Second Phase Evaluation of a Protocol for Testing Fire-Resistant Oil Spill Containment Boom*

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Abstract

A second series of fire tests utilizing the ASTM F-20 draft, Standard Guide for *In Situ* Burning of Oil Spills On Water: Fire-Resistant Containment Boom, as a guideline were conducted in a wave tank at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. The evaluation used six different fire-resistant oil spill containment booms, which included two water-cooled designs. Three of the booms used in the second series evaluation were modified designs of booms used in the first series. A 15 m boom section of each boom was formed in a circle and subjected to a diesel fuel fire, for up to three hours, in the presence of waves. Issues raised from the first series of evaluations such as the boom constraint system, the location of heat flux gauges and thermocouples, and the protocol for water-cooled booms were addressed. The results of the second series evaluation are presented and compared to the first. 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

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minimal equipment and less labor than other techniques. It can be applied in areas 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 and cool down cycle consisting of three one hour long burn periods with a one hour cooling period between each. The wave characteristics to which the boom would be exposed during burning and cooling were not specified. The principal objective of this project was to evaluate the test procedure and was not to rate the booms.

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 two-phase 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).

In the first phase of the project a wave tank designed specifically for evaluating fire-resistant boom was constructed and five fire resistant oil-spill containment booms, selected by the project sponsors, were used in the evaluation of the test procedure (Walton, *et al.*, 1998). Although these tests were largely successful, several issues were identified for further study. Three of those issues, 1) method of boom constraint, 2) protocol for testing water cooled booms, and 3) measurement of heat flux and temperature near the boom, were specifically addressed in the second phase tests.

In the first phase testing, a section of boom formed in a circle was constrained in the wave tank by six vertical water-cooled stanchions, uniformly spaced around the inside of the boom circle. In some cases, there was evidence that contact between the boom and the stanchions caused degradation to the boom. The use of stanchions located inside the boom was selected in the phase-one testing because the stanchions could be quickly adjusted to fit the boom. In all but one of the second-phase tests, the booms were held in position with cables connected to stanchions outside the boom circle.

A single water-cooled boom was used in the first phase evaluation. Due to problems with the water supply, a complete test series with that boom was not accomplished. It was noted; however, that the size of the fire diminished as the test proceeded and the burn duration was much longer than expected. In the second phase testing, the issue of burning rate with water cooled booms was examined more extensively.

The heat flux and fire temperature measurements made during the first phase testing were not entirely satisfactory. Heat flux gauges were located inside the boom circle, above the fuel surface, so as not to interfere with the movement of the boom in the waves. Based on observations during the tests, it appeared that the heat flux gauges were beneath the flames and may not have been exposed to the same heat flux as the boom. In order to measure temperature at the boom surface, attempts were made to mount thermocouples to the boom surface. Because of the variety of boom designs and boom motion during the test, the thermocouples could not be adequately attached to the boom without potential damage to the boom materials.

Six fire-resistant oil-spill containment booms selected by the project sponsors were used to evaluate the changes in the test procedure. Three of the booms were modified designs of booms used in the first phase tests and two of the booms were water-cooled designs. Since the purpose of the project was to evaluate the test procedure and the ASTM standard used to develop the test protocol is a draft, the booms were not rated as passing or failing the test.

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.

A detailed description of the wave tank was given previously (Walton, *et al.*,1998). A plan view of the tank as modified for the second phase tests is shown in Figure 1. 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 the tank was at ground level and two stairways provided access to the top of the tank. The

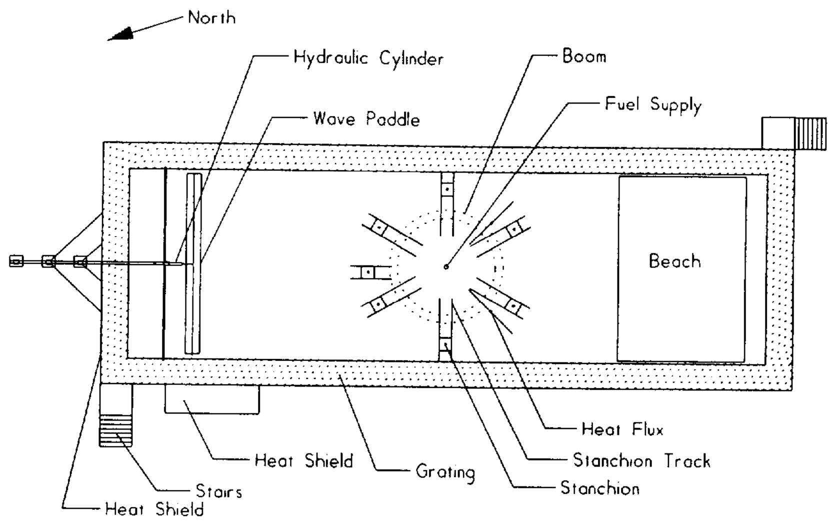

Figure 1 Plan view of wave tank

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.

Bay water with a salt concentration of 0.70% NaCl was used in the tank. 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. Waves were generated with a hydraulically power wave paddle located 3.1 m from the north end of the tank. A steel beach at the south end of the tank was used to dissipate the wave energy.

The boom was kept in position during all but the first test by seven boom constraints or stanchions. The stanchions were constructed of 1 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 outside of the circle. The boom was attached to the stanchions with steel cables tensioned to keep the boom in a circle, but not restricting the vertical movement of the boom in the waves. The stanchions were below the water level in the tank and were not visible during the test.

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 the center of the tank under water and floated to the water surface.

4.0 Instrumentation

Measurements of atmospheric conditions were made at the Coast Guard facility with a weather station located 49 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 and a thermistor to measure temperature. Wind speed, wind direction and temperature data were recorded every 30 s with a computerized data acquisition system.

Two sets of two water-cooled Schmidt-Boelter 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 the center of the tank horizontally and one facing vertically. The heat flux gauges were mounted outside the boom circle, to the south, along lines 45° east and west of the centerline of the tank. The center of the vertical face was adjusted for each boom in still water to be 305 mm above the top of the boom and 305 mm horizontally from outer edge of the boom.

Temperature measurements were made with one 1.6 mm diameter and one 3.2 mm diameter, stainless steel sheathed, type K thermocouple mounted adjacent to each pair of heat flux gauges. Thermocouple measurements were suggested in the ASTM guidelines however the temperature measured is that of the thermocouple and not necessarily the fire gas temperature. 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 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.

Tank surface water temperature was measured with a hand-held type K bare bead thermocouple. The water temperature was measured before each burn, except in some cases where one burn immediately followed another.

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

Six commercially-manufactured fire-resistant booms were used to evaluate the test protocol. Three of the booms were new versions of booms used in the first phase tests. Analysis of boom construction was not a part of project and the booms were not disassembled to inspect the construction details. Table 1 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 1 Boom Description

Boom	Construction	Sections	Freeboard (mm)	Average Inside Diameter (m)	Area (m^2)
1	Water-cooled fabric over flexible flotation	continuous curvature	254	4.27	14.3
2	Water-cooled fabric over flexible flotation	continuous curvature	356	3.66	10.5
3	Stainless Steel sections with stainless steel covered flotation	6	635	3.88	11.8
4	Fabric with steel covered flotation	continuous curvature	279	4.66	17.0
5	Stainless Steel sections with air flotation	7	368	4.83	18.3
6	Fabric over flexible flotation	continuous curvature	240	4.78	17.9

6.0 Test Procedure

The test procedure used in the second phase tests was similar to the procedure used in the first phase tests. 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 outside 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. With the boom in the tank, steel cables were attached to the stanchions and to the bottom of the boom. The water level in the tank was then raised and the cable tension adjusted to maintain the circular shape of the boom, while allowing for vertical movement of the boom when waves were present.

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 a 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

Figure 2 Burn in progress

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 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. Figure 2 shows a burn in progress. 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.

7.0 Measurement Results

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

7.1 Meteorological Conditions

Table 2 gives the ground meteorological conditions measured during each of the burns at the Coast Guard Facility. The values in Table 2 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 2 Ground meteorological conditions

Boom	Burn		Temperature (°C)	Wind Speed (m/s)	Wind Direction (°)	Water Surface Temperature (°C)
1	1	mean	28.4±0.3	2.6±0.5	339±12	30.3±1
		minimum	28.0	1.4	301	
		maximum	29.1	3.8	21	
	2	mean	35.0±0.6	2.4±0.7	51±19	33.3±1
		minimum	33.4	0.2	329	
		maximum	36.0	4.5	125	
	3	mean	29.5±0.4	2.2±0.7	14±18	35±1
		minimum	28.8	0.4	324	
		maximum	30.1	3.9	56	
	4	mean	31.3±0.3	2.7±0.6	21±22	
		minimum	30.7	1.4	335	
		maximum	32.1	4.0	65	
2	1	mean	34.7±0.2	2.4±0.6	167±12	31.9±1
		minimum	34.4	1.6	141	
		maximum	35	3.3	184	
	2	mean	30.1±0.3	1.3±0.4	102±19	31.7±1
		minimum	29.7	0.0	0	
		maximum	30.9	2.1	145	
	3	mean	25.2±0.3	1.2±0.9	356±33	31.7±1
		minimum	24.7	0.0	268	
		maximum	25.6	2.9	82	
	4	mean	26.1±0.3	2.9±0.7	128±25	
		minimum	25.9	1.8	100	
		maximum	26.6	4.0	180	

Table 2 Ground meteorological conditions (continued)

Boom	Burn		Temperature (°C)	Wind Speed (m/s)	Wind Direction (°)	Water Surface Temperature (°C)
3	1	mean	31.1±0.2	2.1±0.9	19±43	27.2±1
		minimum	30.7	0.0	263	
		maximum	31.6	3.9	93	
	2	mean	26.5±0.2	1.0±0.8	139±89	29.6±1
		minimum	26.1	0.0	0	
		maximum	27.1	2.5	253	
	3	mean	28.5±0.2	2.7±0.5	176±11	32.4±1
		minimum	28.1	1.0	149	
		maximum	28.8	4.5	215	
4	1	mean	30.0±0.2	2.2±0.4	94±37	29.4±1
		minimum	29.7	1.2	49	
		maximum	30.5	3.4	181	
	2	mean	25.5±0.1	4.5±1.0	49±11	29.4±1
		minimum	25.3	2.5	24	
		maximum	25.7	7.4	72	
	3	mean	27.0±0.3	3.5±0.7	50±11	34.9±1
		minimum	26.3	1.9	22	
		maximum	27.4	5.2	77	
5	1	mean	24.5±0.1	3.5±1.1	77±13	29.6±1
		minimum	24.4	2.1	55	
		maximum	24.5	5.1	93	
	2	mean	26.6±0.4	4.1±0.8	56±12	27.4±1
		minimum	25.9	2.1	27	
		maximum	27.4	6.2	83	
	3	mean	27.4±0.2	3.9±0.9	81±14	
		minimum	27.1	1.5	42	
		maximum	27.8	6.2	131	
	4	mean	27.4±0.2	4.3±1.0	73±17	
		minimum	27.0	1.8	40	
		maximum	27.7	6.7	133	
6	1	mean	29.2±0.1	4.7±0.8	197±9	28.1±1
		minimum	29.1	3.4	184	
		maximum	29.3	6.8	219	
	2	mean	29.4±0.3	2.3±0.6	229±46	
		minimum	29.1	1.0	160	
		maximum	30.0	3.9	314	

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 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.

Wave measurements were made following the last boom test, at a point 12 m from the north end of the tank and 450 mm from the west edge of the tank. Figure 3 shows a typical wave pattern relative to the tank water level with no waves. From this figure it can be seen that the period of the waves was approximately 4.5 s and a wave height of approximately 120 mm. The irregularities in the wave pattern were caused by reflections from the beach and small waves generated on the back stroke of the wave maker. The wave speed of 2.34 ± 0.02 m/s was determined by timing the wave travel over a fixed distance along the tank.

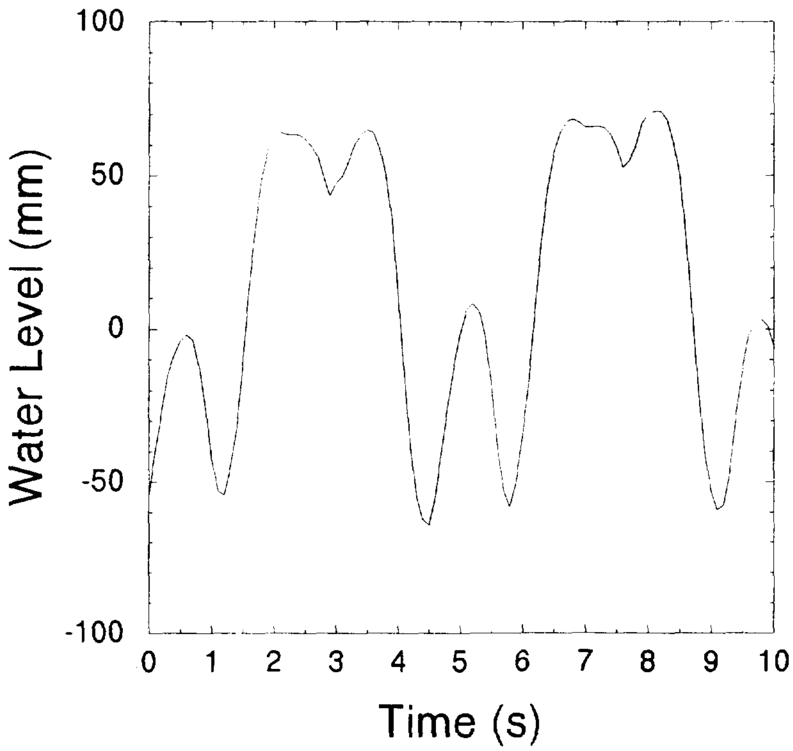

Figure 3 Wave profile

Figure 3 also 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 2.34 m/s, 4.5 s would correspond to a wave length of 10.5 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.

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 3 gives the total quantity of fuel used for each burn with each boom as measured by a fuel flow meter. 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 3 Fuel Quantity

Boom	**Burn 1 (L)**	**Burn 2 (L)**	**Burn 3 (L)**	**Burn 4 (L)**
1	2517*	3146	1575**	1613**
2	144*	878**	1733	250*
3	2514	2514	2514	
4	3751	3308	3308	
5	113*	3308	3422	3422
6	329*	3944		

* Burn terminated before 1 hr
** ½ hr burn

7.4 Burn Chronology

Table 4 gives the burn chronology for each of the booms in hr:min:s. Due to weather conditions and fuel loss, the burn sequence specified in the ASTM draft standard could not be precisely followed in all cases. 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 6 minutes of the desired burn time for all booms except booms 1 and 2, the water-cooled booms. This indicates that the burning rate for diesel fuel and the area of the fuel used were relatively accurate. The first burns for booms 2 and 6 were terminated after the initial fuel was consumed due to a change in wind direction. The first burn for boom 5 was a short demonstration burn for the media.

For boom 6, the manufacturer decided to terminate the test after the first cool-down cycle (burn 2), after observing a problem with the boom.

Table 4 Burn Chronology, time in (hr:min:s)

	Boom 1	Boom 2	Boom 3	Boom 4	Boom 5	Boom 6
Burn1						
ignition	-0:01:17	-0:00:53	-0:00:54	-0:01:25	-0:01:27	-0:01:58
fuel on	0:00:00	**	0:00:00	0:00:00	**	**
waves on	0:00:25	0:00:49	0:00:27	0:00:15	0:00:15	0:00:30
fuel off	0:40:35*		0:54:58	0:55:00		
begin extinction	0:45:55	0:03:12	0:58:42	1:07:55	0:01:15	0:04:25
fire out	0:46:48	0:04:38	0:59:42	1:09:25	0:02:00	0:06:10
waves off	0:48:02	0:04:47	2:00:06	2:18:55	0:03:45	0:05:10
Burn 2						
ignition	-0:01:50	-0:01:29	-0:01:17	-0:01:33	-0:01:31	-0:01:11
fuel on	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00
waves on	0:00:15	0:00:28	0:00:23	0:00:14	0:00:15	0:00:14
fuel off	0:52:50	0:19:35	0:54:58	0:55:04	0:55:29	0:49:59
begin extinction	3:16:40	0:31:50	0:58:13	0:59:49	0:56:35	0:54:20
fire out	3:17:40	0:32:59	0:59:13	1:01:22	0:58:05	0:55:04
waves off	3:29:50	1:03:07	2:00:13	2:01:37	1:29:21	1:54:20
Burn 3						
ignition	-0:01:27	-0:01:47	-0:01:22	0:01:29	0:01:03	
fuel on	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	
waves on	0:00:18	0:00:35	0:00:34	0:00:17	0:00:25	
fuel off	0:23:37	0:55:00	0:54:56	0:55:05	0:55:05	
begin extinction	0:40:03	0:54:45	0:58:16	0:58:59	0:56:05	
fire out	0:41:00	0:56:32	0:59:46	1:00:35	0:59:45	
waves off	1:11:18	1:16:35	1:00:04	0:59:28	1:57:15	
Burn 4						
ignition	-0:00:49	-0:01:35			-0:00:44	
fuel on	0:00:00	0:00:00			0:00:00	
waves on	0:00:43	0:00:25			0:00:23	
fuel off	0:24:27	0:03:21*			0:55:08	
begin extinction	0:40:56	0:05:14			0:56:18	
fire out	0:42:23	0:08:08			0:58:53	
waves off	0:43:00	0:09:48			0:58:53	

* terminated due to fuel loss
** terminated due to weather constraints no fuel added

The events observed for the 4 non-water cooled booms followed the expected protocol. There were several issues related to the water-cooled booms 1 and 2, which resulted in differences when compared with the non-water cooled booms. During

For boom 6, the manufacturer decided to terminate the test after the first cool-down cycle (burn 2), after observing a problem with the boom.

Table 4 Burn Chronology, time in (hr:min:s)

	Boom 1	**Boom 2**	**Boom 3**	**Boom 4**	**Boom 5**	**Boom 6**
Burn1						
ignition	-0:01:17	-0:00:53	-0:00:54	-0:01:25	-0:01:27	-0:01:58
fuel on	0:00:00	**	0:00:00	0:00:00	**	**
waves on	0:00:25	0:00:49	0:00:27	0:00:15	0:00:15	0:00:30
fuel off	0:40:35*		0:54:58	0:55:00		
begin extinction	0:45:55	0:03:12	0:58:42	1:07:55	0:01:15	0:04:25
fire out	0:46:48	0:04:38	0:59:42	1:09:25	0:02:00	0:06:10
waves off	0:48:02	0:04:47	2:00:06	2:18:55	0:03:45	0:05:10
Burn 2						
ignition	-0:01:50	-0:01:29	-0:01:17	-0:01:33	-0:01:31	-0:01:11
fuel on	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00
waves on	0:00:15	0:00:28	0:00:23	0:00:14	0:00:15	0:00:14
fuel off	0:52:50	0:19:35	0:54:58	0:55:04	0:55:29	0:49:59
begin extinction	3:16:40	0:31:50	0:58:13	0:59:49	0:56:35	0:54:20
fire out	3:17:40	0:32:59	0:59:13	1:01:22	0:58:05	0:55:04
waves off	3:29:50	1:03:07	2:00:13	2:01:37	1:29:21	1:54:20
Burn 3						
ignition	-0:01:27	-0:01:47	-0:01:22	0:01:29	0:01:03	
fuel on	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	
waves on	0:00:18	0:00:35	0:00:34	0:00:17	0:00:25	
fuel off	0:23:37	0:55:00	0:54:56	0:55:05	0:55:05	
begin extinction	0:40:03	0:54:45	0:58:16	0:58:59	0:56:05	
fire out	0:41:00	0:56:32	0:59:46	1:00:35	0:59:45	
waves off	1:11:18	1:16:35	1:00:04	0:59:28	1:57:15	
Burn 4						
ignition	-0:00:49	-0:01:35			-0:00:44	
fuel on	0:00:00	0:00:00			0:00:00	
waves on	0:00:43	0:00:25			0:00:23	
fuel off	0:24:27	0:03:21*			0:55:08	
begin extinction	0:40:56	0:05:14			0:56:18	
fire out	0:42:23	0:08:08			0:58:53	
waves off	0:43:00	0:09:48			0:58:53	

* terminated due to fuel loss

** terminated due to weather constraints no fuel added

The events observed for the 4 non-water cooled booms followed the expected protocol. There were several issues related to the water-cooled booms 1 and 2, which resulted in differences when compared with the non-water cooled booms. During is 109 kW/m^2, with a standard deviation of 24 kW/m^2 for the non-smoothed data. The values from the vertical facing heat flux gauge were similar.

Figure 5 is a graph of the temperature measured by the 1.6 mm diameter thermocouple on the west side for boom 5, burn 2. As with the heat flux gauge, the thermocouple responds quickly to changes in the fire and same smoothing routine has been applied. The temperature measurements have not been corrected for thermal radiation gain or loss from the thermocouple and may not be a true measurement of the fire gas temperature. From this graph it seen that the highest values are reached at the beginning of the burn and the mean value is 952 °C, with a standard deviation of 24 °C for the non-smoothed data. The data for the 3.2 mm thermocouple followed closely the 1.6 mm diameter thermocouple, but with a slightly slower response.

Figure 6 is a graph of the heat flux measured by the horizontal facing heat flux gauge on the west side for boom 1, burn 2. This burn was terminated before one hour due to oil loss. This graph shows a similar heat flux trend to figure 4 with slightly higher values. As in the pervious case the highest values are reached at the beginning of the burn and the mean value during full burning is 134 kW/m^2, with a standard deviation of 28 kW/m^2. The heat flux of 25 kW/m^2 measured before burning was significantly greater than for boom 5 due to the strong solar radiation. The total heat flux gauges used are not designed to measure solar radiation, and the flat black face of the gauge is readily heated by the sun. During burning; however, the principal heat transfer to the gauge is from the fire although a component of solar radiation may still be present.

Figure 7 is a graph of the heat flux measured by the horizontal facing heat flux gauge on the east side for boom 1, burn 2. This burn continued for nearly 3 hours and 18 minutes with the quantity of fuel estimated for a one hour burn. From this graph the reduction in burning rate after 30 minutes is reflected in the reduction in heat flux. The return to full burning at the end of the burn can also be seen.

8.0 General Observations

The degree of degradation varied widely amongst the six booms used in the evaluation. Some booms showed basically no degradation, while in others, there was substantial degradation. Further, it appeared that some booms had not reached a steady-state condition in terms of degradation. That is, if they had been subjected to further fire exposure, one would have expected further material degradation to take place. However, with the exception of the portions of two booms that lost flotation, the average freeboard of the booms was the same before and after the burns. 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. Table 5 gives a summary of the observations for each boom.

Although six booms of differing construction were used to evaluate the test protocol and each boom performed somewhat differently, two general observations from the first phase tests were again made in the second phase tests. 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

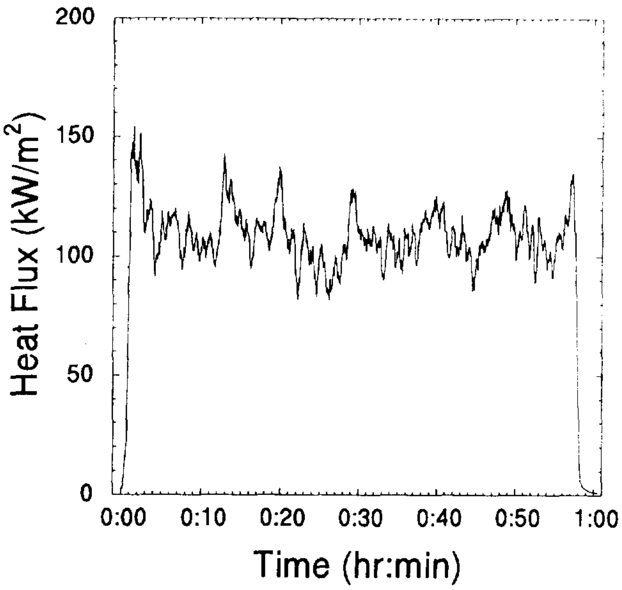

Figure 4 Heat flux - boom 5, burn 2

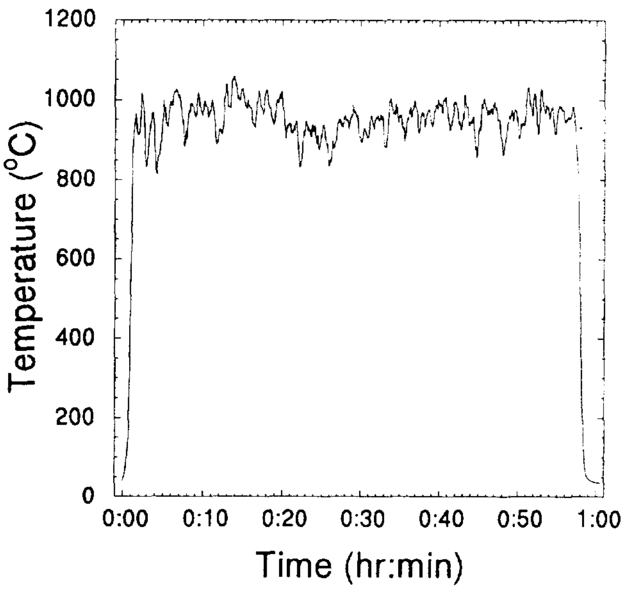

Figure 5 Temperature - boom 5, burn 2

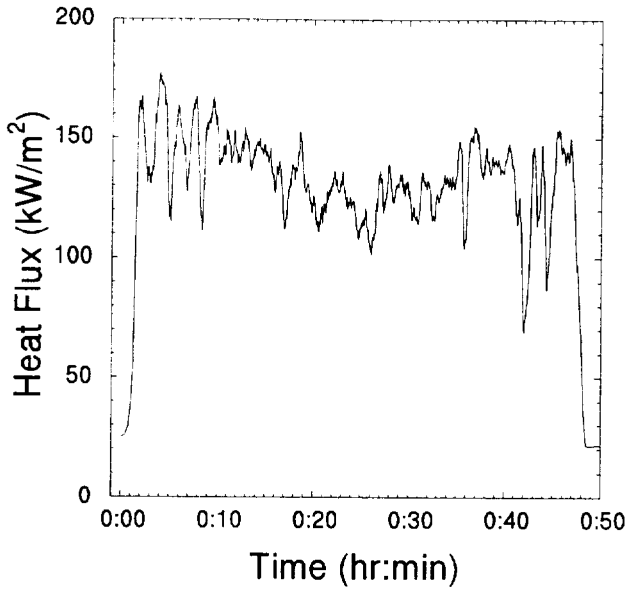

Figure 6 Heat flux - boom 1, burn 1

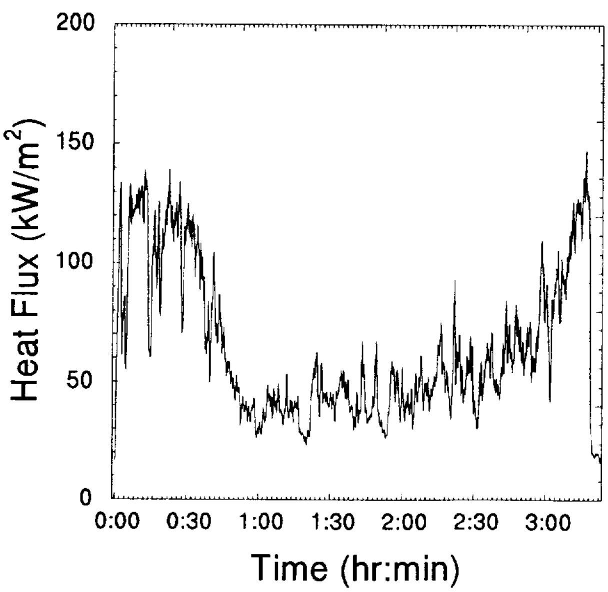

Figure 7 Heat Flux - boom1, burn 2

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 over 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. 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.

Table 5 Boom Observations

Boom	Construction	Observations
1	Water-cooled fabric over flexible flotation	Hole in original boom near internal stanchion resulting in partial loss of flotation, no degradation in replacement boom with external stanchions
2	Water-cooled fabric over flexible flotation	Degradation in boom resulted in partial loss of flotation
3	Stainless Steel sections with stainless steel covered flotation	Small crack at the top of one of the joints otherwise no degradation
4	Fabric with steel covered flotation	Degradation of fabric observed at the conclusion of the burns
5	Stainless Steel sections with air flotation	Expansion and contraction of one air floatation chamber during the burn, otherwise no degradation
6	Fabric over flexible flotation	Terminated by manufacturer after first burn cycle due to substantial degradation

9.0 Issues and Conclusions

Overall, the test protocol and its application were considered to be a success. Further, the three issues from the first phase specifically addressed in the second phase were successfully resolved. The results related to those issues were:

1) Method of boom constraint - The use of stanchions outside the boom circle, connected to the boom with cables, was an effective way of securing the boom without interfering with boom movement. It was; however, more difficult to install the booms with external stanchions and cables than with the internal stanchions. The external stanchions did not come in contact with the boom, which eliminated the possibility of damage to the boom.

2) Protocol for testing water cooled booms - The reduction in the quantity of fuel used for the tests with water cooled booms resulted in the ability to expose the booms to the one hour burn periods in the draft standard. Although the phenomena is not fully understood, the reduction in burning rate did not appear to reduce the thermal exposure to the boom.

3) Measurement of heat flux and temperature near the boom - The relocation of heat flux gauges and the thermocouples to a position just outside and above the boom circle produced improved heat flux and temperature measurements. Even though measurements of maximum thermal exposure were not made for all of the burns due to wind direction, the average maximum downwind exposures agreed with those from previous tests (Walton, *et al.*,1997). Since the maximum thermal exposure from these fires has been characterized, it may not necessary to measure heat flux and temperature in future diesel fuel fire boom tests. The measurements of heat flux and temperature can be used to compare the thermal exposure for diesel fuel fires to fires with other fuels such as propane.

In addition, the criteria for terminating a test before the complete burn cycle if substantial fuel loss occurs appears to be satisfactory. This criteria was applied several times during the two test phases. The test director can readily identify the burning of fuel outside the boom due to a substantial fuel loss. When the fuel flow to the boom is discontinued, extinction of the fire will occur in less than five minutes.

Several issues identified in first phase testing remain. In general, these issues are related to the test philosophy and cannot be readily resolved by further testing. These issues include the following items not necessarily in order of importance.

1) Do 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.

2) How does wind speed and direction affect the thermal exposure to boom? It is nearly impossible to control the wind conditions in an outdoor test. It is not uncommon for the wind direction to change over the course of a test on a single boom. The maximum thermal exposure occurs on the downwind side of the boom circle. Thus, with a constant wind direction the same portion of the boom circle would be exposed to the maximum thermal exposure. With varying wind direction, different parts of the boom would be exposed to the maximum thermal exposure.

3) 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. The most appropriate option appears be a tow test with oil after the fire exposure is completed. In many cases, the condition of the boom can be determined visually, and by comparing the boom freeboard before and after the burn cycle. In some cases however, 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 without a tow test.

The test method evaluated appears to provide a realistic simulation of the thermal and mechanical stresses expected during the use of fire-resistant oil-spill containment boom. However, the use of diesel fuel does generate smoke and other methods of generating the fire exposure may still be worth investigating. Propane with air injection appears to be a viable alternative (McCourt, *et al.*, 1998). The heat flux measurements from this test series may be useful in obtaining thermal exposures with air-injected propane fires comparable to diesel fuel fires.

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