Testing Fire Resistant Boom in Waves and Flames

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Abstract

Recent experience with refractory-fabric fire resistant booms has shown them to be vulnerable to the combined effects of waves and intense heat, and unable to contain thick pools of hot oil. Realistic testing is needed to identify deficiencies in boom design and construction materials; however, offshore testing is expensive to carry out and obtaining permits to release and burn oil is very difficult. To address this, a near full-scale screening test was developed that evaluates a 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 draft protocol was tested on a section of fire-resistant boom obtained from the Canadian Coast Guard. The boom was first flexed under tension for two hours in 0.8-m waves in an indoor wave flume. Then, the boom was deployed in a U-configuration in an outdoor wave tank, where it was exposed repeatedly to waves and current. Propane gas, from an underwater bubbler system, was burned in the pocket of the boom, for one hour out of every two, to simulate the collection and burning phases of an in situ burn. Finally, the boom was returned to the indoor wave flume for another two hours in 0.8-m waves, and then inspected for damage. The boom used in the testing was the same model as the one used in the Newfoundland Offshore Burn Experiment. It suffered damage similar to that of the boom in the sea trial, although not as severe or in as short a time. This indicates that the protocol reproduces the correct stresses, but that they are lower in intensity. Further development of the test protocol is scheduled for the summer of 1997. This work was supported by the U.S. Minerals Management Service.

1.0 Introduction

Since the late 1970s, when fire resistant booms were first proposed and developed, there has been a need to conduct burn tests with such booms in waves. Fire testing of these booms in quiescent conditions has been carried out, and much has been learned from these tests (Buist et al., 1983, Spiltec, 1986, S.L. Ross, 1983, Allen and Fischer, 1988, Alaska Clean Seas, 1991, S.L. Ross, 1995, McCarthy, 1996); however, this type of testing has limitations. The combined effects of exposure to water, wave action, and fire is known to cause much more

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rapid failure in both metallic (Buist et al., 1983) and refractory fabric booms (Fingas et al., 1995) than would be predicted from tests in calm water.

To date, only very limited testing of fire boom in waves has been done. In the early 1980s, some early designs of fire resistant boom were tested at the Oil and Hazardous Materials Simulated Environmental Test Tank (Buist et al., 1983, Borst, 1983); however, the exposure time to fire was limited to a few minutes (i.e., the time it took to tow the boom the length of the tank). This short duration did not adequately simulate the destructive environment of a full-scale in situ burn. Four tests with fire boom have been conducted offshore: one at Spitsbergen (Allen, 1990); one in Alaska (Allen, 1990); one during the Newfoundland Offshore Burn Experiment (NOBE - Fingas et al., 1995) and one in the North Sea (Thornborough, 1997). All involved booms constructed from refractory textile material. For both the test in Spitsbergen and that in Alaska, wave conditions were calm and a single burn was carried out; in each instance no damage to the booms was reported. The offshore test during NOBE involved two individual burns; during the second of these burns, in 0.5 m waves, the boom suffered severe damage. In the recent North Sea test, two short-duration burns were conducted in weather described as "poor"; no structural damage to the boom was reported.

The limited number of offshore tests that have been conducted reflects the fact that they are expensive to carry out and that obtaining permits to release and burn oil is very difficult and time consuming. What is needed is an intermediate step between small-scale, static testing and offshore testing. The objective of this project was to develop the protocols and apparatus for such a test. The protocol was designed to satisfy the following parameters:

i) the test must evaluate the ability of a boom to contain thick, hot oil and to survive extended exposure to wave action and flames;
ii) the test must be realistic, inexpensive, and simple to carry out in a wave tank or possibly at sea; and
iii) the test should have negligible environmental impact, to ease the process of obtaining permits.

The concept for the fire test system was an underwater bubbler that distributed flammable gas in the boom pocket in a 0.5- to 1-m wide area beside the section of the boom to be exposed to flame. The design of the underwater gas distribution system was based on experimental work that modeled the burning of gas from a subsea blowout and developed equations relating gas flow, water depth and flammability using natural gas and propane bubble plumes in test tanks (Brzustowski and Aziz, 1977). Similar concepts have been used to construct fire training facilities for the US Navy and other fire-fighting organizations. This approach offers the advantages of:

i) easy fire control and safety;
ii) no tainting of the water in the test tank with an oil product; and
iii) no visible or noxious emissions.

Both natural gas and propane will burn to completion with little or no soot generation with a properly designed delivery system (Brzustowski and Aziz, 1977, S.L. Ross, 1984, Blackmore and Summers, 1982).

This project was carried out in consultation with the researchers at the National Institute for Standards and Technology (NIST) Building and Fire Research Laboratory who were working on quantifying the external radiant fluxes at a fire's periphery produced by propane, diesel fuel and crude oil flames, and developing small-scale exposure tests for short portions of fire resistant boom.

2.0 Small-Scale Burns

Small-scale burns were conducted in the wind/wave tank at the SL Ross laboratory. The purpose was as follows:

i) determine whether propane or natural gas was the best fuel for the test protocol;
ii) identify the parameters, such as fuel flow rate and fire diameter, that allowed for a smokeless burn;
iii) determine the desired size, shape and heat flux of the full-scale propane fire;
iv) determine the configuration of the full-scale propane bubbler; and
v) test the data acquisition systems.

The wind/wave tank measures 11 x 1.2 x 1.2 m (L x W x H) and was filled with water to a depth of 85 cm. The burns were performed underneath a fume hood that was connected to a 200-m^3/min fan to exhaust all smoke and combustion gases.

2.1 Natural Gas Tests

The natural gas was supplied from a pipe connected to the gas main. The flow of gas was regulated by a ball valve and was measured with the gas company meter. The natural gas underwater bubbler was a 2-cm i.d. elbow clamped to a submerged frame with the outlet facing down. Test burns were conducted with the underwater bubbler positioned at three depths of approximately 3, 5 and 10 cm. In all cases, the flames were very transparent and unstable. The gas flow rate was highly dependent on the depth of the outlet and, rather than being dispersed in a fine cloud like the propane gas plumes discussed below, the bubbles were large and burst violently at the surface of the water.

It became clear that the standard delivery pressure for natural gas of about 2 kPa would be insufficient to supply enough fuel for the full-scale tests. Furthermore, the low delivery pressure precluded its use at the desired position of the underwater bubbler, the bottom of the boom skirt. If natural gas was to be used as a fuel, a source of liquefied natural gas (LNG), which is under much higher pressure, would be needed. Only lab-grade LNG was available, which would have been prohibitively expensive to use in larger-scale tests. As well, natural gas has a lower net heat of combustion per unit volume than propane so a greater volume would have to be used to generate the same heat release rate. For these reasons natural gas was not considered further as a fuel for the larger-scale test program.

2.2 Propane Gas Tests

Propane for the small-scale tests was supplied from 9-kg barbeque cylinders. A header was made from 1.3-cm i.d. copper pipe that permitted up to four cylinders to supply propane to the underwater bubblers simultaneously. The valves on the propane cylinders were used to control the flow of gas. Underwater bubblers were constructed from lengths of 1.3-cm i.d. copper pipe, with small holes drilled at different locations to generate a variety of gas bubble plume sizes and geometries. The bubblers were submerged 45 cm.

For the first tests, the flow rate of propane through one 1.6-mm hole was varied from 0.9 to 2 g/s per hole. The highest flow rate of 2 g/s produced a stable flame (with just a hint of soot), 45 to 50 cm in diameter and 100 cm in height. The dimensions of this flame and the fact that little smoke was produced appeared promising and this flow rate was used as the basis for the full-scale design. A spacing of 40 cm between holes was chosen, which allowed for some overlap between the bubble plumes from other holes to ensure that there was a continuous flame area.

Then, more holes were added to the bubblers and different geometric layouts of holes were tested, namely a triangle with 40-cm long sides with holes at the points, and a square with 40-cm long sides with holes at the points. The best configuration was an "X" layout, similar to the five on a die, with 40-cm spacing between holes (see Figure 1). Based on the small-scale test results, it was felt that the flame area from this layout would be wide enough to produce a heat flux comparable to that of a crude oil fire.

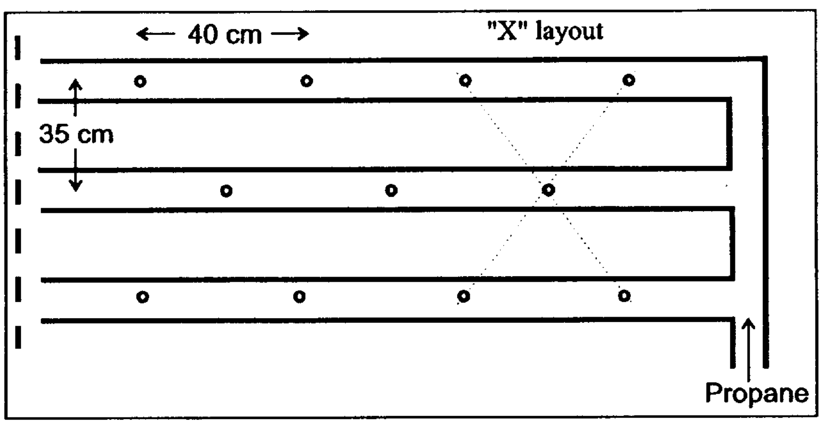

Figure 1: Hole Spacing for Full-Scale Bubbler

For the final test, the five-hole bubbler was subjected to 10-cm amplitude, 2-s period waves, and current from an electric trolling motor, rated at 24-lb thrust. The waves expanded and contracted the flame region as they passed through, which resulted in some surging in flame height at the same frequency as the waves. The current moved the bubbles about 5 cm downstream, but had no other measurable effect on the flame.

3.0 Design of Bubbler System

The purpose of the bubbler system was to generate a continuous, smokeless flame area along a length of fire-resistant boom, and to produce a heat flux equivalent to that produced by a burning crude oil slick. The bubbler system had to maintain a fixed position (in both depth and separation) relative to the test section of boom, and a stable bubble plume configuration while it was exposed to waves and current. The system also had to be safe to operate, simple to control, easy to shut off in an emergency, be an approved gas burning device, and generate no visible emissions.

A mathematical flow analysis was used to determine the sizing of the bubbler system. The basis for this analysis was the need to provide 2 g/s of gaseous propane from a series of holes, in an "X" configuration, submerged about 50 cm. The flames generated were to cover an area approximately 1 m wide directly against an 8-m length of boom.

A flexible, underwater propane bubbler, consisting of two independently fed units, was designed (see Figure 2). Each unit was made of three 4.1-m long sections of 2-cm i.d. hose. The hoses were connected at one end to a 2.5-cm i.d. header pipe 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 3-mm holes in their underside, spaced 40 cm apart, with the centre holes offset 20 cm from the other two to create the "X" configuration. 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 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.

One of the units was designed such that the other could be added to it to make a 2-m wide flame over a 4-m length of boom. Also, the two bubbler units were designed as mirror images so that, when deployed, the header pipes at the end of each unit would be next to each other in the centre of the bubbler system. This simplified the deployment of the two 25-m long, 2.5-cm i.d. feed hoses that supplied propane from the tank-side vaporizers. Each feed hose was ballasted with short lengths of steel reinforcing bar so that they remained underwater.

An ignition pilot light was mounted on each bubbler unit. These 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. Each igniter was independently fed propane from a 9-kg propane cylinder at the side of the test tank. The pilots were manually ignited 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 vaporizers for the entire duration of each burn test. As well, propane gas detectors with audible alarms were placed at all four corners of the wave tank.

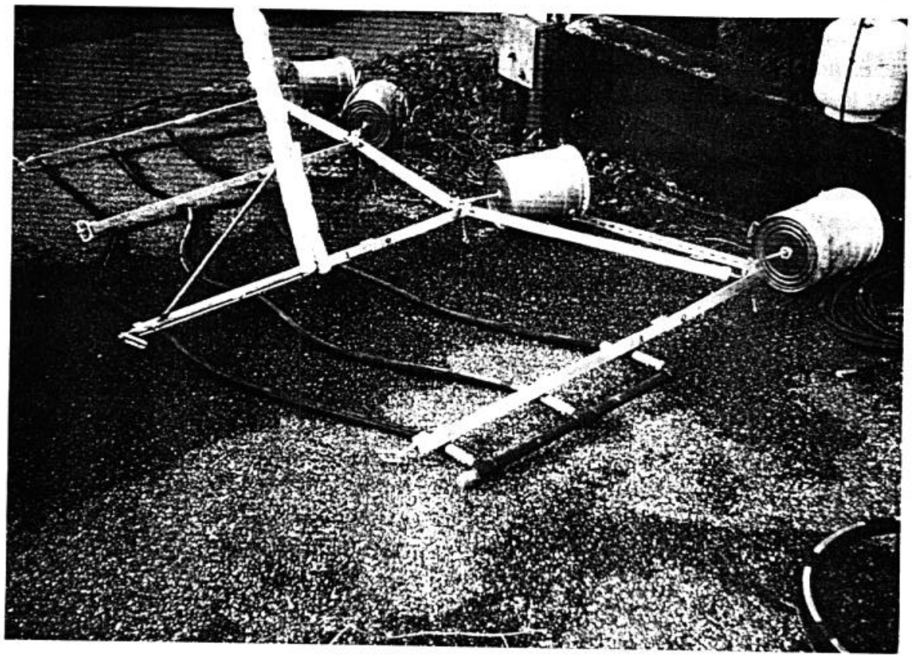

Figure 2: Photo of One Bubbler Unit

A shakedown test of one of the bubbler units was conducted in the Outdoor Ship Maneuvering Basin (OSMB) of the National Research Council (NRC). The purpose was to assess the shape and stability of the flames produced. One end of the bubbler was attached to a weighted wooden spar suspended beneath two 200-L steel drums held at the appropriate position in the tank using wire cables. The pilot was lit from a small boat using a propane soldering torch attached to the end of a metal pole and then the main propane supply was turned on. The propane pilot and the bubbler system functioned well in calm conditions and with waves and current. The flames generated covered an area of the water surface approximately 4 x 1 m, and were approximately 1 to 2 m high. The flame burned very cleanly and produced no visible smoke. The flame radiation level at the side of the tank was quite low, just detectable on bare skin. The flame did not seem to be adversely affected by either waves or current, although the current did move the flame about 0.5 m downstream. The bubbler system suffered no visible damage from the test, and appeared in perfect working order afterwards. The pilot light needed to have a subsurface float installed to help it remain upright. The valving system on the vaporizers at the side of the tank allowed quick control and shut-off for the flame.

4.0 Large-Scale Tests

The test protocol was composed of four discrete stages:

i) a pre-burn wave stress test;
ii) burn tests in waves and current;
iii) a post-burn wave stress tests; and
iv) a thick oil containment test.

Table 1 outlines the conditions and duration of each stage. The tests were conducted at two locations of the National Research Council in Ottawa. The Wave Research Flume (WRF), where the pre- and post-burn wave stress tests were carried out, is located in the Canadian Hydraulics Centre. The static tank for the thick oil containment testing was also to be located there. The Outdoor Ship Maneuvering Basin was the site of the wave/flame tests.

Table 1: Test Conditions of Protocol Stages

Test	**Wave Amplitude (m)**	**Wave Period (s)**	**Flames**	**Duration (h)**
Pre-Burn Stress	0.8	3.7	no	2
Burn Tests in Waves and Current	0.6	2.5	no	1
	0.6	2.5	yes	1
	0.6	2.5	no	1
	0.6	2.5	yes	1
	0.3	1.4	no	1
	0.6	2.5	yes	1
	0.6	2.5	yes	1
	0.6	2.5	yes	1.7
	0.6	2.5	yes	1.3
Post-Burn Stress	0.8	3.7	no	2

The draft protocol was tested using fire resistant boom donated by the Canadian Coast Guard (CCG). The fire boom was a section that had been deployed at NOBE, but never exposed to flames. It had been stored in a sealed ISO container since the NOBE trial. Using this boom offered a unique opportunity to benchmark the test protocol: this model of boom 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, one section was refurbished. The connectors at each end had been damaged and were replaced. At one end, the fabric and stainless mesh near the connector had been torn and one of the two floatation units had come out of the segment. The connector was re-attached to the segment, but with only one floatation unit inside. This shortened the overall length of the test section to 14.6 m as opposed to the original 15 m. Several patches were placed on the orange sacrificial cover material and the skirt where tears were evident. In one segment, the stainless steel mesh had been breached by a sharp object and this area was stitched together with thin steel wire and then patched. None of these pre-test repairs appeared to affect the performance of the boom.

4.1 Pre-burn Wave Stress Test

In the field, deployment of a fire boom will subject it to many cycles of flexing in waves before, during and after any burns. This flexing could damage the boom and affect its ability to retain oil. The pre-burn wave testing involved recreating the flexing of the boom fabric and internal structures.

The flume measures 97 x 2 x 2 m (L x W x H). Its sophisticated wave generator can correctly reproduce the kinematics of deep water as well as shallow water waves. A 19-m long wave absorber at the far end of the flume absorbs over 95% of the energy of the waves arriving at the end of the flume. The floating boom reflected only a small percentage of the wave energy; this meant the waves retained their progressive nature, rather than becoming a series of standing waves.

The fire boom was installed along the centreline of the WRF between two vertical posts, spaced 17 m apart. The upwave end of the boom was attached to the first post, located 45 m from the wave machine, by means of a cable, pulley and winch system. The other end of the boom, 62 m from the wave machine, was attached to the second post by a shackle. The winch enabled the floating boom to be stretched and a pre-tension to be applied. Unfortunately, the boom stretched considerably as the tension was increased; the posts were too close together and the highest pre-tension that could be achieved was 180 N.

A capacitance-wire wave probe, located 19 m from the wave board, measured the wave characteristics. The boom tension was measured by a 8900 N (2000 pound) capacity model 1110-AF Interface pancake load cell. A Neff A/D converter and VAX computer data acquisition system sampled the wave probe and load cell outputs 20 times per second.

The boom was exposed to 0.8-m amplitude, 3.7-s period waves for a total of 2 hours. Boom tension in the waves varied from a minimum of 420 N to a maximum of 1240 N, with a mean of 890 N.

Visual examination of the boom after the tests revealed no damage. The sacrificial plastic outer covering of the boom was removed down to the water line, exposing the fire-resistant fabric, wire mesh and refractory material. Removal of this covering would not affect the subsequent performance of the boom, since the cover is intended to burn upon exposure to flames. In general, the boom was in good condition. The stainless steel mesh was undamaged, except in an area that had been previously repaired. The refractory fabric material was slightly abraded in a few places, but it was uncertain whether this was as a result of the wave stress tests or from the boom's deployment during NOBE. The internal flotation units were undamaged and still fully contained in their packaging of stainless steel and plastic sheeting cover. The skirt, stiffeners and connectors had suffered no further damage as a result of the wave stress tests.

4.2 Burns in Waves and Current

The periphery of a crude oil fire is an extremely harsh environment. This test subjects a boom to continuous waves and current, and cycles of flame in order to evaluate its ability to withstand the combined effects of wave action and intense heat.

The test was conducted in the OSMB, which measures 122 x 61 x 3.3 m (L x W x H). Figure 3 is a schematic representation of the layout of equipment in the basin. A pneumatic wave machine on one end can produce sinusoidal waves of varying amplitude and period. The wave absorber at the opposite end of the basin is ineffective with large waves and allows most of their wave energy to be reflected back into the tank. A standing wave pattern sets up a few minutes after the waves are started. The waves can easily reach 1 m in height at the locations of the nodes. A capacitance wave probe was mounted 33 m from the wave generator, and 6 m upstream of the 16.5-m wide opening to the boom to record the wave characteristics; however, at any one position along the length of the tank, there may be small waves, intermediate waves, or waves with slowly varying amplitude. This means that the wave measurements reported are only an approximate indication of the conditions in the basin.

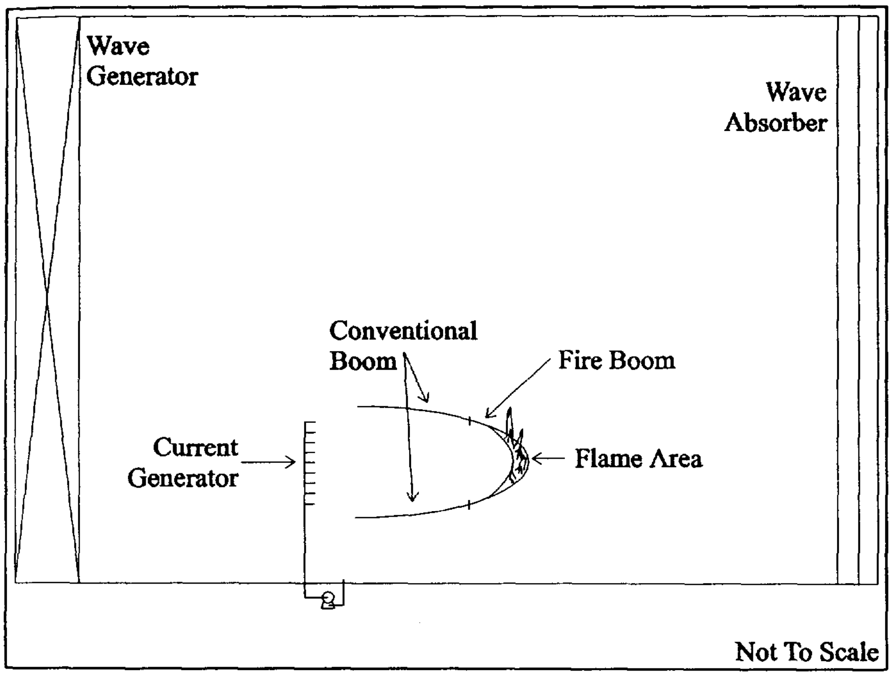

Figure 3: Schematic Diagram of OSMB

The propane bubbler units were attached to the chain in the skirt along the middle 8 m of the fire boom. The fire boom was then connected in the middle of two 16.5-m sections of conventional boom and the entire unit deployed in a catenary formation. Each end of the boom was attached to a 22,000 N (5000 pound) model 1110-AF Interface load cell and float, and a 1-cm diameter wire rope was used to moor the boom to the end wall of the basin. As well, a 3-mm diameter cable was stretched across the basin at right angles to the current and used to keep the boom ends from wandering laterally, but free to move longitudinally in the basin under the action of waves and current. A test showed negligible effect of this cable on the forces measured by the load cells.

The total heat flux at the middle of the boom pocket was measured using two Medtherm model 64-20-20 total heat flux transducers (0 to 200 kW/m^2 with $\pm$3% FS accuracy). The flame temperature was measured using Type K themocouples. A raft, constructed from 6"x 6" lumber and steel framing was used to support the radiometers and thermocouples. The transducers were mounted side-by-side, about 15 cm apart approximately 60 cm above the still water surface. The raft was loosely tethered to the boom at one of the vertical stiffeners, with the transducers looking into the flames at a position corresponding to the back side of the boom. The output signals from the thermocouples and heat flux transducers were fed to a PC Labs model PCLD 7811 analog/digital converter and logged on an IBM-compatible personal computer. Data was acquired from the load cells and wave probe by a Neff A/D converter and VAX computer sampling at 20 Hz. The NRC GEDAP software package was used to process the wave and load data.

A current generator was 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). In future tests, it is recommended that a higher tension be applied to better represent actual towing conditions.

The total amount of propane used for these tests, as determined from the supplier's delivery ticket, was 6117.5 L. Based on the total time the bubbler was operated (always with the valves full open) the average propane flow was 407 kg/hr. This translates to an average power output of 5.7 MW and a unit heat release rate of 0.7 MW/m^2. The temperature and pressure of the gaseous propane were monitored at the distribution header using a pressure gauge and themocouple.

On the first day of testing, the boom was exposed to 0.6-m amplitude, 2.5-s period waves and 0.2 m/s current for one hour, followed by an hour under the same conditions with propane fire (see Figure 4). The propane gas burned very cleanly with continuous, steady flames of 1 to 2 m in height over the entire 8 x 1 m area. No visible air emissions were observed. For the hour that the flames were on, the average liquid propane flow rate was 13.3 L/min, giving a total heat release rate of 5.7 MW, which was slightly lower than planned. The average propane flow per hole in the bubbler was 1.7 g/s, again slightly lower than the target 2 g/s. In part, this can be attributed to the fact that the vaporizers were supplying propane at only 19 psig and not the 20 psig that was desired. The sizing of the holes on the bubbler system could also have been a factor. The holes drilled in the soft rubber piping tended to collapse slightly after the drill bit was removed. Using an oversize drill bit to enlarge the holes would help to increase the flow of propane. The average heat release rate per unit water surface area was 0.7 MW/m^2, compared to 1.76 MW/m^2 for Alaska North Slope crude and 2.34 MW/m^2 for diesel in situ fires (McGrattan et al., 1997).

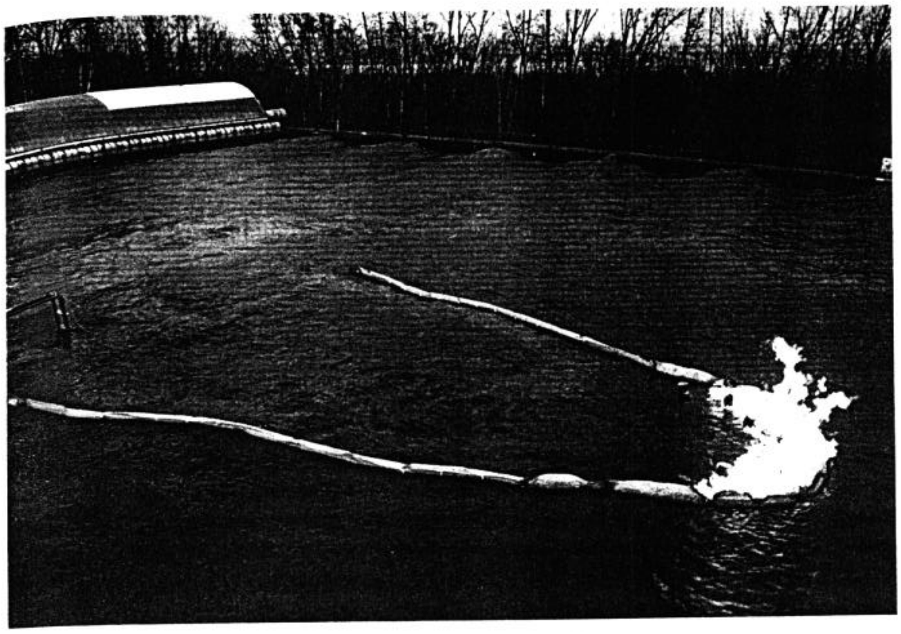

Figure 4: Photo of Boom with Waves, Flames and Current

During this test, problems were encountered with the data acquisition system for the heat flux transducers and thermocouples. Whenever the metal sensors contacted the stainless steel mesh of the fireboom (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 for subsequent tests in order to overcome this problem; however, for future tests the heat flux and thermocouple data acquisition system need to be re-designed.

The next day, the condition of the boom was visually assessed from a small boat. Although there was some charring evident on the surface of the boom facing the fire, the boom appeared to be in good shape, and the next test was started.

For the second test, the wave settings were 0.6-m amplitude and 2.5-s period. The waves and current were run for one hour, then the propane fire was started and run for another 61 minutes. The wind was blowing from the east, toward the wave generator and angled the flames away from the boom. This resulted in low heat flux readings from the transducers and low temperatures recorded by the thermocouple. In future tests, the heat flux transducers should be moved in order that they better measure the heat flux impinging on the fire side of the boom surface. Reinspection of the boom revealed significant charring above the wave splash zone on the fire side of the boom, and some abrasion near the vertical stiffeners.

On the third day, two periods of fire testing were conducted. In the morning the wave generator was set to produce 0.3-m amplitude, 1.4 s period waves for one hour. At the end of this hour, the propane fire was ignited and the waves increased to 0.6-m amplitude, 2.5-s period. For this run the wind was blowing lightly from the northwest, angling the flames generally across the boom pocket. The transducers measured heat fluxes between 0 and 7 W/cm^2, averaging about 2 W/cm^2. The thermocouple temperature ranged from 100° to 800°C. After this test run, the waves were shut off while one of the load cells on the boom mooring cables was replaced.

When the load cell had een changed the waves were restarted and, in order to make up lost time, it was decided to immediately restart the propane fire. The test run continued for a full 63 minutes. After about 30 minutes of calm conditions, while adjustments were made to the instrument raft, the waves and burning were continued for another 103 minutes. Inspection revealed that the charring had increased, and that significant abrasion and ablation of the refractory fabric had taken place, especially in the vicinity of the vertical stiffeners.

The final fire test ran for 85 minutes in 0.6 m amplitude, 2.5 s period waves, until the propane supply tank was empty. This time the wind was from the west and angled the flames toward the instrument raft and on occasion the heat flux transducers were briefly immersed in flame. The heat flux measured for this test run was higher than for others, ranging as high as 9.5 W/cm^2.

On completion of the tests the boom was inspected. At the end of the approximately 7 hours of flame exposure it was apparent that the boom suffered significant degradation (see Figure 5). The refractory fabric had worn through at several vertical stiffeners, and the entire surface exposed to flame had been charred. The boom sail material had begun to sag at the vertical stiffeners, to the point where the top of the stiffeners were almost underwater.

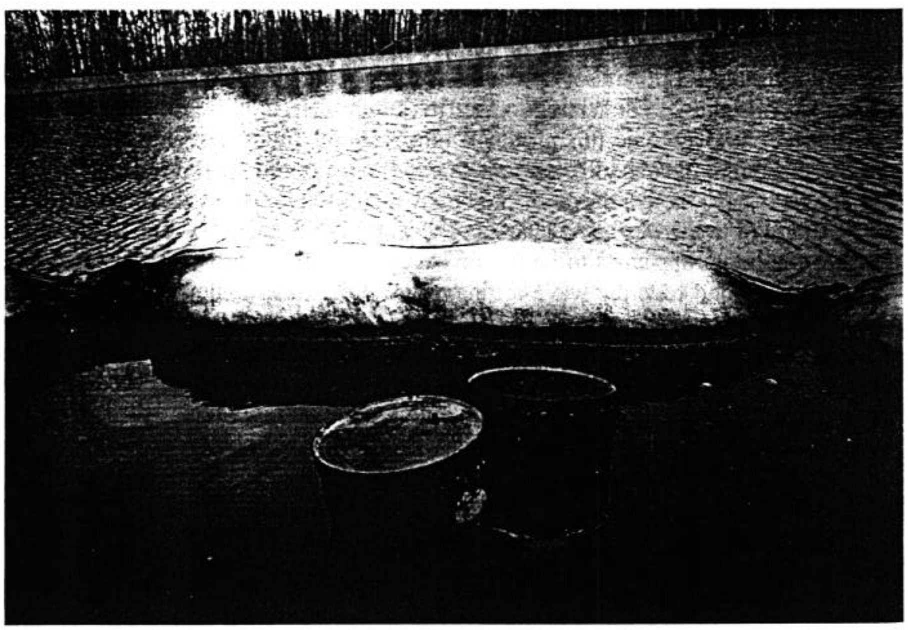

Figure 5: Photo of Boom after Burn Tests

4.3 Post-burn Wave Stress Test

The boom was returned to the WRF for a final wave stress test. The boom was subjected to 130 minutes of 0.8-m amplitude, 3.7-s period waves, for a total of 2,130 cycles. The mooring posts in the WRF had been moved farther apart and the desired pre-tension of 900 N could be achieved. The test was stopped periodically and the boom re-tensioned to 900 N because the stainless steel mesh carrying the longitudinal load in the boom began to fail and the boom stretched. The forces measured by the load cell varied between approximately 1350 and 2550 N each wave cycle with a mean of just over 1800 N.

After the two hour test period had elapsed, the boom was examined carefully. Considerable degradation of the refractory fabric had continued in the areas that had been exposed to flames and several portions of the stainless steel mesh had failed (see Figure 6).

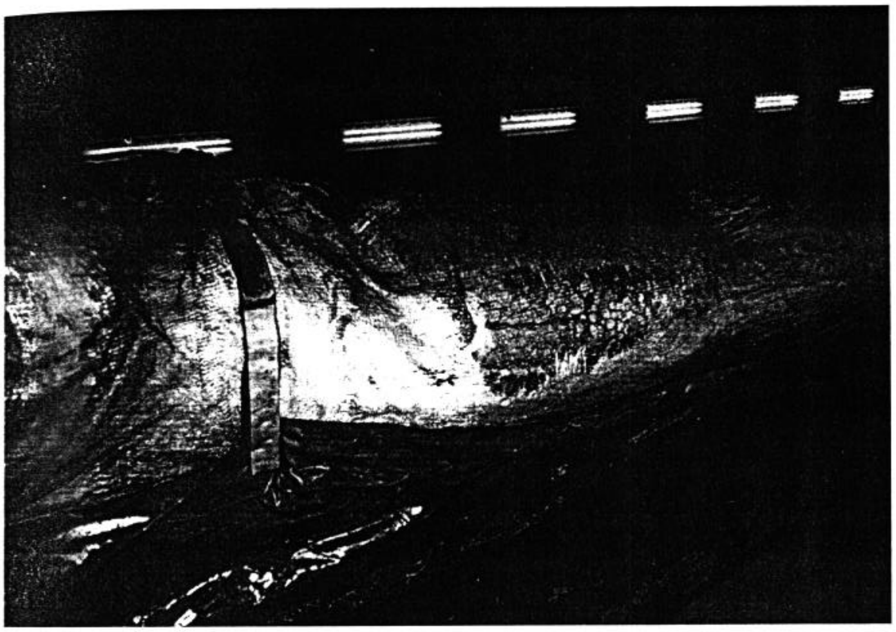

Figure 6: Photo of Boom after Wave Stress Test

4.4 Thick Oil Containment Test

The final test was to assess the ability of the boom to contain thick slicks of low viscosity oil, simulating a layer of burning oil in the pocket of a boom under tow. A 4.5-m diameter, 1-m deep portable tank was obtained for this portion of the testing. It was planned for a section of the test boom that had been exposed to the propane flames to be clamped in a triangle and floated in the tank. A thick layer of low viscosity, dyed vegetable oil was to be poured onto the water surface contained by the three sections and the leak rate of oil through the boom measured by monitoring the decrease in contained slick thickness over time.

After the two hour stress test period in the WRF, considerable degradation of the refractory fabric had occurred in the areas that had been exposed to flames and several portions of the stainless steel mesh had failed. It was evident that the boom would not contain oil, so the thick oil containment test was modified. While still in the WRF, water containing a soluble dye was blown against one side of various sections of the boom using a small compressed air stream directed at the water surface. It was observed that the dyed water moved quickly though the boom in areas that had suffered severe degradation. It should be noted that the dyed water did not penetrate the boom in undegraded areas. On completion of the dye test the boom was removed from the WRF and thoroughly examined, videoed and photographed.

5.0 Comparison with Boom Damage at NOBE

In August 1993, 212 m of the same boom tested here was used to contain burning crude oil at NOBE. These burns were conducted 45 km offshore of St. John's, NF in 0.5-m amplitude waves with 8 to 11 km/hr winds (Environment Canada, 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 subsequently 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 (Environment Canada, 1993).

One hour and 15 minutes into the second NOBE 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 (Environment Canada, 1993; Raloff, 1993). The damage to the boom after NOBE, was strikingly similar to the damage observed as a result of these tests. Anecdotal 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.

The boom tested in the WRF and OSMB suffered degradation similar to that of the boom at NOBE, although not as intense or in as short a time. By the end of the draft test protocol the boom had been exposed to propane flames for approximately 7 hours and waves for approximately 13 hours (4 hours in the WRF with 0.8-m amplitude, 3.7-s period waves; and, 1 hour with 0.3-m amplitude, 1.4-s period plus 8 hours with 0.6-m amplitude, 2.5-s period waves in the OSMB). The boom was charred and had lost significant amounts of refractory fabric to the combined effects of heat and abrasion; particularly, but not exclusively, in the vicinity of the vertical stiffeners. As well, some of the structural components had started to fail. The test section would not have contained oil after the tests. This indicates that the draft test protocol reproduces the mechanical and heat stresses; but they need to be increased in intensity to better simulate real in situ burning conditions.

6.0 Conclusions and Recommendations

Four areas for improving the test protocol are suggested:

i) increasing the heat flux to the boom;
ii) improving the heat flux measurement;
iii) increasing the tension in the fire boom during flame testing; and
iv) improving the characterization of the waves near the fire boom.

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. The heat release rate for a liquid propane fire on water, as tested by NIST at the USCG test site in Mobile, was about 1.6 MW/m^2. The burning of liquid propane on water at this rate did result in some smoke being generated. The heat release rate for the draft protocol fire boom tests reported here using propane gas was about 0.7 MW/m^2. This heat release rate, a direct function of the flow rate of propane, was kept intentionally low in order to avoid smoke production from the fire for these initial protocol tests. The test boom could be subjected to a more rigorous environment by increasing the flow rate of gaseous propane by up to a factor of three (to 2.1 MW/m^2). The addition of combustion air, either by bubbling or from compressed air jets, could further increase heat flux to the boom, while maintaining a nearly-smokeless burn.

The fire data acquisition system needs to be revised. The heat flux transducers should be mounted at the mid-way point of the surface of the boom facing the fire and the thermocouples should be embedded in the boom surface material.

The exposure of the appropriately pre-tensioned test boom to waves in the WRF after the boom tests appeared to accelerate the degradation of the boom. In future tests the boom should be mechanically pre-tensioned during the fire tests in waves to see if this causes more rapid deterioration; the loads imposed by the current on the boom deployed in a "U" in the Basin were far lower than would be expected in a full-scale deployment offshore. Pre-tensioning would also make the protocol better suited to many other test tanks where the generation of a current is not readily possible.

Measurement of the waves at one location near the mouth of the boom provided little information about the motions of the boom in the burn pocket, which may be important for defining the flexing and wear of the boom materials. In future tests, the waves should be measured closer to the apex of the boom. A pressure cell wave sensor resting on the bottom of the tank directly beneath the boom apex, would be able to measure the surface motions of the boom and yet be unaffected by the flames. Alternatively, accelerometers mounted on the lee side of the boom itself could be used to measure the boom motions.

7.0 References

Alaska Clean Seas, "Long Duration Test Burn: 3M 8-inch Fire Containment Boom", *ACS Newsletter*, Vol. 1, No. 1, 1991.

Allen, A.A., "Contained Controlled Burning of Spilled Oil During the *Exxon Valdez* Oil Spill", in *Proceedings of the Thirteenth AMOP Technical Seminar,* Environment Canada, Ottawa, ON, pp. 305-313, 1990.

Allen, A.A. and E.M. Fischer, "Test and Evaluation of a New and Unique Fire Containment Boom", in *Proceedings of the Eleventh AMOP Technical Seminar,* Environment Canada, Ottawa, ON, pp. 185-199, 1988.

Blackmore, D.R. and G.G. Summers, "Dispersion and Combustion Behavior of Gas Clouds Resulting from Large Spillages of LNG and LPG on to the Sea", *Trans. I. Mar. E.,* Vol. 94, Paper 29, pp. 2-18, 1982.

Borst, M., "GEMENG Lightweight Fireproof Boom: Oil Containment Testing at OHMSETT", Environment Canada Report No. EPS 4-EP-83-5, Environment Canada, Ottawa, ON, 18 p., 1983.

Brzustowski, T. and K. Aziz, "In Situ Burning of the Products of a Subsea Blowout", APOA Report No. 108-1, 48 p., 1977.

Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy, and I.R. McAllister, "The Development and Testing of a Fireproof Boom", in *Proceedings of the Sixth AMOP Technical Seminar",* Environment Canada, Ottawa, ON, pp. 70-84., 1983.

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

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.* American Petroleum Institute, Washington, DC, pp. 123-132, 1995.

McCarthy, M.W., "Small-Scale In Situ Burn Tests to Develop Operational Proficiencies", in *Proceedings of the Nineteenth AMOP Technical Seminar,* Environment Canada, Ottawa, ON, pp. 979-986, 1996.

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", National Institute of Standards and Technology, Gaithersburg, MD, Report No. NISTIR 5958, 1997.

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

S.L. Ross Environmental Research Ltd., "Demulsifiers and Modified Heli-Torch Fuels to Enhance In Situ Burning of Emulsions", Report to Alaska Clean Seas, Anchorage, AK, 1995.

S.L. Ross Environmental Research Ltd., "An Experiment to Simulate Subsea Blowouts", Report to Mobil Oil Canada Ltd., St. John's, NF, 1984.

S.L. Ross Environmental Research Ltd., "Evaluation of Industry's Oil Spill Countermeasures Capability in Broken Ice Conditions in the Alaskan Beaufort Sea", Report to the Alaska Department of Environmental Conservation, Juneau, AK, 1983.

Spiltec, "Test and Evaluation of Fire Containment Boom", Report to Alaska Clean Seas, Anchorage, AK, 1986.

Thornborough, J., "United Kingdom In Situ Burn Trials, Lowestoft, 1996", in *Proceedings of the 1997 Oil Spill Conference,* American Petroleum Institute, Washingon, DC, pp. 131-136, 1997.