U.S. Coast Guard Research and Development Center

1082 Shennecossett Road, Groton, CT 06340-6096

Report No. CG-D-07-99

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

FINAL REPORT
FEBRUARY 1999

This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Marine Safety and Environmental Protection (G-M)
Washington, DC 20593-0001

and

U.S. Department of Interior
Minerals Management Service
Technology Assessment and Research Branch
Herndon, VA 22070

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

The contents of this report reflect the views of the Coast Guard Research and Development Center. This report does not constitute a standard, specification, or regulation.

Marc B. Mandler, Ph.D.
Technical Director
United States Coast Guard
Research & Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-07-99		

4. Title and Subtitle	5. Report Date
Evaluating a Protocol for Testing a Fire Resistant Oil Spill Containment Boom	February 1999
	6. Performing Organization Code Project No. 4120.5.1 / UDI 286
7. Author(s) Kenneth R. Bitting	8. Performing Organization Report No. R&DC 11/98
9. Performing Organization Name and Address U.S. Coast Guard Research & Development Center 1082 Shennecossett Road Groton, CT 06340-6096	10. Work Unit No. (TRAIS) 11. Contract or Grant No. MIPR E00181
12. Sponsoring Organization Name and Address U.S. Department of Transportation United States Coast Guard Marine Safety and Environmental Protection (G-M) Washington, DC 20593-0001 U.S. Department of Interior Minerals Management Service Technology Assessment and Research Branch Herndon, VA 22070	13. Type of Report & Period Covered Final Report 14. Sponsoring Agency Code Commandant (G-MOR) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

The R&D Center's technical point of contact is Dr. Robert Hiltabrand, 860-441-2701.

16. Abstract (MAXIMUM 200 WORDS)

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 booms to evaluate the anticipated performance of different booms. The 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 general guidelines and does not specify the details of the test procedure. Utilizing the guidelines in the draft standard, a series of experiments was conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves. A wave tank capable of evaluating a 15 m section of boom by subjecting it to a 5 m diameter fire with 0.15 m high waves was designed and constructed at the U.S. Coast Guard Fire and Safety Test Detachment in Alabama. The draft ASTM F-20 test protocol was evaluated using five typical fire-resistant oil spill containment booms, and the results of this evaluation are presented. The strengths and weaknesses of the protocol are discussed, along with areas for possible improvement.

17. Key Words	18. Distribution Statement
diesel fuel, fire-resistant booms, oil spills, pool fires	This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized.

METRIC CONVERSION FACTORS

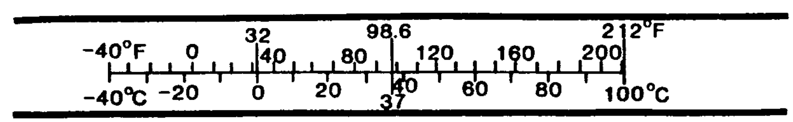
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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 a fire-resistant boom to evaluate the anticipated performance of different booms. The 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 series of experiments was conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves.

Five booms were subjected to the test procedure based on the draft standard. Three of the booms were of fabric based construction, one was water-cooled fabric and one was stainless steel. All of the booms showed some degradation over the course of the tests, and the test for one of the fabric booms was terminated after one hour of burning due to fire damage to the boom. During the test of the water-cooled boom, the fire became less intense and continued at a reduced rate for a total of almost two hours. This resulted in an inefficient burn, as a loss in cooling water resulted in fire damage to the boom which led to fuel loss. There was difficulty in applying the test protocol to water-cooled booms. Further study of the impact of water-cooled booms on the burning rate is recommended.

During the test series, the fire size appeared to be an adequate simulation of a real burn. The thermal impact on the boom was influenced by wind speed and direction. During the test series, internal stanchions were used to position the boom in the middle of the tank. It was noted during most of these tests that the boom appeared to be damaged by contact with the stanchions. It is recommended that alternative methods of boom constraint, such as cables attached to the boom skirt, be considered.

Overall, the test protocol and its application were considered to be a success. The test appeared to provide a realistic simulation of the thermal stresses expected during the use of a fire-resistant oil spill containment boom. The tests served to raise a number of issues concerning the application of the draft ASTM F20 protocol which was used in the test series. One of the most important aspects of the tests is the evaluation criteria. It appears unlikely that a numerical rating of fire-resistant booms can be developed from these tests. The most appropriate evaluation appears to be either to report the condition of the boom at the end of the test, or the use of a simple pass/fail criterion.

Table of Contents

List of Figures

List of Tables

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, leaving a small percentage of smoke particulate and other unburned and residue byproducts. In-situ burning requires minimal equipment and less labor than other techniques. It can be applied in areas 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 (0.04 in) to 5 mm (0.2 in) 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 the draft standard, "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 including 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 in the draft standard. 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).

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

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

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

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

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

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

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

After examining a number of options, it was determined that the construction of an outdoor wave tank designed to accommodate burning was the most appropriate option. A description of the wave tank is given in the next section. A number of designs were considered that would allow the boom to be configured in the horseshoe or catenary shape observed when towing a boom at sea. No economically feasible designs were developed which would assure that a liquid fuel would remain in a prescribed area of the boom apex during burning. A circular boom pattern was chosen to contain the fuel even though the boom would be turned through a smaller radius than would be expected at sea. This could cause increased stress in the boom, particularly at the connections between boom sections. Further, the circular pattern did not allow the boom to be tensioned to simulate the tow stress. Tow stress would tend to stretch the boom, potentially causing separation in areas weakened by the heat from the fire.

The wave tank was designed to accommodate a nominal 15 m (50 ft) boom section forming a circle approximately 5 m (16 ft) in diameter. The heat flux at the base of a liquid pool fire and the burning rate are functions of the fire diameter. The heat flux and the burning rate increase with increasing fire diameter for small fires. Once the diameter reaches 5 m (16 ft), the heat flux and burning rate are nearly constant as the fire diameter increases (Walton, *et al.*, 1993). Thus, the fire within the boom containment would be large enough to represent the thermal exposure from a larger fire.

Ideally, a wave tank should have a length-to-width ratio of at least 5 to 1 and preferably 10 to 1 or more. This would allow the waves time to fully develop before exposing the test item and there would be a sufficient distance, over which the wave energy could be absorbed, possibly preventing some reflections. Due to economic constraints, a length-to-width ratio of 3.3 to 1 was used which was considered the minimum necessary for a 5 m (16 ft) diameter boom circle.

The tank was designed to produce 0.3 m (1 ft) high waves with a period of 3 seconds to 5 seconds. Normally, in-situ burning would not be considered as a response option in the presence of large or breaking waves. In-situ burning could be considered with waves larger than 0.3 m (1 ft), particularly long period sea swells. The 0.3 m (1 ft) short period waves were chosen to generate significant boom flexing without requiring the water depth and wave maker power required by larger waves.

3.0 Test Configuration

The boom test evaluations were conducted in a wave tank designed specifically for evaluating fire-resistant boom. The tank specifications were developed by National Institute of Standards and Technology (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, fabricated and installed in the tank by NIST.

The wave tank design was based in part on the experience gained from installing and using a 15 m (50 ft) square static burn tank at Fire and Safety Test Detachment (Walton, *et al.*,1994). A plan view of the tank is shown in Figure 1 and a pictorial view in Figure 2. The wave tank was constructed of steel and is 1.5 m (5 ft) deep with two perimeter walls 1.2 m (4 ft) apart forming an inner and outer area of the tank. The inside dimensions of the inner area of the tank are 30.5 m (100 ft) by 9.1 m (30 ft). The base of the tank is at ground level, and two stairways provided access to the top of the tank. The outer area of the tank forms a moat around the inner area and contains a walk-on steel grating 115 mm (4.5 in) below the top of the tank. The moat serves several purposes. During test setup, the water level in the moat is maintained below the grating which provides walk-around access to the test area. During a test, the water level in the moat is brought to the top of the tank which provides cooling for the inner tank walls and acts as secondary containment for the inner tank area. A movable bridge, which spans the tank, is supported on both ends by wheels which 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 (4 ft) or 0.31 m (1 ft) 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 (10.3 ft) from the north end of the tank and attached to the beam with seven hinged connections allowing it to swing in the north-south direction. A pulley and cable system attached to the bottom of the wave paddle and the floor of the tank was designed so that the paddle remains perpendicular to the long axis of the tank at all times. The overhead suspended

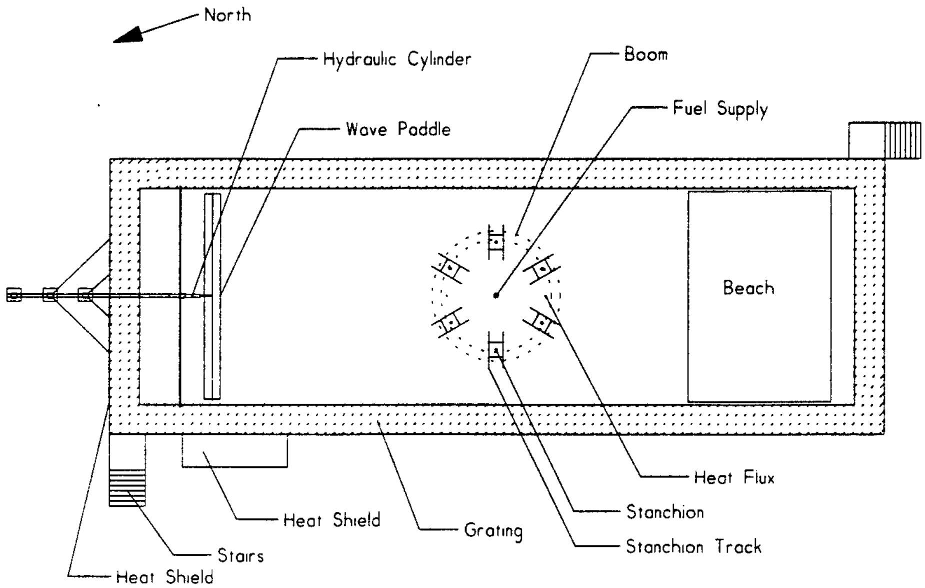


Figure 1. Plan view of wave tank

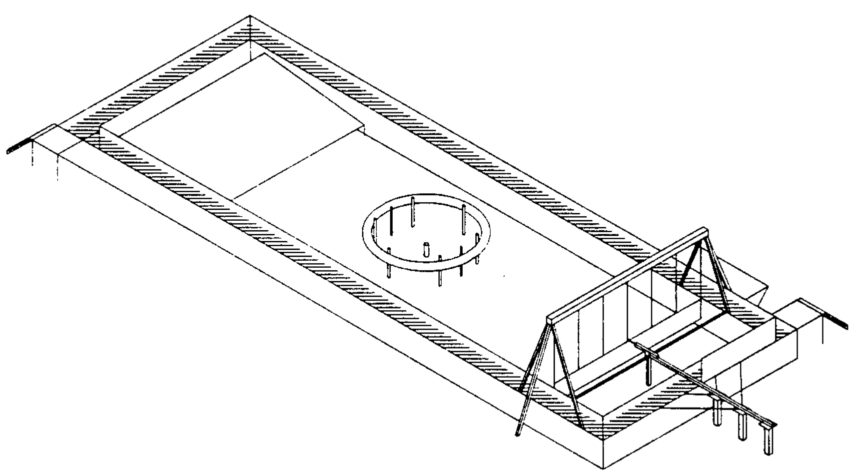


Figure 2. Pictorial view of wave tank

wave paddle was selected to maintain the hinge points out of the water and so that the bottom of the tank would not have to be reinforced. The wave paddle has adjustable steel plates forming the paddle face which move the water. The plates extend across the width of the tank to within 80 mm (3 in) of the sides of the tank and are positioned 0.58 m (1.9 ft) above the tank floor and extend to 0.38 m (1.25 ft) above the still water level.

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 pan. The hydraulic cylinder is powered with a hydraulic pump driven with 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 reverses strokes to reduce stress on the paddle when changing direction. The piston motion is set to 280 mm (11 in) 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 pan area and extends from 6.1 m (19.8 ft) to 1.0 m (3.25 ft) from the south end of the tank. The north edge of the beach is 0.61 m (2.0 ft) above the tank floor rising to 1.4 m (4.5 ft) above the tank floor at the south edge. The separation of the beach at the south end of the tank allows waves to break on the beach and wash over the end without leaving the tank.

The boom is kept in position during the test by six boom constraints or stanchions. The stanchions are constructed of 1.5 m (5 ft) lengths of 50 mm (2 in) nominal diameter steel pipe and mounted vertically in a pattern forming a circle around the center of the tank. The base of each stanchion is attached to a plate which can be moved along a track attached to the tank floor. The tracks extend radially from the center of the tank. Each stanchion can be moved along the track to form a circular pattern of slightly smaller diameter than the inside diameter of the boom circle. The position of the stanchions was adjusted for each boom such that the boom formed a circle with stanchions around the inside of the circle. The stanchions extend above the water and the tops were plugged. A cooling water supply tube entered the base of the stanchion and extended to the top. Cooling water was pumped through the tube, into the stanchion and discharged at the base.

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 on the boom surface were attempted to determine the temperature of exterior materials. Wave height measurements were made to characterize the wave conditions to which the booms were subjected. 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 55 m (180 ft) south of the burn tank and 2.1 m (6.9 ft) 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 seconds with a computerized data acquisition system.

Two sets of two water-cooled Gardon total heat flux gauges were used in each of the experiments. Each pair of gauges was mounted in a water-cooled fixture with one facing horizontally and one vertically. The center of the vertical face was 250 mm (10 in) above the still water surface and the horizontal face was 320 mm (12.75 in) above the still water surface. The heat flux gauges were mounted inside the boom circle along the north-south centerline of the tank. The vertical faces were toward the center of the boom circle and the horizontal faces upward. The elevation of the gauges was held constant for all burns, even though the freeboard of the booms was different. The radial distance from the gauges to the center of the boom circle was adjusted for each boom as given in Table 1.

Table 1. Radial Distance From Boom Circle Center to Heat Flux Gauges

Boom	**North**	**South**
1	1.12 m (3.67 ft)	1.12 m (3.67 ft)
2	1.55 m (5.08 ft)	1.55 m (5.08 ft)
3	0.99 m (3.25 ft)	1.55 m (5.08 ft)
4	1.04 m (3.42 ft)	1.07 m (3.5 ft)
5	1.60 m (5.25 ft)	1.80m (5.92 ft)

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

The wave profiles were determined from measurements of the water level in the tank. The water level was measured with a vertical cylindrical probe which had a capacitance proportional to the water level in the tank. The effect of 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 seconds. At that recording speed, the water level measures provided a good indication of the wave profile. Since the water level probe could not withstand high temperatures, wave profiles could only be measured without a fire in the tank.

5.0 Boom Description

Five commercially-manufactured fire-resistant booms were used to evaluate the test protocol. The basic features of the booms are given in Table 2. Figures 11, 15, 19, 23 and 27 in Appendix A show photographs of the booms 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 2, "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.

6.0 Test Procedure

Water in the inner tank was lowered to approximately 0.6 m (2 ft) 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. Figure 3 shows a boom being lifted into the tank, and Figure 4 shows a boom setting on the bottom of the tank.

The water level in the inner tank was raised to 1.22 m (4 ft) above the tank floor, and the freeboard and inside diameter of the boom circle was measured from the movable bridge. The movable bridge was then removed from the tank and the water level in the moat brought to the top edge of the tank. Using the inside diameter of the boom circle, the area within the 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.

Table 2. Boom Description

Boom	Manufacturer	Construction	Sections	Freeboard	Average Inside Diameter	Area
1	Applied Fabric Technologies	Fabric with steel covered flotation	continuous curvature	235 mm (9.25 in)	3.71 m (12.2 ft)	10.8 m^2 (116 ft^2)
2	American Marine	Fabric over rigid flotation sections	7	270 mm (10.5 in)	4.34 m (14.2 ft)	14.8 m^2 (159 ft^2)
3	Oil Stop	Water-cooled fabric over flexible flotation	continuous curvature	255 mm (10 in)	4.14 m (13.6 ft)	13.5 m^2 (151 ft^2)
4	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)
5	Kepner Plastics Fabricators	Fabric over flexible flotation	continuous curvature	240 mm (9.5 in)	5.08 m (16.7 ft)	20.3 m^2 (218 ft^2)

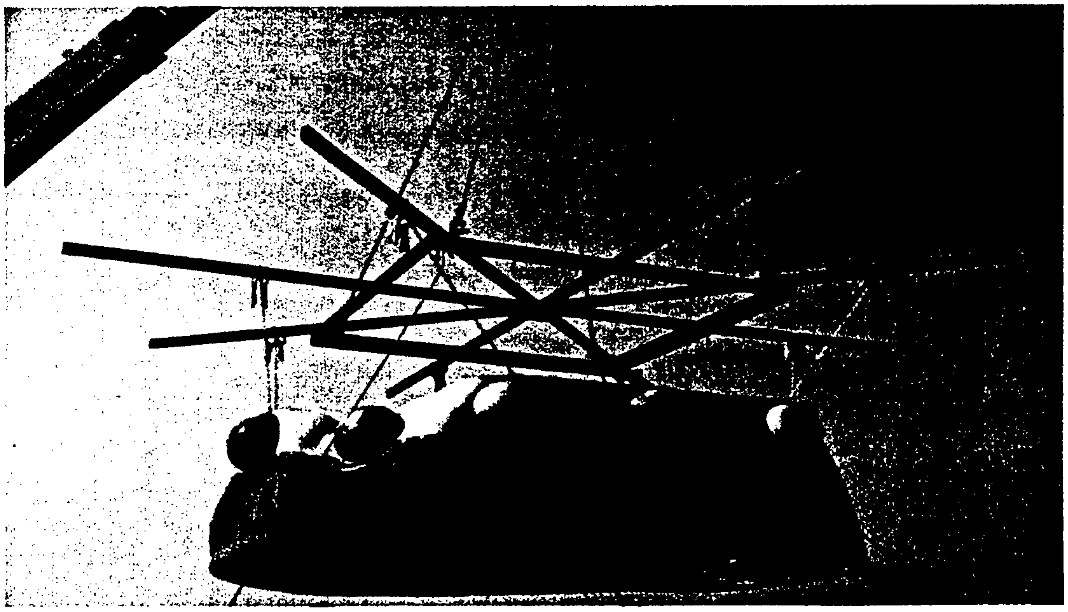


Figure 3. Boom being lifted into tank

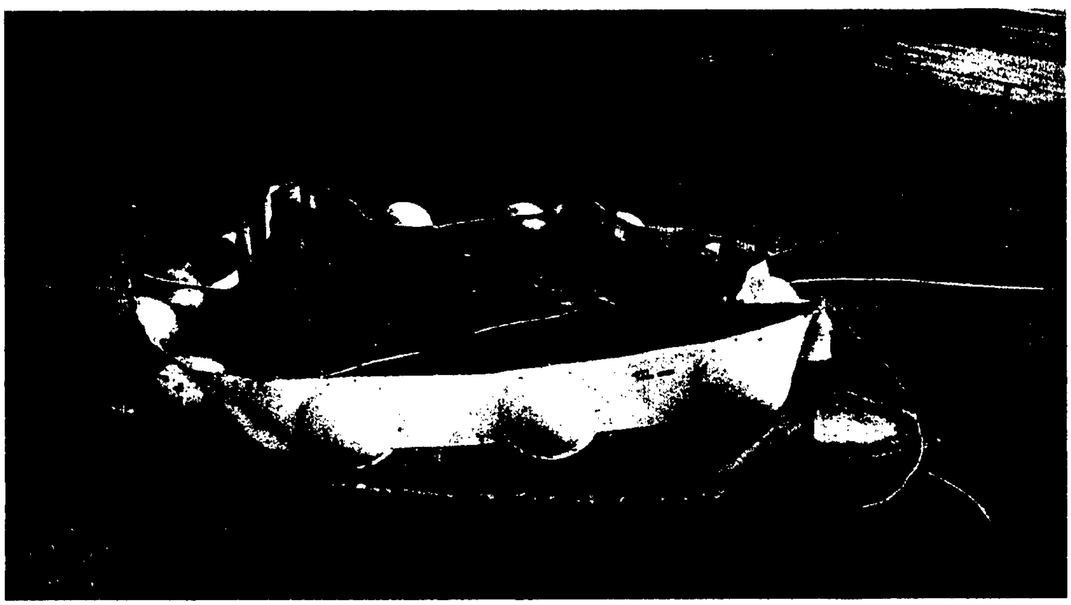


Figure 4. Boom setting on tank floor

After performing a safety check, the cooling water to the stanchions, 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. Three burns were conducted on each boom according to ASTM-F20 protocol. 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 terminated according to protocol, 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 the 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 5 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.

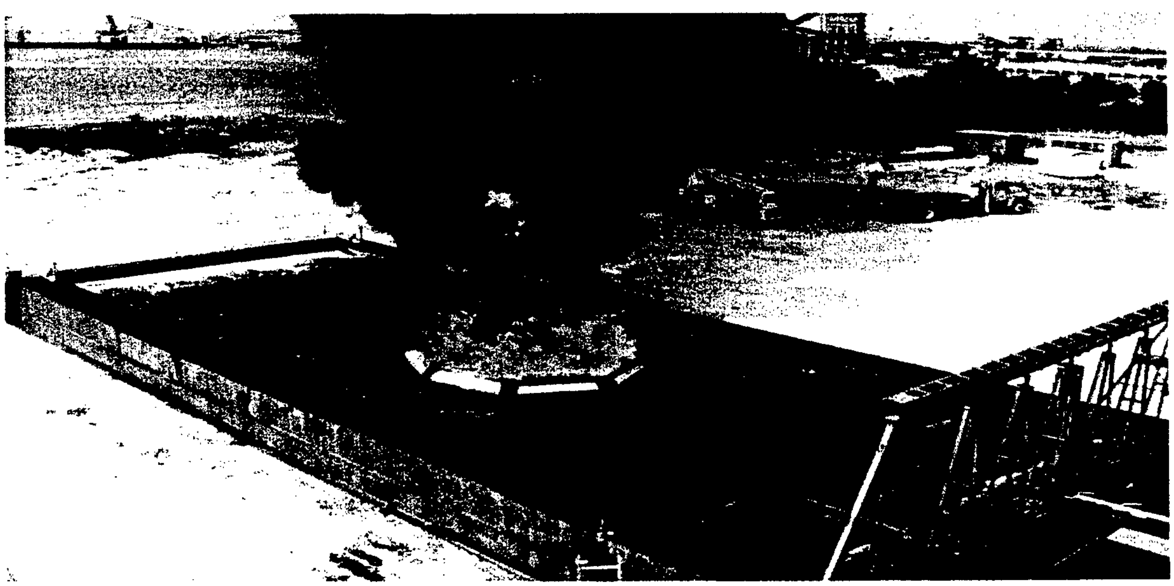


Figure 5. Wave tank with burn in progress

7.0 Measurement Results

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

7.1 Meteorological Conditions

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

7.2 Wave Observations and Measurements

Observations during the tests showed a wave being generated with each complete cycle of the wave paddle. Since the wave paddle changed direction quickly, small waves were superimposed on the principal wave at the end of each stroke. These small waves dissipated as the principal wave traveled down the tank. When the paddle motion was started at the beginning of a test, the first waves traveling down the tank were smooth with no chop observed. As the waves reached the boom and beach, there were reflections resulting in the appearance of random ripples or chop on the principal wave structure. When waves reached the boom, the wave energy was concentrated along the edges of the tank. Along side the boom the waves appeared to approach breaking and the wave crests were 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.

A series of wave measurements was made following the test with the last boom while the boom was still in the tank. A diagram of the measurement points is shown in Figure 6. The measurement points were 5 m (16 ft), 8 m (26.2 ft) , 12.25 m (40.2 ft), and 16.5 m (54.1 ft) from the wave paddle and 0.9 m (3.0 ft) and 1.8 m (6.0 ft) from the inside edge of the tank. A single probe was used and moved amongst the measurement points. Figure 7 shows the typical wave patterns for the six measurement points. From this figure it can be seen that the period of the waves was approximately 4 seconds. The waves at all six points show similar patterns. For the wave closest to the wave paddle, the small superimposed waves can be seen. The wave farthest from the wave paddle has a higher base height than the waves closer to the paddle. This appears to be due to the accumulation of water near the beach and the reflection of waves from the beach, since the height increased from paddle start time until it reached the steady value shown.

Table 3. Ground meteorological conditions

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

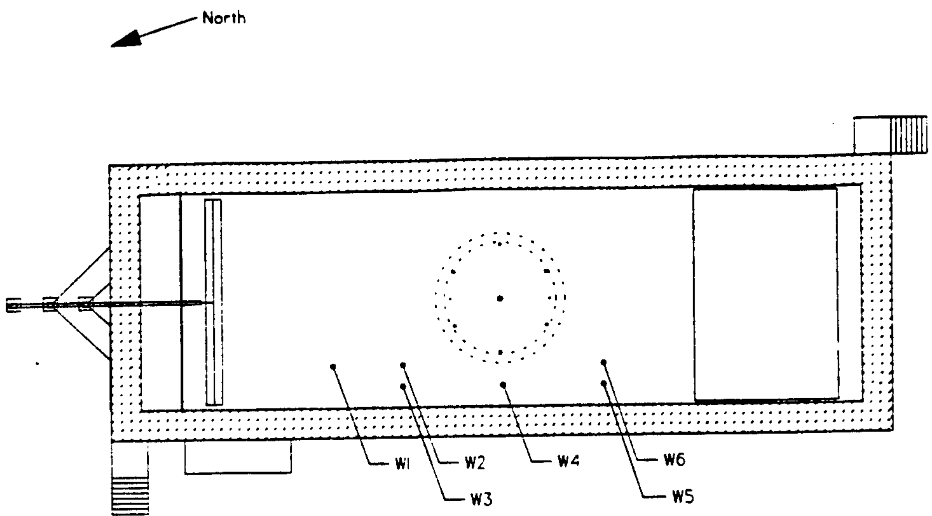


Figure 6. Wave measurement points

Figure 7 can also be viewed as a geometric representation of the wave patterns with the x axis being distance instead of time. Since the waves were traveling at a speed of approximately 1.8 m/s (5.8 ft/s), 4 seconds would correspond to a distance of 7.1 m (23.2 ft). The wave patterns are distorted in this view in that the scales on the axes are not the same resulting in an exaggeration of the wave shape in the vertical direction. The measured wave length and speed do not correspond to those predicted from linear wave theory (Leenknecht, *et al.*,1992). Using an average wave height of 15 cm (0.5 ft), a water depth of 1.22 m (4 ft) and a period of 4 seconds yields a velocity of wave propagation of 3.28 m/s (10.8 ft/s) and a wavelength of 13.1 m (43.1 ft). The difference in the measured and predicted wavelength may be due to the reflections from the beach and the boom, the length of the tank and the use of a top pivoted wave paddle.

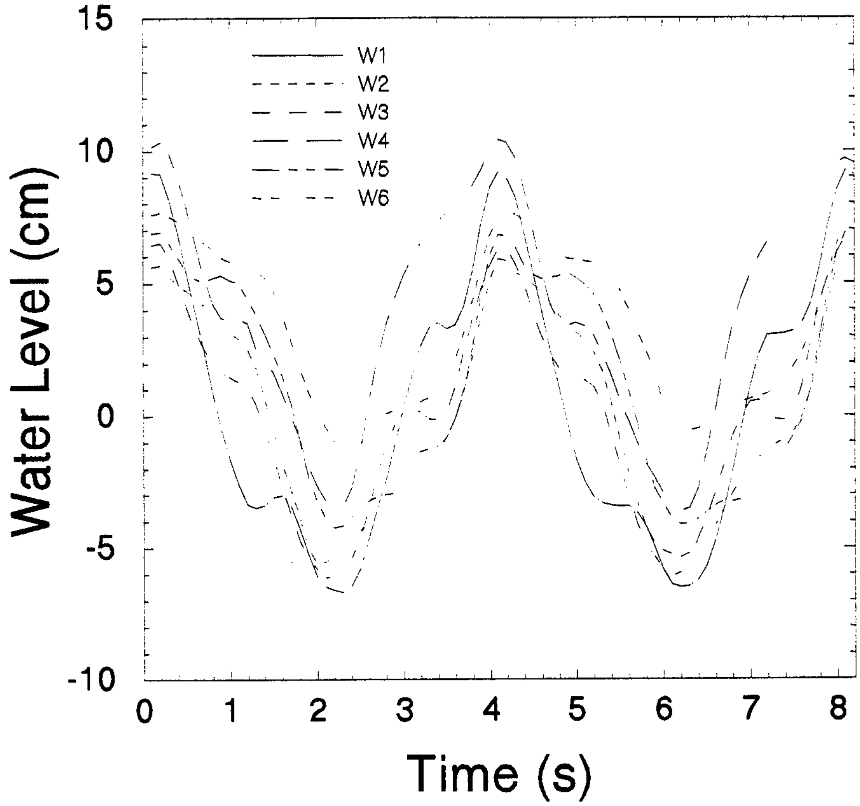


Figure 7. Wave profiles

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 (5.4 gal/hr-ft^2). Table 4 gives the total quantity of fuel used for each burn with each boom. The initial quantity of fuel placed in the boom corresponded to a burn time of five minutes and an initial fuel depth of 18 mm (0.72 in). Since fuel was added at the rate it burned, the fuel depth would remain approximately constant until the last five minutes of the burn when the fuel supply was terminated.

Table 4. Fuel Quantity

Boom	Burn 1	Burn 2	Burn 3
1	2363 L (624 gal)	2310 L (610 gal)	2306 L (609 gal)
2	3244 L (857 gal)	3244 L (857 gal)	3244 L (857 gal)
3	1856*L (490 gal)	3085 L (815 gal)	
4	2601 L (687 gal)	2515 L (664 gal)	2515 L (664 gal)
5	4449 L (1175 gal)		

* Burn terminated before 1 hr

7.4 Burn Chronology

Table 5 gives the burn chronology for each of the booms in hours, minutes, and seconds. Zero time is the time at which burning covered the entire fuel surface within the boom area and the fuel flow was started. This zero 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 four minutes of the desired burn time for all booms except boom 3, the water-cooled boom. This indicates the burning rate for diesel fuel and the area of the fuel used were relatively accurate. For boom 5, the manufacturer decided to terminate the test after the first cool down cycle after observing a problem with the boom.

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

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

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

* terminated due to oil loss

** burns 2 and 3 conducted 3 days after burn 1 due to weather constraints

*** fuel loss from boom

7.5 Heat Flux Measurements

Table 6 gives the mean heat flux as measured by the two heat flux gauges in the north end of the fire and the two gauges in the south end of the fire. Also shown in these tables are the maximum and minimum values measured during the burn and the uncertainty given by one standard deviation. The

Table 6. Heat Flux

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

heat flux gauges respond quickly to changes in the fire and substantial fluctuation is normal for these measurements. The gauges were mounted inside the boom on stanchions since it was impractical to develop custom mounting for each boom construction. As a result, the heat flux measurements are only an indication of the total heat flux to the boom and may not represent the actual value. Further, since the sector of boom that received maximum thermal exposure changed with wind direction, the measurements may not indicate the maximum exposure.

Table 6 shows that the vertical face gauge generally measured a higher heat flux than the horizontal face gauge. The heat flux measured ranged from near 0 kW/m^2 to over 200 kW/m^2. The maximum means ranged form 77 kW/m^2 to 100 kW/m^2 for the non-water cooled booms. These are lower than the 100 kW/m^2 to 150 kW/m^2 averages previously measured for liquid pool fires (Walton, *et al.*, 1977). This is most likely a result of gauge placement and wind fluctuation. In the previous tests, the gauges were placed at the edge of the fire in the position where the boom would be. There were periods in the present tests where the mean total heat flux was in the range measured in the previous tests, particularly at the beginning of a burn. After a number of burns, soot was observed on the face of the heat flux gauges, indicating the gauges were in a fuel rich area of the fire. That is, the gauge was in the area between the fuel surface where the fuel was being vaporized and the combustion zone above the fuel surface. Total heat flux in this fuel rich area would typically be lower than in the combustion zone.

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

8.0 General Observations

In general, as would be expected, there was some degradation of materials in all of the booms. Table 7 summarizes the condition of each of the booms at the end of the test. Appendix A shows photographs of each of the booms before, during, and after the test. A close-up view of the boom after burning is also shown. It appeared that the booms had not reached a steady state condition in terms of degradation. That is, for most of the booms, if they had been subjected to further fire exposure, one would have expected further material degradation to take place. Since the principal purpose of this project was to evaluate the test protocol, the booms were not rated as passing or failing; however, as mentioned previously, two of the booms did not complete the full test protocol burn cycle.

Although five booms of differing construction were used to evaluate the test protocol and each boom performed somewhat differently, several general observations were made in all of the burns. First, the burn characteristics were substantially influenced by 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.

Table 7. Condition of the booms at the end of the test

Boom	Observations	Notes
1	Degradation of the fabric coating, fabric substrate visible	Abrasion and tears in the area of the stanchions
2	Loss of sacrificial cover, some degradation of the fabric beneath the metal mesh near the joints	Small fuel leak at connector after burn 1
3	Damage to the cover and flotation in a portion of the boom, no visible change to the rest of the boom	Test terminated after the first burn when the cooling water was shut down
4	Tears and holes in the boom on the downwind side	
5	Loss of sacrificial cover, tears in the fabric along some of the coils	Abrasion and tears in the area of the stanchions - test terminated after 1 hour of burning

There is no known practical way to control the wind during the burns to ensure complete uniform exposure over time. The possibilities would include conducting the tests only when the wind speed and direction were within a narrow window and unlikely to change over the course of a test. This condition would be very difficult to meet at the test site. Another possibility would be to surround the test tank with a wind screen which would not only be difficult, but very costly. Finally, providing large fans which could overcome the wind and impose air velocity would also be difficult and prohibitively expensive.

A second phenomena observed for all of the booms was intermittent burning outside of the boom. Figure 8 shows normal burning, Figure 9 shows burning beginning outside the boom, and Figure 10 shows significant burning outside of the boom. Although it might appear that oil had leaked under or through the boom, it looks as though 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 (3.3 ft) to 2 m (6.6 ft) 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 with the burning area within a few meters of the boom.

Figure 8. Normal burning

Figure 9. Burning beginning outside boom

Figure 10. Burning outside boom

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

9.0 Issues and Conclusions

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

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

2) How does wind speed and direction affect the thermal exposure to boom? The impact of the wind speed and direction on the thermal exposure are difficult to quantify. Observations of the booms following the tests show, as would be expected, greater degradation in the downwind direction than in either the crosswind or upwind directions. A significant number of heat flux gauges would be required to characterize the thermal exposure over the entire area of the boom. Even if these measurements were available, they would be difficult to use for adjusting the test results for wind speed and direction. Since the tests have to be conducted outdoors, the fact that tests will be conducted with differing wind speeds and directions should be considered in developing evaluation criteria.

3) Do thermocouples provide an adequate measurement of fire intensity? Mounting thermocouples on the boom proved difficult due to the wide variety of boom constructions. Heat flux measurements around the boom would provide the best measure of thermal exposure, but these are also difficult to attach to the boom and a significant number would be required to adequately profile the thermal exposure along the length of the boom. Heat flux measurements inside the boom circle appear to result in lower measured heat fluxes than the heat fluxes expected at the boom. It is recommended that heat flux gauges and thermocouples be mounted just outside the boom circle and above the top of the boom. At that location, the heat flux gauges and thermocouples would be in the area of maximum heat flux and temperature while not in contact with the boom. During the test series, the burning rate of diesel fuel appeared to be relatively constant for the fire sizes used. This would lead to the conclusion that measuring temperature and heat flux for each test may not be necessary.

4) Is the test protocol adequate for water-cooled booms? Although only one water-cooled boom was tested, and none of the burns with that boom were completed, it appears that cooling water affects the burning rate. If water cooling affected the burning rate in the same way for an at-sea burn then the test would be a reasonable representation of a real burn. If water vapor from the boom is responsible for the change in burning rate then the use of the relatively small circle in the test may enhance the effect. Further tests with water-cooled booms will be required to verify that a reduction in burning rate takes place and if it does, to quantify the reduced burning rate.

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

6) Should replicate tests be required? When evaluating a test method, it is usually desirable to conduct multiple tests with the same product to determine if the method is repeatable. Production and prototype fire booms are expensive to manufacturer and the tests are expensive to conduct.

7) What criteria should be used to terminate a test before the complete burn cycle has been executed? In the case of a substantial oil loss it is impossible to continue the burn and the test must be terminated. A small oil leak around the connector was noticed with one of the booms when the oil was added to the boom at the start of the second burn. In this case, the test was continued without significant impact on the test. This indicates that tests need only be terminated if there is a significant loss of fuel.

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

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

10.0 Acknowledgments

This work was funded by the Research and Development Center, U.S. Coast Guard and the Technology Assessment and Research Branch, Minerals Management Service, U.S. Department of Interior. The tests were conducted under the technical direction of Doug Walton of the Building and Fire Research Laboratory, National Institutes of Standards and Technology. Dave Beene of the Coast Guard Research and Development Center, and the Fire and Safety Test Detachment in Mobile, Alabama, under the direction of Chief Warrant Officer Byrd, provided outstanding assistance in preparing for and conducting the tests.

11.0 References

Bitting, K. and Coyne, P.M., "Oil Containment Tests of Fire Booms," Proceedings of the Twentieth Arctic and Marine Oilspill Program (AMOP), Environment Canada, Ottawa, Ont., pp. 735-754, 1997.

Buist, I.A., Ross, S.L., Trudel, B.K., Taylor, E., Campbell, T.G., Westphal, P.A., Myers, M.R., Ronzio, G.S., Allen, A.A., and Nordvik, A.B., "The Science, Technology and Effects of Controlled Burning of Oil Spills at Sea," Marine Spill Response Corporation, Washington, D.C., MSRC Technical Report Series 94-013, 328p., 1994.

Leenknecht, D.A., Szuwalski, A, and Sherlock, A.R, "Automated Coastal Engineering System," Waterways Experiment Station, Corps of Engineers, Dept. of the Army, Vicksburg, MS, Version 1.07, 1992.

McCourt, J., Buist, I. Pratte, B., Jamieson, W., and Mullin, J., "Testing Fire Resistant Boom in Waves and Flames," Proceedings of the Twentieth Arctic and Marine Oilspill Program (AMOP), Environment Canada, Ottawa, Ont., pp. 823-839, 1997.

Walton, W., Evans, D., McGrattan, K., Baum, H., Twilley, W., Madrzykowski, D., Putorti, A., Rehm, R., Koseki, H., and Tennyson, E., "*In Situ* Burning of Oil Spills: Mesoscale Experiments and Analysis," Proceedings of the Sixteenth Arctic and Marine Oilspill Program (AMOP), Environment Canada, Ottawa, Ont., pp. 679-734, 1993.

Walton, W., McElroy, J., Twilley, W., and Hiltabrand R., "Smoke Measurements Using a Helicopter Transported Smoke Sampling Package," Proceedings of the Seventeenth Arctic and Marine Oilspill Program (AMOP), Environment Canada, Ottawa, Ont., pp. 735-764, 1994.

Walton, W., McElroy, J., Twilley, W., and Mullin, J., "An Evaluation of Propane as a Fuel for Testing Fire-Resistant Oil Spill Containment Booms," Proceedings of the Twentieth Arctic and Marine Oilspill Program Technical Seminar, Ministry of Supply and Services Canada, pp. 755-767, 1997.

Appendix A. Boom Photographs

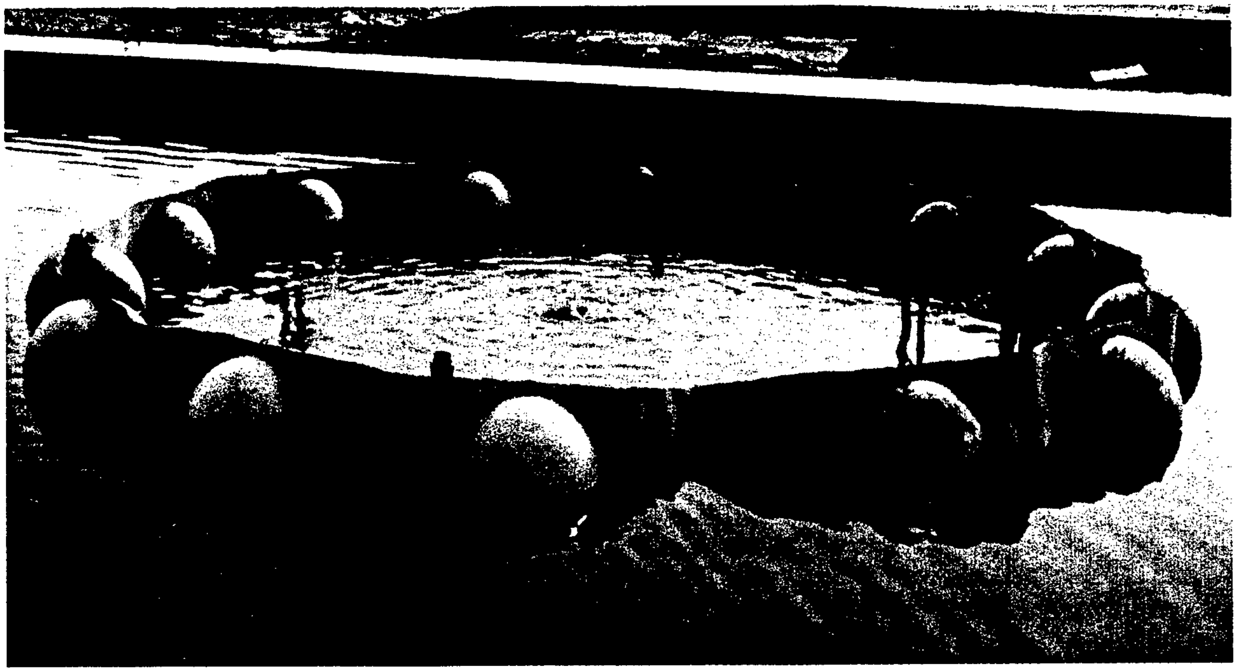


Figure 11. Boom 1, before burning

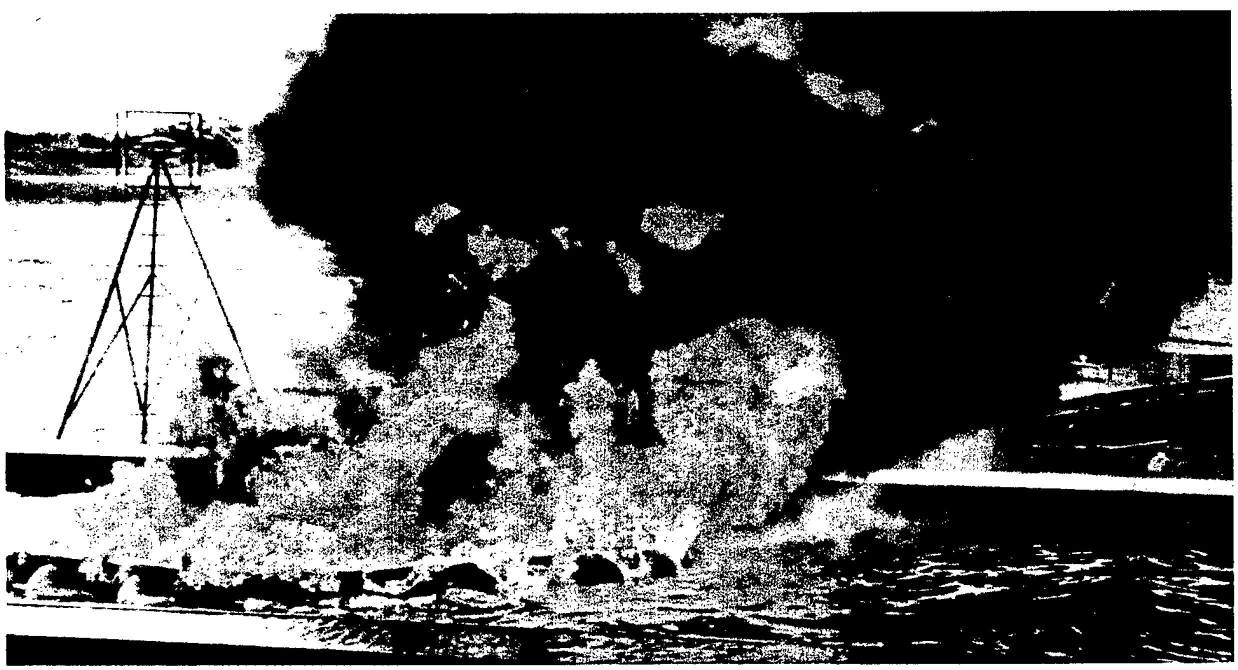


Figure 12. Boom 1, during burning

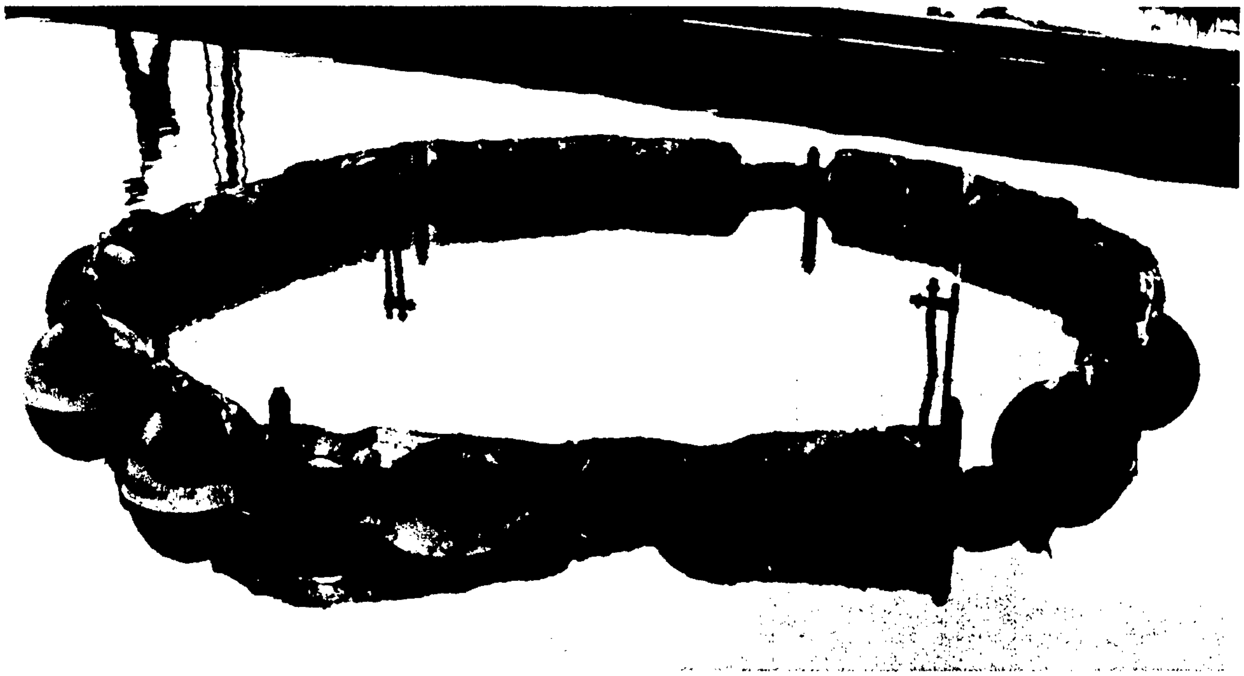


Figure 13. Boom 1, after burning

Figure 14. Boom 1, after burning close-up

Figure 15. Boom 2, before burning

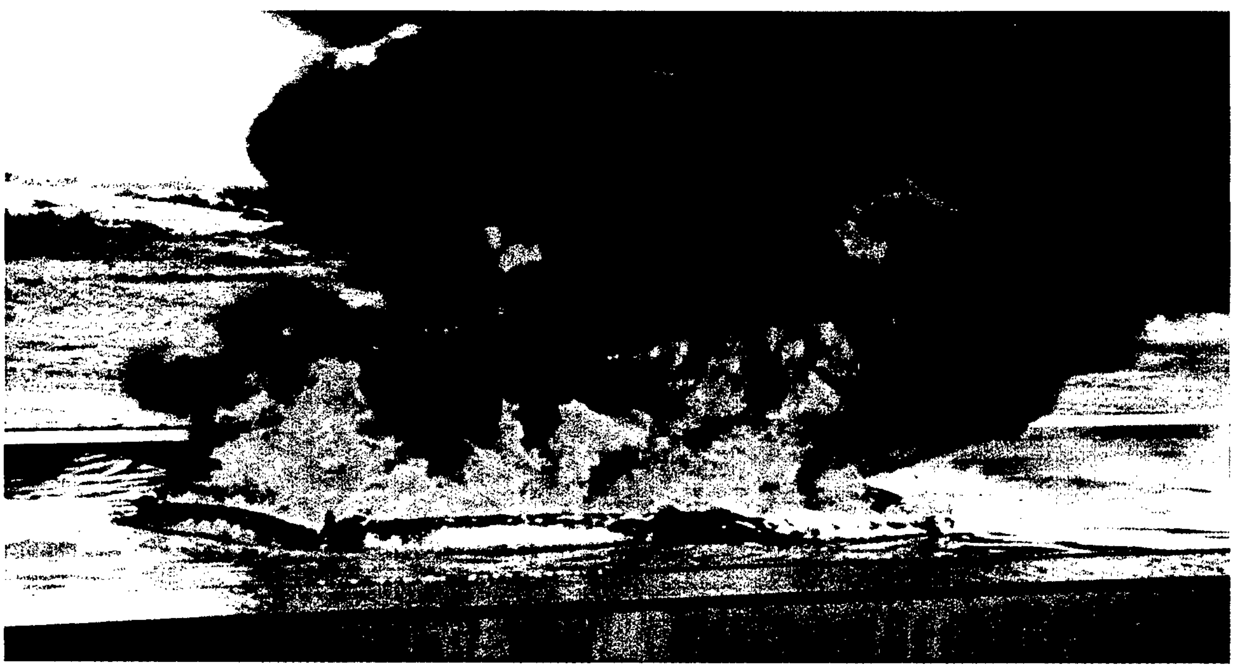


Figure 16. Boom 2, during burning

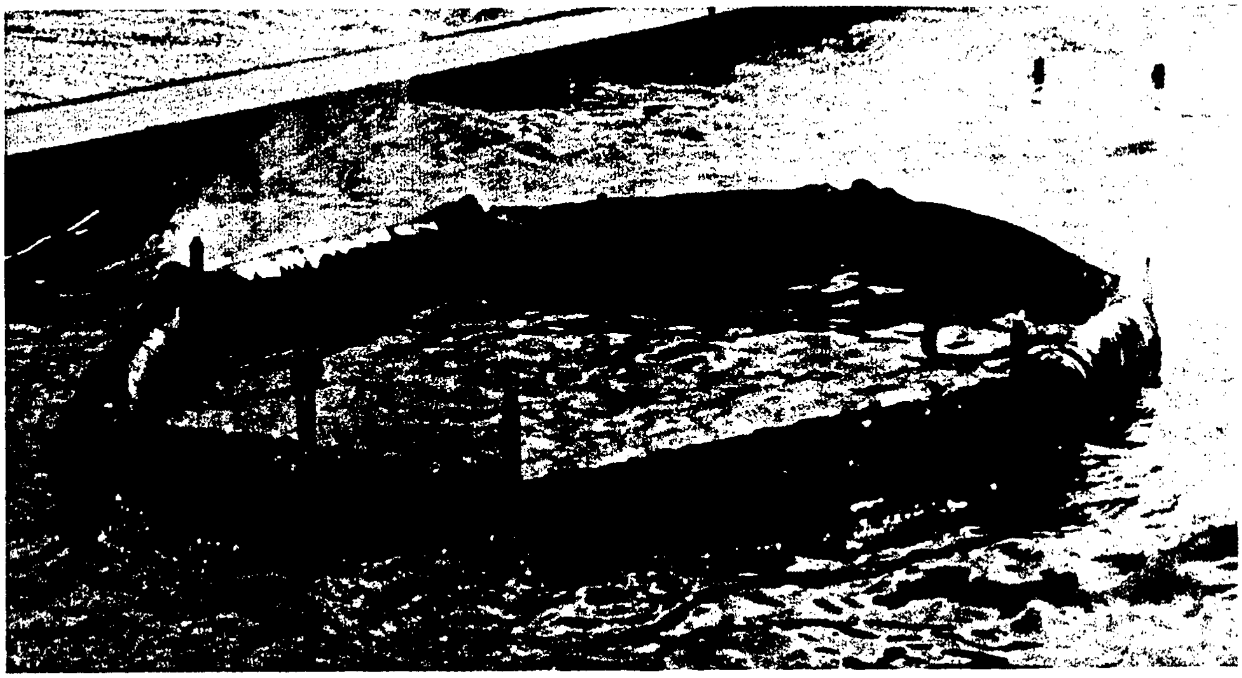


Figure 17. Boom 2, after burning

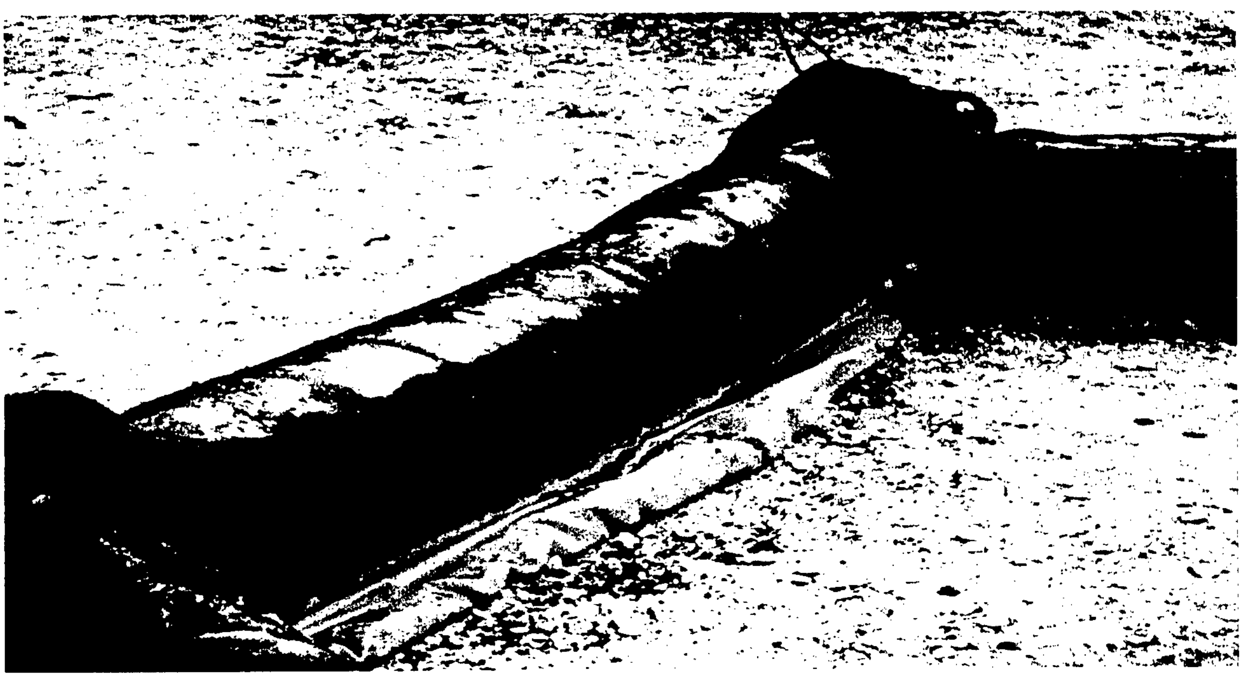


Figure 18. Boom 2, after burning close-up

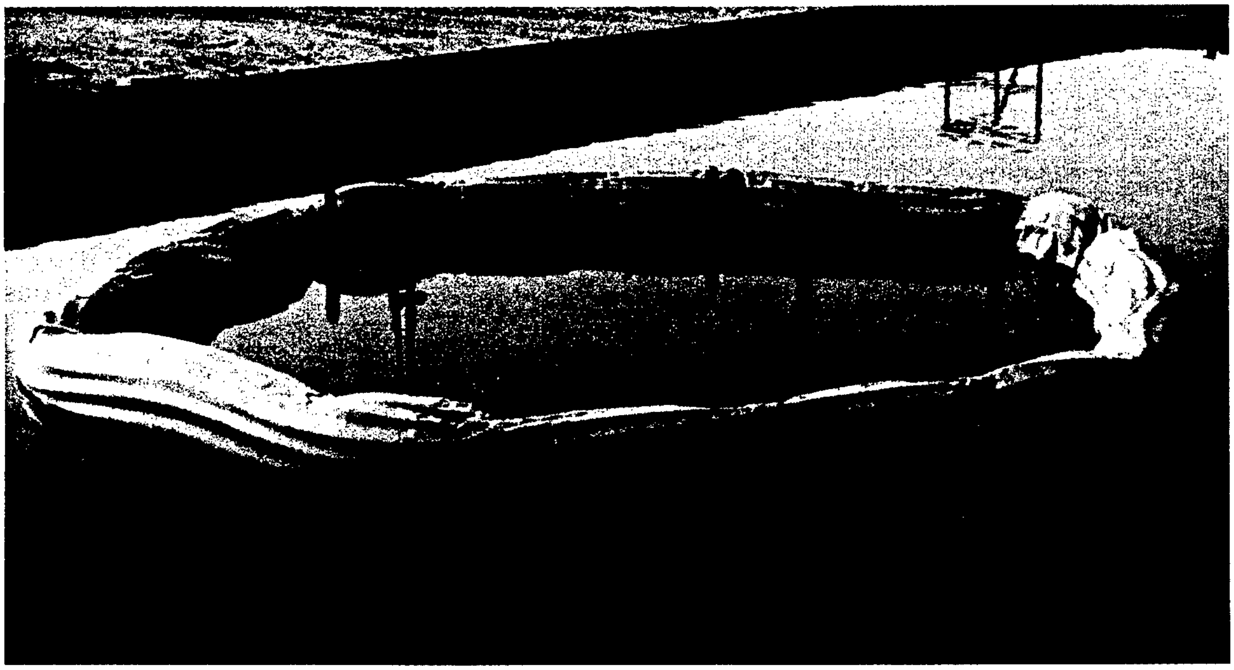


Figure 19. Boom 3, before burning

Figure 20. Boom 3, during burning

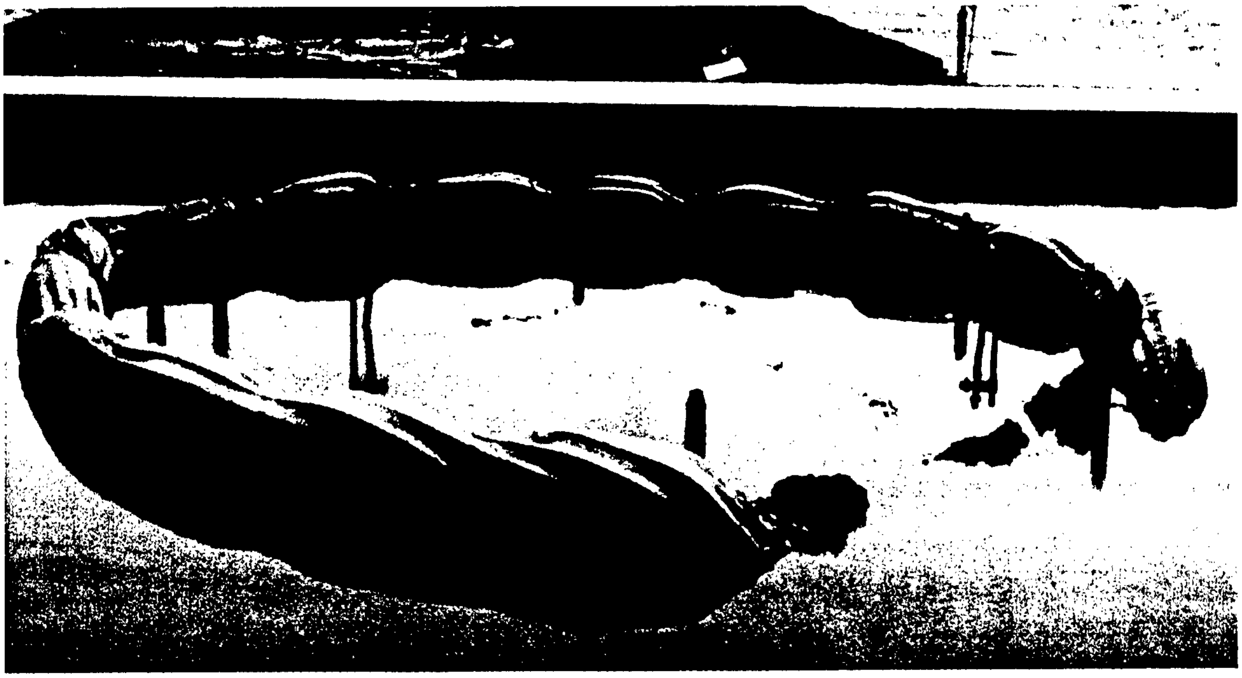


Figure 21. Boom 3, after burning

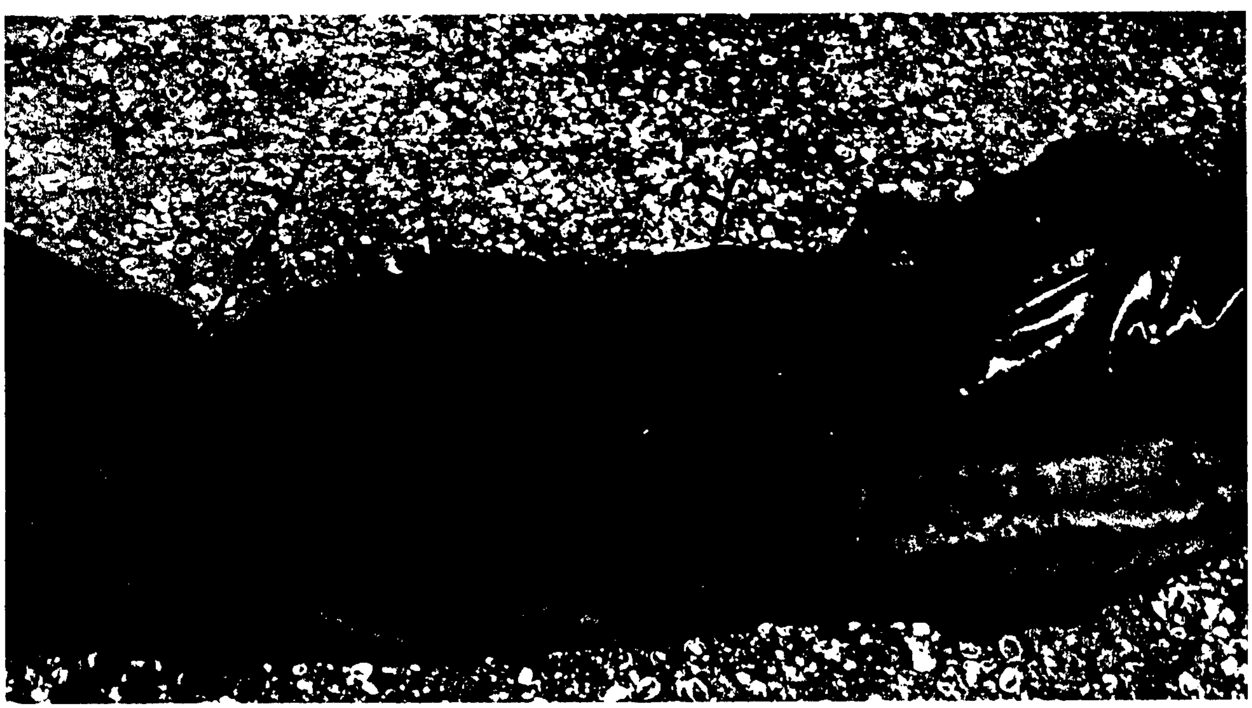


Figure 22. Boom 3, after burning close-up

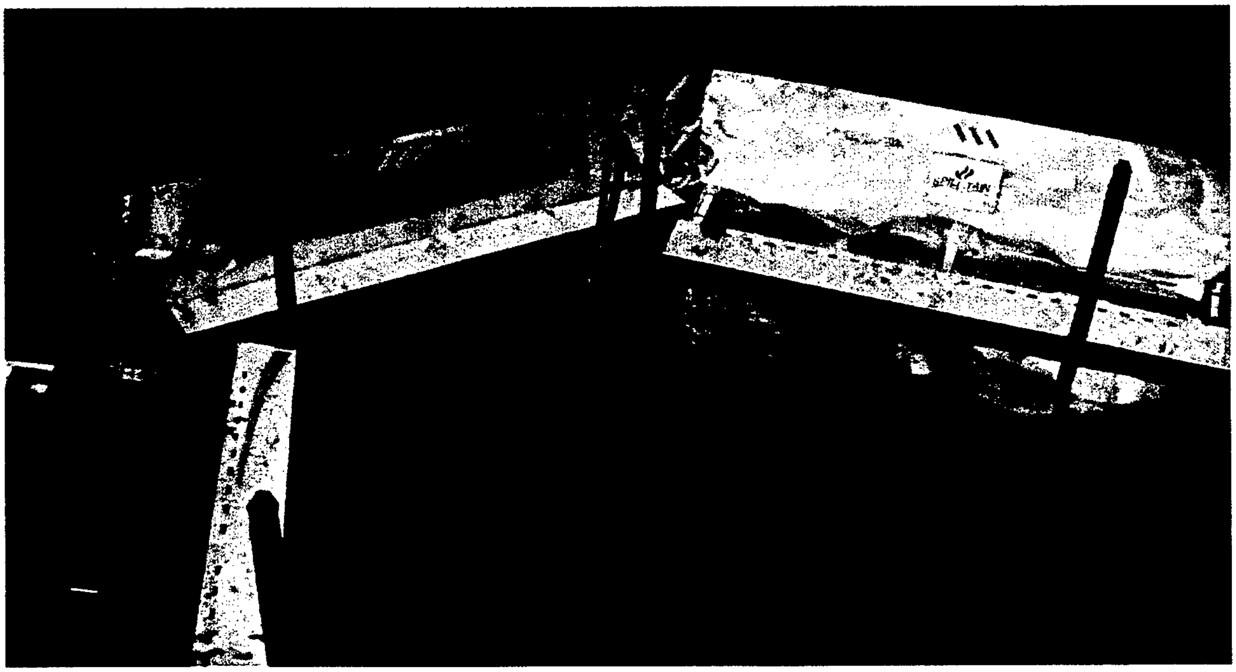


Figure 23. Boom 4, before burning

Figure 24. Boom 4, during burning

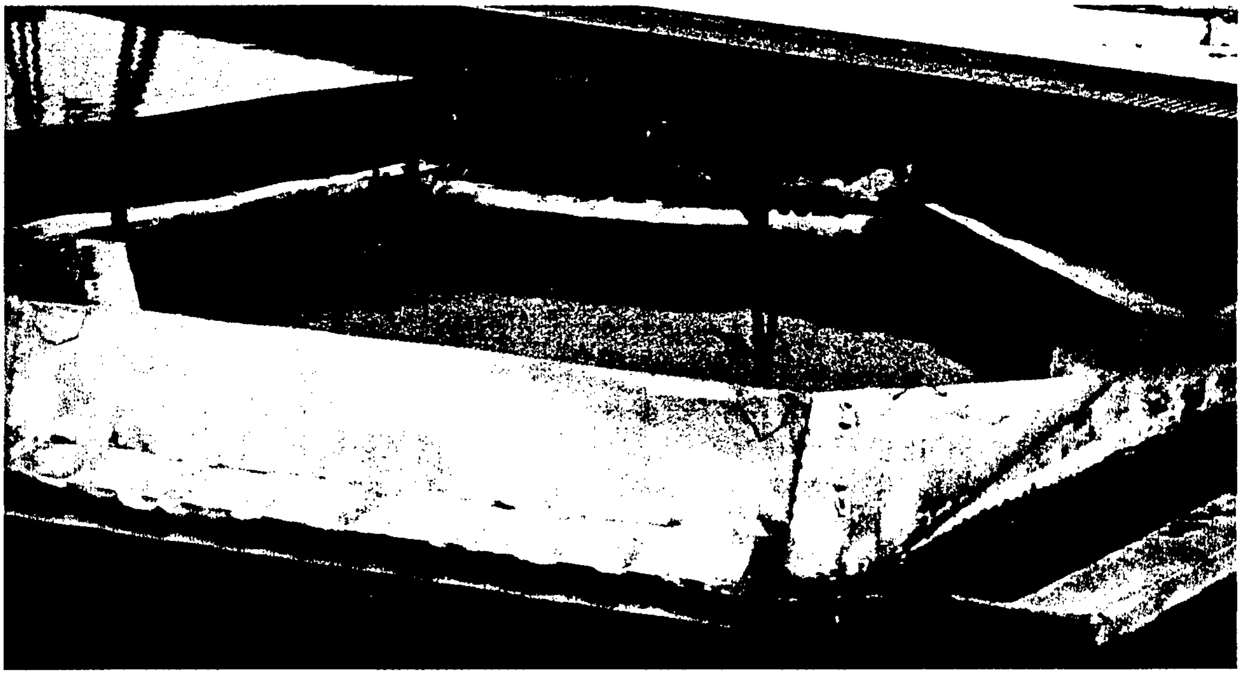


Figure 25. Boom 4, after burning

Figure 26. Boom 4, after burning close-up

Figure 27. Boom 5, before burning

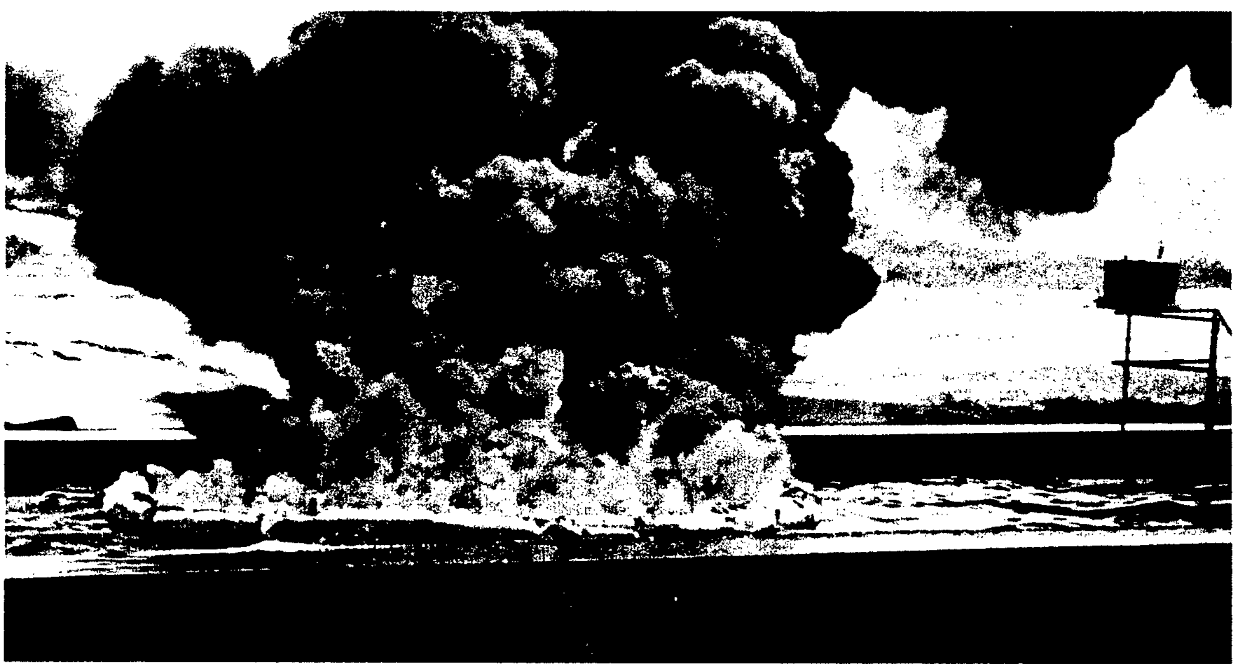


Figure 28. Boom 5, during burning

Figure 29. Boom 5, after burning

Figure 30. Boom 5, after burning close-up