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

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16. Abstract

A second series of fire tests utilizing the American Standard for Testing Materials (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, during August-September 1998. The test series used six different fire-resistant oil spill containment booms, including two water-cooled designs. Three of the booms used in the evaluation were modified designs of booms used in the first series conducted in 1997. A 15-meter section of each boom was formed in a circle and subjected to a diesel fuel fire, for up to three hours, while waves were produced. Testing issues, such as the boom constraint system, the location of the heat flux gauges and thermocouples, and special procedures for water-cooled booms, were addressed. The results of the second test series are presented, and the strengths and weaknesses of the protocol are discussed, along with areas for possible improvement.

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Executive Summary

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 American Standard for Testing Materials (ASTM) F-20 Committee has developed a draft standard, 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 second series of experiments was conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves.

For the first phase tests, a wave tank capable of assessing the capabilities of a section of boom by subjecting it to a fire and waves was designed and constructed at the U.S. Coast Guard Fire and Safety Test Detachment in Alabama. A hydraulically powered paddle at one end of the tank was used to generate waves, and a sloped beach at the opposite end was used to dissipate the wave energy. The boom tested was formed into a circle, floated on water in the center of the tank, and held in position during the tests with water-cooled vertical stanchions located inside the boom circle. Number 2 diesel fuel was pumped into the center of the boom circle to provide fuel for the tests. The test cycle consisted of three one-hour burning periods with two one-hour cool-down periods between the burning periods. The test cycle was terminated early if degradation of the boom resulted in substantial fuel loss. Five booms were subjected to the test procedure based on the draft standard in the first phase.

Although the first phase 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 second phase, six booms were subjected to the test procedure based on the draft standard. Two of the booms were of fabric-based construction, two were water-cooled fabric and two were stainless steel. The degradation to the booms during the tests ranged from minimal to substantial, and the test for one of the fabric booms and one of the water-cooled booms was terminated before the complete test cycle due to fire damage to the booms.

An improved method of boom constraint was successfully used in the second phase tests. The vertical stanchions inside the boom circle in contact with the boom were replaced with vertical stanchions outside the boom circle. The boom was connected to the external stanchions with cable beneath the water that held the boom in a circular pattern, while allowing the boom to freely move up and down with the waves. During the first test of a water-cooled boom, the fire became less intense as the fire progressed, and the fire continued to burn for more than two hours. This burning pattern was also observed in the first phase tests. Using short duration burns, a revised fuel delivery rate for the water-cooled booms was calculated and used successfully to obtain the desired one-hour full intensity burn.

Based on the experience gained in the first phase testing, the heat flux and temperature measurement devices were relocated from inside the boom circle in the first phase tests, to just outside the boom circle near the top of the boom in the second phase tests. This resulted in improved heat flux and temperature measurements. Although the maximum heat flux and temperature were not determined

in all of the tests due to wind direction, adequate data were collected to characterize the maximum thermal exposure to the boom.

The improvements to the test protocol in the second phase testing were a success. The test appears to provide a realistic simulation of the thermal loading expected during the use of fire-resistant oil spill containment boom. 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 are: 1) adequacy of thermal and wave exposure, 2) the impact of varying natural wind on the test conditions, and 3) selection of an evaluation criteria.

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1.0 Introduction

In-situ burning of spilled oil has distinct advantages over other countermeasures. It offers the potential to rapidly convert large quantities of oil into its primary combustion products, carbon dioxide and water, along with some smoke particulate and other unburned and residual byproducts. In-situ burning requires 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. The oil is mainly converted to airborne products of combustion by burning. Thus, 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 that 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 the 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 booms. 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 draft guide states that fire-resistant oil spill containment booms should be able to withstand oil fires on calm or turbulent, fresh or salt water. Minimum requirements should include the following:

1) Performance and survival in temperatures of up to 1300°C.

2) Containment of burning oil for a total of three hour-long burn periods with a one hour cooling period between each.

3) Maintain a post-burn positive freeboard.

4) Maintain a post-burn buoyancy to weight ratio of 1.5:1.

The wave characteristics to which the boom would be exposed during burning and cooling were not specified. The standard states that the boom maintain adequate floatation during the exposure and contain a layer of oil 10 mm (0.4 in) to 20 mm (0.8 in) 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).

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 (Bitting, 1999). 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 stanchion caused degradation to the boom. Locating the stanchions inside the boom was initially chosen because the stanchions could be quickly adjusted to fit the boom. In the second-phase tests, the booms were held in position with cables connected to stanchions outside the boom circle in all but one test.

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 completed. 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. 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 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, fabricated and installed in the tank by NIST.

The wave tank used in the second-phase testing was the same as in the first phase except for changes in the stanchions and some of the piping. A plan view of the tank is shown in Figure 1. The wave tank was constructed of steel and is 1.5 m deep with double exterior walls 1.2 m apart forming a "moat" around the perimeter of the tank. The inside dimensions of the inner area of the tank are 30.5 m by 9.1 m. The base of the tank is at ground level and two stairways provide access to the top of the tank. Around the perimeter is a steel grating with its surface located 115 mm below the top edge of the tank. The moat serves several purposes. During test setup, the water level in the moat is maintained below the grating to allow walk-around access to the test area. During a test, the water level in the moat is brought to the top of the tank to provide cooling for the inner tank walls and act as secondary containment for the inner tank area. A movable bridge, which spans the tank, is supported on both ends by wheels that move on the grating. The bridge can be positioned to provide access over any area in the tank. The bridge was removed from the tank during the burns.

The tank is filled and drained through six individually valved floor sumps. Four are 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 is a paddle suspended from a beam 4.9 m (16 ft) above the tank floor. The wave paddle is 3.1 m from the north end of the tank and attached to the beam with seven hinged connections allowing it to oscillate 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 remains perpendicular to the long axis of the tank at all times. Overhead suspension of the wave paddle was selected to keep the hinge points out of the water and to eliminate the need for reinforcing the bottom of the tank. The wave paddle face consists of adjustable steel plates that push the water. The plates span the width of the tank coming within 80 mm of the interior walls, and rise vertically from 0.58 m above the tank floor to 0.38 m above the still water level.

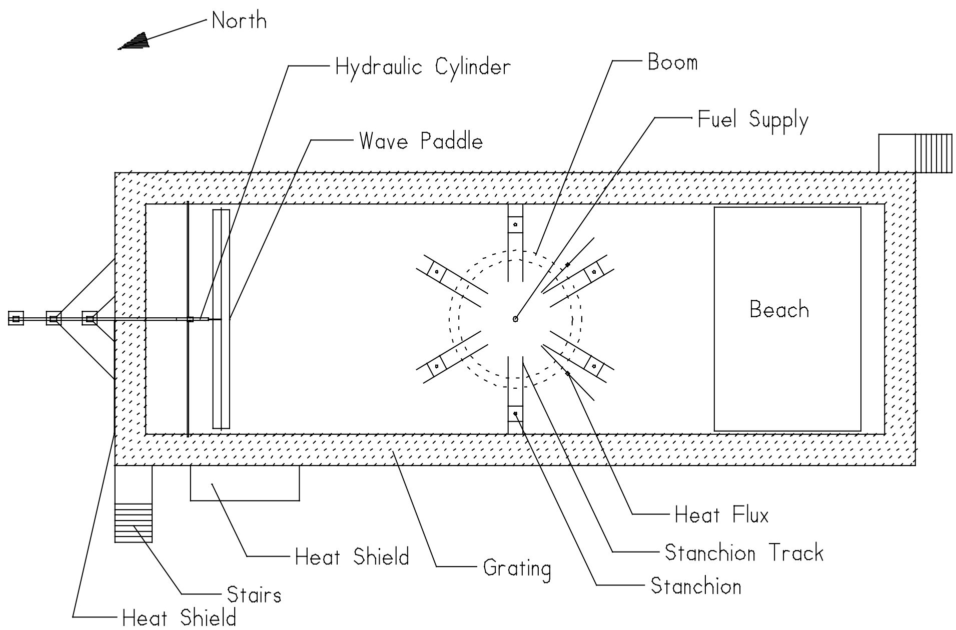

Figure 1. Plan view of wave tank.

The wave paddle is 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 is attached to a horizontal beam that is connected to three vertical beams driven into the ground. This transmits the force to move the paddle to the ground and not to the tank wall. The hydraulic cylinder is powered with a hydraulic pump driven by a tractor. The motion of the cylinder is controlled with two limit switches mounted on the cylinder which activate a control valve. The control valve slows the piston travel at the end of the forward and reverse strokes to reduce stress on the paddle when changing direction. The piston motion is 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 spans the width of the inner tank area and extends for a length of 5.1 m starting 1.0 m from the south end of the tank. The north edge of the beach is 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 allows waves to break on the beach and wash over the end without leaving the tank.

The boom was kept in position during all but the first test by seven boom constraints or stanchions. The stanchions were constructed of steel pipe 1.0 m long with a nominal diameter of 50 mm. The stanchions are mounted vertically in a pattern forming a circle around the center of the tank. The base of each stanchion is attached to a plate that can be moved along a track attached to tank floor. The tracks extend 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. [Note: The stanchions seen in the photographs in Appendices A-F are the taller, interior stanchions used during Phase I testing. These stanchions remained in the tank in the Phase II tests, but did not interfere with the booms.]

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

4.0 Instrumentation

Four types of measurements were made in conjunction with the tests. Atmospheric measurements were made to characterize the meteorological conditions during the tests. Heat flux measurements were taken near the boom to measure the total heat flux from the fire to the boom. Temperature measurements were taken with thermocouples located adjacent to the heat flux gauges. Wave height measurements were made to characterize the wave conditions that the booms were subjected to. The draft ASTM standard only specifies temperature measurements and does not indicate how these measurements are to be taken.

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. Wind speed and direction 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 still water surface.

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. Figure 2 shows the heat flux gauge and thermocouple assembly in the tank. 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.

The wave profiles were determined from measurements of the water level in the tank. The water level was measured with a vertical cylindrical probe that had a capacitance proportional to the water level in the tank. The effect of water coating on the probe above the true liquid level was compensated for with 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

Figure 2. Heat flux gauge, thermocouple assembly.

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 commercial fire-resistant booms were used to evaluate the test protocol. The basic features of the booms are given in Table 1. Appendices A-F include photographs of the booms on the ground and in the water before testing. Analysis of boom construction was not a part of the project and the booms were not disassembled to inspect the construction details. In table 1, "fabric" is used to describe a flexible fabric based material that included a polymeric coating in some cases. 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.

6.0 Test Procedure

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. Measurements of the inside diameter of the boom circle were taken and the stanchions in the tank were adjusted to fit inside the boom circle. Using a truck mounted crane and a lifting spreader, the boom was placed in the tank. 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 of eight horizontal radial arms that 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

Table 1. Boom Description

Boom	**Manufacturer**	**Construction**	**Sections**	**Freeboard**	**Average Inside Diameter**	**Area**
1	Elastec/ American Marine	Water-cooled fabric over flexible flotation	continuous curvature	254 mm (10 in)	4.27 m (14 ft)	14.3 m^2 (154 ft^2)
2	Environmental Marine Technology Associates	Water-cooled fabric over flexible flotation	continuous curvature	356 mm (14 in)	3.66 m (12 ft)	10.5 m^2 (113 ft^2)
3	Spill-Tain Division MCD Company	Stainless Steel sections with stainless steel covered flotation	6	635 mm (25 in)	3.88 m (12.7 ft)	11.8 m^2 (127 ft^2)
4	Applied Fabric Technologies	Fabric with steel covered flotation	continuous curvature	279 mm (11 in)	4.66 m (15.3 ft)	17.0 m^2 (183 ft^2)
5	Applied Fabric Technologies	Stainless Steel sections with air flotation	7	368 mm (14.5 in)	4.83 m (15.8 ft)	18.3 m^2 (197 ft^2)
6	Kepner Plastics Fabricators	Fabric over flexible flotation	continuous curvature	240 mm (9.5 in)	4.78 m (15.7 ft)	17.9 m^2 (193 ft^2)

then removed from the tank and the water level in the moat brought to the top edge of the tank. Using the average 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 (Bitting, 1999).

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 were 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.

For boom 1, the wind direction did not permit the second and third burns to be completed immediately after the first burn and one hour cool-down period. In that case, the second and third burns were conducted three days later.

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 2 gives the ground meteorological conditions and tank surface water temperature in the tank 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 of 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. Figure 4 shows the tank with the wave maker operating.

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 5 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 the wave height was 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 crest over a fixed distance along the tank.

Figure 5 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, a 4.5 s period 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 within the boom and a burning rate of diesel fuel of 220 L/hr-m^2 (Bitting, 1999). 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.

Figure 4. Tank with wave maker in operation.

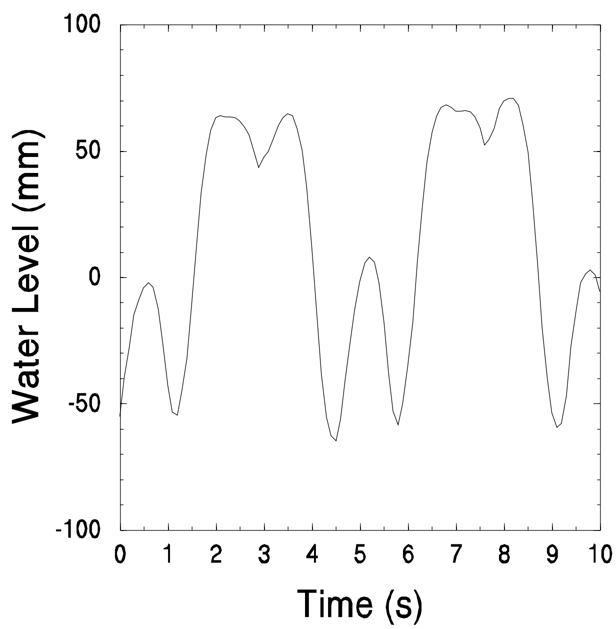

Figure 5. Wave profile.

Table 3. Fuel Quantity

Boom	Burn 1	Burn 2	Burn 3	Burn 4
1	2517 L* (665 gal)	3146 L (831 gal)	1575 L** (416 gal)	1613 L** (426 gal)
2	144 L* (38 gal)	878 L** (232 gal)	1733 L (458 gal)	250 L* (66 gal)
3	2514 L (664 gal)	2514 L (664 gal)	2514 L (664 gal)	
4	3751L (991 gal)	3308 L (874 gal)	3308 L (874 gal)	
5	113 L* (30 gal)	3308 L (874 gal)	3422 L (904 gal)	3422 L (904 gal)
6	329 L* (87 gal)	3944 L (1042 gal)		

* Burn terminated before 1 hr
** ½ hr burn

7.4 Burn Chronology

Table 4 gives the burn chronology for each of the booms. 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.

The test sequence observed for the four non-water-cooled booms followed the expected protocol. However, there were several occurrences during the water-cooled boom testing (booms 1 and 2) which resulted in differences when compared with the non-water-cooled booms. During burn 1 for boom 1, a portion of the boom lost buoyancy and the test was terminated due to fuel loss. Upon inspection, a hole was noted in the boom near one of the stanchions which resulted in fire damage to the boom flotation. The exact cause of the hole could not be determined since it appeared to be a cut in the boom and may have occurred prior to the test. Because the cause of the failure could not be determined, a replacement section of boom was used for burns 2 through 4. The stanchions inside the boom circle were replaced with stanchions outside the boom circle connected to the boom with cable below the water line. After approximately 30 minutes into burn 2, the fire became substantially smaller and remained that way until near the end of the burn when it returned to full burning prior to extinction. The total burn time exceeded 3 hours. This was the same phenomenon observed in a first-phase test with a different water-cooled boom. For burns 3 and 4 the quantity of fuel calculated for a 30 min burn was used. With the water-cooled boom the burn time was approximately 40 min for burn 3, and 41 min for burn 4. This indicated that the burning rate per unit area for the water-cooled boom was less than the burning rate for the non-water-cooled boom. These tests do not isolate the reason for the overall reduction in burning rate for the water-cooled booms or why, in burn 2, the fire became substantially smaller after 30 min.

Using the fuel quantities and burn times for burns 3 and 4 a new burning rate per unit area for water cooled booms of 165 L/hr-m^2 was calculated. This was 75 % of the value used for the non water-cooled booms. The reduced burning rate per unit area was used to calculate the fuel quantity for boom 2. The first burn for boom 2 was terminated after initial fuel was consumed due to a change in wind direction. Some damage to the outer cover of the boom occurred during this burn since the cooling water was not started prior to the burn. The boom was repaired, but this repair may have affected the performance of the boom. For burn 2, the quantity of fuel for a one-half hour burn was used and the actual burn time was approximately 32 minutes. For burn 3 the quantity of fuel for a one-hour burn was used and the burn time was approximately 57 minutes. These results indicate the reduced burning rate was appropriate for water-cooled booms in this test configuration.

7.5 Heat Flux and Temperature Measurements

The heat flux gauges and thermocouples were located downwind based on the expected wind direction during testing. Although heat flux and temperature measurements were made for all of the tests, in many cases the heat flux gauges and thermocouples were not directly downwind of the fire for the entire one-hour burn. As a result, in these cases the measurements were not indicative of the maximum thermal exposure on the boom. The measurements for several cases in which the heat flux gauges and thermocouples were downwind of the fire are presented below.

Figures G-1 through G-12 are the graphs of the total heat flux measured by the horizontally and vertically facing gauges located to the west of booms 4 and 5. The heat flux gauges respond quickly to changes in the fire and substantial fluctuation is normal for these measurements. The values graphed have been smoothed to show the average values during the test. From these graphs, it can be seen that the highest values are reached at the beginning of the burn and the horizontal and vertical facing gauges generally agree quite closely. Table 5 gives the mean values and standard deviations for the non-smoothed data during full burning.

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

Figure G-13 is a graph of the heat flux measured by the horizontally facing heat flux gauge on the west side and figure G-14 the vertically facing gauge for boom 1, burn 1. This burn was terminated before one hour due to oil loss. This graph shows a heat flux trend similar to those for booms 4 and 5 with slightly higher values. The heat flux of 25 kW/m^2 measured before burning for boom 1 was significantly greater than for booms 4 and 5, possibly 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.

Figures G-15 and G-16 show the horizontal and vertical heat flux measured by the gauge to the east of boom 1 during burn 2. This burn continued for nearly 3 hours and 18 minutes with the quantity of fuel estimated for a one-hour burn. From these graphs 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.

Figures H-1 through H-4 show the comparison between the 1.6 mm diameter and 3.2 mm diameter thermocouples. The data for the 3.2 mm thermocouple followed closely the 1.6 mm diameter thermocouple, but with a slightly slower response. Figures H-5 through H-7 are graphs of the temperature measured by the 1.6 mm diameter thermocouples corresponding to the heat fluxes shown in Figures G-1/2, G-7/8, and G-9/10. Table 6 gives the mean values and standard deviations for the non-smoothed data during full burning. The thermocouples were subject to occasional failure and their replacement required draining most of the water from the tank. As a result, all thermocouple measurements are not available for each burn.

As with the heat flux gauges, the thermocouple responds quickly to changes in the fire and the 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 these graphs it is seen that the highest values are generally reached at the beginning of the burns.

Table 5. Mean heat flux during full burning

		Gauge Position	Average Total Heat Flux (kW/m^2)
Boom 4	**Burn 1**	Horizontal	103±25
		Vertical	107±33
	Burn 2	Horizontal	116±19
		Vertical	100±26
	Burn 3	Horizontal	120±23
		Vertical	114±28
Boom 5	**Burn 2**	Horizontal	109±24
		Vertical	107±26
	Burn 3	Horizontal	96±24
		Vertical	100±26
	Burn 4	Horizontal	102±22
		Vertical	101±25
Boom 1	**Burn 1**	Horizontal	134±28
		Vertical	149±36

Table 6. Mean temperature during full burning

		Thermocouple Diameter (mm)	Temperature (°C)
Boom 1	**Burn 1**	1.6	846±117
	Burn 1	3.2	862±89
Boom 4	**Burn 1**	1.6	832±135
Boom 5	**Burn 2**	1.6	952±72
	Burn 3	1.6	872±82

8.0 General Observations

The degree of degradation varied widely amongst the six booms used in the evaluation. Appendices A-F include photographs of the booms during and after testing. Photographs of the booms in the water, on the ground and a close-up after testing are provided. 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 7 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 influenced substantially 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 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 phenomenon observed during all of the tests 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 7. 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 flotation 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 phenomenon 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 (Bitting, 1999). Since the maximum thermal exposure from these fires has been characterized, it may not be 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, using substantial fuel loss as the criteria for terminating a test before the burn cycle is completed 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 receive the most heat and flame. The wind speed will determine the vertical profile of the burn, and affect the thermal exposure to the boom. One consideration should be to limit testing to times when the wind speed is not expected to exceed a velocity which would prohibit an actual in-situ burn.

3) What evaluation criteria should be applied to the booms at the end of the test? Determining criteria for evaluating a boom is one of 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 loading 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.

10.0 Acknowledgments

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Appendix A. Boom 1 Photographs

Figure A-1. Boom 1, before burning, on ground.

Figure A-2. Boom 1, before burning, in water.

Figure A-3. Boom 1, during burning.

Figure A-4. Boom 1, after burning, in water.

Figure A-5. Boom 1, after burning, on ground.

Figure A-6. Boom 1, after burning, close-up.

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Appendix B. Boom 2 Photographs

Figure B-1. Boom 2, before burning, on ground.

Figure B-2. Boom 2, before burning, in water.

Figure B-3. Boom 2, during burning.

Figure B-4. Boom 2, after burning, in water.

Figure B-5. Boom 2, after burning, on ground.

Figure B-6. Boom 2, after burning, close-up.

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Appendix C. Boom 3 Photographs

Figure C-1. Boom 3, before burning, on ground.

Figure C-2. Boom 3, before burning, in water.

Figure C-3. Boom 3, during burning.

Figure C-4. Boom 3, after burning, in water.

Figure C-5. Boom 3, after burning, on ground.

Figure C-6. Boom 3, after burning, close-up.

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Appendix D. Boom 4 Photographs

Figure D-1. Boom 4, before burning, on ground.

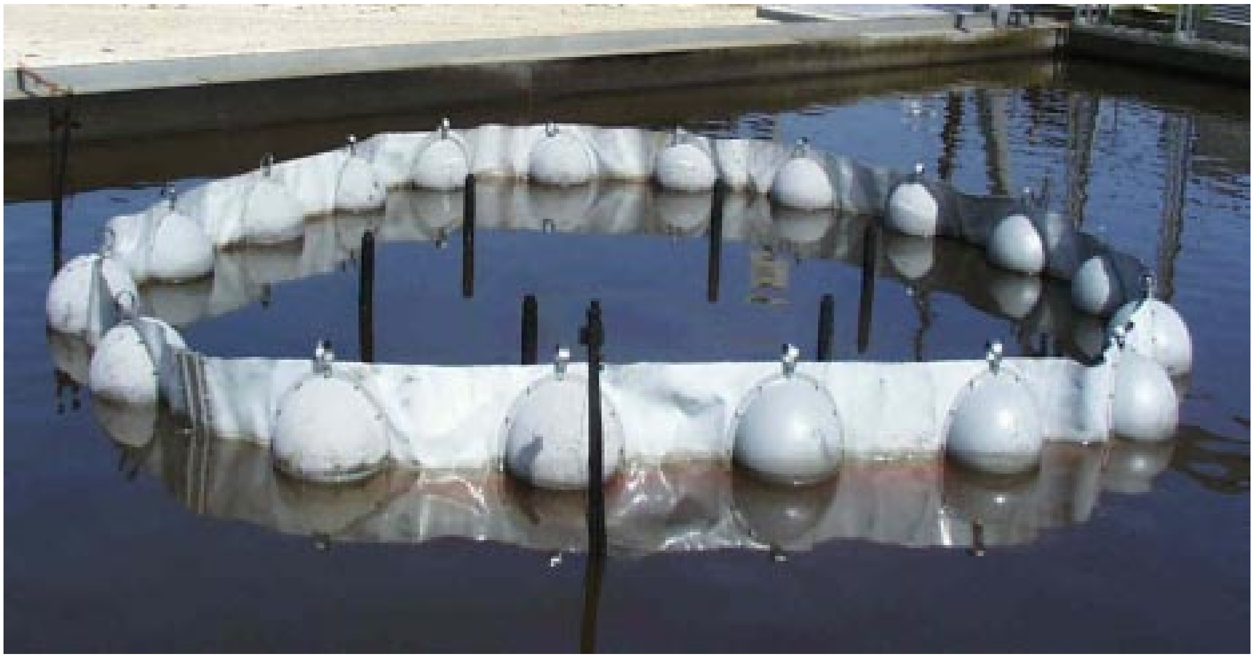

Figure D-2. Boom 4, before burning, in water.

Figure D-3. Boom 4, during burning.

Figure D-4. Boom 4, after burning, in water.

Figure D-5. Boom 4, after burning, on ground.

Figure D-6. Boom 4, after burning, close-up.

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Appendix E. Boom 5 Photographs

Figure E-1. Boom 5, before burning, on ground.

Figure E-2. Boom 5, before burning, in water.

Figure E-3. Boom 5, during burning.

Figure E-4. Boom 5, after burning, in water.

Figure E-5. Boom 5, after burning, on ground.

Figure E-6. Boom 5, after burning, close-up.

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Appendix F. Boom 6 Photographs

Figure F-1. Boom 6, before burning, on ground.

Figure F-2. Boom 6, before burning, in water.

Figure F-3. Boom 6, during burning.

Figure F-4. Boom 6, after burning, in water.

Figure F-5. Boom 6, after burning, on ground.

Figure F-6. Boom 6, after burning, close-up.

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Appendix G. Heat Flux Gauge Measurements

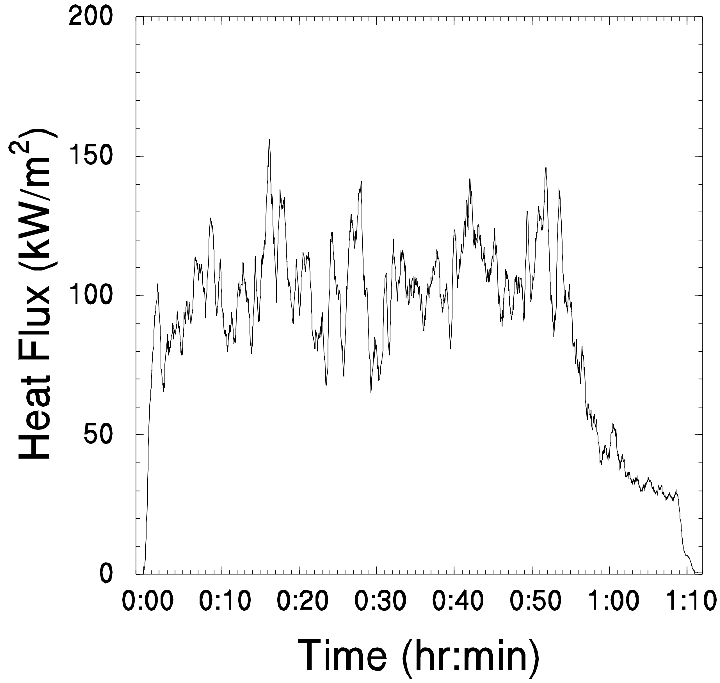

Figure G-1. Boom 4, Burn 1, horizontal.

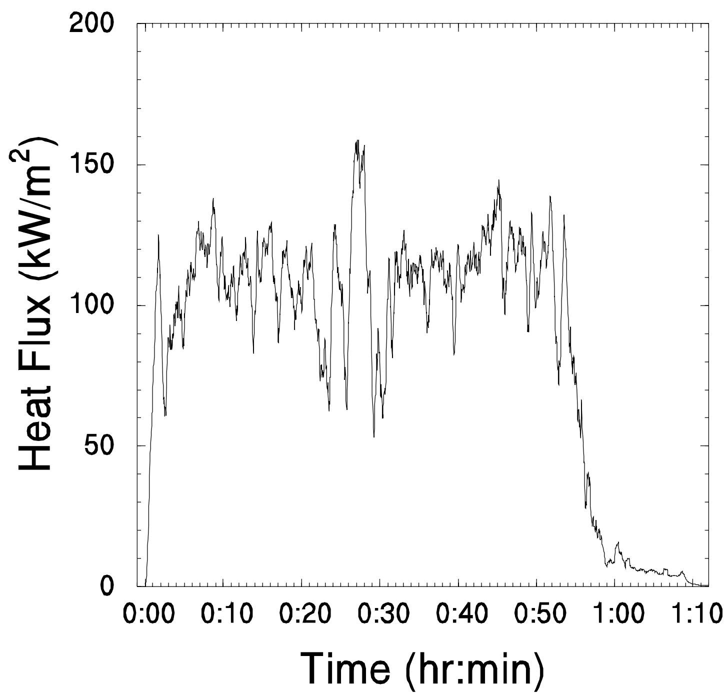

Figure G-2. Boom 4, Burn 1, vertical.

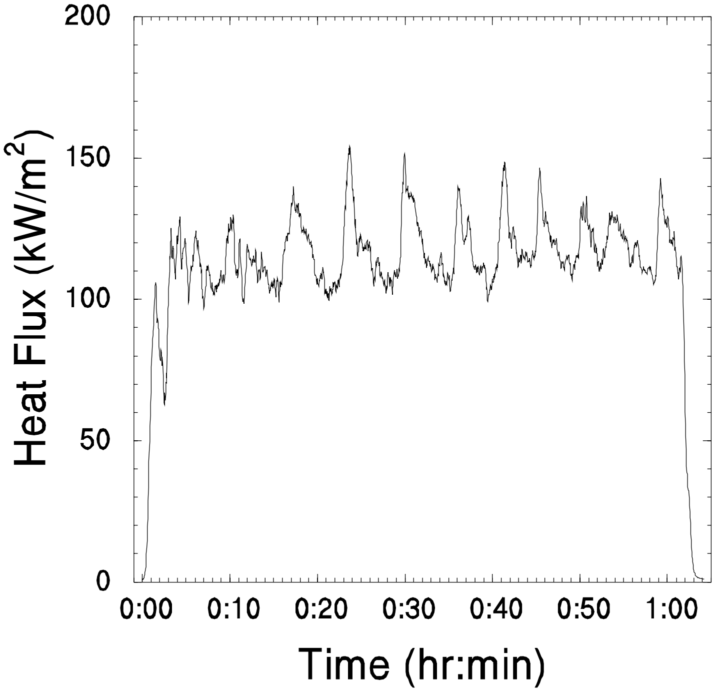

Figure G-3. Boom 4, Burn 2, horizontal.

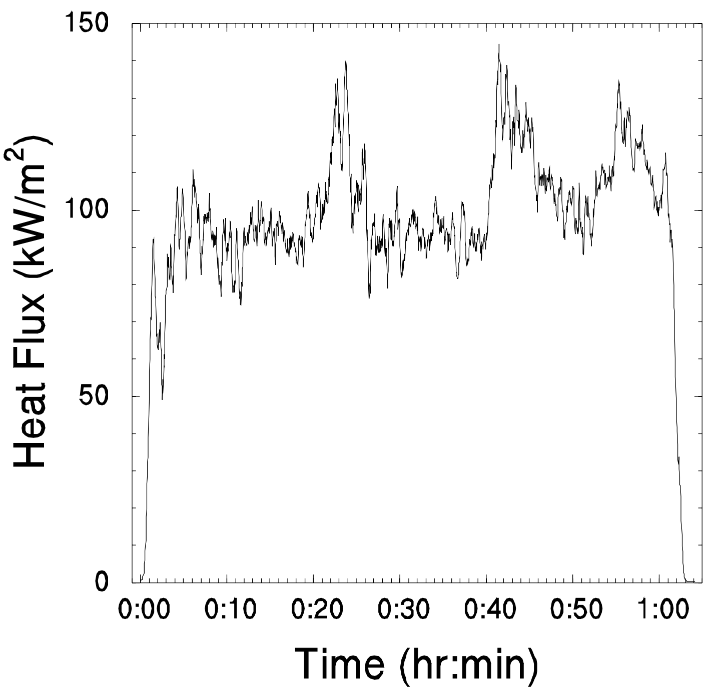

Figure G-4. Boom 4, Burn 2, vertical.

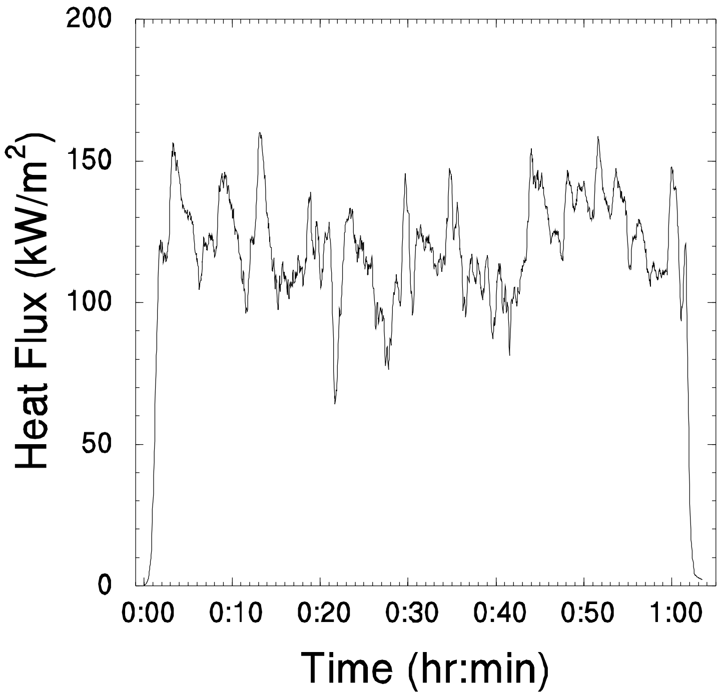

Figure G-5. Boom 4, Burn 3, horizontal.

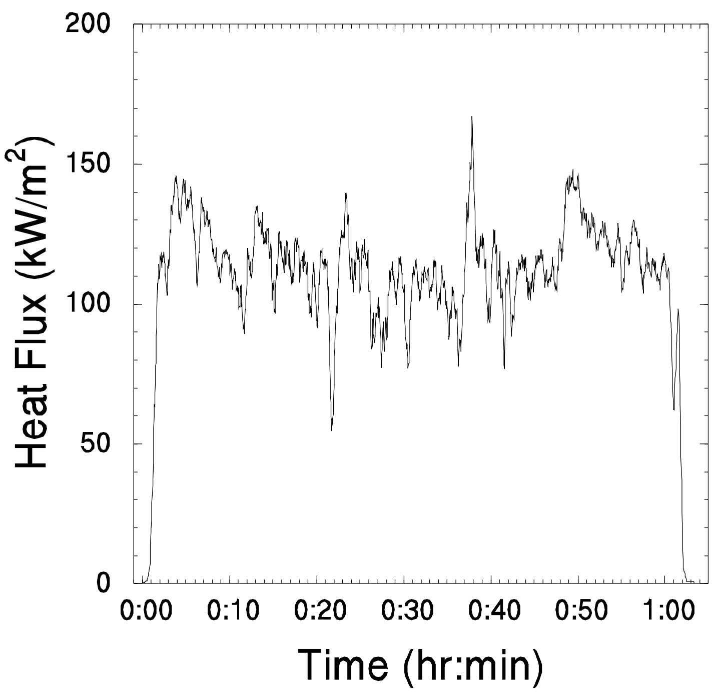

Figure G-6. Boom 4, Burn 3, vertical.

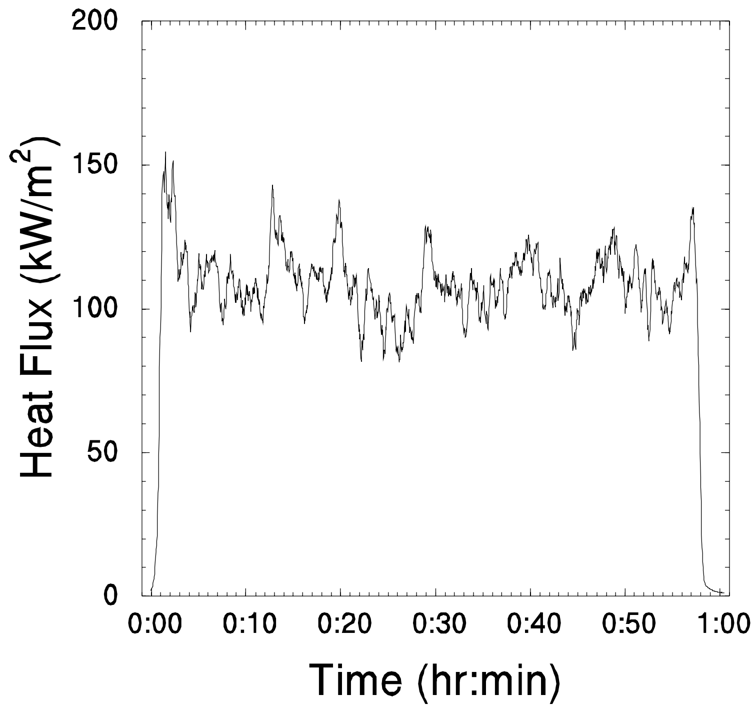

Figure G-7. Boom 5, Burn 2, horizontal.

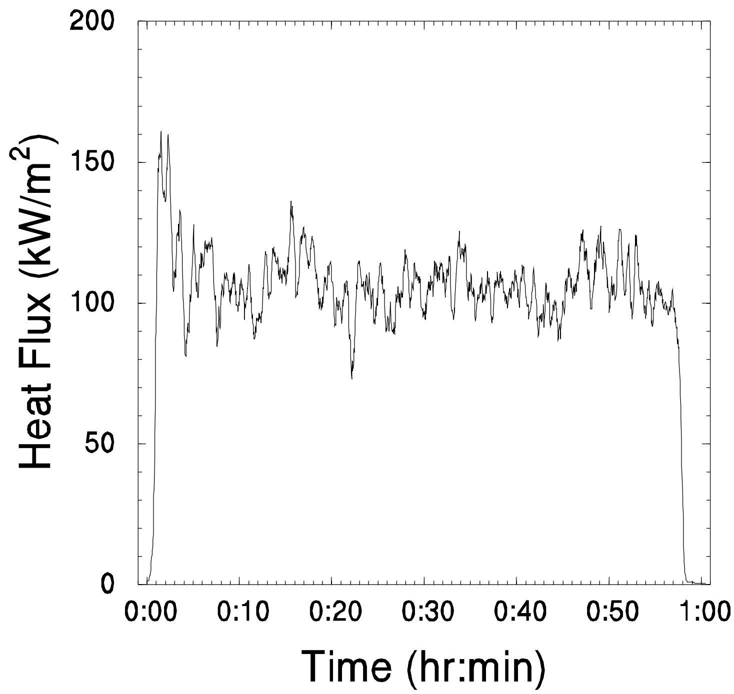

Figure G-8. Boom 5, Burn 2, vertical.

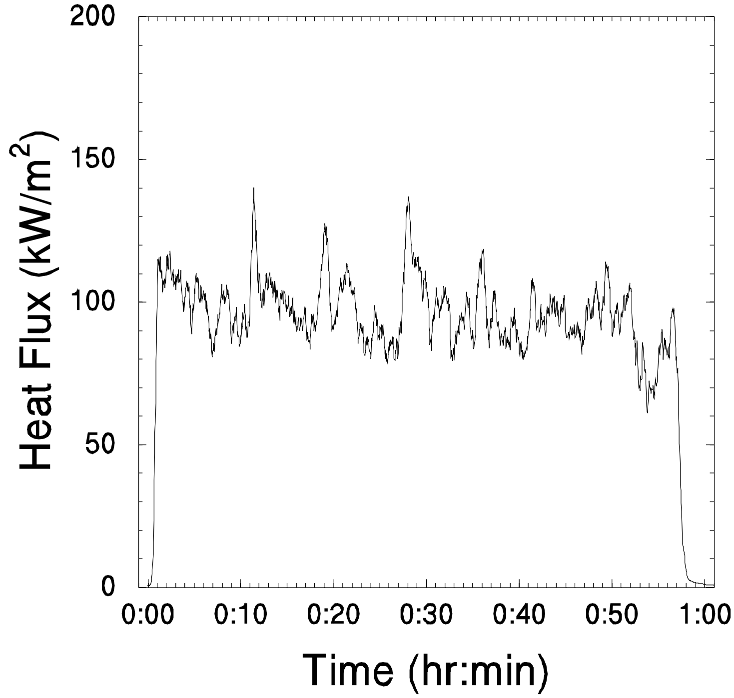

Figure G-9. Boom 5, Burn 3, horizontal.

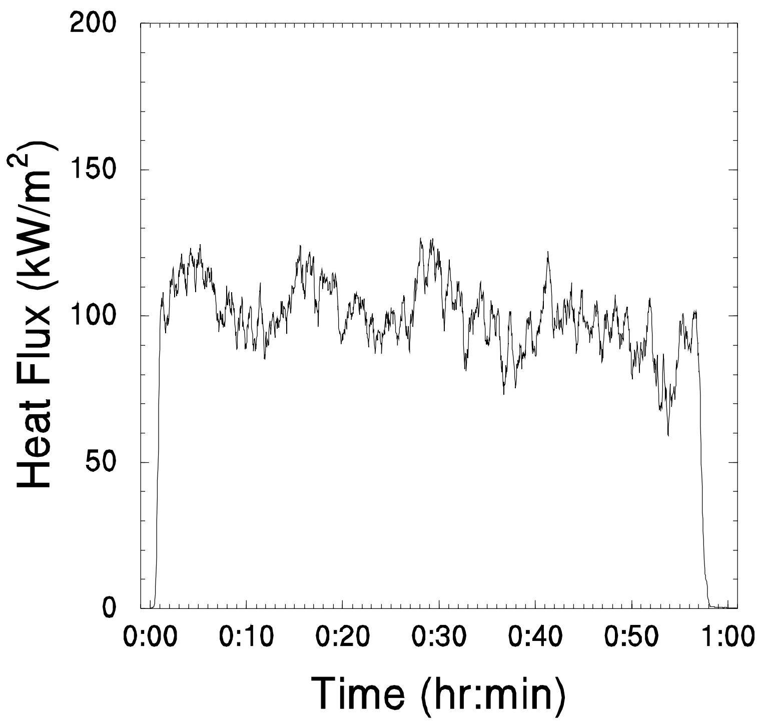

Figure G-10. Boom 5, Burn 3, vertical.

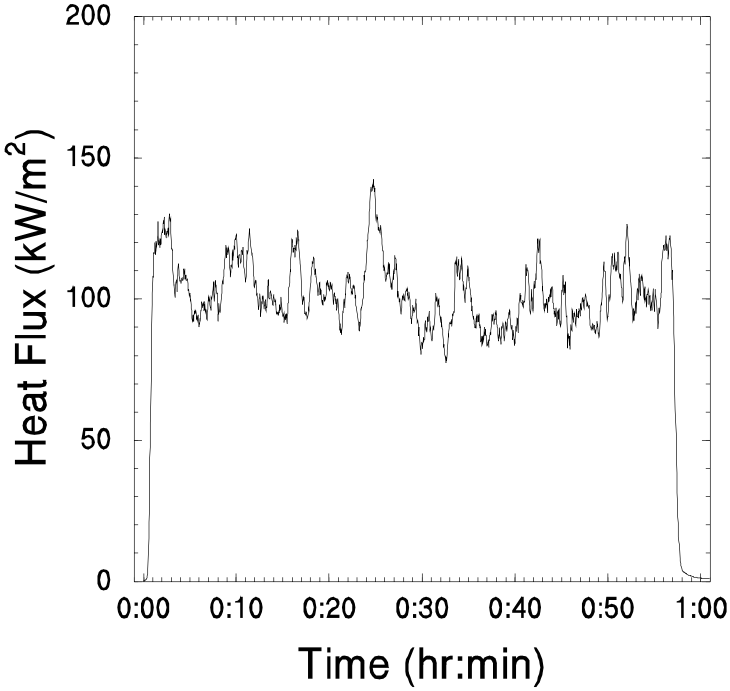

Figure G-11. Boom 5, Burn 4, horizontal.

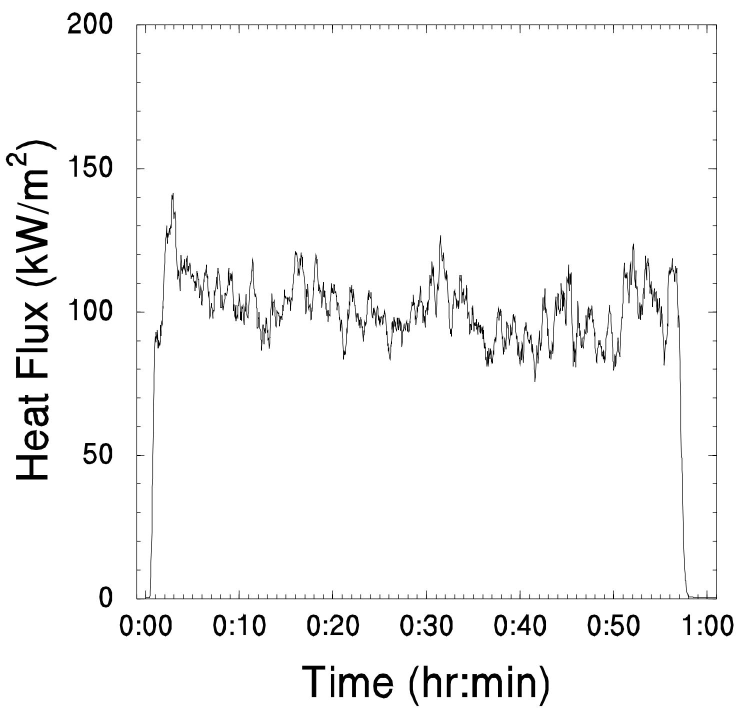

Figure G-12. Boom 5, Burn 4, vertical.

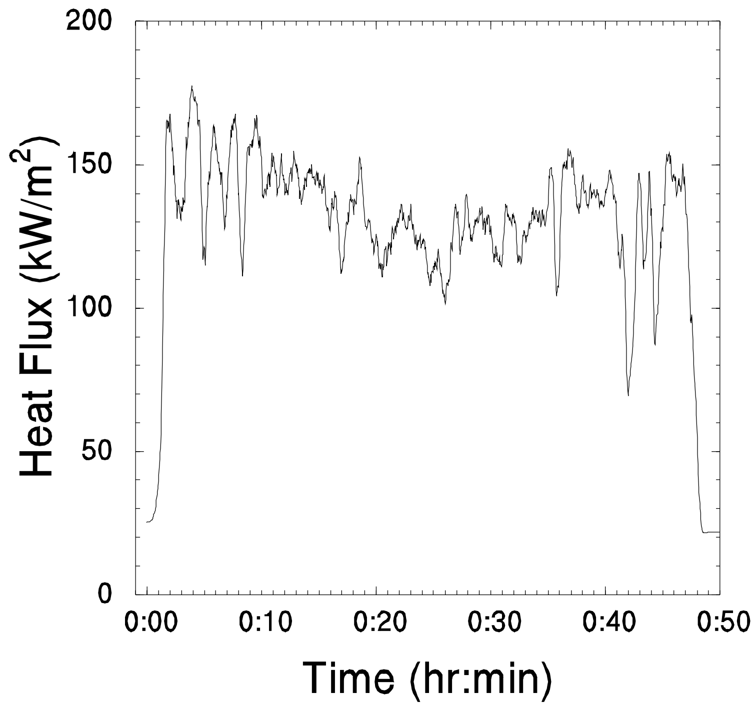

Figure G-13. Boom 1, Burn 1, horizontal.

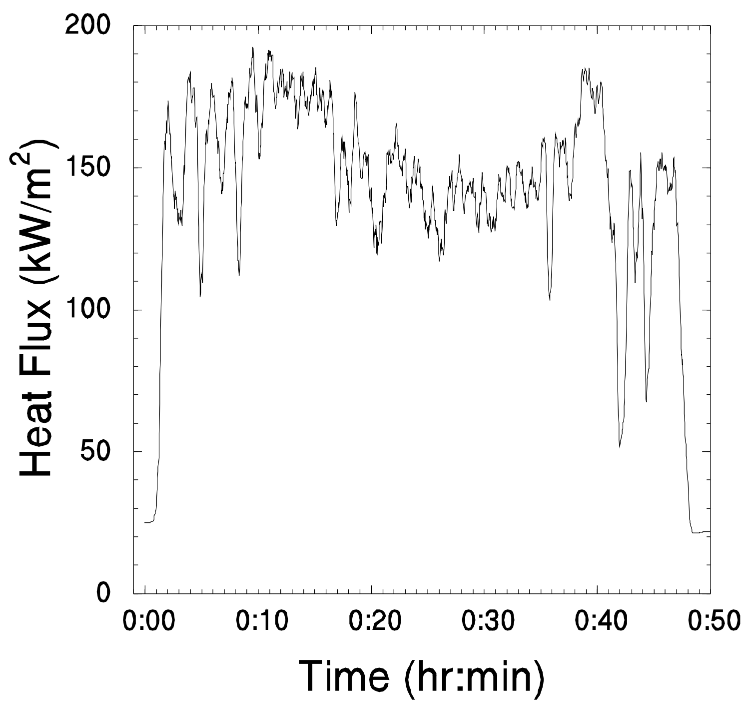

Figure G-14. Boom 1, Burn 1, vertical.

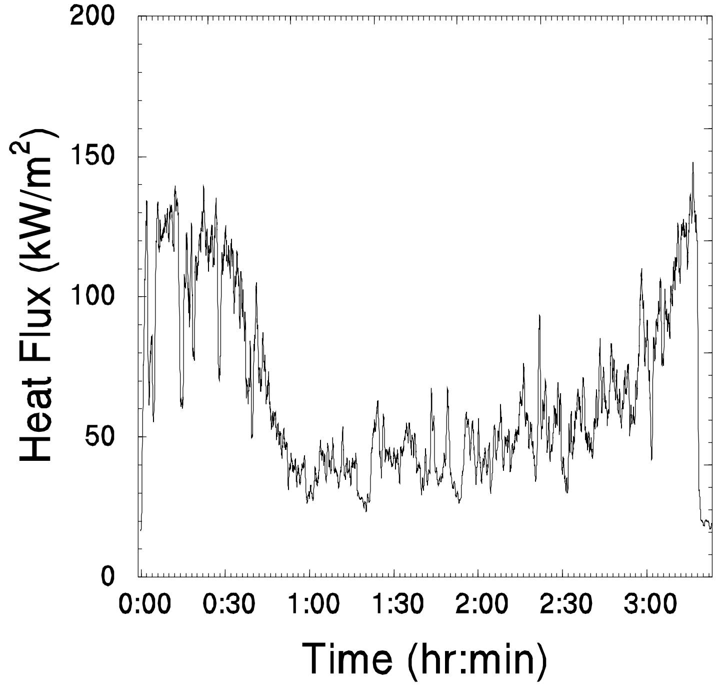

Figure G-15. Boom 1, Burn 2, horizontal.

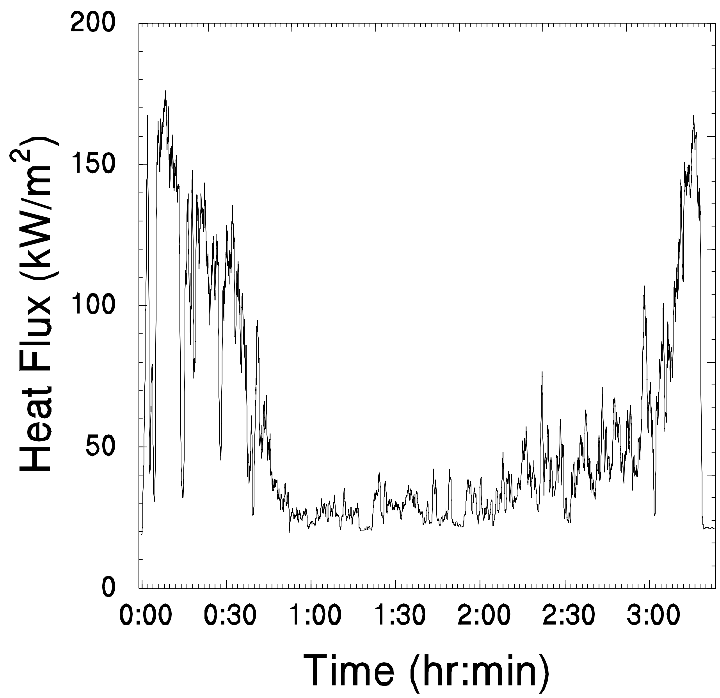

Figure G-16. Boom 1, Burn 2, vertical.

Appendix H. Temperature Measurements

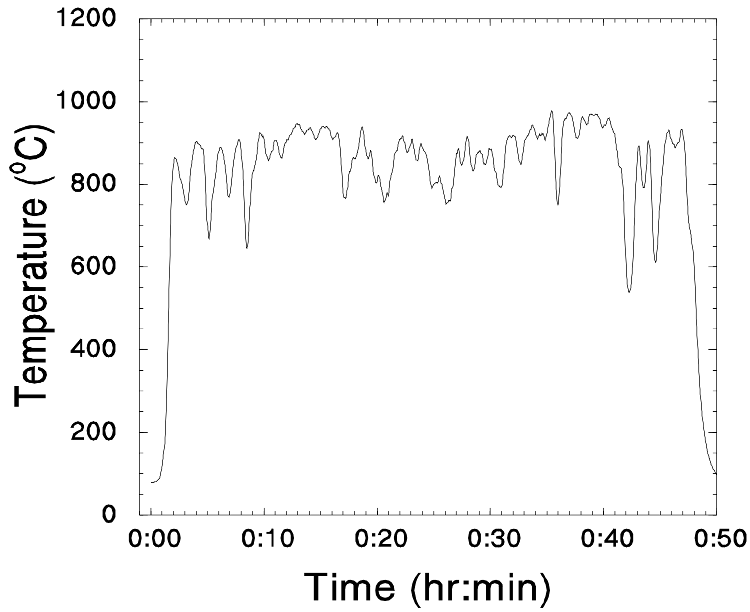

Figure H-1. Boom 1, burn 1, 3.2 mm diameter.

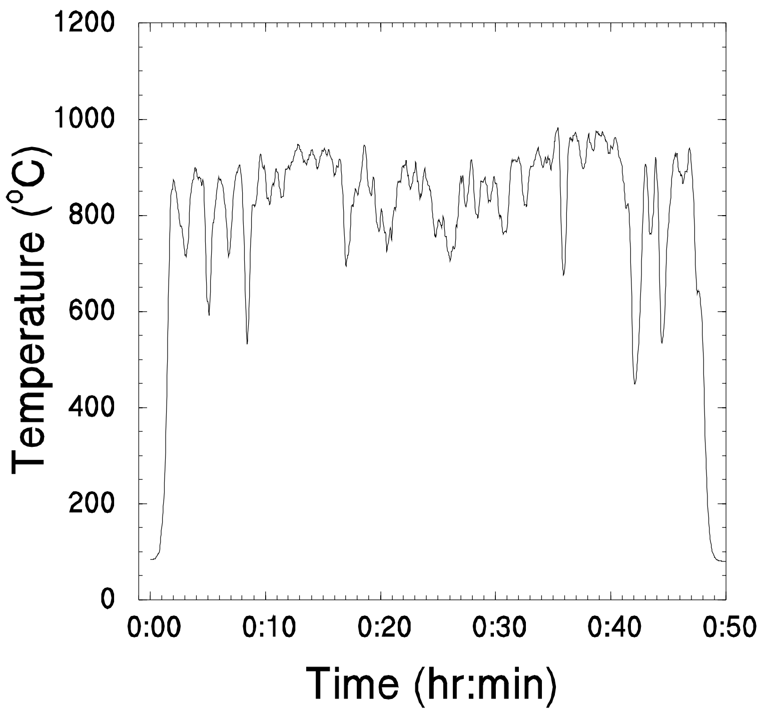

Figure H-2. Boom 1, burn 1, 1.6 mm diameter.

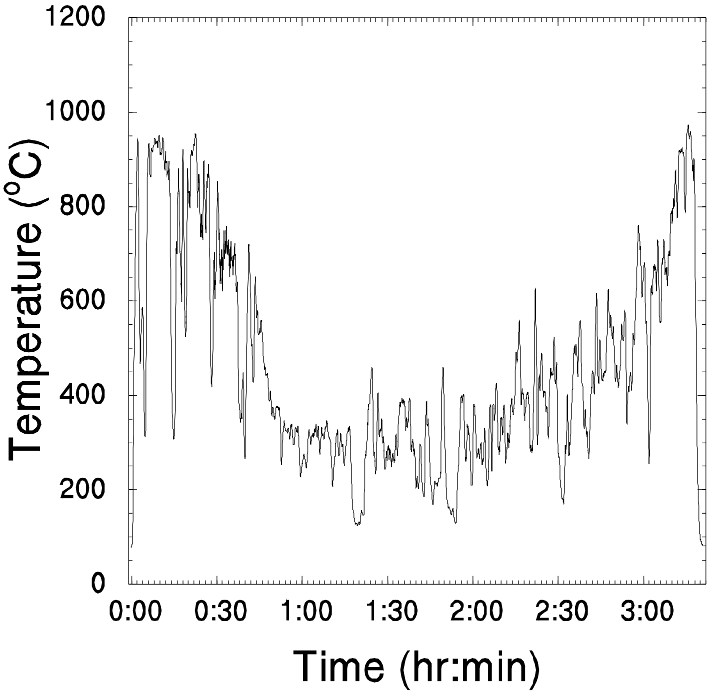

Figure H-3. Boom 1, burn 2, 3.2 mm diameter.

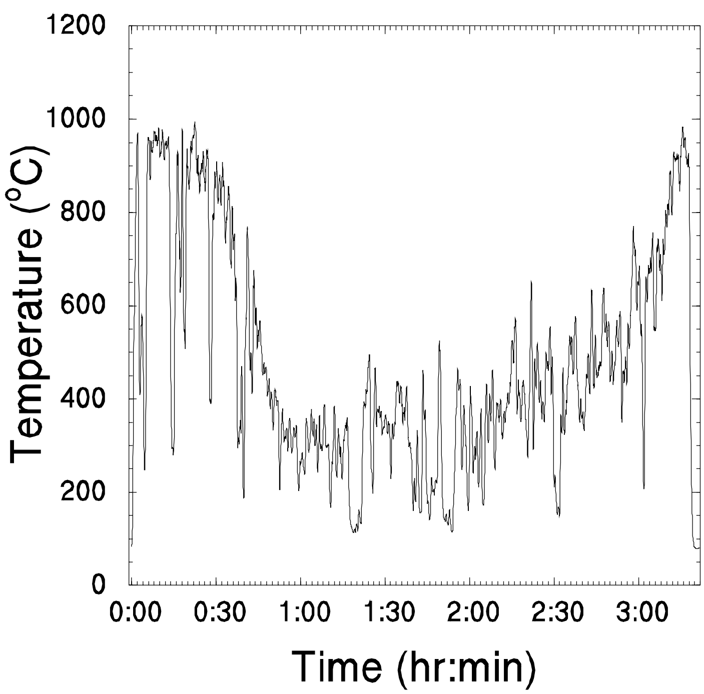

Figure H-4. Boom 1, burn 2, 1.6 mm diameter.

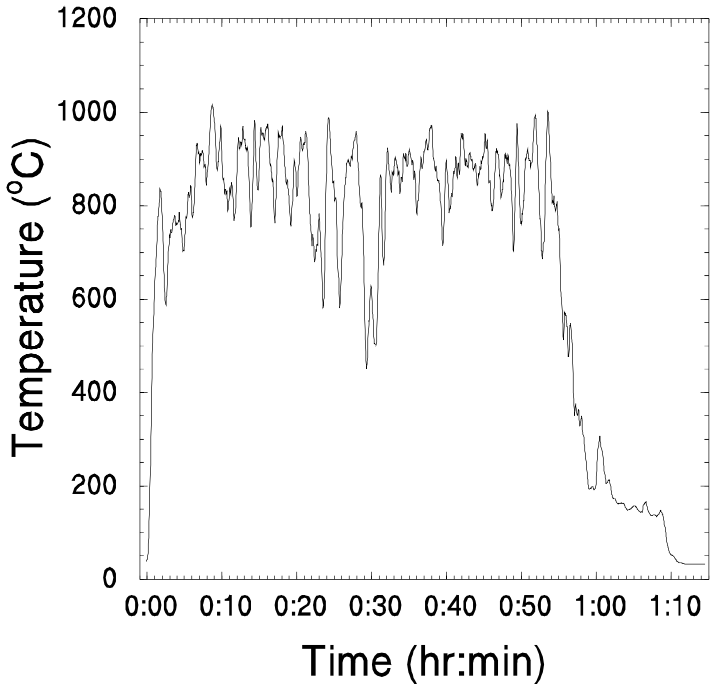

Figure H-5. Boom 4, burn 1, 1.6 mm diameter.

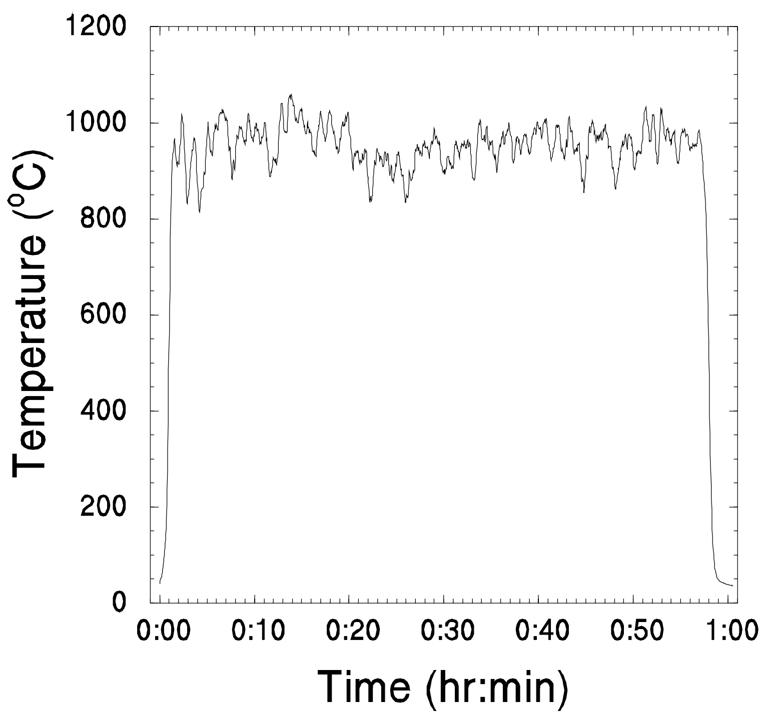

Figure H-6. Boom 5, burn 2, 1.6 mm diameter.

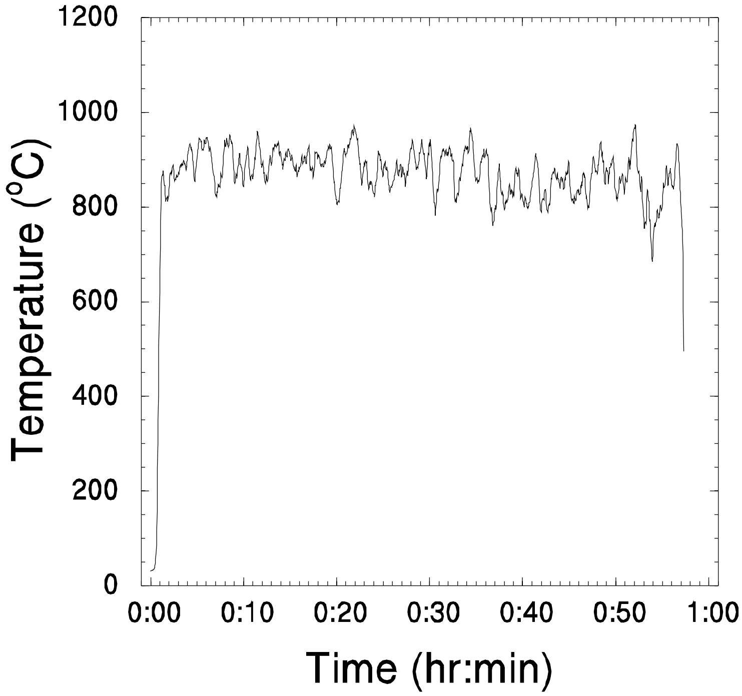

Figure H-7. Boom 5, burn 3, 1.6 mm diameter.