire performance of a number of booms. There are a number of containment areas, pits, tanks or pans which are designed and permitted for burning liquid fuels. Most of these are fire training areas and some have been used in the past to evaluate fire-resistant boom. However, these do not have the capability to produce waves which are considered an important aspect in evaluating fire-resistant boom. Wave tanks designed for oil-spill research are generally not designed to withstand a fire and the environmental permits necessary for burning may be unavailable for these sites. Although burning could be conducted in some existing wave tanks using a gaseous, relatively clean burning fuel, efforts to achieve the same thermal exposure as obtained with liquid hydrocarbon fuels have not been successful (McCourt, *et al.*, 1997 and Walton, *et al.*, 1997).

After examining a number of options, it was determined that the construction of a wave tank, designed to accommodate burning, was the most appropriate option. A description of the wave tank is given in the next section. A number of designs were considered that would allow the boom to be configured in the horseshoe or catenary shape observed when towing a boom at sea. No economically feasible designs were developed which would assure that a liquid fuel would remain in a prescribed area of the boom apex during burning. A circular boom pattern was chosen to contain the fuel even though the boom would be turned through a smaller radius than would be expected at sea. Further, the circular pattern did not allow the boom to be tensioned to simulate the tow stress.

The wave tank was designed to accommodate a nominal 15 m boom section forming a circle approximately 5 m in diameter. The heat flux at the base of a liquid pool fire and the burning rate are functions of the fire diameter. The heat flux and the burning rate increase with increasing fire diameter for small fires. Once the diameter reaches 5 m, the heat flux and burning rate are nearly constant as the fire diameter increases (Walton, *et al.*, 1993). Thus, the fire within the boom containment would be large enough to represent the thermal exposure from a larger fire.

Ideally, a wave tank should have a length to width ratio of at least 5 to 1 and preferably 10 to 1 or more. This would allow the waves time to fully develop before exposing the test item and there would be a sufficient distance, over which the wave energy could be absorbed, to prevent reflections. Do to economic constraints, a length to width ratio of 3.3 to 1 was used which was considered the minimum necessary for a 5 m diameter boom circle.

The tank was designed to produce 0.3 m high waves with a period of 3 s to 5 s. Normally, *in situ* burning would not be considered as a response option in the presence of large or breaking waves. *In situ* burning could be considered with waves larger than 0.3 m, particularly long period sea swells. The 0.3 m short period waves were chosen to generate significant boom flexing without requiring the water depth and wave maker power required by larger waves.

3.0 Test Configuration

The boom test evaluations were conducted in a wave tank designed specifically for evaluating fire-resistant boom. The tank specifications were developed by NIST and the construction was directed by the United States Coast Guard, Fire and Safety Test Detachment. The tank is located at the Fire and Safety Test Detachment facility on Little Sand Island in Mobile Bay, Alabama. A wave maker, beach, fuel delivery system, boom constraints and instrumentation were designed and fabricated and installed in the tank by NIST.

The wave tank design was based in part on the experience gained from installing and using a 15 m square static burn tank at Fire and Safety Test Detachmer (Walton, *et al.*,1994). A plan view of the tank is shown in Figure 1 and a pictorial view in Figure 2. The wave tank was constructed of steel and was 1.5 m deep with two perimeter walls 1.2 m apart forming an inner and outer area of the tank. The inside dimensions of the inner area of the tank were 30.5 m by 9.1 m. The base of th tank was at ground level and two stairways provided access to the top of the tank.

The outer area of the tank formed a moat around the inner area and contained a walk-on steel grating 115 mm below the top of the tank. The moat served several purposes. During test setup, the water level in the moat was maintained below the grating which provided walk-around access to the test area. During a test, the water level in the moat was brought to the top of the tank which provided cooling for the inner tank walls and acted as secondary containment for the inner tank area. A movable bridge, which spanned the tank, was supported on both ends by wheels which moved on the grating. The bridge could be positioned to provide access over any area in the tank. During burns the bridge was removed from the tank.

The tank was filled and drained through six individually valved floor sumps. Four were located along the center of the inner area of the tank and two at opposite corners of the moat area. Bay water with a salt concentration of 0.70% NaCl was pumped to the tank via an underground piping system. Water taps in the piping system, allowed cooling water to be extracted from the tank and pumped through instrumentation and boom constraints. At the beginning of a test, the water level in the inner tank was 1.2 m or 0.31 m below the top edge and the moat was filled to the top.

The principal feature of the wave maker was a wave paddle suspended from a beam 4.9 m above the tank floor. The wave paddle was 3.1 m from the north end of the tank and attached to the beam with seven hinged connections allowing it to swing in the north-south direction. A pulley and cable system attached to the bottom of the wave paddle and the floor of the tank was designed so that the paddle would remain perpendicular to the long axis of the tank at all times. The overhead suspended wave paddle was selected to maintain the hinge points out of the water and so that the bottom of the tank would not have to be reinforced. The wave paddle had adjustable steel plates forming the paddle face which moved the water. The plates extended across the width of the tank to within 80 mm of the sides of the tank and were positioned 0.58 m above the tank floor and extended to 0.38 m above the still water level.

The wave paddle was moved with a hydraulic cylinder connected to the center of the paddle. A cylinder with a double ended piston was used so that the piston speed in both directions was the same. The cylinder was attached to a horizontal beam which was connected to 3 vertical beams driven into the ground. This transmitted the force to move the paddle to the ground and not to the pan. The hydraulic cylinder was powered with a hydraulic pump driven with a tractor. The motion of the cylinder was controlled with two limit switches mounted on the cylinder which activated a control valve. The control valve slowed the piston travel at the end of the forward and reverse strokes to reduce stress on the paddle when changing direction. The piston motion was set to 280 mm forward and backward of the vertical position. The piston cycle time was kept constant by maintaining a constant engine speed.

The beach was constructed of a corrugated steel deck on a steel frame. The deck spanned the width of the inner pan area and extended from 6.1 m to 1.0 m from the south end of the tank. The north edge of the beach was 0.61 m above the tank floor rising to 1.4 m above the tank floor at the south edge. The separation of the beach at south end of the tank allowed waves to break on the beach and wash over the end without leaving the tank.

The boom was kept in position during the test by 6 boom constraints or stanchions. The stanchions were constructed of 1.5 m lengths of 50 mm nominal diameter steel pipe. The stanchions were mounted vertically in a pattern forming a circle around the center of the tank. The base of each stanchion was attached to a plate which could be moved along a track attached to tank floor. The tracks extended radially from the center of the tank. Each stanchion could be moved along the track to form a circular pattern. The position of the stanchions was adjusted for each boom such that the boom formed a circle with stanchions around the inside of the circle. The stanchions extend above the water and the tops were plugged. A cooling water supply tube entered the base of the stanchion and extended to the top. Cooling water was pumped through the tube, into the stanchion and discharged at the base.

The fuel used for the tests was number 2 diesel fuel. The fuel was stored in a storage tank and pumped to the tank via an underground piping system. The fuel entered center of the tank under water and floated to the water surface. A check valve prevented water from entering the fuel system.

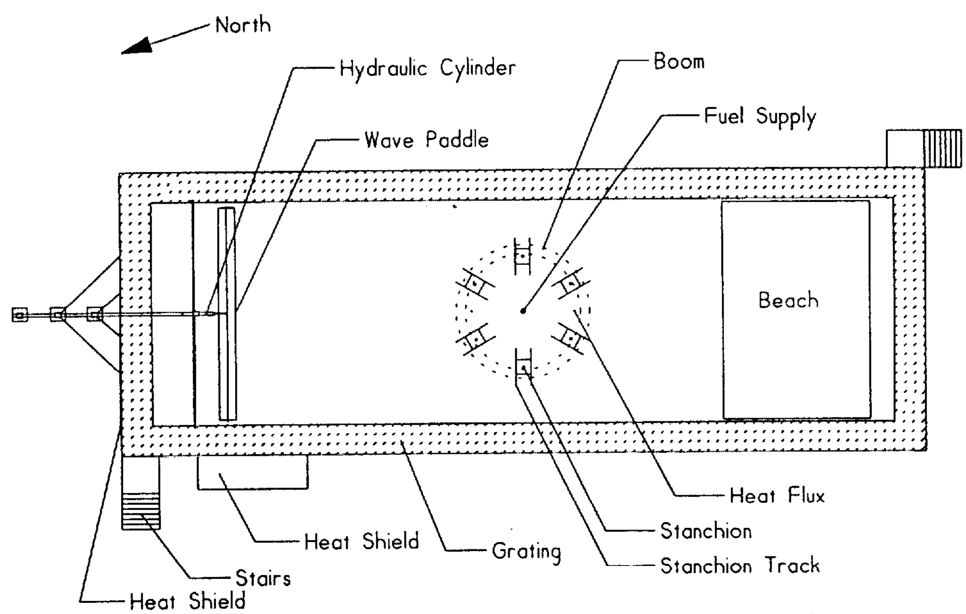

Figure 1 Plan View of Wave Tank

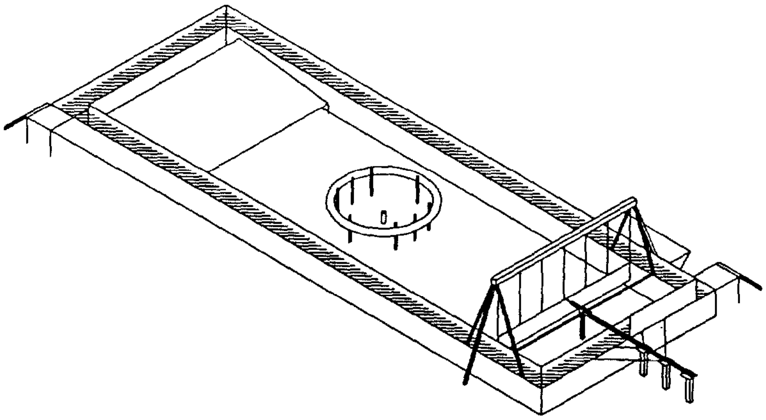

Figure 2 Pictorial View of Wave Tank

4.0 Instrumentation

Measurements of atmospheric conditions were made at the Coast Guard facility with a weather station located 55 m south of the burn tank and 2.1 m above the ground. The ground station included a propeller on vane anemometer to measure wind speed and direction. Wind speed and direction data were recorded every 30 s with a computerized data acquisition system.

Two sets of two water-cooled Gardon total heat flux gauges were used in each of the experiments. Each pair of gauges was mounted in a water-cooled fixture with one facing horizontally and one vertically. The center of the vertical face was 250 mm above the still water surface and the horizontal face was 320 mm above the still water surface. The heat flux gauges mounted inside the boom circle along the north-south centerline of the tank. The vertical faces were toward the center of the boom circle and the horizontal faces upward. The elevation of the gauges was held constant for all burns, even though the freeboard of the booms was different. The radial distance from the gauges to the center of the boom circle was adjusted for each boom, as given in Table 1.

Table 1 Radial Distance from Boom Circle Center to Heat Flux Gauges

Boom	North (m)	South (m)
1	1.12	1.12
2	1.55	1.55
3	0.99	1.55
4	1.04	1.07
5	1.60	1.80

Temperature measurements were attempted with thermocouples attached to the booms. These measurements were suggested in the ASTM guidelines however the measurements were not successful. Since a variety of boom designs was used, there was no standard way to connect the thermocouples to the boom without potentially causing damage to the boom. Thermocouples measure the temperature difference between the thermocouple junction and a reference junction. Heat is transferred to the junction by conduction, convection and thermal radiation. A thermocouple attached to a boom near a large oil fire may gain or loose heat from conduction to adjacent materials, convection from hot fire gases, radiation from the fire and radiation to the surroundings. As a result, it is difficult to interpret the meaning of the temperature measured by a thermocouple near a fire.

The wave profiles were determined from measurements of the water level in the tank. The water level was measured with a vertical cylindrical probe which had a capacitance proportional to the water level in the tank. The effect of the water coating on the probe, above the true liquid level, was compensated for by the electronics provided with the probe. Output from the probe was recorded with a computerized data acquisition system every 0.1 s. At that recording speed, the water level measures provided a good indication of the wave profile. Since the water level probe could not withstand high temperatures, wave profiles could only be measured without a fire in the tank.

5.0 Boom Description

Five commercially-manufactured fire-resistant booms were used to evaluate the test protocol. The basic features of the booms are given in Table 2. Analysis of boom construction was not a part of project and the booms were not disassembled to inspect the construction details. Table 2 gives a brief description of the boom construction. In this table, fabric is used to describe a flexible fabric based material which in some cases included a polymeric coating. Some of the booms consisted of a series of relatively rigid sections while others were flexible and formed a continuous curvature when connected end to end to form a circle. The freeboard is the average freeboard as measured prior to burning and average inside diameter is the diameter of a circle with an area equal to the area of the oil contained within the boom.

Table 2 Boom Description

Boom	Construction	Sections	Freeboard (mm)	Average Inside Diameter (m)	Area (m^2)
1	Fabric with steel covered flotation	continuous curvature	235	3.71	10.8
2	Fabric over rigid flotation sections	7	270	4.34	14.8
3	Water-cooled fabric over flexible flotation	continuous curvature	255	4.14	13.5
4	Stainless Steel sections with stainless steel covered flotation	6	635	3.88	11.8
5	Fabric over flexible flotation	continuous curvature	240	5.08	20.3

6.0 Test Procedure

The water in the inner tank was lowered to approximately 0.6 m above the floor to allow personnel wearing waders to work in the tank. The section of boom to be evaluated was placed on the ground next to the tank and formed into a circle with the ends of the boom connected. The inside diameter of the boom circle was measured and the stanchions in the tank were adjusted to fit inside the boom circle. The boom was placed in the tank using a truck mounted crane and a lifting spreader. The spreader was designed specifically for these tests so that the boom could be lifted as a circle. The spreader was connected to the crane hook with a four cable sling and consisted for eight horizontal radial arms which were positioned over the boom circle. The boom was attached to the arms with chains or rope slings. With the boom in the tank the stanchions were adjusted to ensure the boom would remain in a circle while floating freely.

The water level in the inner tank was raised to 1.22 m above the tank floor and the freeboard and inside diameter of the boom circle was measured from the movable bridge. The movable bridge was then removed from the tank and the water level in the moat brought to the top edge of the tank. Using the inside diameter of the boom circle, the area within boom was determined. The burning rate for the boom was calculated from the area within the boom and the burning rate per unit area of diesel fuel.

After performing a safety check, the cooling water to the stanchions and heat flux gauges and instrument recording were started. Using the calculated burning rate for the boom area, fuel for a 5 minute burn was added to the contained area within the boom through the underwater supply line. The boom was inspected for leaks and the fuel was ignited using a high output propane torch with a long wand. When the fire had spread to cover the entire area within the boom circle, the wave maker and fuel flow were started. Fuel was added to the contained area at a rate equal to the calculated burning rate. After 55 minutes the fuel flow was terminated and the fire allowed to burn out. After the first and second of the three burns the wave maker continued to operate for an hour after extinction of the fire. At that time the waves were stopped and the procedure repeated beginning with pumping fuel for a 5 minute burn to the contained area. At the end of the third burn the waver maker was turned off immediately and the boom and tank allowed to cool. The boom freeboard was measured and boom was removed from the tank. Any oil residue that remained in the tank was removed from the water surface with absorbents.

Figure 3 shows a burn test in progress in the tank. The boom in this picture was constructed specifically to check the operation of the tank and was not used in the evaluation of the test protocol.

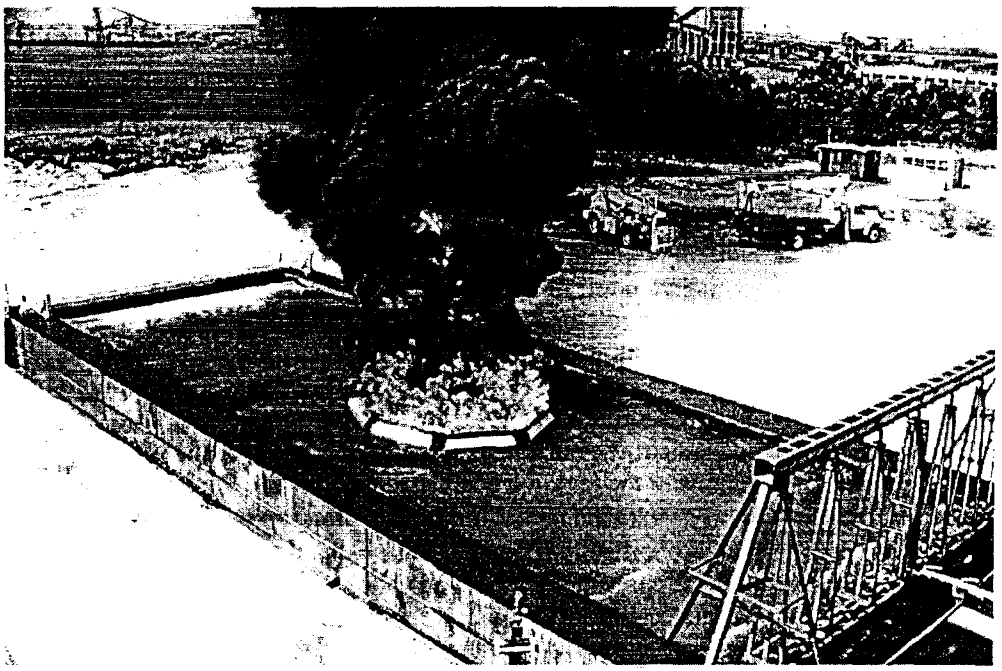

Figure 3 Wave Tank with Burn in Progress

7.0 Measurement Results

Measurements were made of the meteorological conditions, waves, fuel quantity, test chronology and heat flux.

7.1 Meteorological Conditions

Table 3 gives the ground meteorological conditions measured during each of the burns at the Coast Guard Facility. The values in Table 3 are averages over the time from ignition to extinction. Wind directions are the direction from which the wind originates with 0° being true north. Also shown in this table are the maximum and minimum values measured during the burn and the uncertainty given by one standard deviation. Although the meteorological conditions varied during the burns, the burns were of relatively short duration and the averages are representative of the actual conditions.

Table 3 Ground meteorological conditions

Boom	Burn		Temperature (°C)	Relative Humidity (%)	Barometric Pressure (kPa)	Wind Speed (m/s)	Wind Direction (°)
1	1	mean	28.7 ± 0.6	67 ± 3	101.56 ± 0.01	2.1 ± 0.7	30 ± 19
		minimum	27.4	61	101.53	0.0	324
		maximum	29.8	72	101.57	3.6	71
	2	mean	22.3 ± 0.4	86 ± 1	100.49 ± 0.01	3.3± 0.8	312 ± 13
		minimum	21.6	84	100.46	1.6	274
		maximum	23.4	88	100.52	5.3	348
	3	mean	22.4 ± 0.4	85 ± 2	100.40 ± 0.04	2.1± 0.7	299 ± 19
		minimum	21.1	80	100.34	0.0	250
		maximum	23.4	88	100.47	4.2	333
2	1	mean	26.1 ± 0.3	57 ± 2	100.55 ± 0.02	3.2 ± 0.8	23 ± 18
		minimum	25.7	53	100.52	1.1	331
		maximum	26.9	61	100.58	5.1	66
	2	mean	27.4 ± 0.3	51 ± 1	1004.2 ± 0.01	3.1 ± 0.8	33 ± 16
		minimum	26.8	48	100.40	1.1	337
		maximum	28.2	55	100.45	4.9	61
	3	mean	27.1 ± 0.6	57 ± 4	100.46 ± 0.02	2.1 ± 1.0	16 ± 36
		minimum	25.4	52	100.43	0.0	209
		maximum	28.6	64	100.49	5.2	106
3	1	mean	25.0 ± 0.3	75 ± 2	101.17 ± 0.02	2.2 ± 0.8	296 ± 28
		minimum	24.4	72	101.14	0.9	236
		maximum	25.7	78	101.19	3.9	331
	2	mean	26.1 ± 1.6	78 ± 5	101.35 ± 0.01	0.9 ± 0.6	317 ± 93
		minimum	23.4	66	101.32	0.0	199
		maximum	29.3	85	101.37	2.4	174
4	1	mean	25.3 ± 0.4	76 ± 3	101.28 ± 0.01	1.7 ± 0.4	317 ± 17
		minimum	24.2	70	101.26	0.0	282
		maximum	26.1	81	101.29	2.7	40
	2	mean	28.3 ± 0.5	59 ± 3	101.26 ± 0.01	3.1 ± 0.7	25 ± 12
		minimum	27.3	54	101.24	1.1	336
		maximum	29.5	66	101.29	5.2	54
	3	mean	30.3 ± 0.3	46 ± 1	101.09 ± 0.02	3.9 ± 0.7	28 ± 11
		minimum	29.7	43	101.05	2.1	357
		maximum	31.0	49	101.13	6.1	64
5	1	mean	25.3 ± 0.3	33 ± 2	101.35 ± 0.03	2.5 ± 0.9	15 ± 30
		minimum	24.5	28	101.31	0.0	293
		maximum	26.3	37	101.40	5.4	88

7.2 Wave Observations and Measurements

Observations during the tests showed a wave being generated with each complete cycle of the wave paddle. Since the wave paddle changed direction quickly, small waves were superimposed on the principal wave at the end of each stroke. These small waves dissipated as the principal wave traveled down the tank. When the paddle motion was started at the beginning of a test, the first waves traveling down the tank were smooth with no chop observed. As the waves reached the boom and beach, there were reflections resulting in the appearance of random ripples or chop on the principal wave structure. When waves reached the boom, the wave energy was concentrated along the edges of the tank. Along side the boom the waves appeared to approach breaking and the wave crest of the waves was at the top edge of the tank. This indicated that the maximum practical wave height for the initial water level was reached. Higher waves would have overflowed the tank as they passed around the boom.

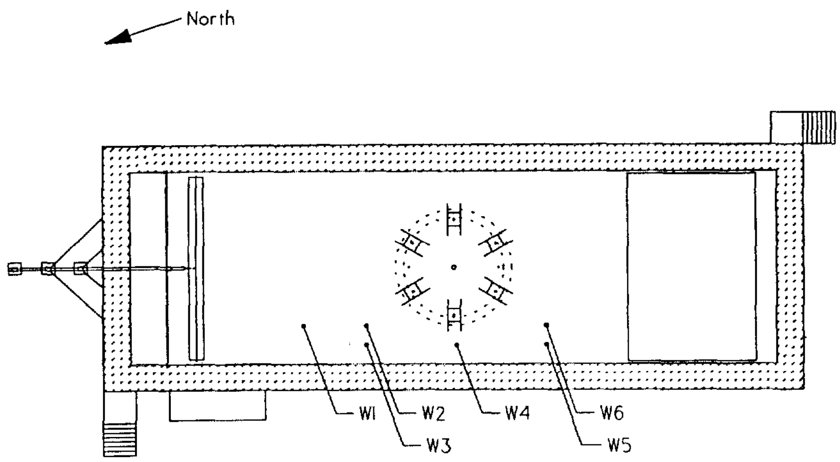

Figure 4 Wave Measurement Points

A series of wave measurements was made following the test with the last boom while the boom was still in the tank. A diagram of the measurement points is shown in Figure 4. The measurement points were 5 m, 8 m, 12.25 m, and 16.5 m from the wave paddle and 0.9 m and 1.8 m from the inside edge of the tank. A single probe was used and moved amongst the measurement points. Figure 5 shows the typical wave patterns for the 6 measurement points. From this figure it can be seen that the period of the waves was approximately 4 s. The waves at all six points show similar patterns. For the wave closest to the wave paddle the small superimposed waves can be seen. The wave farthest from the wave paddle has a higher base height than the waves closer to the paddle. This appears to be due to the accumulation of water near the beach and the reflection of waves from the beach since the height increased from paddle start time until it reached the steady value shown.

Figure 5 can be viewed as a geometric representation of the wave patterns with the x axis being distance instead of time. Since the waves were traveling at a speed of approximately 1.8 m/s, 4 s would correspond to a distance of 7.1 m. The wave patterns are distorted in this view, in that the scales on the axes are not the same, resulting in an exaggeration of the wave shape in the vertical direction. The measured wave length and speed do not correspond to those predicted from linear wave theory (Leenknecht, *et al.*,1992). Using an average wave height of 15 cm, a water depth of 1.22 m and period of 4 seconds yields a velocity of wave propagation of 3.28 m/s and a wavelength of 13.1 m. The difference in the measured and predicted wavelength may be due to the reflections from the beach and the boom, the length of the tank and the use of a top pivoted wave paddle.

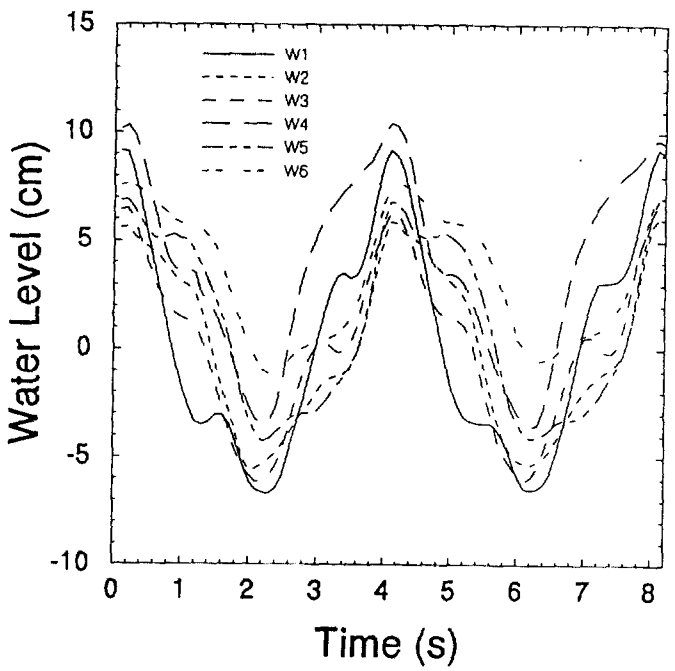

Figure 5 Wave Profiles

7.3 Fuel Quantity

The quantity of fuel used for each boom was determined from the measured area of oil contained with the boom and burning rate of diesel fuel of 220 L/hr-m^2. Table 4 gives the total quantity of fuel used for each burn with each boom. The initial quantity of fuel placed in the boom corresponded to a burn time of 5 min and an initial fuel depth of 18 mm. Since fuel was added at the rate it was consumed, the fuel depth would remain approximately constant until the last 5 min of the burn when the fuel supply was terminated.

Table 4 Fuel Quantity

Boom	Burn 1 (L)	Burn 2 (L)	Burn 3 (L)
1	2363	2310	2306
2	3244	3244	3244
3	1856*	3085	
4	2601	2515	2515
5	4449		

* Burn terminated before 1 hr

7.4 Burn Chronology

Table 5 gives the burn chronology for each of the booms in hr:min:s. Zero time is the time at which burning covered the entire fuel surface within the boom area and the fuel flow was started. This time was used to eliminate the variability in ignition. The "begin extinction" time is the most consistent measure of the end of fire exposure. In some cases, small pockets of fuel or fuel that had wicked into the boom continued to burn for some time. As can be seen from the table, the burn time or the time to begin extinction was within 4 minutes of the desired burn time for all booms except boom 3, the water-cooled boom. This indicates that the burning rate for diesel fuel and the area of the fuel used were relatively accurate. For boom 5, the manufacturer decided to terminate the test after the first cool-down cycle, after observing a problem with the boom.

The events observed for the 4 non-water cooled booms followed the expected protocol. There were several issues related to the water-cooled Boom 3, which resulted in differences when compared with the non-water cooled booms. During burn 1, the hose supplying water to the boom became disconnected from the boom. The loss of cooling water led to a loss of buoyancy in part of the boom on the downwind side resulting in a fuel leak and sustained burning outside the boom. Since the boom could no longer contain oil, the test was terminated. For burn 2 a new section of boom was used. Fuel was added to the boom at the same rate per unit area as for the non-water cooled booms. During the burn, it was observed that the fire appeared substantially smaller than for the non-water cooled booms, although other than a smaller fire, there was no visible difference. At the end of an hour the fire did not burn out, but rather, continued for a total of almost 2 hours. The cooling water for the boom was being drawn from a drain at the bottom of the tank. The water passed through a large filter provided by the manufacturer before entering the boom. Over the course of 2 hours, small rust particles in the water loaded the filter to the point where water flow to the boom was restricted. Although the fire was still burning, it was decided to shut down the cooling water and change the filter. A fire hose was used in an attempt to cool the boom, but it did not appear to be effective. Water flow was restored to the boom after approximately 3 minutes, but within 5 minutes, a part of boom on the downwind side lost buoyancy and sustained burning was observed outside the boom. This continued until the unknown quantity of remaining fuel within the boom was consumed.

Table 5 Burn Chronology, time in (hr:min:s)

	Boom 1	Boom 2	Boom 3	Boom 4	Boom 5
Burn1					
ignition	-0:00:46	-0:01:17	-0:01:09	-0:00:29	-0:01:33
fuel on	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00
waves on	0:00:15	0:00:10	0:00:12	0:00:23	0:00:07
fuel off	0:56:16	0:54:45	0:31:15*	0:54:52	0:54:56
begin extinction	1:03:23	0:59:28	0:33:50	1:03:33	0:59:45
fire out	1:04:33	1:02:33	0:35:36	1:04:18	1:00:27
waves off	2:03:49	2:00:15	0:35:36	2:00:33	2:00:36
Burn 2					
ignition	-0:00:42**	-0:01:14	-0:01:14	-0:00:39	
fuel on	0:00:00	0:00:00	0:00:00	0:00:00	
waves on	0:01:24	0:00:09	0:00:11	0:00:20	
fuel off	0:55:26	0:57:52	0:55:08	0:55:10	
begin extinction	1:01:43	0:58:59	1:58:48***	0:58:40	
fire out	1:02:56	1:00:37	2:11:48	1:00:25	
waves off	1:59:58	1:59:58	2:12:48	2:00:25	
Burn 3					
ignition	-0:00:38	-0:01:17		-0:00:33	
fuel on	0:00:00	0:00:00		0:00:00	
waves on	0:00:23	0:00:09		0:00:25	
fuel off	0:54:58	0:54:52		0:54:44	
begin extinction	0:59:31	0:59:43		1:00:53	
fire out	1:00:26	1:01:08		1:02:13	
waves off	1:00:26	1:01:53		1:05:43	

* terminated due to oil loss
** burns 2 and 3 conducted 3 days after burn 1 due to weather constraints
*** fuel loss from boom

7.5 Heat Flux Measurements

Table 6 gives the mean heat flux as measured by the two heat flux gauges in the north end of the fire and the two gauges in the south end of the fire. Also shown in these tables are the maximum and minimum values measured during the burn and the uncertainty given by one standard deviation. The heat flux gauges respond quickly to changes in the fire and substantial fluctuation is normal for these measurements. The gauges were mounted inside the boom on stanchions since it was impractical to develop custom mounting for each boom construction. As a result, the heat flux measurements are only an indication of the total heat flux to the boom and may not represent the actual value. Further, since the sector of boom that received maximum thermal exposure changed with wind direction, the measurement may not indicate the maximum exposure.

Table 6 Heat Flux

Boom	Burn		North Vertical Face (kW/m²)	North Horizontal Face (kW/m²)	South Vertical Face (kW/m²)	South Horizontal Face (kW/m²)
1	1	mean	79±19	45±20	85±21	100±35
		minimum	14	2	39	19
		maximum	149	137	171	208
	2	mean	89±19	66±30	79±11	66±22
		minimum	41	8	39	17
		maximum	168	180	124	167
	3	mean	70±10	46±15	77±13	53±17
		minimum	37	5	45	14
		maximum	121	95	132	109
2	1	mean	72±15	21±13	104±29	85±29
		minimum	34	3	43	26
		maximum	141	105	191	198
	2	mean	45±7	16±9	83±23	67±16
		minimum	26	4	35	24
		maximum	71	48	180	118
	3	mean	44±7	15±8	78±21	73±20
		minimum	26	3	42	23
		maximum	71	63	207	140
3	1	mean	109±21	66±33	89±23	62±33
		minimum	57	13	35	5
		maximum	192	202	188	179
	2	mean	66±20	48±43	58±24	27±23
		minimum	18	2	7	1
		maximum	135	180	161	170
4	1	mean	87±18	78±25	77±19	82±27
		minimum	33	9	32	22
		maximum	168	170	188	214
	2	mean	63±19	78±19	83±16	87±22
		minimum	25	31	34	20
		maximum	141	156	157	163
	3	mean	57±27	69±28	82±13	97±19
		minimum	20	25	43	39
		maximum	154	171	139	167
5	1	mean	70±18	34±21	89±21	93±24
		minimum	34	5	45	37
		maximum	139	148	184	177

Table 6 shows that the vertical face gauge generally measured a higher heat flux than the horizontal face gauge. The heat flux measured ranged from near

0 kW/m^2 to over 200 kW/m^2. The maximum means ranged form 77 kW/m^2 to 100 kW/m^2 for the non-water cooled booms. These are lower than the 100 kW/m^2 to 150 kW/m^2 averages previously measured for liquid pool fires (Walton, *et al.*, 1977). This is most likely a result of gauge placement and wind fluctuation. In the previous tests, the gauges were placed at the edge of the fire in the position where the boom would be. There were periods in the present tests where the mean total heat flux was in the range measured in the previous tests, particularly at the beginning of a burn. After a number of burns, soot was observed on the face of the heat flux gauges, indicating the gauges were in a fuel rich area of the fire.

The mean total heat fluxes for the long duration water-cooled boom test, boom 3 - burn 2, are lower than those for the non-water cooled booms. Although the heat flux for the water-cooled boom burn started in the same range as the non-water cooled boom burns, it diminished throughout the course of the burn.

8.0 General Observations

In general, as would be expected, there was some degradation of materials in all of the booms. Further, it appeared that the booms had not reached a steady state condition in terms of degradation. That is for most of the booms, if they had been subjected to further fire exposure, one would have expected further material degradation to take place. Since the principal purpose of this project was to evaluate the test protocol, the booms were not rated as passing or failing; however, as mentioned previously, two of the booms did not complete the full test protocol burn cycle. Although 5 booms of differing construction were used to evaluate the test protocol and each boom performed somewhat differently, several general observations were made in all of the burns. First, the burn characteristics were substantially influenced by the wind speed and direction. When the wind speed was low, the smoke and flames rose nearly vertically providing a relatively uniform thermal exposure to the entire boom circle. With increased wind speed, the most significant thermal exposure was observed to take place over approximately one quarter of the boom circle in the downwind direction. If the wind direction was relatively constant of the course of the three burns for a given boom, the same quadrant of the boom circle received repeated thermal exposure. If the wind direction changed during the burns, differing sections of the boom received the most intense thermal exposure.

A second phenomena observed for all of the booms was intermittent burning outside of the boom. Figure 6 shows normal burning and Figure 7 shows burning outside of the boom. Although it might appear that oil had leaked under or through the boom, it appears that this burning was a result of a small quantity of oil being transported over the boom by the fire. The burning outside the boom always took place in the downwind direction even when the wind was perpendicular to the direction of wave travel. Further, burning outside the boom was observed early in the burns even though no oil was observed leaking from the boom during the initial fueling. Prior to observing burning outside the boom, oil was observed on the water surface within approximately 1 m to 2 m of the boom in the downwind direction. The flames would heat the oil outside the boom resulting in a visible vapor emission followed by ignition. After a brief period of burning, the oil outside the boom would be consumed and the fire outside the boom would self-extinguish. This process was observed periodically during the course of the one hour burn.

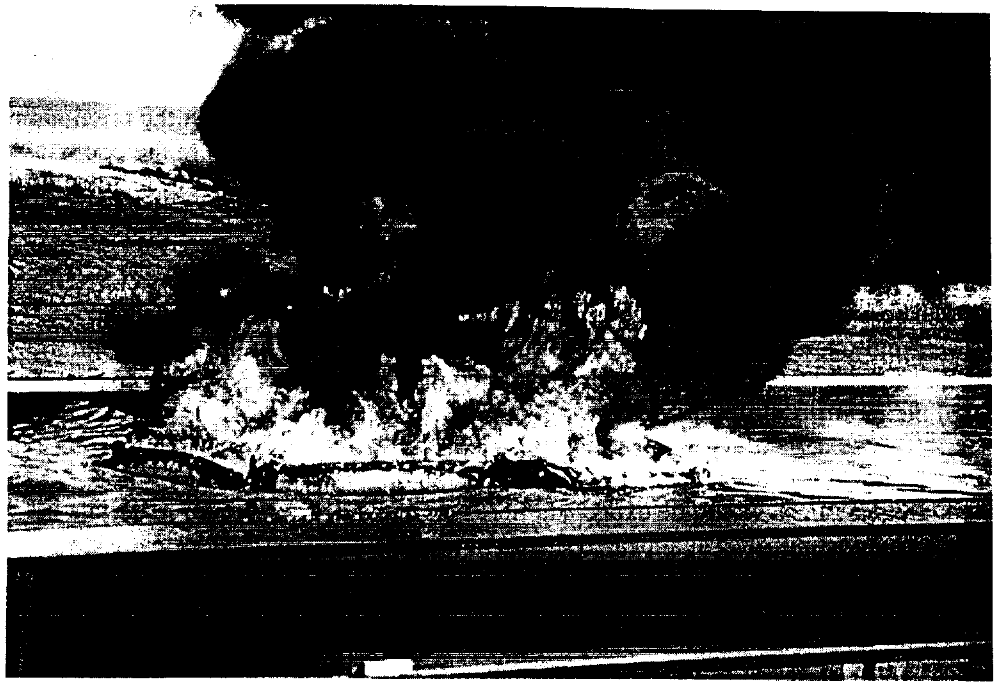

Figure 6 Boom with Normal Burning

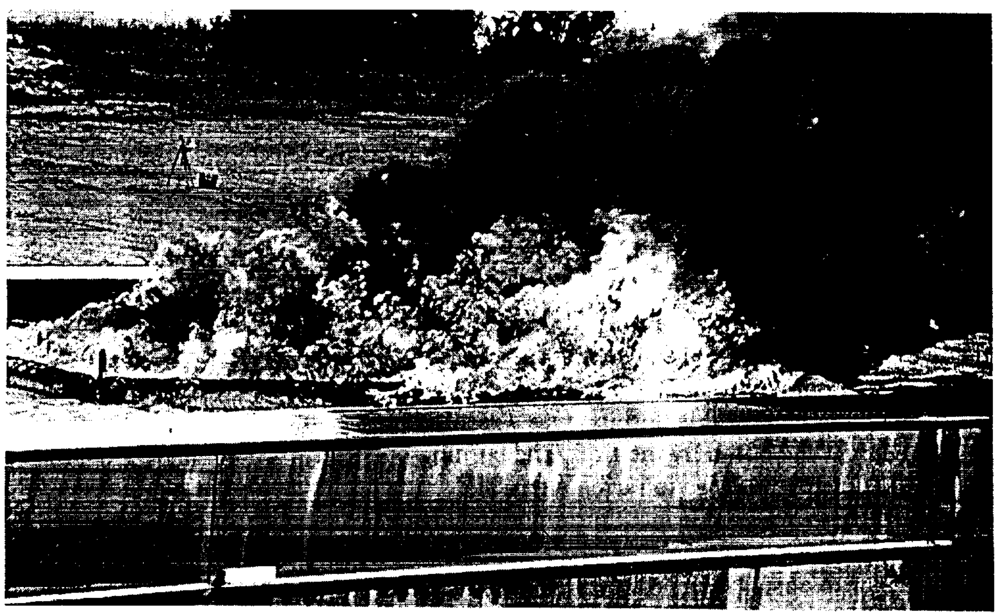

Figure 7 Boom with Burning Outside

The effect of the circular boom configuration and affect of the water-cooled stanchions used to constrain the boom was not uniform for all of the booms. When boom is towed from both ends at sea it forms a horseshoe or catenary shape. The booms in the wave tank were connected end to end to from a circle. The curvature formed by this circle is smaller than the curvature normally expected when booms are towed at sea. Most of the booms were not affected by the short turn radius although the sections of the relatively rigid stainless steel boom were touching on the inside of the circle. The six stanchions used inside the boom circle to constrain the boom generally did not interfere with boom movement. However in some cases, the contact of the boom with the stanchions caused wear which would not be expected at sea.

9.0 Issues and Conclusions

Overall, the test protocol and its application were considered to be a success. Based on the results of these tests several issues have been identified for possible further consideration. These issues include the following items not necessarily in order of importance.

1) Does the fire size and duration coupled with the wave action represent a realistic thermal and mechanical exposure? Although it is a largely subjective observation, the fire and wave exposure appeared to provide a reasonable representation of actual *in situ* burn conditions. However, at present, there is not adequate data available to compare the test performance to performance in an actual at sea burn under given fire and wave conditions. It was unclear from this test series if the burns for a given boom conducted over a period of several days produced different results as compared to burns conducted in a single day.

2) How does wind speed and direction affect the thermal exposure to boom? The impact of the wind speed and direction on the thermal exposure are difficult to quantify. Mounting thermocouples on the boom proved difficult due to the wide variety of boom constructions. Heat flux measurements around the boom would provide the best measure of thermal exposure, but these are also difficult to attach to the boom and a significant number would be required to adequately profile the thermal exposure along the length of the boom. Heat flux measurements inside the boom circle appear to result in lower measured heat fluxes than the heat fluxes expected at the boom. Alternative heat flux gauge locations should be considered.

3) Is the test protocol adequate for water-cooled booms? Although none of the burns with the water-cooled boom was completed and only one boom was used, it appears that the cooling water affects the burning rate. If water cooling affected the burning rate in the same way for an at sea burn then the test would be a reasonable representation of a real burn. If water vapor from the boom is responsible for the change in burning rate then the use of the relatively small circle in the test may enhance the effect.

4) What is the best method to constrain the booms? The use of water-cooled stanchions inside the boom circle worked well for some of the booms. However, for some booms, the stanchions caused material degradation that would not be present in a towed configuration. The boom constraint system used provided no tension on the boom. It appears that wave action is the most important factor in flexing the boom however tension may play a role.

5) Should replicate tests be required? When evaluating a test method it usually desirable to conduct multiple tests with the same product to determine if the

method is repeatable. Production and prototype fire booms are expensive to manufacturer and the tests are expensive to conduct.

6) What criteria should be used to terminate a test before the complete burn cycle has been executed? In the case of a substantial oil loss, it is impossible to continue the burn and the test must be terminated. A small oil leak around the connector was noticed with one of the booms when the oil was added to the boom at the start of the second burn. In this case the test was continued without significant impact on the test, but it points out the need for clear criteria for terminating a test.

7) What evaluation criteria should be applied to the booms at the end of the test? The criteria for evaluating a boom is one if the most difficult and sensitive issues. One option is to report the condition of the boom including attributes such a freeboard which can be measured. In some cases, holes in the booms above the waterline were noted and the impact of these holes on the expected performance of the boom is difficult to judge. It is unlikely that a numerical rating could be developed from this test so a pass or fail criteria may be the best option.

The test method evaluated appears to be the most realistic simulation to date of the thermal and mechanical stresses expected during the use of fire-resistant oil-spill containment boom. However, the issues presented above and the fact that these tests do generate smoke would suggest that other methods of generating the fire exposure may still be worth investigating. Propane diffusion flames alone do provide an adequate thermal exposure (McCourt, *et al.*, 1997 and Walton *et al.*, 1997), but premixed propane and liquid spray exposure fires are a testing option that has not been thoroughly investigated for use in this application.

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