Continued Development of a Test for Fire Booms in Waves and Flames

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Abstract

A near full-scale screening test protocol was developed in 1996 that evaluates a fire resistant boom's durability and its ability to contain oil during an *in situ* burn. Benchmarking the screening test protocol showed that it reproduced the correct stresses (both mechanical and heat) of an *in situ* burning operation, but that their intensity needed to be increased. This was accomplished in 1997, with the most significant change being the enhancement of the heat flux to the boom by increasing the flow of propane per unit surface area by a factor of three and injecting compressed air into the base of the flame.

The revised fire exposure portion of the test protocol was benchmarked in October 1997. These tests involved exposing a 15 m section of the NOBE fire boom to four one-hour cycles of enhanced propane flames and waves and four one-hour cycles of waves alone. The sustained average heat fluxes ranged from 110 to 130 kW/m^2 with some averages as high as 150 kW/m^2, a significant increase over earlier measured heat fluxes from propane fires and in line with heat fluxes from diesel and crude oil fires. Temperatures on top of the test section of boom ranged from 900 to 1100°C. After the second burn cycle, the boom was beginning to show signs of deterioration. By the end of the third burn cycle the boom fabric was obviously severely degraded and would not have contained oil at the vertical stiffeners exposed to flames. On completion of the fourth cycle there were large holes in the membrane at the vertical stiffeners and severe damage at the sides and the top of adjacent float sections. This is consistent with the damage observed at NOBE and in the same fire exposure time frame.

1.0 Introduction

A near full-scale test protocol was developed in 1996 that evaluates a fire resistant boom's durability and its ability to contain oil during an *in situ* burn without the environmental problems of burning crude oil or the costs of testing offshore. The screening test was comprised of four discrete stages:

1. The pre-burn wave stress stage, where the test boom was flexed under tension in waves to simulate deployment of the boom and transit to the spill site.
2. The burn in waves stage, where the test boom was exposed to waves and repeated one hour cycles of a propane gas fire to simulate oil burning operations.
3. The post-burn wave stress stage, where the test boom was again flexed under tension in waves to simulate retrieval of the boom.

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4. The oil-containment stage, where the ability of the boom to contain thick pools of hot oil was assessed.

The screening test is described in detail in SL Ross, 1997, and summarized in McCourt et al., 1997.

The key to the screening test is the fire system for the burn stage. This is an underwater bubbler that distributes propane gas to an area adjacent to a section of fire-resistant boom. The heat from the burning propane is meant to simulate that generated by burning crude oil. Using propane gas offers the advantages of:

1. easy fire control and safety;
2. no tainting of the water in the test tank with an oil product; and
3. no visible or noxious emissions.

The 1996 screening test protocol was benchmarked using a section of fire-resistant boom obtained from the Canadian Coast Guard that was the same as the one used in the Newfoundland Offshore Burn Experiment (NOBE). Comparing the damage suffered at NOBE with that produced by the test led to the conclusion that the protocol reproduced the correct stresses (both mechanical and heat) of an *in situ* burning operation, but that their intensity needed to be increased. Three recommendations were made after the 1996 test program, all of which centered on the burns-in-waves stage of the screening test:

1. Increase the heat generated by the fire.
2. Increase the tension on the boom.
3. Improve the data acquisition system.

The objective of the current program was to implement these recommendations and improve the screening test protocol so that it produced the same degree of damage to the benchmark fire-resistant boom in the same time frame as was noted at NOBE (almost 3 hours of exposure to fire). This was accomplished as follows.

1.1 Increase Generated Heat

Heat release rates for *in situ* oil fires on water range from 1.76 MW/m^2 for ANS crude to 2.34 MW/m^2 for diesel fuel (McGrattan et al., 1997). The heat release rate for a liquid propane fire on water, as tested by NIST in 1996 at the USCG test site in Mobile, was about 1.6 MW/m^2 (Walton et al., 1997). The heat release rate for the 1996 fire boom tests using propane gas was about 0.7 MW/m^2 of water surface. This heat release rate, a direct function of the flowrate of propane, was kept intentionally low in order to avoid smoke production from the fire for the initial protocol tests.

It was recommended that the heat flux imposed on the fire boom be increased by a factor of three (to 2.1 MW/m^2), while maintaining a nearly-smokeless burn. This was accomplished by increasing the propane flow rate almost threefold and by adding compressed air to the fire to speed up the combustion reaction, and thereby further increase the heat, and also to help control smoke generation.

1.2 Increase Boom Tension

The 1996 screening test protocol specified that the boom be deployed in a U-configuration. The boom was tensioned by a current generator, installed at the mouth of the boom. This consisted of three banks of nozzles connected to a 25 kW, high pressure pump. The water from the nozzles entrained surrounding water and created a current approximately 6 m wide and 1 m deep at the mouth of the boom. At full flow, a current of 0.6 m/s was measured. Unfortunately, this magnitude of current dampened the wave action and boom motion in the pocket, and it was decided to carry out most of the testing with a current of only 0.2 m/s. This was sufficient to maintain the shape of the catenary, but imparted very little tension in the boom (about 90 N).

It was recommended that the tension be increased to a more realistic value, on the order of 900 N (Nordvik et al., 1995). This was done by dispensing with the current generator and positioning the boom lengthwise along the tank and tensioning it with long cables and winches.

1.3 Improve Data Acquisition

Whenever the sensors that measured the heat flux and flame temperatures contacted the steel components of the fire-resistant boom in the 1996 tests (which happened often in waves), a ground loop was set up that caused the readings to fluctuate wildly. The instrument raft and its connection to the fire boom were modified midway through the 1996 tests in order to overcome this problem.

It was recommended that for future tests the wiring and mounting of the heat flux transducers and thermocouples be re-designed. To accomplish this, the total heat flux transducers (THFTs) were mounted directly on the boom and the thermocouples were embedded in the boom fabric to more accurately measure the conditions to which the boom was subjected. To control electrical interference, shielded wire was used for the thermocouples and twisted pair wire was used for the THFTs. Also, the thermocouples and THFTs were grounded.

2.0 Full-Scale Equipment and Setup

A schematic representation of the test site, showing the layout of key pieces of equipment, is given in Figure 1. The equipment at the site was composed of five subsystems:

1. The test tank
2. The propane system
3. The air system
4. The fire-data acquisition system
5. The test boom.

2.1 Test Tank

The tests were conducted at site M-42 on the Montreal Rd campus of the National Research Council of Canada in Ottawa. This is the Canadian Hydraulic Centre's (CHC) Outdoor Ship Maneuvering Basin (OSMB), which measures 120 m long, 60 m wide and 3.3 m deep. A pneumatic wave machine is located at one end that uses eight blowers and a system of valves to force air into and draw it out of inverted chambers near the water surface. This forces the water surface to fall and rise, and waves to be propagated from beneath the chambers. Both period and amplitude can be controlled and sinusoidal waves up to 0.6 m in height can be generated. The waves used for the burn tests averaged 0.34 m high with periods of approximately 2 seconds.

At the other end of the basin is a short, sloping perforated wave absorber. It is inefficient for long or large waves, reflecting about 17% of the incident energy back into the tank. Reflections created slowly migrating regions of nodes (low waves) and anti-nodes (higher waves) during long tests in the basin that interfered with the

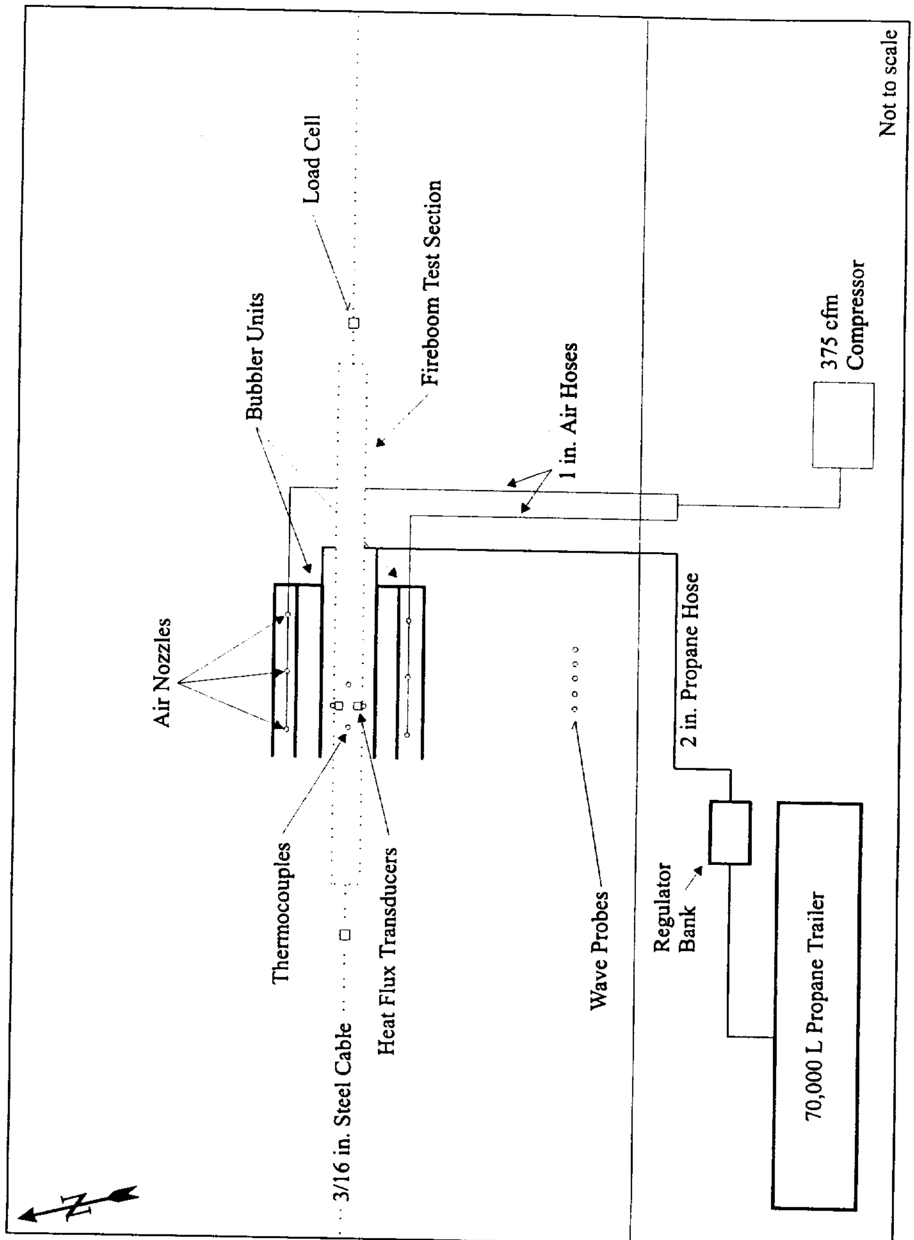

Figure 1 Test equipment layout

predominantly traveling waves. For the purposes of the present tests, however, the wave conditions in the OSMB were quite acceptable.

An array of five, 1 m long, Robertshaw capacitance wire wave probes was mounted on a frame 3 m from the basin side wall. The probes were spaced 0.9 m apart (approximately 1/8 of a wavelength) and centered on the middle of the underwater bubbler. By comparing the readings of each wave probe in the array, it was possible to detect the nodes and anti-nodes of the reflected wave pattern. A VAX computer running NRC's GDAC (data acquisition and control) software, and a Neff A/D converter, were used to sample the voltage output from the wave probes. CHC's GEDAP software was then used to analyze and plot the time series results.

2.2 Propane System

Propane was supplied from a 69,000 L tanker. The propane in the tanker was in two phases: liquid at the bottom of the tank and vapor at the top. Vapor was drawn off the top and fed through a bank of 5 regulators that reduced the pressure from approximately 550 kPa to a near-constant 140 kPa. The pressure of the gas after the regulators was routinely measured with a pressure gauge and the temperature was monitored with a type K thermocouple. A ball valve located just after the bank of pressure regulators was used to start, stop and control the flow of propane to the underwater bubbler.

The flow of propane from the tanker was estimated by taking readings of the %full, liquid temperature and pressure gauges mounted on the side of the tanker. The mass of propane remaining was calculated by determining the density of propane at the tank condition then converting the %full reading to a mass. Periodic readings were taken over the course of a test; the flow rate (kg/hr) was determined by subtracting the calculated mass and dividing by the elapsed time. Repeated readings and calculations while no propane was being drawn from the tanker indicate that this estimating technique was probably accurate to only ± 100 kg/hr or approximately 10% of full flow.

At the time of delivery, the tanker was 82% full (56,580 L) at a temperature of 3°C and a pressure of 476 kPa. As the test were conducted and the gaseous propane was drawn from the tank, it cooled as the liquid propane evaporated. This resulted in a drop in tank pressure as the tests progressed. To keep the cooling as even as possible and to promote warming of the liquid between tests, a recirculation circuit was set up where liquid propane was pumped from the bottom of the tank to the top.

The propane vapor outlet on the tanker was equipped with an emergency safety shutoff valve that is designed to prevent the tank from emptying if the line is accidentally severed. The valve activated if the velocity of propane exiting the tanker exceeded a certain value. During the first full burn cycle, the valve did not activate at full flow (1055 kg/hr); however, the valve activated as the tank cooled (and the density of the vapor increased). This became a problem during the second, third and fourth burn cycles, and the flow had to be restricted to 75 to 80% of full flow.

The propane was carried out to the underwater bubbler attached to the fire resistant boom by a 40-m length of 2-in. hose. At the boom, the 2-in. hose divided into two 2-m lengths of 1 in. hose, one going to each bubbler unit manifold. The 2-in. hose was ballasted with short lengths of iron reinforcing bar (re-bar) so that it remained submerged.

The underwater propane bubbler consisted of two independently fed units. Each unit was made of three 4.1-m long sections of ¾ in. i.d. hose. The hoses were connected at one end to a 1 in. i.d. manifold and capped at the other. The three hoses were held parallel by a framework of four aluminum cross-bars. The hoses were clamped to the bars, 35 cm apart, using U-bolts. The hoses had holes in their underside to release the propane, spaced 40 cm apart, with the holes in the center hose offset 20 cm from the other two to create an "X" configuration. To accommodate the increased flow over the 1996 tests, the 64 holes in the bubbler were enlarged from 2.5 mm to 4.5 mm. One end of the aluminum bars was connected with a carabiner to the ballast/tension chain at the bottom of the skirt of the boom. This allowed the frame to pivot while connected to the boom. The other end of each bar was supported by a 20 L metal float connected by rings and snaps so that it would freely follow the waves. The spacing between floats was maintained by braces between adjacent bars.

An ignition pilot light was mounted on one bubbler unit. This consisted of 1 m of 1.3-cm copper pipe in an L-shape clamped to one of the aluminum cross-bars such that the end of the copper pipe extended above the water surface. The copper pipe had many small (1.6-mm) holes drilled in it, both above and below the waterline, to ensure a steady flow of propane in all wave conditions. The copper pipe was wrapped in Fibrefrax refractory batting to diffuse the propane and provide a large, stable flame in wind. The igniter was independently fed propane from a 9-kg propane cylinder at the side of the test tank. The pilot was manually lit prior to each test.

The underwater propane bubbler was constructed to code by International Code Systems of Markham, ON and connected to the propane supply system by ICG Propane of Toronto, ON. The system met all the regulatory requirements for an outdoor propane burning device. For safety, a technician attended the valves located on the regulators for the entire duration of each burn test. As well, propane gas detectors with audible alarms were placed around the test site.

2.3 Air-Injection System

An air-injection system was constructed and added to the propane bubbler units. The air was supplied by a compressor rated at 11 m^3/min at 690 kPa. From the compressor, air flowed through a 7.5-m long section of 2 in. hose to a manifold where it was split into two hoses, one for each bubbler unit. The flow of air to each unit was regulated with a 1 in. gate valve and measured with an in-line pneumatic flow meter. During operation, the valves were adjusted so that air was flowing equally to both bubbler units. The pressure and temperature of the air were measured with a pressure gauge and type K thermocouple, respectively. From the manifold, the air was fed through 40-m of 1 in. hose, where it was again split in three, one for each nozzle. The hose was weighted with sections of re-bar to keep it submerged.

Each bubbler unit had three air nozzles, spaced equally apart. The air nozzles were 2 in. steel pipes oriented vertically and terminated in a pipe cap. The caps had six equally spaced ½ in. holes drilled around their circumference. Initially, the air nozzles were made buoyant with metal cans but these were changed to Styrofoam floats after the first trial burn (see Section 3.1). Because the air nozzles were made of steel, they were somewhat top-heavy and swayed considerably in waves. To restrict their freedom of movement, the nozzles were tethered to the boom (either with wire or submerged 1/8-in. nylon rope).

2.4 Fire-Data Acquisition System

The fire monitoring equipment on the boom consisted of two total heat flux transducers (THFTs) and two type K thermocouples. A harness was put on the boom floatation unit between the central and west air nozzles. One THFT was attached to the harness on each side of the boom. The harness was fabricated such that the heads of the THFTs could be rotated 360°; three different orientations were used during the tests (see Section 3). The thermocouples were placed on the top of the boom to the east and west of the THFT harness. The tips of the thermocouples pointed upwards at a height of roughly two to three centimeters from the surface of the boom.

Output signals from the THFTs and the thermocouples were fed to an amplifier and multiplexer board and then to an analog/digital conversion card in an IBM-compatible personal computer, sampling once every three seconds.

2.5 Test Boom

The section of fire-resistant boom utilized for this test was one that had been deployed at the Newfoundland Offshore Burning Experiment (NOBE - Fingas et al. 1995), but never exposed to flames. The section used had been stored by the Canadian Coast Guard (CCG) in St. John's, NF in a sealed ISO container since the NOBE trials. The CCG kindly donated it for use. Using this boom offered a unique opportunity to benchmark the test protocol: the boom being tested had failed during a full-scale *in situ* burn at sea in a known manner after an accurately measured period of exposure to flames and waves in a well-documented environment.

On receipt of the boom from St. John's, a section was refurbished; the connectors at each end had been damaged and were replaced. At one end, the fabric and stainless steel mesh near the connector had been torn and one of the float units had come out of the segment. The connector was re-attached to the segment, but with only one floatation unit inside. This reduced the overall length of the test section to 14.6 m (48 feet) as opposed to the as-built specification of 15 m (50 feet).

Prior to the tests, the sacrificial covering, which is designed to burn on exposure to flames, was carefully cut away. Each float section of the boom was carefully photographed and inspected for damage. Other than the missing connector that was replaced, the boom was in good condition.

The test section of fire-resistant boom was deployed 15 m out from the edge of the wave tank. The boom was moored to winches located at either end of the tank with 3/16 in. steel rope. Figure 2 shows the boom and underwater bubbler deployed in the tank. The tension on the boom was measured with two 22,000-N load cells, one at either end of the boom. Data acquisition from the load cells used a Neff A/D converter and a VAX computer sampling at 20 Hz. CHC's GEDAP software package was used to acquire, analyze and present the measured data.

Prior to each test, the boom was pre-tensioned to 890 N. This represents the tension that would be produced when towing 150 m of this boom at 0.3 m/s (0.5 knots, Nordvik et al., 1995).

3.0 Full Scale Tests

The full-scale tests involved repeatedly exposing a section of fire-resistant boom to one hour of waves and enhanced propane flames followed by one hour of waves alone. Figure 3 shows the appearance of the boom and flames during a typical

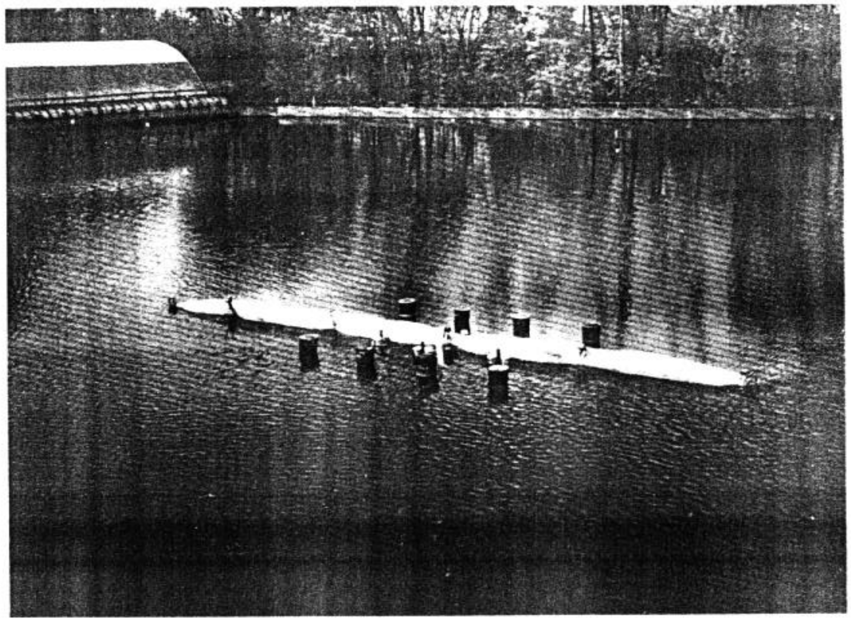

Figure 2 Photo of Boom Deployed in Tank

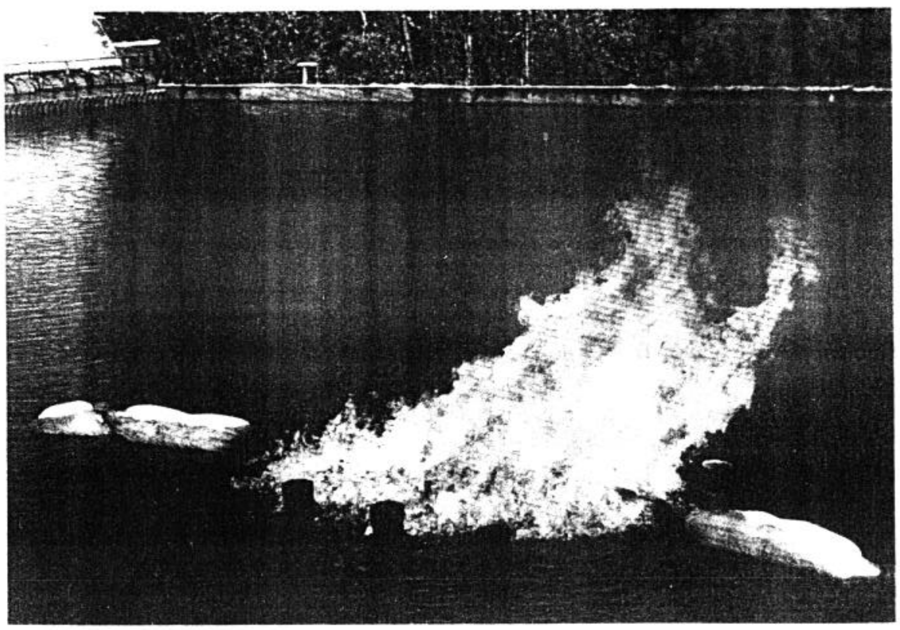

Figure 3 Photo of Typical Burn

burn. Each two-hour cycle subjected the boom to flexing from approximately 3600 waves. A total of four cycles were completed between October 29 and 30, 1997.

3.1 Trial Burn

The first burn on 29 October 1997, lasted approximately three minutes and served to test the propane and air delivery systems, and the data acquisition systems to ensure that they were operating as designed. The waves were not activated during the trial burn. The average environmental conditions and propane and air flow rates for the trial burn are given in Table 1.

Table 1 Trial burn conditions

Wind Speed:	2.6 m/s	**Wind Direction:**	250°
Air Flow Rate:	746 kg/hr 9.6 m^3/min	**Propane Flow Rate (Vapor):**	1030 kg/hr 8.7 m^3/min
Air Temperature:	4°C	**Propane Temperature (Liquid):**	1°C

The total heat flux transducers (THFTs) were mounted about 15 cm above the top of the boom looking out from the outer edge of the float radius. The north transducer was located on the lee side of the boom looking downwind (north) and the south transducer was located on the windward side of the boom looking upwind (south, see Figure 4). The two thermocouples were located 45 cm to either side of the THFTs, on the south (upwind) side of the boom approximately 15 cm below the top. The data from the THFTs and thermocouples is summarized in Table 2.

All systems functioned as designed.

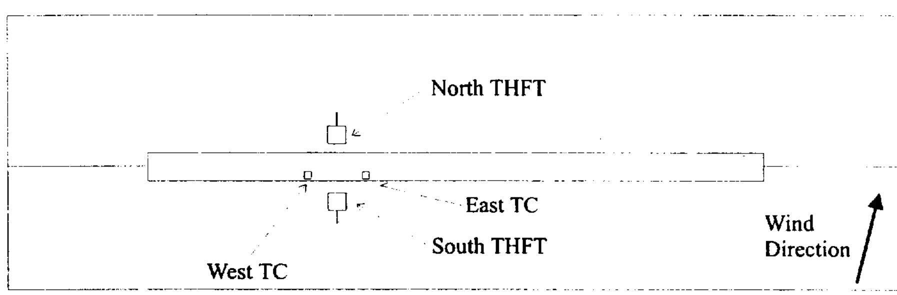

Figure 4 Layout of THFTs and thermocouples for trial burn

The wind was blowing across the boom from south to north. It had a considerable effect on the flames (and thus on the heat flux readings) forcing them to lean to the north and east. This resulted in the south THFT being exposed to a much shorter path of flame than the north THFT. Consequently, average reading from the south THFT, at 46 kW/m^2, were less than half that of the north THFT, which was 118 kW/m^2. The west thermocouple, which was closer to the edge of the fire, had a slightly lower average temperature (841°C) than the east thermocouple (876°C).

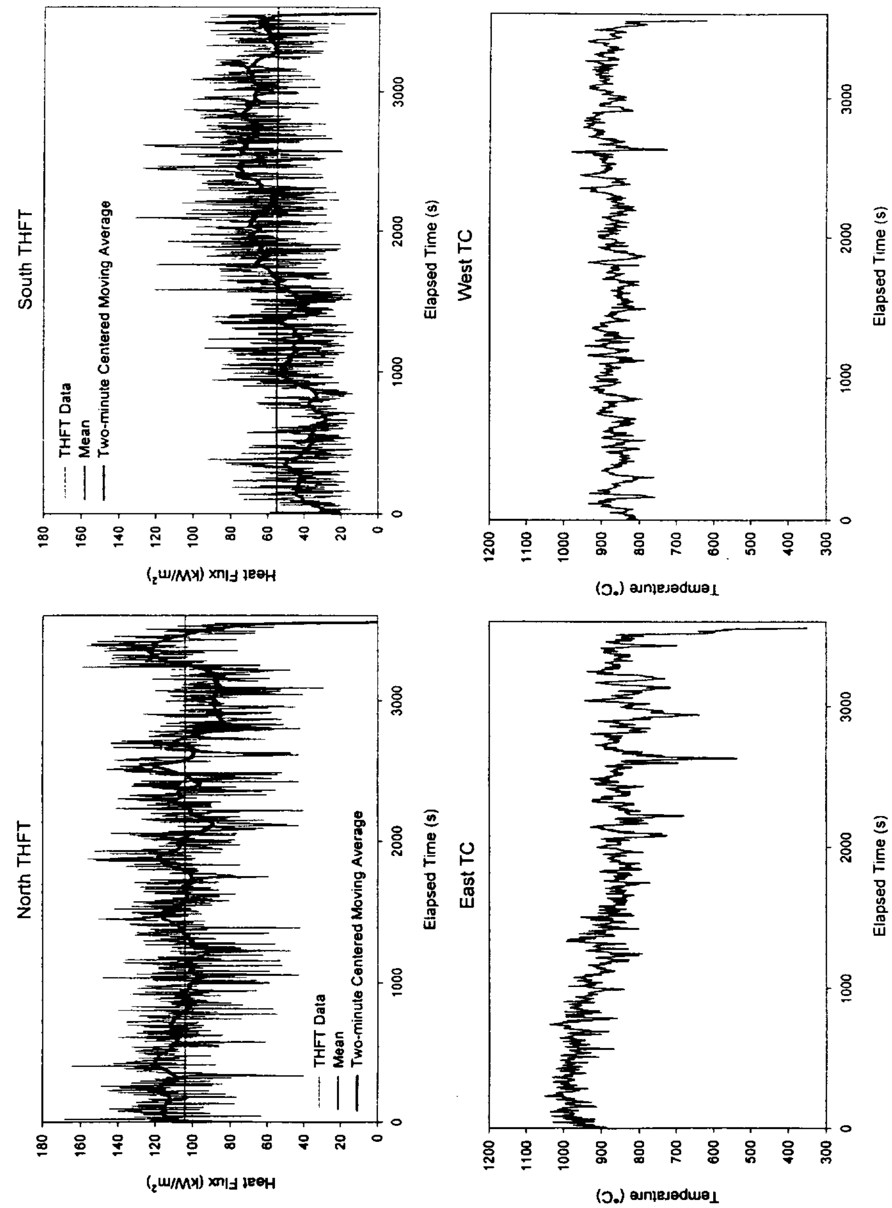

Figure 5 THFT and Thermocouple Data for Burn One

Table 2 Statistics from trial burn

	Mean	Std. Dev.	95^{th} %	5^{th} %
North THFT (kW/m^2)	118	19	144	86
South THFT (kW/m^2)	46	23	90	18
East Thermocouple (°C)	876	28	922	832
West Thermocouple (°C)	841	33	879	788

This burn, because of its short duration and the absence of waves, did negligible damage to the test boom. After the trial burn, the metal cans providing floatation for the air nozzles were replaced with solid Styrofoam floats.

3.2 Burn One

The first full burn was conducted near noon on October 29. The average environmental conditions and propane and air flow rates during the burn are given in Table 3.

Table 3 Conditions for Burn One

Wind Speed:	2.6 m/s	**Wind Direction:**	250°
Air Flow Rate:	746 kg/hr 9.6 m^3/min	**Propane Flow Rate (Vapor):**	1030 kg/hr 8.7 m^3/min
Air Temperature:	5°C	**Propane Temperature (Liquid):**	1 to -1.8°C

The THFTs and thermocouples were positioned in the same manner as for the trial burn (see Figure 4). The readings from the THFTs and thermocouples for this burn are presented graphically in Figure 5; the data from the THFTs, thermocouples and load cells is summarized in Table 4.

Table 4 Statistics from burn one

	Mean	Std. Dev.	95^{th} %	5^{th} %
North THFT (kW/m^2)	104	23	136	60
South THFT (kW/m^2)	55	24	94	21
East Thermocouple (°C)	883	81	999	75
West Thermocouple (°C)	872	35	926	814
Up-wave Load Cell (N)	706	100	871	542
Down-wave Load Cell (N)	646	82	781	511

The elapsed time in Figure 5 is measured from the moment the first wave impacted the boom. At this point, the propane and air systems were operating at the flow rates given in Table 3. Twenty-two minutes into the burn, some of the wires holding the air nozzles close to the boom let go. This had little effect except that those nozzles had greater freedom to move with the waves. Other than this, the burn went smoothly.

The results from burn one are very similar to those of the trial burn. This was expected since the wind speed, direction and air temperature, and propane tanker temperature and pressure were almost identical. The average total heat flux (estimated from the two-minute centered moving average) for the north THFT starts out at 115 kW/m^2 and declines slowly to about 105 kW/m^2 after about 40 minutes; following a dip to 90 kW/m^2, it increases to over 120 kW/m^2 by the end of the test. The average total heat flux for the south THFT increases from about 40 to over 70 kW/m^2, then falls to 60 kW/m2 by the end of the test.

The average heat flux measured by the north transducer was 104 kW/m^2, while by the south was 55 kW/m^2. The south transducer was looking upwind, and for much of the early part of the run was barely covered by flame. As in the trial burn, the wind was forcing the flames to the north side of the boom. There was also a clear influence of gusts of wind on the measured heat flux, as the decreases and increases in average total heat flux appear to correspond to wind changes.

The temperatures measured by the west thermocouple were quite steady, and centered on a mean temperature of 872°C. The east thermocouple was initially very hot, with an upper boundary around 1000°C, but cooled towards the middle of the burn. For the last half of the burn, the measurements showed considerable variability. After the first burn, the tension on the boom had decreased from 885 N to 543 N. This decrease of 342 N was caused by gradual stretching of the boom components.

After the burn, there was some charring and some deterioration of the fabric evident at the central vertical stiffener. Following the post-burn inspection, the boom was re-tensioned to 890 N and the waves were turned back on for one hour.

3.3 Burn Two

The second burn was conducted in the late afternoon on October 29. The average environmental conditions and propane and air flow rates are given in Table 5.

Table 5 Conditions for Burn Two

Wind Speed:	1.0 m/s	**Wind Direction:**	240°
Air Flow Rate:	746 kg/hr 9.6 m^3/min	**Propane Flow Rate (Vapor):**	890 kg/hr 7.5 m^3/min
Air Temperature:	5.7°C	**Propane Temperature (Liquid):**	-1.5 to -5.5°C

The winds were lighter and had swung to the west-southwest, blowing at 45° to the boom; however, they were still strong enough to force the flames toward the north side of the boom.

The THFTs were positioned in the same manner as for the trial burn and for burn one (see Section 3.1); however, for this cycle, the thermocouples were relocated from down on the south side of the boom to the top of the boom. The east thermocouple was located 60 cm east of the transducers in the vicinity of the vertical stiffener and the west thermocouple was located 60 cm west of the transducers. The readings from the THFTs and thermocouples are presented graphically in Figure 6; the data from the THFTs, thermocouples and load cells is summarized in Table 6.

Table 6 Statistics from burn two

	Mean*	Std. Dev.*	95th %	5th %
North THFT (kW/m²)	98	24	136	45
South THFT (kW/m²)	45	19	79	18
East Thermocouple (°C)	997	108	1078	817
West Thermocouple (°C)	863	82	914	784
Up-wave Load Cell (N)	914	82	1049	779
Down-wave Load Cell (N)	870	46	946	794

*Data does not include periods where propane flow and waves were off

At approximately 9 minutes into the burn, the third blower of the wave machine stopped working. The waves were shut off at this point and restarted at 18 minutes to see if the third blower would restart. It did not, so an electrician was called in. The waves were left on, although the third blower was directly in line with the boom and its loss greatly diminished the height of the waves impacting the boom. The electrician managed to restart the fan at 35 minutes.

The average propane flow for this test was only 890 kg/hr and indications are that the flow decreased from an initial high of approximately 1000 kg/hr as the cycle progressed. The reason for this is likely the cooling of the liquid propane as the test progressed reducing the vapor pressure and temperature in the tank. This cooling and pressure reduction was also likely the cause of two instances during this test cycle when the safety valve on the propane tank activated and shut off the flow. Based on experience with the propane supply system up to this point, the safety valve would activate under the following circumstances: when the vapor valve was fully open, the pressure in the tank dropped below 50 psig and the liquid propane temperature dropped below -4°C.

From Figure 6, a steady decline in total heat flux from an initial average of about 130 kW/m^2 to 90 kW/m^2 over the duration of the cycle is evident. This was likely due to the declining propane flow rate. The periods when the safety valve activated are also evident. The total heat fluxes measured by the south transducer were much lower than on the north side of the boom because the flames were being blown past the transducer. The east thermocouple measured extremely high temperatures, averaging 997°C, with peaks to 1100°C. This was in part due to its new position, being closer to the central air nozzle, where it was subjected to more intense flames. The readings from the west thermocouple were similar to those of the other two burns, averaging 863°C.

The tension on the boom dropped from 890 N to 769 N over the course of the second burn. This decrease of 121 N was much less than what was observed during the first burn, indicating that the boom was not stretching as much.

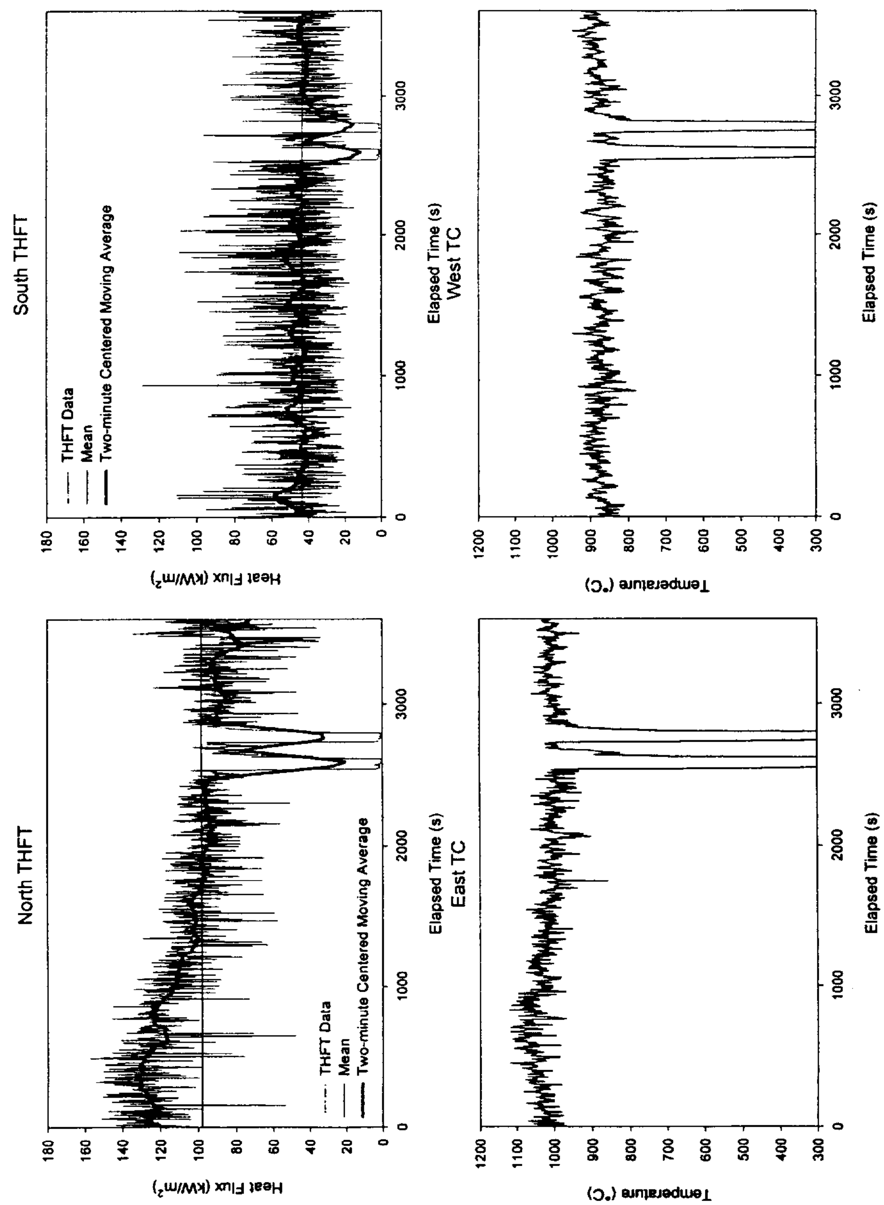

Figure 6 THFT and Thermocouple Data for Burn Two

Considerably more charring had taken place and there were now large gaps in the fabric at the central and west vertical stiffeners.

3.4 Burn Three

The third burn was conducted on the morning of October 30. The average environmental conditions and propane and air flow rates are given in Table 7.

Table 7 Conditions for Burn Three

Wind Speed:	4.6 m/s	**Wind Direction:**	275°
Air Flow Rate:	746 kg/hr 9.6 m^3/min	**Propane Flow Rate (Vapor):**	1055 kg/hr 8.9 m^3/min
Air Temperature:	7.2°C	**Propane Temperature (Liquid):**	-1.8 to -3.3°C

For this burn the main propane valve was only opened 80% to prevent the safety shutoff from activating. However, the temperature in the propane tank had risen overnight from -5.5 to -1.8 °C, which raised the pressure in the tank from 50 to 61 psig. This accounted for the higher average propane flow of 1055 kg/hr. The wind had strengthened and swung to the west and was now blowing along the boom.

For this cycle the south heat flux transducer was rotated 90° counter-clockwise to face east, downwind along the top of the boom from the center of the fire. The north transducer and both thermocouples remained in the same position as for the second (see Figure 7). Prior to engaging the waves, the boom was pre-tensioned to 890 N.

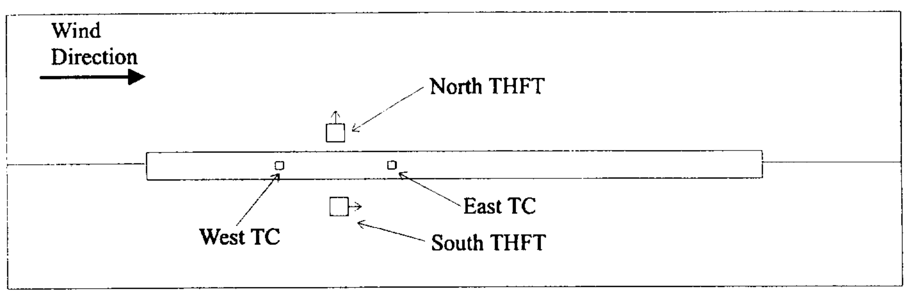

Figure 7 Layout of THFTs and thermocouples for burn three

The readings from the THFTs and thermocouples are presented graphically in Figure 8; the data from the THFTs, thermocouples and load cells is summarized in Table 8.

The average heat flux measured by the north transducer was lower than in the previous two burn cycles, at 87 kW/m^2, because the wind was now blowing the flames across the transducer and reducing the thickness of flame it was looking through. The average total heat flux measured by the south transducer facing east (downwind) ranged from approximately 100 to 140 kW/m^2, with some peaks exceed-

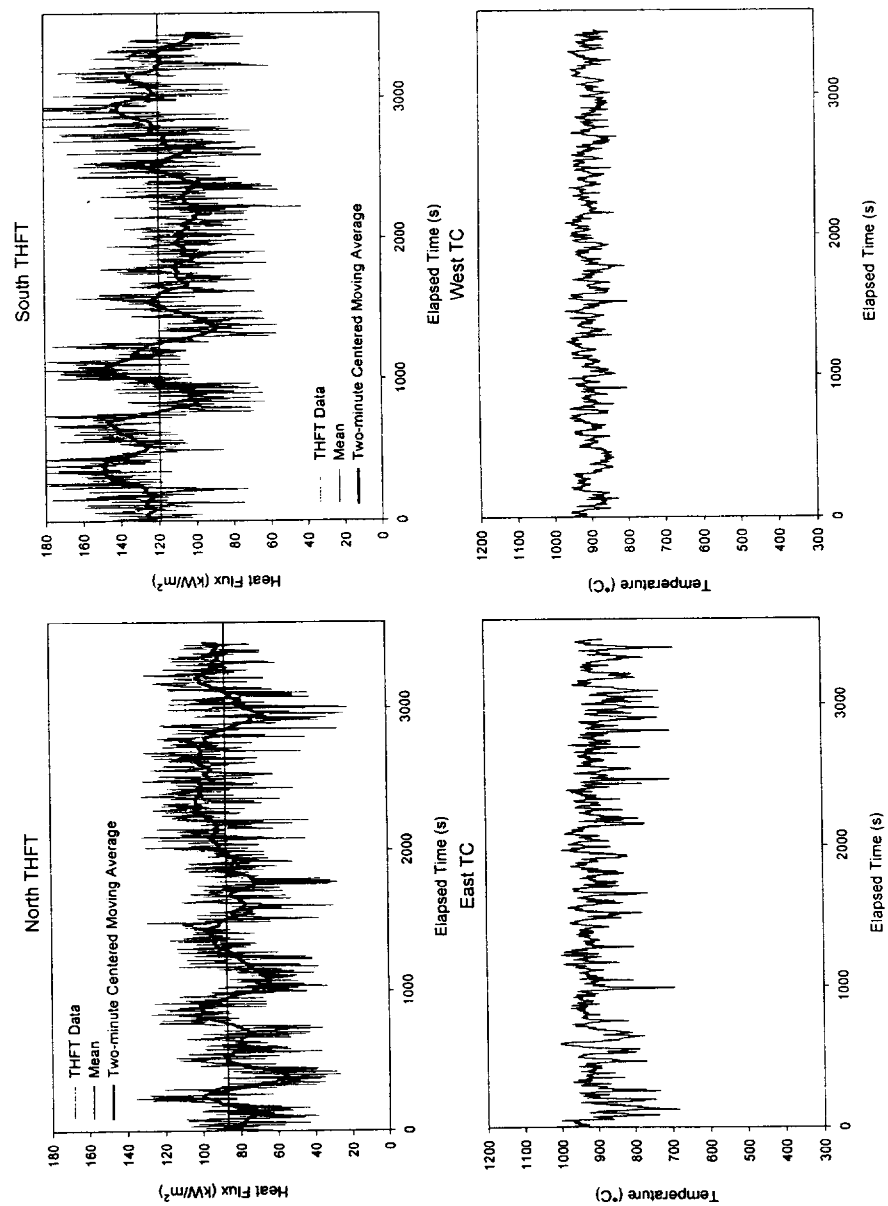

Figure 8 THFT and Thermocouple Data for Burn Three

ing 160 kW/m^2 depending on the wind. The total heat flux averaged 119 kW/m^2. The sensitivity of the heat flux measured to wind is evident; as in the first burn, when one transducer was measuring an increase in heat flux, the other was usually measuring a decrease. The east and west thermocouples both measured similar average temperatures (900 and 903°C, respectively) although the east thermocouple measured much greater variations.

Table 8 Statistics from burn three

	Mean	Std. Dev.	95th %	5th %
North THFT (kW/m^2)	87	22	119	45
South THFT (kW/m^2)	119	26	163	75
East Thermocouple (°C)	900	56	968	789
West Thermocouple (°C)	903	29	945	852
Up-wave Load Cell (N)	949	81	1082	816
Down-wave Load Cell (N)	890	62	992	788

The post-burn inspection revealed a large hole in the fabric at the central vertical stiffener; another smaller hole was noticeable at the west stiffener. Furthermore, the fabric on top of the east-most and west-most float units was being rapidly abraded as the floats shifted due to wave action. Interestingly, the sections of boom not exposed to fire were exhibiting little or no degradation from the waves.

After the inspection, the waves were turned on for one hour.

3.5 Burn Four

The fourth burn was conducted in the mid-afternoon of October 30. The average environmental conditions and propane and air flow rates are given in Table 9.

Table 9 Conditions for Burn Four

Wind Speed:	4.1 m/s	**Wind Direction:**	270°
Air Flow Rate:	746 kg/hr 9.6 m^3/min	**Propane Flow Rate (Vapor):**	820 kg/hr 6.9 m^3/min
Air Temperature:	8.8°C	**Propane Temperature (Liquid):**	-3 to -6.5°C

The winds remained from the west, generally blowing along the boom. For this cycle the heat flux transducers were rotated to look across the boom (i.e., the north transducer faced south and the south transducer faced north). The thermocouples remained in the same place as for burn three (see Figure 9).

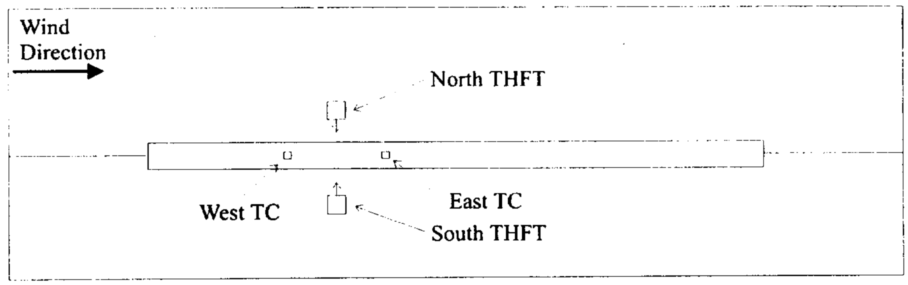

Figure 9 Layout of THFTs and thermocouples for Burn Four

The readings from the THFTs and the thermocouples are presented graphically in Figure 10; the data from the THFTs, thermocouples and load cells is summarized in Table 10.

Table 10 Statistics from burn four

	Mean*	Std. Dev.*	95th %	5th %
North THFT (kW/m²)	114	28	148	61
South THFT (kW/m²)	132	24	164	91
East Thermocouple (°C)	896	59	959	819
West Thermocouple (°C)	889	46	944	851
Up-wave Load Cell (N)	987	93	1140	834
Down-wave Load Cell (N)	923	51	1007	839

*Data does not include periods where propane flow was off

The main propane valve was initially opened to 80%, but after about 13 minutes the safety valve shut off the flow. Re-igniting the propane took about six minutes and the valve was set back to 70% of full flow for the rest of the burn test.

The total heat flux measured by the north THFT during the burn averaged 114 kW/m^2. The average reading from the south transducer was 132 kW/m^2. These were the highest readings achieved, despite the fact that the propane flow rate was much lower than the other burns. The reason for this is that the heat flux transducers were now looking through an additional boom-width (approximately 50 cm) of flame. This indicates that the fire to each side of the boom is not optically thick and that there is further opportunity to increase the heat flux to the boom by widening the flame zone.

Again, the temperatures measured by each thermocouple were similar, with the east measuring 896°C and the west measuring 889°C. The east thermocouple still measured a greater variation in temperature. The tension on the boom after the fourth burn test was almost the same as the pre-tension, indicating that no further stretching of the boom was occurring.

The sections of boom exposed to fire had suffered severe degradation by this point. The holes in the fabric at the central and west stiffeners were so large that the

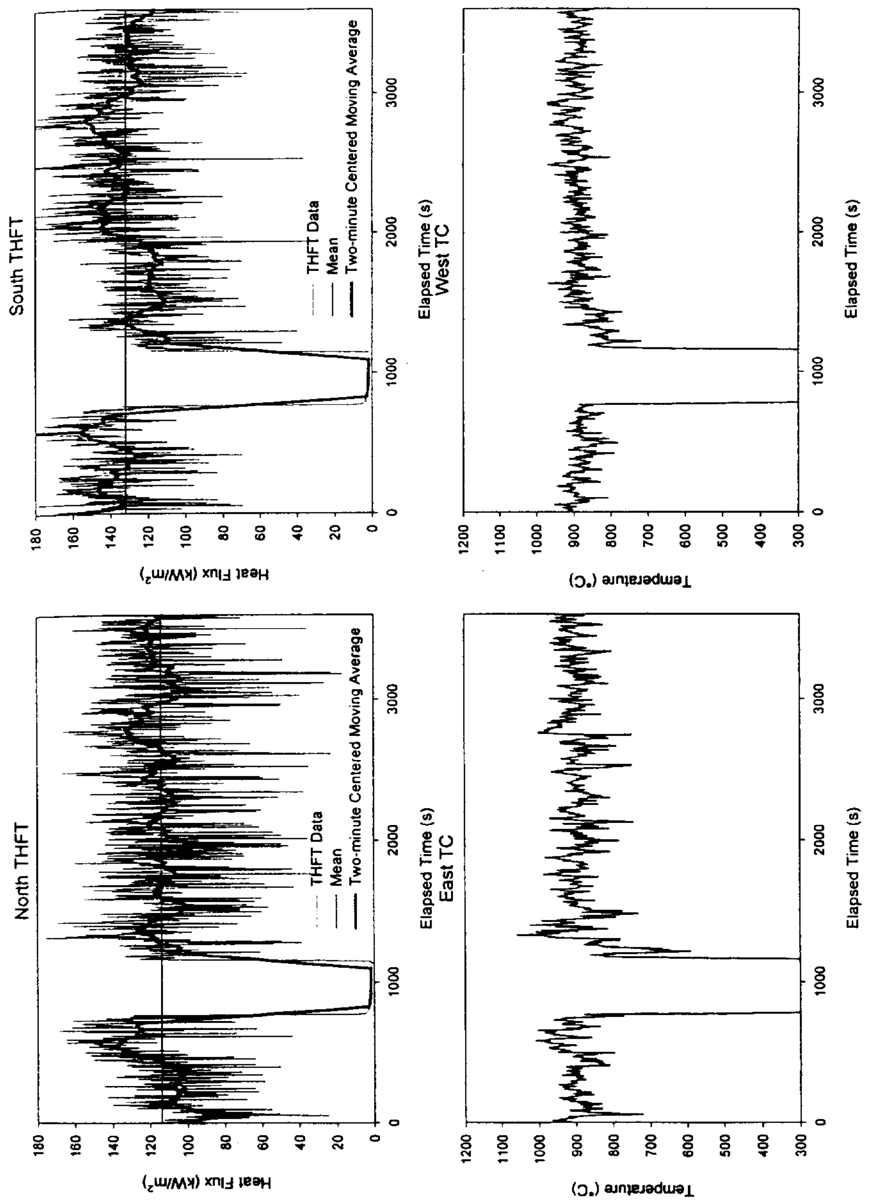

Figure 10 THFT and Thermocouple Data for Burn Four

boom would not have contained oil. Furthermore, the fabric around the central and east float units was almost completely worn away.

4.0 Comparisons with Other Studies

4.1 Comparison with Boom Damage at NOBE

In August 1993, 212 m of the same boom as tested here was used to contain the burning oil at the Newfoundland Offshore Burning Experiment (NOBE). These burns were conducted 45 km offshore of St. John's, Newfoundland in 0.5 m waves with 8-11 km/hr winds (OSIR, August 19, 1993; NOBE Newsletter, September 1993). Two discrete burns were conducted. The first involved 48.3 m^3 of slightly weathered Alberta Sweet Mixed Blend (ASMB) crude oil burned over a 1.5 hour period. Initially, some splash over of the oil was observed; however, most of this oil was reportedly retained in the stagnation zone aft of the boom and later ignited and burned by the main fire. At the end of the first burn, the boom was inspected. Some signs of fatigue in the stainless steel mesh were observed at a point about 10 cm from the vertical stiffeners and some of the refractory fabric was missing; however, the boom was considered fit enough for a second burn (NOBE Newsletter, September 1993).

One hour and 15 minutes into the second burn several flotation sections from the boom came loose, oil began to leak rapidly and the oil pumping was stopped. After the fire had stopped (28.9 m^3 had burned) the boom was again inspected. A prototype section of the boom that incorporated a middle tension member (the boom tested here did not have this member) had lost 3 flotation sections and a number of other sections were completely missing refractory fabric near the vertical stiffeners (NOBE Newsletter September 1993; Raloff 1993). Anectdotal accounts from the crew that recovered the burned sections of the boom after the experiment confirmed that the damage to the floats, mesh and refractory fabric of the NOBE boom was severe enough that the boom could not have safely contained oil.

The total time during NOBE where the boom was exposed to fire was 2 hours and 45 minutes. After three hours of exposure to fire during the tests repeated here, the boom was showing the same signs of degradation as noted at NOBE: missing fabric at the stiffeners and serious charring. Photos (Raloff 1993) confirm that the damage to the boom after NOBE was strikingly similar to the damage observed as a result of these tests.

The fact that the same degree of damage as occurred at NOBE (not including the loss of floatation units on the prototype section) was reproduced during the propane-fire tests indicate that this method is closely simulating real *in situ* burning conditions.

Further evidence is given in Figure 11, which is a temperature record from the first burn at NOBE. The temperatures generated by the crude oil fire, as measured by the top thermocouple, are in the same range as measured during these tests.

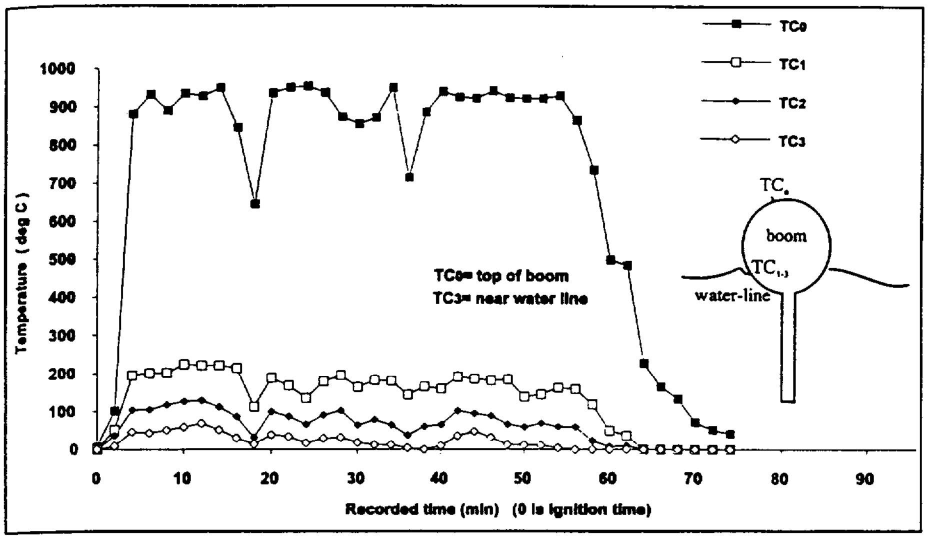

Figure 11 Temperature records from the NOBE burns.

4.2 Comparison with other Experimental Fires

Several experimental fires were conducted by scientists at NIST to evaluate the potential for propane as a fuel for testing fire-resistant oil containment booms. They conducted several experiments with propane fires and compared the heat output to experimental fires of diesel and JP-8. They concluded that without enhancement, the heat flux from a propane fire was too low to serve as an analog for a crude oil fire (Walton et al. 1997).

Figure 12 is a plot of the average heat flux data measured from the NIST experimental fires. Included in the plot are the average heat fluxes measured during the burns at M-42. It is clear that the addition of air increases the heat flux from propane fires to a point where it is approximately equivalent to JP-8 and diesel fires.

Figure 13, reproduced from Lazes (1994), shows temperatures measured on a fire-resistant boom manufactured by Oil-Stop Inc. that was exposed to a crude oil fire. The measured temperatures are consistent with those recorded in the current tests.

The heat release rates achieved with the enhanced propane system ranged from 1.4 MW/m^2 (820 kg/hr or 11.4 MW total) to 1.8 MW/m^2 (1055 kg/hr or 14.7 MW total). Literature values range from 1.76 MW/m^2 for Alaska North Slope crude to 2.3 MW/m^2 for diesel fuel (McGrattan et al. 1997) Walton et al. (1997) report a value of 1.6 MW/m$_2$ for a liquid-propane fed fire on water.

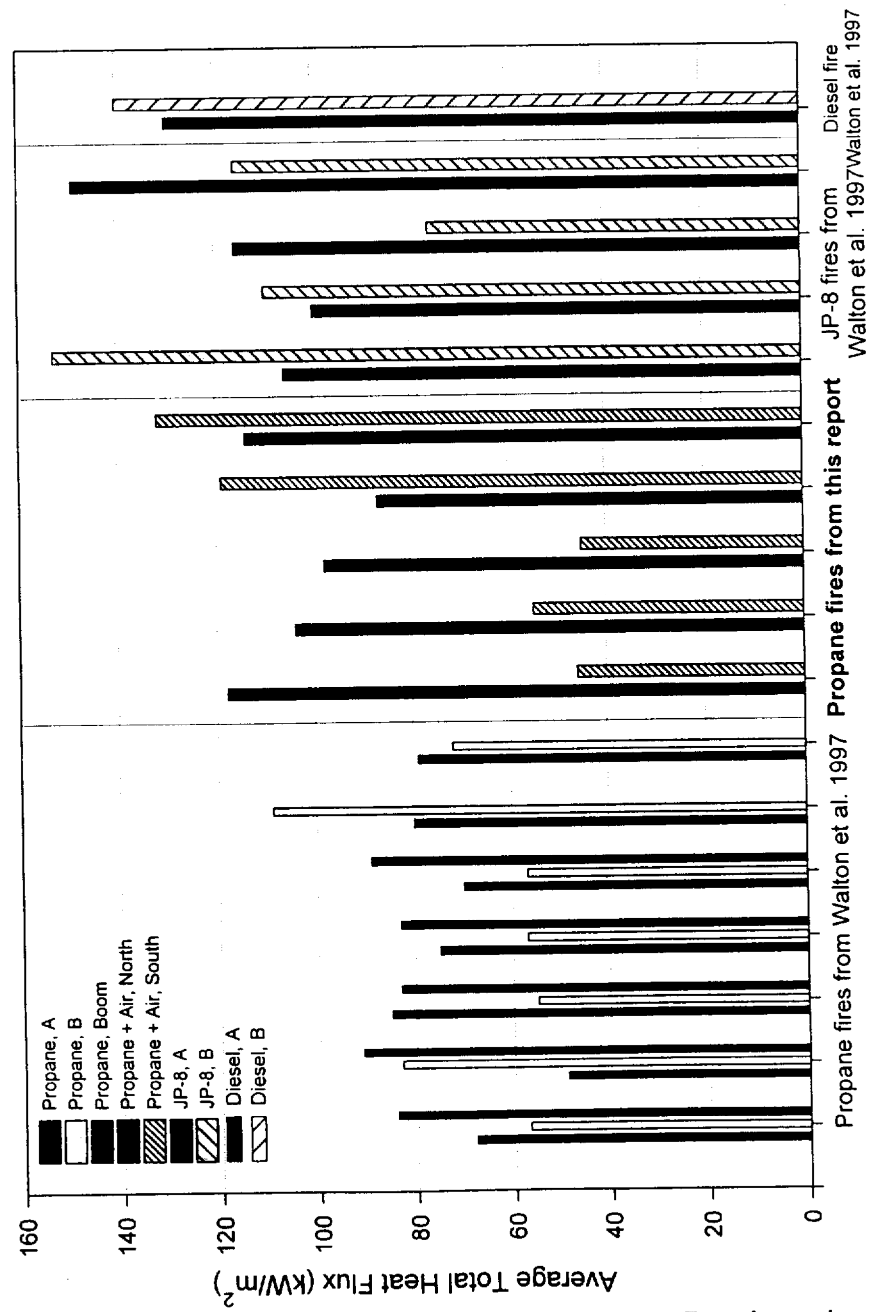

Figure 12 Comparison of THFT Readings from Other Experimental Fires

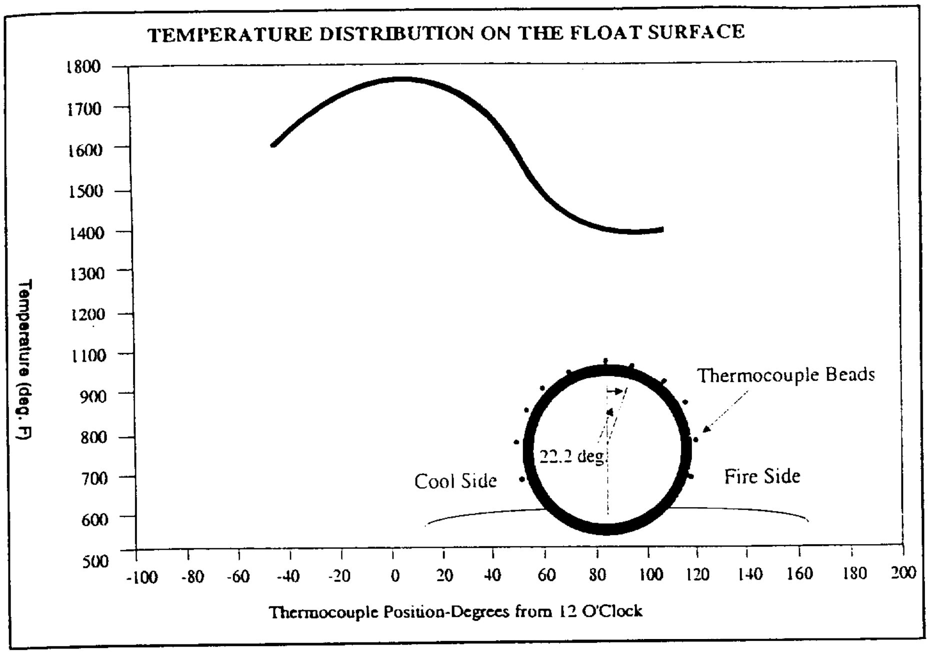

Figure 1 3 Temperature snapshot; reproduced from Lazes (1994)

5.0 Conclusions and Recommendations

- Increasing the flow of propane per unit area, and adding compressed air to the middle of the combustion zone, increased the total heat flux from the fire.
- Tensioning the boom with winches lengthwise along the tank produces realistic strain loads on the boom, without the complications involved with a current generating system.
- Propane fires, when enhanced with additional air, were reasonable analogs for crude oil fires, producing comparable heat fluxes and temperatures.
- There is potential to increase the heat flux of the fire even further by adding a fourth outlet pipe to the underwater bubbler, thus widening the fire zone; this will require increasing the propane vapor flow from the tanker.
- The revised test protocol, incorporating the burns in waves with enhanced propane flames, did subject a boom to a realistic *in situ* burning environment.
- The difference in the degree of damage to the sections of boom exposed to fire and those outside the fire zone (complete versus very little) proved that testing of fire-resistant booms must be done in waves and flames simultaneously.
- It is recommended that the enhanced screening test protocol be further benchmarked by using it on another make of fire-resistant boom.

6.0 Acknowledgments

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7.0 References

Fingas, M.F., G. Halley, F. Ackerman, R. Nelson, M. Bissonnette, N. Laroche, Z. Wang, P. Lambert, K. Li, P. Jokuty, G. Sergy, E.J. Tennyson, J. Mullin, L. Hannon, R. Turpin, P. Campagna, W. Halley, J. Latour, R. Galarneau, B. Ryan, D.V. Aurand and R.R. Hiltabrand, "The Newfoundland Offshore Burn Experiment – NOBE", in *Proceedings of the 1995 Oil Spill Conference*, API, Washington, D.C., pp. 123-132, 1995.

Lazes, R., "A Study on the Effects of Oil Fires on Fire Booms Employed During the *In Situ* Burning of Oil", in *Spill Science and Technology Bulletin*, Vol. 1, No. 1, pp. 85-87, 1994.

McCourt, J., I. Buist, B. Pratte, W. Jamieson and J. Mullin, "Testing Fire Resistant Boom in Waves and Flames", in *Proceedings of the 20th AMOP Technical Seminar*, Environment Canada, Ottawa, ON, pp. 823-839, 1997.

McGrattan, K.B., H.R. Baum, W.D. Walton and J. Trelles, *Smoke Plume Trajectory from In Situ Burning of Crude Oil in Alaska - Field Experiments and Modeling of Complex Terrain*, NISTIR 5958, United States Department of Commerce, National Institute of Standards and Technology, 127 p., 1997.

NOBE Newsletter, September 1993. Environment Canada, Ottawa, ON.

Nordvik, A., K. Bitting, P. Hankins, L. Hannon and R. Urban, "Full Scale Oil Containment Boom Testing at Sea", in *Proceedings of the 1995 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 31-38, 1995.

OSIR (Oil Spill Intelligence Report), Cutter Information Corp., Arlington, MA, 19 August 1993.

Raloff, J., "Burning Issues", in *Science News*, Vol. 144, No. 14, pp. 220-223, 1993.

SL Ross Environmental Research Ltd., *Development of a Protocol for Testing Fire-resistant Oil Containment Boom in Waves and Flames,* Report to U.S. Minerals Management Service, Herndon, VA, 98 p., 1997.

Walton, W.D., W.H. Twilley and J.V. Mullin, "An Evaluation of Propane as a Fuel for Testing Fire-Resistant Oil Spill Containment Booms", in *Proceedings of the Twentieth AMOP Technical Seminar*, Environment Canada, Ottawa, ON, pp. 755-767, 1997.