Re-engineering of a Stainless-steel Fire Boom for Use in Conjunction with Conventional Fire Booms

Final Report

Prepared for

U.S. Department of the Interior, Minerals Management Service
Engineering and Research Branch
381 Elden Street, MS4021
Herndon, VA 20170-4817

Prepared by

SL Ross Environmental Research
200-717 Belfast Road
Ottawa, ON K1G 0Z4

August 31, 1999

NOTICE

This report was prepared by SL Ross Environmental Research in the course of performing work contracted for and sponsored by: Alaska Clean Seas; the Alaska Department of Environmental Conservation; Amoco Canada; the Canadian Coast Guard; Clean Sound; Cook Inlet Spill Prevention and Response Inc.; Exxon Production Research Company; the Minerals Management Service; the New York State Energy Research and Development Authority; Petro-Canada; and, the US Coast Guard. The opinions expressed in this report do not necessarily reflect those of the Sponsors or the State of New York, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Further, the Sponsors and the State of New York make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any process, methods, or other information contained described, disclosed, or referred to in this report. The Sponsors, the State of New York, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

ABSTRACT

Many existing refractory fabric fire booms will deteriorate quickly in use and may require frequent replacement in a large-scale burn operation. These problems can be minimized, or even eliminated, by using a highly durable and fire-resistant material in the pocket of the boom where the highest heat and stress loads exist.

A large stainless-steel fire resistant boom, known as the “Dome Boom”, was designed and successfully tested in the early 1980s. However, this boom was expensive, heavy and cumbersome to deploy. This report presents the results of a study to re-engineer the “Dome Boom” to reduce its size, weight and cost.

The project was completed in nine phases: (i) the existing boom was redesigned to reduce its cost, size, weight, and handling problems, and to make it compatible with existing boom systems; (ii) a prototype section of the re-engineered boom was constructed for testing; (iii) the boom was tested in Lake Erie to evaluate its towing and sea-keeping characteristics; (iv) the prototype was tested at the Minerals Management Service’s National Oil Spill Response Test Facility, commonly known as Ohmsett, to quantify its oil-containment capability; (v) three hours of burn tests in waves were conducted in a diesel fire at the US Coast Guard Fire and Safety Test Detachment in Mobile, AL; (vi) post-burn tow tests were performed at Ohmsett to confirm the containment capability of the boom after the diesel-fire exposure; (vii) three hours of burn tests in waves were carried out in enhanced propane flames at Ohmsett; and, (viii) destructive testing was used to estimate the operational life of the flexible connector sections and the tensile strength of several key load-bearing components. Finally, the design of the boom was refined and final detailed engineering drawings and a technical paper were produced.

The boom successfully passed all the required engineering and burn tests. The final design is presented in this report and is freely available to interested parties.

Key Words: oil spill, burning, boom, containment, fire resistant

ACKNOWLEDGMENTS

This report was written by Messrs. Ian Buist, James McCourt and Stephen Potter, of SL Ross Environmental Research, and Mr. Larry Hillebrand, of Applied Fabric Technologies. Ms. Sharon Buffington was the Minerals Management Service Contracting Officer's Technical Representative for this project.

The authors would like to acknowledge the late Ian R. McAllister, P.Eng. for his design of the original Dome boom.

The authors would like to thank the expert staff of MAR, Inc, who maintain and operate Ohmsett, the National Oil Spill Response Test Facility in Leonardo, NJ for the Minerals Management Service, the staff of the Building and Fire Research Laboratory of the National Institute for Standards and Technology, and the US Coast Guard Fire and Safety Test Detachment personnel, who operate the test tank on Little Sand Island in Mobile, AL.

TABLE OF CONTENTS

Section Page

EXECUTIVE SUMMARY S-1

1 INTRODUCTION 1-1

Objective 1-3

Report Contents 1-4

2 INVESTIGATION OF BOOM COMPATIBILITY 2-1

Overall Height 2-2

Buoyancy-to-weight Ratio 2-3

Water-line Beam 2-3

Connector Compatibility 2-3

3 THE NEW DESIGN 3-1

4 TOWING, STABILITY AND SEA-KEEPING TRIALS 4-1

5 OIL CONTAINMENT TESTING AT OHMSETT 5-1

6 DIESEL FIRE TESTING 6-1

7 POST-BURN TOW TESTING AT OHMSETT 7-1

8 ENHANCED PROPANE BURN TESTS AT OHMSETT 8-1

9 COMPONENT DESTRUCTIVE TESTING AND STEEL SELECTION 9-1

10 DEPLOYMENT AND RETRIEVAL 10-1

11 CONCLUSIONS 11-1

12 REFERENCES 12-1

APPENDIX A - Boom Design A1

APPENDIX B - Sea-keeping Trials B1

APPENDIX C - Oil Containment Testing C1

APPENDIX D - Diesel Fire Testing D1

APPENDIX E - Post-burn Containment Testing E1

APPENDIX F - Enhanced Propane Burn Testing F1

APPENDIX G - Component Destructive Testing G1

FIGURES

Figure Page

3-1 General Layout of Original Dome Boom. 3-4

3-2 General Layout of Redesigned Pocket Boom. 3-5

3-3 Redesigned Pocket Boom as Built by Applied Fabric Technologies. 3-6

3-4 Redesigned Connector for Pocket Boom (Foam Joint Covers and Omegas not Installed) 3-7

4-1 Map of Buffalo Harbor Where the Towing, Sea-keeping and Stability Trials Were Held 4-2

4-2 Pocket Boom Straight-line Towing Trials in Lake Erie 4-3

4-3 Towing in a U Configuration off Buffalo 4-3

5-1 First Loss Tow Test at Ohmsett 5-1

6-1 Second Pocket Boom Fire Test at Mobile, AL. 6-2

6-2 Total Heat Flux Measured on Downwind Side of Pocket Boom - 2nd Burn 6-3

6-3 Temperature Measured During Second Test Burn with Pocket Boom. 6-3

6-4 Total Heat Flux Measured on Downwind Side of Pocket Boom - 3rd Burn 6-4

6-5 Temperature Measured During Third Test Burn with Pocket Boom. 6-4

6-6 View of Flotation Unit After Crumpling Incident at End of Third Burn. 6-5

6-7 Total Heat Flux Measured on Downwind Side of Pocket Boom - 4th Burn 6-6

6-8 Temperature Measured During Fourth Test Burn with Pocket Boom. 6-7

7-1 Post-diesel Burn Containment Test at Ohmsett in Waves with Calsol Test Oil. 7-2

8-1 Pocket Boom in Enhanced Propane Flames at Ohmsett. 8-1

8-2 Total Heat Flux Readings for Enhanced Propane Test. 8-2

8-3 State of Pocket Boom after Ohmsett Burn Test. 8-4

9-1 Jig for Cycling Connector Sections. 9-1

9-2 Crack Propagation in Connectors Cycled Through a 15-cm (6-in.) Stroke. 9-3

9-3 Crack in Pleat Material of Connector 1 after 500,000 Cycles. 9-4

9-4 Crack Propagation in Connectors Cycled Through a 10-cm (4-in.) Stroke. 9-5

9-5 Crack Propagation in Connectors Cycled Through a 13-cm (5-in.) Stroke. 9-5

10-1 Sketch of Pocket Boom Layout Inside an ISO Container. 10-2

10-2 Deployment of 15 m (50 ft) of Pre-connected Pocket Boom. 10-2

TABLES

Table Page

2-1 Summary of Key Parameters for Existing Booms 2-2

3-1 Fire Resistant Boom Redesign Summary 3-3

5-1 Ohmsett Containment Test Summary - Calsol Test Oil 5-3

5-2 Ohmsett Containment Test Summary - Hydrocal Test Oil 5-4

7-1 Post-diesel Burn Ohmsett Containment Test Summary - Calsol Test Oil 7-3

EXECUTIVE SUMMARY

Many existing refractory fabric fire booms will deteriorate quickly in use and may require frequent replacement in a large-scale burn operation. The concept of this project was to build a short section of special boom to be connected to and used as the pocket of currently available fabric booms deployed in a U configuration. The special boom would have to be highly durable and highly resistant to thermal degradation because it is the apex of the U that experiences the highest heat and mechanical stress loads. The fabric-based fire boom "arms" of this system would be exposed only to transient heat loads as they would only direct oil into the burn pocket area and would not have to contain thick slicks of burning oil.

In this project an existing, large stainless steel boom was re-engineered to reduce its size, weight and cost. The large boom was designed, constructed and tested successfully in the early 1980s; however, because of the rigorous criteria used for the original design, it is expensive, heavy, and cumbersome to deploy.

The project was completed in nine phases: (i) the existing boom was redesigned to reduce its cost, size, weight, and handling problems, and to make it compatible with existing boom systems; (ii) a prototype section of the re-engineered boom was constructed for testing; (iii) the boom was tested in Lake Erie to evaluate its towing and sea-keeping characteristics; (iv) the prototype was tested at Ohmsett to quantify its oil-containment capability; (v) three hours of burn tests in waves were conducted in a diesel fire at the US Coast Guard Fire and Safety Test Detachment in Mobile, AL; (vi) post-burn tow tests were performed at Ohmsett to confirm the containment capability of the boom after the diesel-fire exposure; (vii) three hours of burn tests in waves were carried out in enhanced propane flames at Ohmsett; and, (viii) destructive testing was used to estimate the operational life of the flexible connector sections, and the tensile strength of several key load-bearing components. Finally, the design of the boom was refined and final detailed engineering drawings and a report were produced.

The final design of the new boom, called the Pocket Boom, has resulted in considerable cost, weight and size reductions over the original design and a corresponding improvement in ease of handling. With a buoyancy-to-weight ratio of 3, a tensile strength in excess of 1.8×10^5 N (40,000 lbf) and an overall height of 100 cm (39 in.) the boom will perform well in its intended operating environment (calm or protected environments with waves up to 1 m [3 ft]) in conjunction with commercially-available fabric booms.

Deployment, sea-keeping, towing and retrieval characteristics of the Pocket Boom are all good. Oil containment tests at Ohmsett showed that the boom will contain oil up to the normal limits (0.4 m/s = 0.75 knots) and can withstand catenary tow speeds up to 1.5 m/s (3 knots) without mechanical failure. Exposure to burning oil does not affect the oil containment characteristics of the boom.

The boom was exposed to six hours of fire with full-scale heat fluxes: three hours of diesel fires in Mobile, AL, and three hours of enhanced propane fires at Ohmsett. The boom survived this heat insult with only minor damage, none of which would have detracted significantly from its oil containment abilities. The final design of the connector section incorporates modifications to ensure that the boom's service life will be at least 1,000,000 wave cycles. This is equivalent to greater than 45 days at sea in Sea State 3.

The complete design and fabrication drawings for the boom are contained in Appendix A. The design is freely available. The boom may be obtained commercially from Applied Fabric Technologies, Inc.

Section 1

INTRODUCTION

The Minerals Management Service (MMS) is designated as the lead federal agency for *in situ* burn research in the Oil Pollution Research and Technology plan, prepared under the authority of Title VII of the Oil Pollution Act of 1990. Results from more than 10 years of *in situ* burn research continue to indicate that burning is a rapid, effective and environmentally safe means for removing large quantities of oil from the surface of the water. 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. Oil can be burned on water only if the oil slick is thick enough (2 to 3 mm) to ignite. Oil on the sea spreads rapidly so booms are used to concentrate it to a burnable thickness . The purpose of this Joint Industry Project was to develop a highly durable pocket boom to be used in conjunction with existing fabric-based fire resistant booms.

There are two basic types of fire-resistant boom presently available to contain oil for *in situ* burning (ISB): fabric-based and metallic. Only the fabric-based booms have been stockpiled in appreciable quantities, because the metallic versions have been too heavy, cumbersome, and expensive. The fire-resistant fabrics are woven from mineral, ceramic, or glass-like fibers. Unfortunately, the operating life of these fabric-based booms has proved to be significantly less than originally thought: 2 or 3 hours as opposed to 48+ hours.

Since the 1970s, when fire resistant booms were first proposed and developed (Purves 1978, Buist *et al.* 1983, Spiltec 1986), many fire tests of these booms in quiescent conditions have been carried out (Buist *et al.* 1983, SL Ross 1983, Spiltec 1986, Allen and Fischer 1988, Allen 1990, Alaska Clean Seas 1991, S.L. Ross 1995). Generally, the results have been encouraging and have been used to promote the current interest in fire booms, especially of the fabric or textile variety. However, from the beginning of research in this area (Roberts and Chu 1978, Dome 1981) there have been concerns that the intrinsically low abrasion resistance of the fibers in the fabric-type booms would be a problem. Once the fabric-based boom is exposed to fire the sacrificial plastic cover burns off, exposing the underlying fabric to the water. Wave action mechanically flexes the boom fabric, causing self-abrasion that is exacerbated by the fabric being wet. Eventually the refractory material will fail to contain the burning oil. At the 1995 Newfoundland Offshore Burn Experiment (NOBE) burn off Newfoundland (Fingas *et al.* 1995) the combined effect of exposure to water, moderate wave action (0.5 m wave height), and high temperature flames (for 2¾ hours) caused severe damage to and ultimately failure of the fabric-based boom. The failure of this fabric boom did not affect the success of the NOBE project.

Another, previously unidentified, problem with fabric-based booms is that they can leak oil at significant rates after the sacrificial plastic cover burns off. Previous testing of fabric-based booms conducted in static conditions with slick thicknesses of a few millimetres or less indicated no serious leakage problem, but recent work (S.L. Ross 1995, McCarthy 1996) has shown that such booms can become highly permeable to oil when exposed to fire and a large slick thickness (i.e., 17 cm = 6 in)[1]. The hot oil seeps through the exposed boom fabric. A "head" of hot, low-viscosity oil is created in the apex, or pocket, when towing a U of boom full of burning oil. This seeping phenomenon may be one reason that burning was observed on the downstream side of the fire boom during the NOBE trials (Fingas *et al* 1995).

To counter the problems associated with fabric booms, a revised operating strategy that calls for frequent replacement of deteriorated sections of fabric boom during ISB operations has been espoused. There are obvious cost and efficiency problems with this approach.

A technical study of fire booms completed in 1994, by the Southwest Research Institute (Burkes 1994) concluded that there are inherent problems associated with fabric fire booms and that new designs should be researched. A better solution would be to design a new boom system that can be used with the existing stockpiles of fabric booms to enhance their effectiveness. The concept would be to build a short section of special boom to be connected to and used as the pocket of currently available fabric booms deployed in a U configuration. The special boom would have to

---

[1] A slick thickness of 17 cm would be at the low end of thicknesses expected in towed booms at an oil spill, more typically these would be in the 25 to 35 cm range.

be highly durable and highly resistant to thermal degradation because it is the apex of a U of a fire boom that experiences the highest heat and mechanical stress loads.The fabric-based fire boom "arms" of this system would be exposed only to transient heat loads as they would only direct oil into the burn pocket area and would not have to contain thick slicks of burning oil. Higher operational efficiency for controlled *in situ* burning operations would also be expected because of reduced down-time for replacing degraded boom.

One stainless steel boom, called the Dome boom (Buist *et al.* 1983), was a good candidate as a starting point for the work. This non-commercial product, although it had shortcomings, was “tried and tested” and known to have high durability and high resistance to heat, the two most important qualities needed for the present application.

The Dome boom was originally developed as a high-strength, offshore system for response to blowouts in Arctic seas. As such, it was designed to survive high, steep seas (up to Sea State 5), carry high tensile loads, withstand impacts with ice, and operate in flames for very long periods (Buist *et al.* 1983). This boom was successfully tested at Ohmsett (Dome 1981) and at sea (Dome 1983) and was found to be capable of surviving long-term exposure in waves without any loss in integrity. The final version of the boom presently forms part of the Canadian Coast Guard's Arctic response stockpile. This version was successfully tested again at Ohmsett in 1996 (Bitting and Coyne 1997). The major disadvantages of the Dome boom are that it is expensive, heavy, and difficult to deploy.

OBJECTIVE

The objective of this project was to produce a smaller, less expensive, lighter, and less cumbersome version of the Dome boom for use as a highly durable burn pocket in conjunction with refractory fabric fire booms.

REPORT CONTENTS

Section 2 of this report describes the key physical characteristics of commercially available fabric fire booms and how these influenced the steel boom re-engineering. Section 3 delineates the new design in detail (full drawings may be found in Appendix A). Section 4 covers the towing, stability, and sea-keeping trials held in Lake Erie, near Buffalo, NY, in June 1998. Section 5 details the first series of oil containment trials held at Ohmsett. Section 6 describes the first series of burn tests conducted with diesel-fueled fires in Mobile, AL. Section 7 covers the post-Mobile oil containment trials, conducted again at Ohmsett. Section 8 details the second series of burn tests using propane-fueled fires at Ohmsett. Section 9 describes the destructive tests carried out to determine the strength and service life of key components of the new design. Section 10 describes the deployment and retrieval of operational lengths of the new boom. The conclusions arising from the project are contained in Section 11.

Section 2

INVESTIGATION OF BOOM COMPATIBILITY

Although there are as many as 10 designs of existing fire containment booms, there are only four that have been commercially produced and that are available in the inventories of various response organizations (Buist *et al.* 1994). These products are:

American Marine (models 1218 and 1824)
    Formerly produced by and also known as the 3M boom
    Curtain-type boom
    Ceramic-based fabric and stainless steel mesh over solid flotation

Applied Fabrics (Pyro30)
    Fence-type boom
    Ceramic-based fabric and wire mesh with spherical steel floats

Oil Stop (Harbor and Offshore models)
    Curtain-type boom
    Ceramic-based fabric and stainless steel mesh with pressure-inflated flotation

Kepner (models 1418 and 1823)
    Curtain-type boom
    Ceramic-based fabric with air chambers that automatically inflate (to atmospheric pressure) as the boom is deployed

The purpose of this project was to produce a fire-resistant boom that would complement existing boom products. As such, the proposed boom had to be compatible with existing fire booms in terms of physical dimensions and wave response.The key physical properties of these four boom designs are given in Table 2-1. A discussion of the influence of these properties on the steel boom re-design follows.

Table 2-1. Summary of Key Parameters for Existing Booms.

Manufacturer	**American Marine**		**AFTI**	**Oil Stop**		**Kepner**
Model	**1218**	**1824**	**Pyro30**	**Harbor**	**Offshore**	**1418**
Height, cm (in.)	76 (30)	110 (43)	76 (30)	76 (30)	107 (42)	84 (33)
Freeboard, cm (in.)	23 (9)	38 (15)	30 (12)	25 (10)	36 (14)	28 (11)
Draft, cm (in.)	53 (21)	71 (28)	46 (18)	51 (20)	71 (28)	56 (22)
Buoyancy:Weight ratio	3*	3*	3.5	5.5*	6*	>10*
Beam, cm (in.)	25* (10)	38* (15)	15* (6)	20* (8)	29* (11)	18* (7)
Connector	Quick	Quick	ASTM	ASTM	ASTM	ASTM
Estimated inventory, m (ft)	6900 (22,500)	2300 (7500)	1200 (4000)	1700 (5500)	900 (3000)	900 (3000)

* estimated values

Note: the buoyancy-to-weight ratio of American Marine boom is reported to be 4.8 and 5.7 for the 1218 and 1824 models, respectively. However, observations of this boom in field tests suggest that these higher values are a result of buoyancy contained within the sacrificial cover, and this additional buoyancy is lost immediately upon exposure to an oil fire. The estimated buoyancy-to-weight ratio of 3, listed above, is more indicative of the boom's performance in a burning operation.

OVERALL HEIGHT

The draft and freeboard of the redesigned boom should be appropriate to the intended operating environment. The fabric booms listed above would be applicable to calm or protected water environments according to ASTM F1523[2], that is, wave heights of up to 1m (3 ft). It would be unnecessary to design the new boom for conditions more severe than this because the operation would be limited by the performance of the existing booms which form the arms of the U and direct oil into the burn pocket.

Secondly, the freeboard and draft dimensions of the proposed boom should be close to that of existing booms to limit stress differentials resulting from current, wave, and wind effects. Small

---

[2] Refers to American Society for Testing and Materials Standard F1523-94: Selection of Booms in Accordance With Water Body Classifications

differences in freeboard/draft could be accommodated by designing an adapter for the connection point.

BUOYANCY-TO-WEIGHT RATIO

There is a direct relation between a boom's buoyancy-to-weight ratio and its heave response (i.e., its response to waves). The higher the ratio the greater the heave response. The buoyancy-to-weight ratio of the proposed boom should be comparable to that of existing booms to limit stress at the connection point that would result from differing heave response.

WATER-LINE BEAM

The water-line beam, defined as the average width of the boom at the water-line, also affects heave response. As with buoyancy-to-weight ratio, the beam of the proposed boom should be comparable to that of existing booms to limit stress at the connection point that would result from differing heave response.

CONNECTOR COMPATIBILITY

It was impractical to design a single connector that would mate with all existing boom types. A more practical design alternative would be to develop a series of adapters to suit existing boom products. The US Navy (or shotgun) connector used with the Dome stainless steel boom offers some advantages for making connections with the boom in the water Therefore, the US Navy connector should be retained in the redesigned boom with adapters to be designed and produced as necessary.

Section 3

THE NEW DESIGN

The overall redesign philosophy was to downsize the Dome stainless steel boom, reduce its weight, increase its buoyancy, and improve its handling, while maintaining its superior strength and durability. This involved engineering assessments of materials, scaling, layout, production, and operating aspects of the boom system. Handling, sea-keeping, stowage, and durability were key characteristics optimized during this re-engineering task.

The original Dome Boom design (Figure 3-1) involved 14-gauge 310 stainless steel flotation units of pentagonal cross-section joined by accordion-pleated connector sections of 321 stainless steel. Loads were passed through the connector sections by a universally-jointed box beam located beneath the water-line.

For the new boom, the cross-sectional profile of the flotation unit was redesigned to maximize reserve buoyancy, minimize weight, and improve heave response. The thickness of the metal used to construct the flotation chamber was reduced to 18 gauge from 14 gauge; this was felt to be reasonable because the redesigned boom is not intended to be subjected to severe ice impacts, as was the Dome boom. The grades of stainless steel used for above-water components remain unchanged; although several flotation sections of the prototype were constructed with type 304 stainless instead of type 310 to see if the lower cost 304 could perform as well as the 310 does in a high-temperature salt water environment. There is considerable incentive to use type 304 instead of type 310, because the cost of 310 can be up to 4 times that of the same in 304.

Particular attention was paid to the redesign of the connector unit in terms of durability and service life. The fundamental design of the pleated connector with a universally jointed through-beam was retained because of its proven performance characteristics. The use of 321 stainless for the pleats was retained because of its superior yield strength and its availability in the required thickness. The location of the through-beam was lowered from the center-line of the connector to ensure that it remains below the water-line with the increased overall buoyancy of the redesigned boom. This relocation should also help resist planing failure of the redesigned boom while being towed in a catenary, a known drawback of the larger boom. The design of the joint in the through-beam itself remains unchanged from the larger boom, although the box beam was reduced in size. The likelihood of oil leaking through the hinges was reduced by adding steel hinge cover strips extending the full height of the hinge. From the top of the foam joint covers to the top of the hinge, a loop (denoted as an “omega” for its shape in plan view) of fire boom fabric was installed to provide further leak protection. The key characteristics of the original Dome boom and the redesigned boom, hereafter referred to as the Pocket Boom, are compared in Table 3-1 and depicted in Figures 3-1 and 3-2.

The design of the connector between the Pocket Boom and the fabric fire boom was also considered. Ultimately, the design chosen was a simple metal adapter that converts the stainless steel boom’s US Navy standard double-male connector (i.e., the double-barrelled shotgun type) to a standard ASTM-type or Quick-type connector for attaching directly to the conventional fabric fire booms. This type of transition connector was selected on the basis of simplicity, ease of connection in the water, and acceptable performance during the various tow tests performed throughout the project. The transition connector is intended to connect a flotation section to the fabric boom.

Table 3-1. Fire Resistant Boom Redesign Summary.

NOMINAL DIMENSIONS	DOME BOOM	POCKET BOOM
Float Section		
height, cm (in.)	178 (70)	100 (39)
freeboard, cm (in.)	58 (23)	35 (14)
beam, cm (in.)	71 (28)	43 (17)
length, cm (in.)	175 (69)	167 (65)
weight, kg (lb)	100 (224)	50 (110)
Connector Section		
height, cm (in.)	170 (67)	91 (36)
freeboard, cm (in.)	55 (22)	31 (12)
length, cm (in.)	95 (38)	60 (24)
weight, kg (lb)	127 (279)	49 (108)
Overall		
weight, kg (lb)	229 (503)	99 (218)
length, m (ft)	2.8 (9)	2.3 (8.5)
weight/length, kg/m (lb/ft)	82 (56)	40 (27)
buoyancy to weight ratio	1.8	3
tensile strength, N (lbf)	3.3×10^5 (75,000)	1.8×10^5 (40,000)
stored length [11 sections: 11 connectors + 12 floats], m (ft)	9 (30)	6 (19)

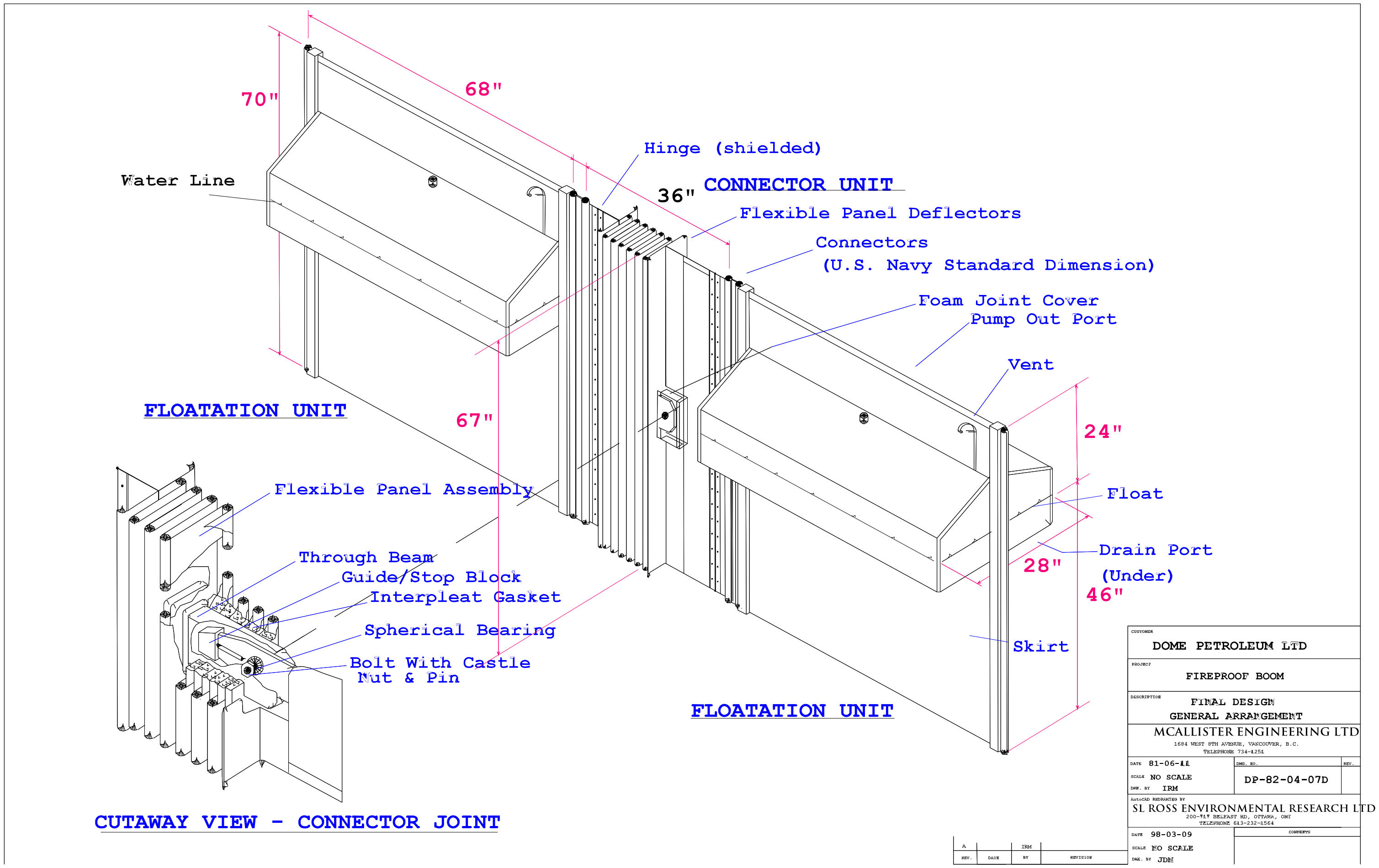


Figure 3-1. General Layout of Original Dome Boom.

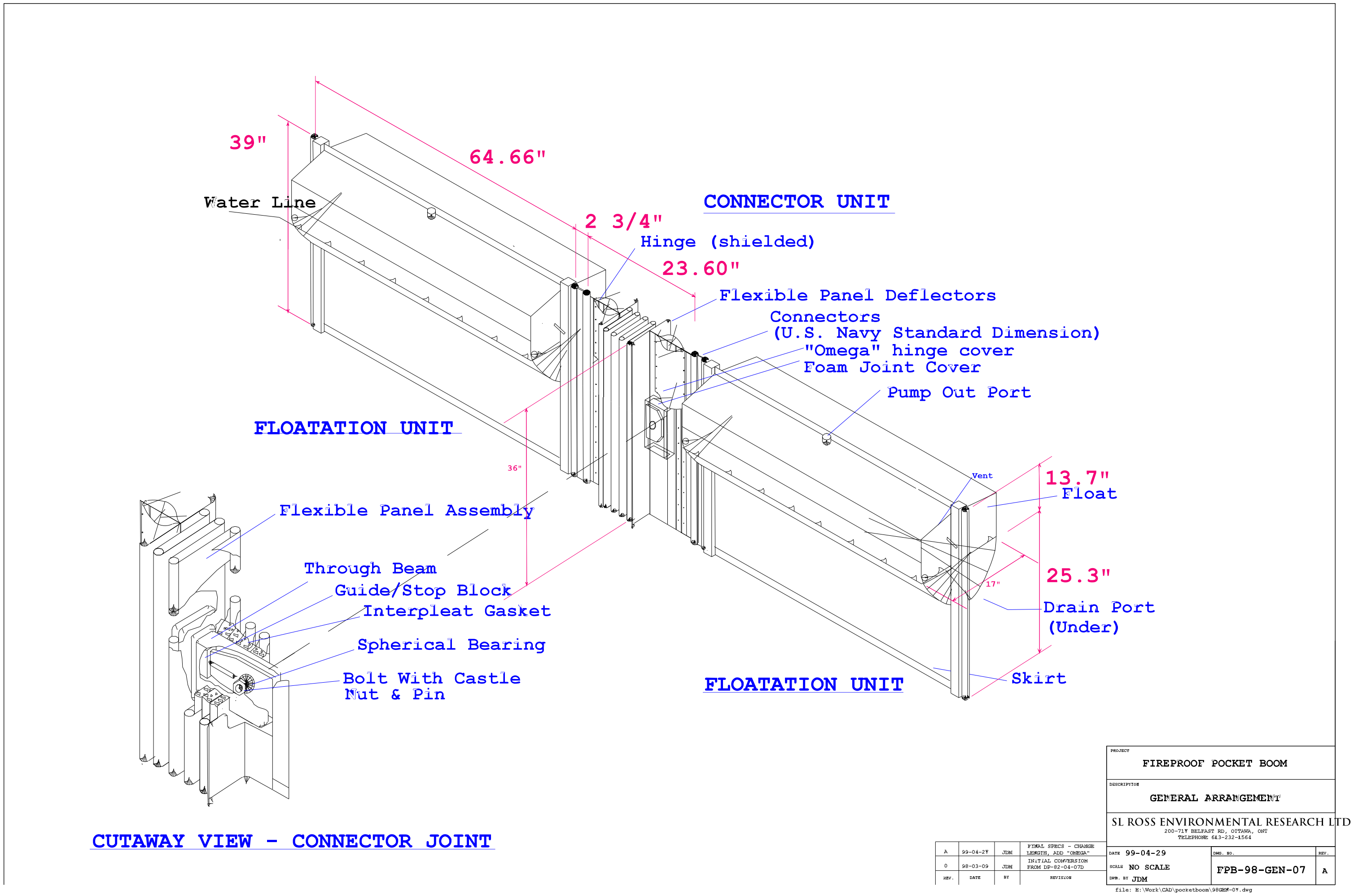


Figure 3-2. General Layout of Redesigned Pocket Boom.

As designed, 58 m (188 ft) of pre-connected stainless steel boom, weighing 2600 kg (5600 lb), could be stored, ready for deployment in two pieces, in a standard 20-foot ISO container.

A prototype length (16 m or 52 ft) of the new boom, consisting of seven flotation units and seven flexible connector units, was constructed by Applied Fabric Technologies, Inc. in Orchard Park, NY. Figures 3-3 and 3-4 show the boom as built. Complete fabrication drawings may be found in Appendix A, and are available in digital form as AutoCad 12 files.

Figure 3-3. Redesigned Pocket Boom as Built by Applied Fabric Technologies.

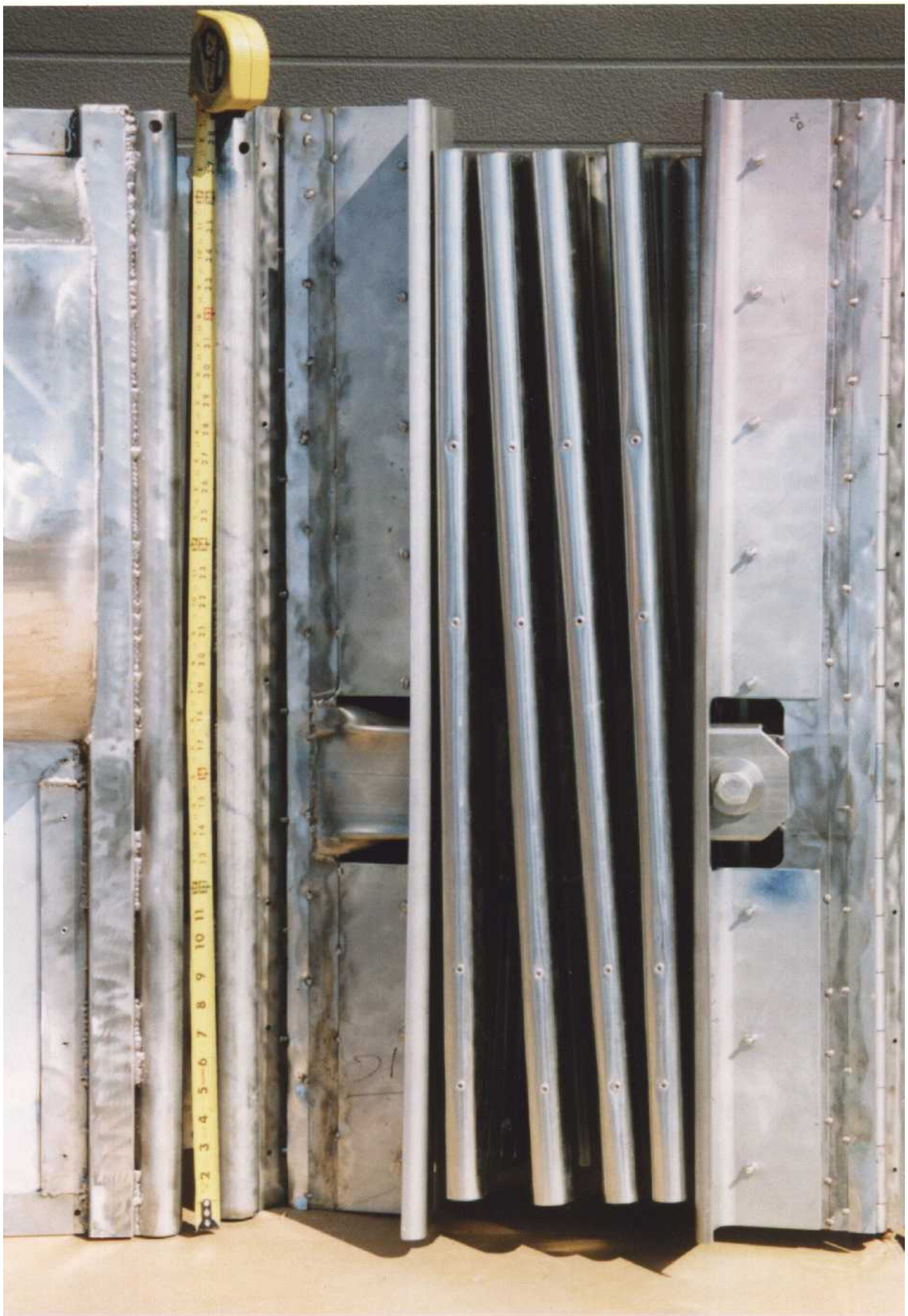


Figure 3-4. Redesigned Connector for Pocket Boom (Foam Joint Covers and “Omegas” not Installed).

Section 4

TOWING, STABILITY AND SEA-KEEPING TRIALS

Straight line and catenary tow tests of the prototype Pocket Boom section, alone and inserted between two lengths of conventional boom were conducted to assess stability, heave response, flexibility, righting moment, and medium-term durability.

The tests were held on June 17 and 18, 1998 in Lake Erie, just south of Buffalo, NY, in the harbor area off the mouth of the Buffalo River (Figure 4-1). The test protocol, weather observations, and field notes may be found in Appendix B. On June 16, a crane was used to launch the pre-connected Pocket Boom from its storage box at the US Coast Guard (USCG) base in Buffalo. The measured freeboard was 35 cm (14 in.), which matched the design specification.

The next day the boom (seven floats and six connecters) was towed, with a towing bridle attached to each end float section, in a straight line by one tow vessel in calm water to evaluate its stability and tendency to “corkscrew”. The boom towed well, with only a slight heel to one side or the other, and followed the waves well. The tow speed was approximately 0.75 m/s (1.5 knots). The second tow vessel then took up the other end of the Pocket Boom and the boom was towed in a U configuration. In the U configuration, the Pocket boom towed well, with only a slight tendency to plane at speeds of 1 m/s (2 knots) or more. Wave conformance was excellent, even in 1-metre waves with a 3-second period.

The boom was then towed back to the USCG dock and left in the water overnight. The following morning it was noted that two float units were lower in the water than the others. Their pump-out ports were opened and it was found that they had water in them. These units were pumped dry. After this, 8-m (25-ft) sections of conventional 36-in. Globe boom were added to each end of the Pocket Boom. These were attached to simulate the connection of the Pocket Boom to conventional fabric fire boom. The entire test series was then repeated, with particular attention paid to the reaction of the transition from steel to conventional boom, in waves and currents. With the conventional boom attached, the Pocket boom towed even better in a straight line, with

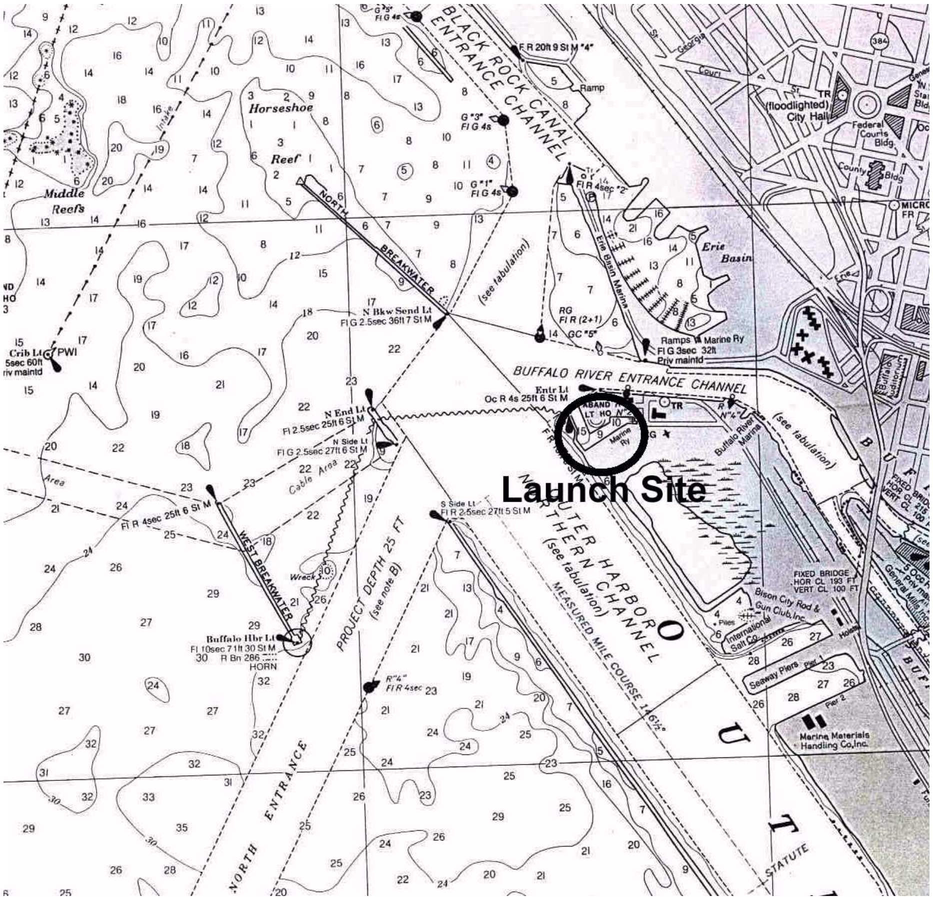


Figure 4-1. Map of Buffalo Harbor Where the Towing, Sea-keeping and Stability Trials Were Held.

no evidence of heel, at speeds of up to 2.5 m/s (5 knots). It also followed the waves very well in this configuration (Figure 4-2). No overtopping was observed in 0.6 to 1-m (2 to 3-ft) waves and 30 km/hr (15 knot) winds and no planing was noted at U tow speeds up to 0.8 m/s (1.5 knots) as shown in Figure 4-3. The attachment of the Globe boom directly to the Pocket Boom end floats worked very well, with no wear or undue motion noted.

The 33-m (100-ft) combined section was then returned to the dock for recovery and re-packing the next day. When the prototype was removed from the water the following morning it was examined closely for signs of wear, fatigue, leakage, and damage. Other than the two float

Figure 4-2. Pocket Boom Straight-Line Towing Trials in Lake Erie.

Figure 4-3. Towing in a U Configuration off Buffalo.

sections having taken on more water, no other damage was noted. The boom had been in the water for a total of 68 hours. The boom was returned to Applied Fabric Technologies, examined closely, the leaks identified and repaired in the two float sections, and the boom repackaged for shipment to Ohmsett - the National Oil Spill Response Test Facility located in Leonardo, NJ, for the next test series.

Section 5

OIL CONTAINMENT TESTING AT OHMSETT

The Pocket Boom was tested at Ohmsett from July 20 through 31, 1998 using the standard protocol for testing fire booms (Bitting and Coyne 1997). The prototype was connected to two 8-m (25-ft) lengths of conventional boom to form a 30-m (100-ft) test section. The tests included: establishing the pre-load volume for subsequent loss tests; tests to determine first and gross loss tow speeds; loss-rate tests; and a critical tow speed test. The test protocol and complete data may be found in Appendix C.

The first loss tests consisted of towing the boom at increasing speeds to determine the speed at which oil was first lost from the boom (Figure 5-1). Subsequently, the boom was towed at a higher speed to determine the speed at which gross amounts of oil were lost past the boom. In each case the mode of failure was noted along with general observations of boom behavior.

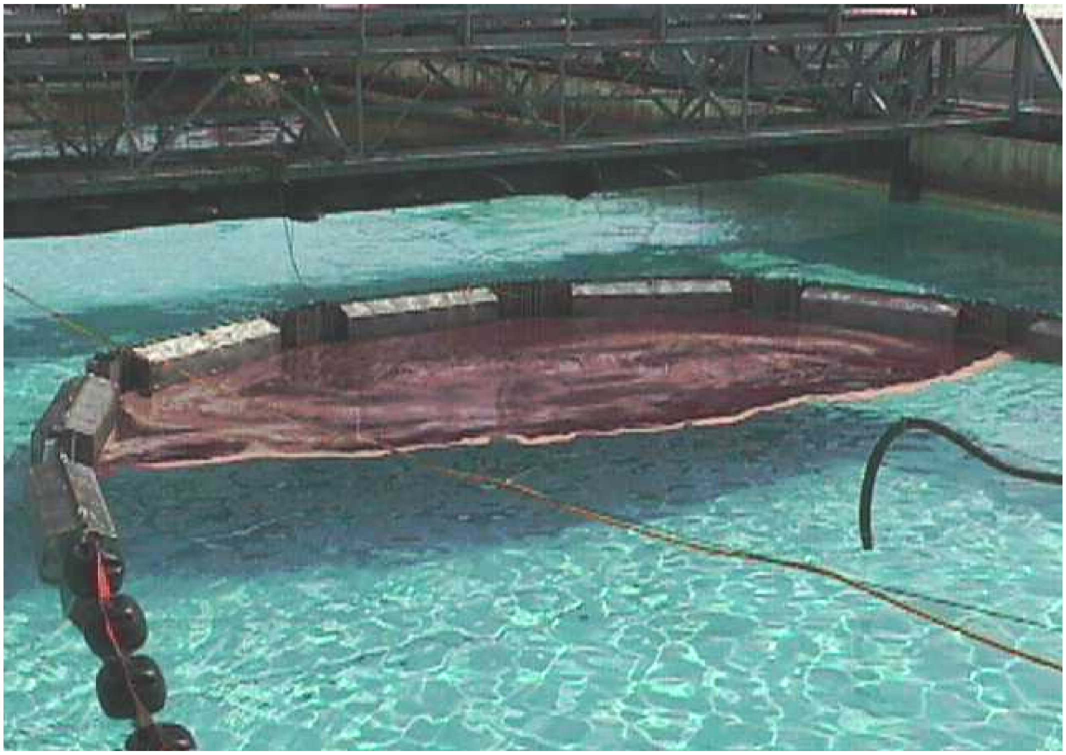


Figure 5-1. First Loss Tow Test at Ohmsett.

A total of 21 tests were run using Calsol 8240 oil (viscosity 1200 mm^2/s [cSt] @ 27 C [80 F]), followed by an additional 13 tests using Hydrocal 300 oil (viscosity 200 mm^2/s [cSt] @ 27 C [80 F]). The additional group of tests with the lighter oil was performed to confirm that the results of the previous testing were not solely related to the higher viscosity and higher interfacial tension of the Calsol oil. Table 5-1 summarizes the results of the tests with Calsol; Table 5-2 summarizes the results of the tests with Hydrocal.

The first seven tests with the Calsol test oil (denoted as Preload tests in Table 5-1) involved towing the boom with increasing volumes of oil in the apex to determine the minimum volume of oil required to ensure that slick size does not affect the first loss tow speed. This minimum volume was determined to be approximately 1140 L (300 gal). All subsequent tests were conducted with oil volumes well in excess of this minimum.

With the medium-viscosity test oil (Calsol) the first loss tow speed in calm conditions, harbor chop (wave #3) and long regular waves (wave #1), was determined to be 0.45 m/s (0.9 knots). Gross loss was noted at 0.6 m/s (1.2 knots). In short, regular waves (wave #2) the first loss tow speed was 0.35 m/s (0.7 knots) and the corresponding gross loss tow speed was 0.45 m/s (0.9 knots).

In comparison, with the low-viscosity oil (Hydrocal) the first and gross loss tow speeds in calm conditions and harbour chop waves were unchanged; however, they were slightly lower in the regular waves. In longer regular waves the first and gross loss tow speeds averaged 0.41 m/s (0.83 knots) and 0.59 m/s (1.18 knots) respectively. In the shorter waves the corresponding average speeds were 0.35 m/s (0.7 knots) and 0.42 m/s (0.85 knots).

Comparison of the test data for the two oils indicates that the measured loss rates with the less-viscous oil were two to three times higher than with the medium-viscosity oil.

Table 5-1. Ohmsett Containment Test Summary - Calsol Test Oil.

Test #	Test Type	Waves	Loss Speed, m/s (knots)	Preload Volume, L (gal)	Comments	
1	Preload	none	0.6 (1.2)	230 (60)		
2	Preload	none	0.5 (1)	460 (120)		
3	Preload	none	0.48 (0.95)	680 (180)		
4	Preload	none	0.45 (0.9)	910 (240)		
5	Preload	none	0.43 (0.85)	1140 (300)		
6	Preload	none	0.45 (0.9)	1360 (360)		
7	Preload	none	0.45 (0.9)	1590 (420)		
8	1st and Gross	none	0.45 (0.9) 0.6 (1.2)	1590 (420)		
9	1st and Gross	Wave #3 3"-30 HC[1]	0.45 (0.9) 0.6 (1.2)	1320 (350)	wave data averaged from tests 9 and 10 gives	
10	1st and Gross	Wave #3 3"-30 HC	0.45 (0.9) 0.6 (1.2)	1510 (400)	$H_{1/3}$= 30 cm (12")[2]	
11				test aborted		
12	1st and Gross	Wave #2 3"-35 Reg[1]	0.35 (0.7) 0.45 (0.9)	1510 (400)	wave data averaged from tests 12 and 13 gives	
13	1st and Gross	Wave #2 3"-35 Reg	0.38 (0.75) 0.45 (0.9)	1510 (400)	$H_{1/3}$= 25 cm (10")[2]; = 4.4 m (14.4 ft); P=1.68 s	
14	1st and Gross	Wave #1 6"-19 Reg[1]	0.45 (0.9) 0.6 (1.2)	1510 (400)	wave data averaged from tests 14 and 15 gives	
15	1st and Gross	Wave #1 6"-19 Reg	ND[3] 0.6 (1.2)	1510 (400)	$H_{1/3}$= 28 cm (11")[2]; =12.8 m (42.1 ft);P=3.14 s	
					Dist. Rate, L/min. (gpm)	Loss Rate, L/min. (gpm)
16	Loss Rate	none	0.5 (1)	1510 (400)	100 (26)	12 (3.2)
17	Loss Rate	none	0.6 (1.2)	1740 (460)	400 (105)	160 (41)
18	Loss Rate	none	0.5 (1)	1510 (400)	100 (26)	10 (2.7)
19	Loss Rate	none	0.6 (1.2)	1740 (460)	400 (105)	220 (59)
20	Critical Tow	none	1.5 (3)	none	planed slightly at 0.75 m/s and remained stable to 1.5 m/s	
21	Critical Tow	none	1.5 (3)	none	Repeat, behavior as above	

1. 3"-30 means 3-in. wave paddle stroke with a frequency of 30 cycles per minute; HC means harbor chop (i.e., wave beach lowered to allow reflection), Reg means wave beach raised to minimize reflection

2. $H_{1/3}$ is the average of the highest one third of all waves; is the average wavelength; P is the average apparent wave period

3. ND = no data - underwater visibility too poor to ascertain first loss speed

Table 5-2 Ohmsett Containment Test Summary - Hydrocal Test Oil.

Test #	Test Type	Waves	Loss Speed, m/s (knots)	Preload Volume, L (gal)	Comments	
22	1st and	none	0.45 (0.9)	1510 (400)		
	Gross		0.6 (1.2)			
23	1st and	none	0.42 (0.85)	1510 (400)		
	Gross		0.58 (1.15)			
					Dist. Rate, L/min. (gpm)	Loss Rate, L/min. (gpm)
24	Loss Rate	none	0.5 (1)	1510 (400)	100 (26)	25 (6.6)
25	Loss Rate			test aborted		
26	Loss Rate	none	0.5 (1)	1510 (400)	100 (26)	20 (5.1)
27	Loss Rate	none	0.6 (1.2)	1510 (400)	400 (105)	670 (178)
32	Loss Rate	none	0.6 (1.2)	1510 (400)	400 (105)	480 (126)
28	1st and	Wave #1	0.42 (0.85)	1510 (400)	wave data averaged from tests 28	
	Gross	6"-19 Reg[1]	0.6 (1.2)		and 29 gives	
29	1st and	Wave #1	0.4 (0.8)	1510 (400)	$H_{1/3}$= 28 cm (11")[2];	
	Gross	6"-19 Reg	0.6 (1.15)		=12.8 m (42.1 ft);P=3.14 s	
30	1st and	Wave #2	0.38 (0.75)	1510 (400)	wave data averaged from tests 30	
	Gross	3"-35 Reg	0.45 (0.9)		and 31 gives	
31	1st and	Wave #2	0.33 (0.65)	1510 (400)	$H_{1/3}$= 25 cm (9.8")[2];	
	Gross	3"-35 Reg	0.4 (0.8)		= 4.5 m (14.9 ft); P=1.71 s	
33	1st and	Wave #3	0.45 (0.9)	1510 (400)	wave data averaged from tests 33	
	Gross	3"-30 HC[1]	0.6 (1.2)		and 34 gives	
34	1st and	Wave #3	0.43 (0.85)	1510 (400)	$H_{1/3}$= 25 cm (10")[2]	
	Gross	3"-30 HC	0.55 (1.1)			

1. 3"-30 means 3-in. wave paddle stroke with a frequency of 30 cycles per minute; HC means harbor chop (i.e., wave beach lowered to allow reflection), Reg means wave beach raised to minimize reflection
2. $H_{1/3}$ is the average of the highest one third of all waves; is the average wavelength; P is the average apparent wave period

In the critical tow speed test, the boom was towed at increasing speeds up to a maximum of 1.5 m/s (3 knots) to determine the ultimate mode of failure of the boom. A maximum of 1.5 m/s (3 knots) was chosen to ensure that the boom was not severely damaged for subsequent testing. Note that even this speed is much greater than would be experienced in a typical containment operation. As the tow speed increased above 0.75 m/s (1.5 knots), the boom began to plane slightly more, but remained stable. The design decision to relocate the through-beam below the center-line of the Pocket Boom had the desired effect in reducing the planing behavior that was observed with the old Dome boom.

Following the critical tow speed test, the boom was lifted from the water and inspected for damage. Only three minor problems were found:

1. One piece of foam, which is used to cover each end of the box beam that passes through the pleats, had separated from the boom mid-way through the test program.
2. One of the four rivets used to hold a pleat-backing tube had pulled through the pleat material.
3. One of the connector sections had a tear in it where a pleat-backing tube had over stressed the material during the critical tow speed test.

None of this damage compromised the structural integrity, flotation or containment ability of the boom.

Section 6

DIESEL FIRE TESTING

Following the Ohmsett testing of the Pocket Boom, it was shipped to the USCG Fire and Safety Test Detachment in Mobile, AL for fire testing in waves. The tests followed the protocol established by the National Institute for Standards and Technology (NIST) for the US Coast Guard and the Minerals Management Service (Walton *et al.* 1998). The protocol and data may be found in Appendix D.

A total of four test burns was conducted: a short demonstration burn on September 10, 1998 for a group of observers, and three one-hour burns on September 17 that constituted the test protocol. The intervening week was spent waiting for wind from a direction that would satisfy the burn permit for the facility.

The boom was formed into a circle in the middle of the test tank. The diameter of the circle was estimated as 4.8 m (15 ft 10 in.). The test protocol involved three cycles of one hour of burning followed by one hour of cool-down with waves. The wave paddle was operated with a period of 4.6 s for all tests.

The short demonstration involved burning 114 L (30 gal) of No. 2 diesel fuel over a period of approximately three minutes. No leakage or component failure was observed. The second burn (the first one-hour burn) consumed 3310 L (874 gal) of No. 2 diesel over a period of 58.5 minutes (approximately 51 minutes of full flame coverage). Figure 6-1 shows the boom during this test, and Figures 6-2 and 6-3 show the total heat flux from the fire (measured using Medtherm model 64-20-20) and the flame temperature. The transducers and thermocouples were located 30 cm (1 ft) downwind and 30 cm (1 ft) above the downwind side of the boom (i.e., on the right-hand side of Figure 6-1). One total heat flux transducer looked up into the flame blowing over it (denoted as the vertical transducer) and the other looked downwind into the flame blowing towards it (denoted the horizontal transducer).

It was observed that a low flame persisted on the top of the fabric "omega" protecting each connector hinge. This could have been due to the fabric wicking fuel up from the water surface between the "omega" and the hinge. No leaks were observed during the burn test and the boom appeared undamaged afterwards. At the end of the subsequent one-hour cool-down, during the filling of the boomed area with the diesel for the next burn, some minor leakage from the downwind connectors was noted.

The third burn (the second one-hour burn) consumed 3420 L (904 gal) of fuel over a total time of 62 minutes (approximately 54 minutes of full flame coverage). No leakage or boom failure was noted during the third burn. Figures 6-4 and 6-5 show the heat flux from the fire and the temperature of the boom. Just before the flames extinguished, one of the downwind flotation

Figure 6-1. Second Pocket Boom Fire Test at Mobile, AL.

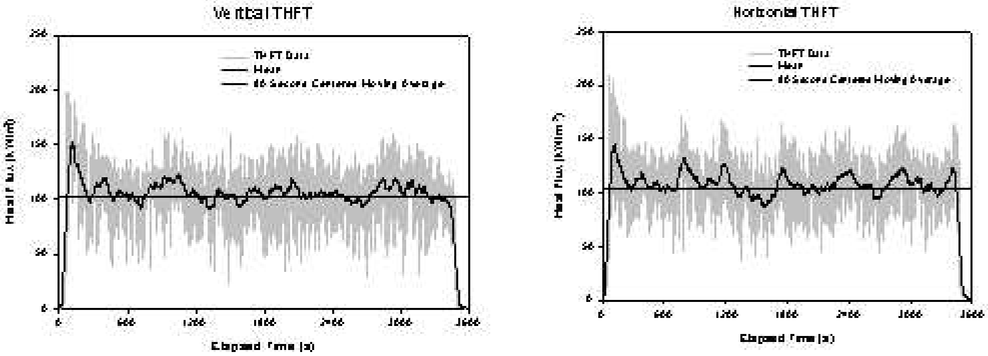


Figure 6-2. Total Heat Flux Measured on Downwind Side of Pocket Boom - 2nd Burn.

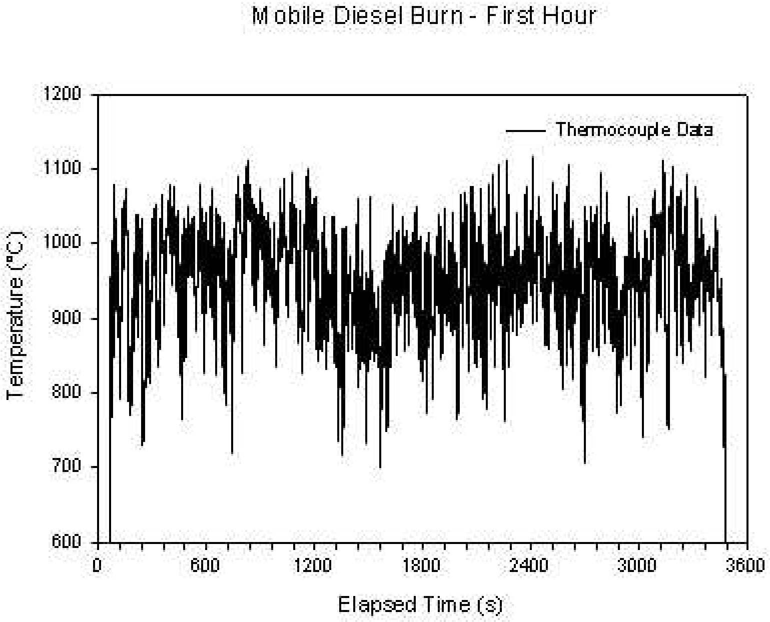


Figure 6-3. Temperature Measured during Second Test Burn (First Hour-long Burn) with Pocket Boom.

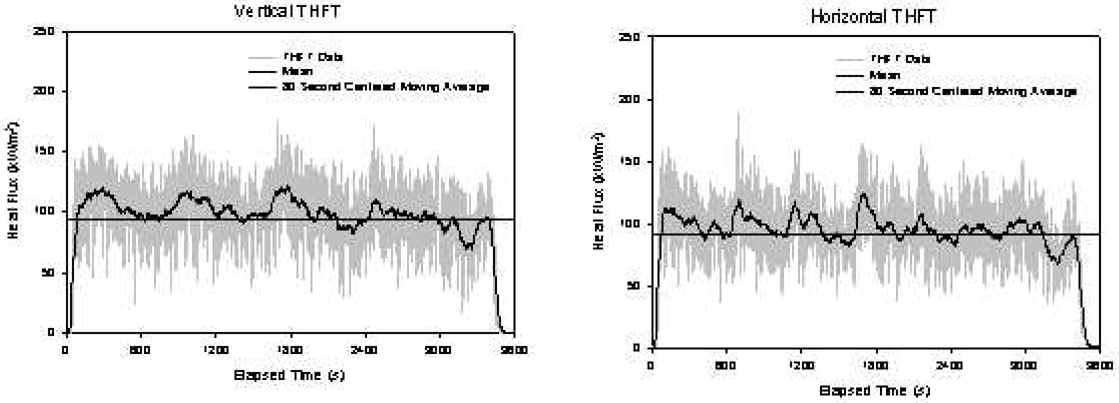


Figure 6-4. Total Heat Flux Measured on Downwind Side of Pocket Boom - 3rd Burn.

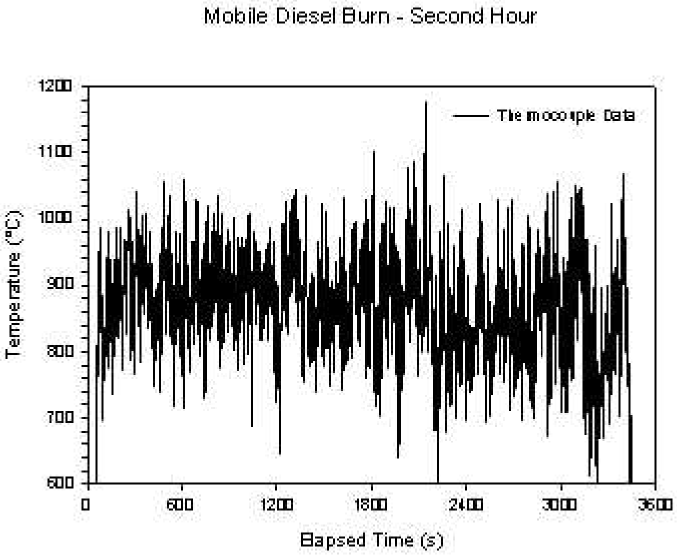


Figure 6-5. Temperature Measured during Third Test Burn (Second Hour-long Burn) with Pocket Boom.

units crumpled inward, apparently due to low pressure developing inside the unit. Figure 6-6 shows the affected section. It was suspected that this was due to the presence of tank sealant used to fill small leaks in the flotation unit during previous tests. Something (perhaps this sealant), under fire conditions, restricted the vent tube (designed to allow the free flow of air into and out of the tank) and caused the crumpling. The crumpling did not appear to detract from the boom's ability to contain oil or float. The vent tube diameter has been increased in the final design to alleviate this problem. No other damage was noted after the second burn. Again, as the boom was filled with the pre-load of diesel for the third one-hour burn, slight leakage from the connectors on the downwind side of the boom was again noted.

Figure 6-6 View of Flotation Unit After Crumpling Incident at End of Third Burn

The fourth burn (the third one-hour burn) consumed 3420 L (904 gal) of fuel and lasted 58 minutes (56 minutes of full flame coverage). Figures 6-7 and 6-8 show the heat flux and temperature data for this burn. Four minutes after ignition the crumpled float unit re-expanded to nearly its original shape: it did not re-crumple at the end of the third one-hour burn. No leakage or boom failure was noted during the third one-hour burn. At the end of the burn the boom was re-inspected and it appeared that a flotation unit adjacent to the one that crumpled had expanded slightly due to over-pressure. Again, the vent tube must have been restricted. Despite this, the boom appeared to be maintaining its freeboard and no other damage was noted.

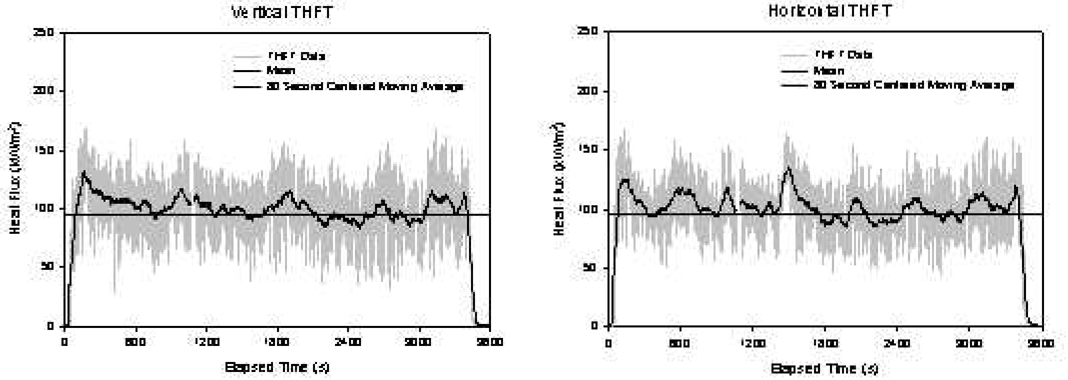


Figure 6-7. Total Heat Flux Measured on Downwind Side of Pocket Boom - 4th Burn.

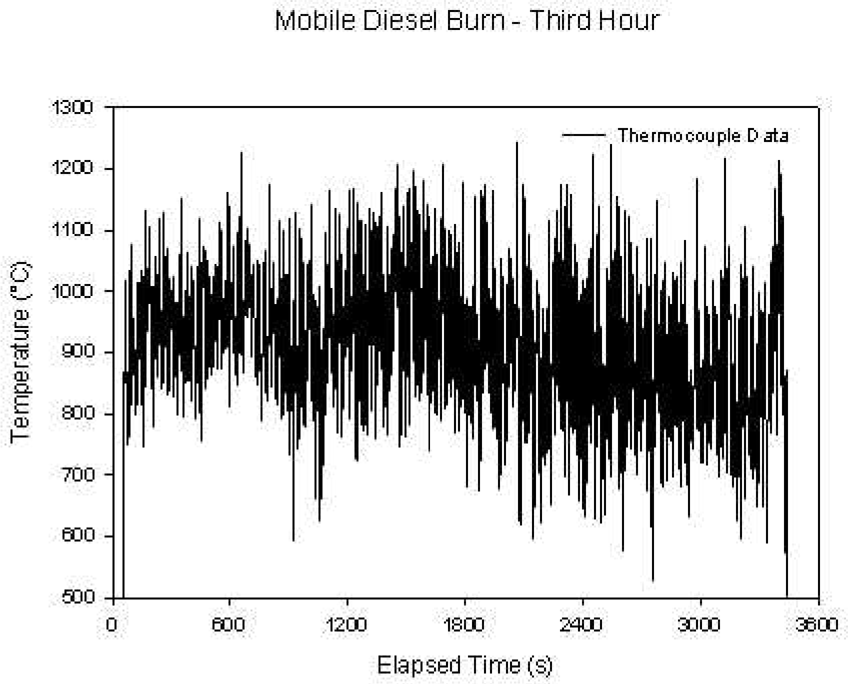


Figure 6-8. Temperature Measured during Fourth Test Burn (Third Hour-long Burn) with Pocket Boom.

Section 7

POST-BURN TOW TESTING AT OHMSETT

Following the burn testing in Mobile, AL, the Pocket Boom was shipped back to Ohmsett for more tow testing.

The boom was unpacked and inspected at Ohmsett on October 5. Two of the float sections had suffered minor damage from the burn tests in Mobile as noted above, but were considered sound. The fire resistant fabric that formed the “omegas” at the hinges of the connectors had degraded somewhat, but was also deemed serviceable.

The Ohmsett fire boom tow testing protocol (see Section 5) was repeated with the Calsol test oil (Figure 7-1). The test data may be found in Appendix E. A summary of the results is given in Table 7-1. The viscosity of the Calsol test oil, at the 18 C (64 F) water temperature, was 3000 mm^2/s (cSt).

The boom performed in the same manner as during the initial tow testing. This test series resulted in slightly higher first loss speeds than the earlier tests, possibly due to the higher viscosity of the test oil (3000 vs. 1200 mm^2/s [cSt]) at the lower ambient temperatures. First loss in calm conditions and in long, regular waves occurred at approximately 0.5 m/s (1 knot) with gross loss recorded at 0.65 m/s (1.3 knots). In short regular waves, first loss occurred at approximately 0.4 m/s (0.8 knots) and gross loss occurred at 0.45 m/s (0.9 knots). In harbor chop waves first loss occurred at about 0.45 m/s (0.9 knots) with gross loss recorded at 0.58 m/s (1.15 knots).

The boom behaved in the same manner as before during the critical tow tests, with some planing observed at speeds above 0.75 m/s (1.5 knots).

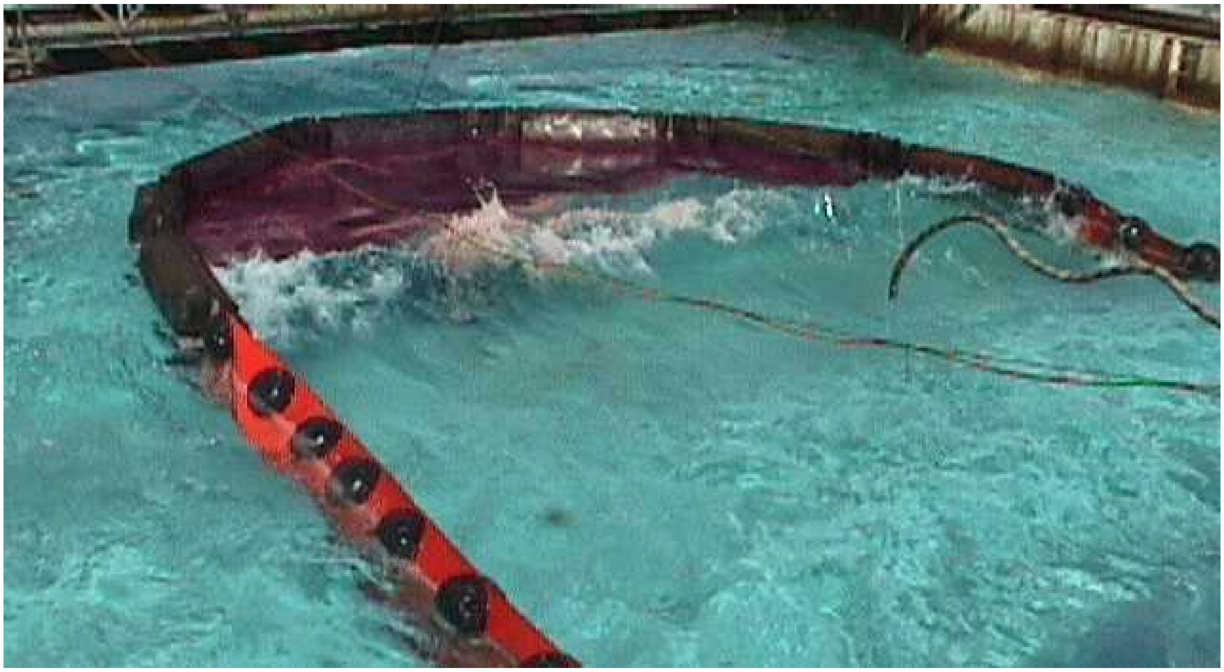


Figure 7-1. Post-Diesel Burn Containment Test at Ohmsett in Waves with Calsol Test Oil.

Table 7-1. Post-Diesel Burn Ohmsett Containment Test Summary - Calsol Test Oil.

Test #	Test Type	Waves	Loss Speed, m/s (knots)	Preload Volume, L (gal.)	Comments	
54	Preload	none	0.6 2 (1.25)	230 (60)		
55	Preload	none	0.58 (1.15)	460 (120)		
56	Preload	none	0.48 (0.95)	680 (180)		
57	Preload	none	0.48 (0.95)	910 (240)		
58	Preload	none	0.48 (0.95)	1140 (300)		
59	Preload	none	0.45 (0.9)	1360 (360)		
60	Preload	none	0.48 (0.95)	1590 (420)		
61	1st and	none	0.48 (0.95)	1510 (400)		
	Gross		0.62 (1.25)			
					Dist. Rate, L/min. (gpm)	Loss Rate, L/min. (gpm)
62	Loss Rate	none	0.5 (1)	1510 (400)	100 (26)	11 (3)
63	Loss Rate	none	0.6 (1.2)	1510 (400)	400 (105)	95 (25)
64	Loss Rate	none	0.5 (1)	1510 (400)	100 (26)	19 (5)
65	Loss Rate	none	0.6 (1.2)	1510 (400)	400 (105)	115 (30)
66	1st and	Wave #2	0.4 (0.8)	1510 (400)	shotgun connector loose due to no nut and bolt holding it in	
	Gross	3"-35 Reg[1]	0.45+ (0.9+)			
67	1st and	Wave #2	0.42 (0.85)	1510 (400)	some splash over on and off during entire run	
	Gross	3"-35 Reg	0.48 (0.95)			
68	1st and	Wave #3	0.42 (0.85)	1320 (350)		
	Gross	3"-30 HC[1]	0.58 (1.15)			
69	1st and	Wave #3	0.45 (0.9)	1510 (400)	full gross loss speed exceeds 0.58 m/s (1.15 knots)	
	Gross	3"-30 HC	0.58+ (1.15+)			
70	1st and	Wave #1	0.5 (1)	1510 (400)		
	Gross	6"-19 Reg[1]	0.6 5(1.3)			
71	1st and	Wave #1	0.52 (1.05)	1510 (400)	full gross loss speed exceeds 0.6 m/s (1.2 knots)	
	Gross	6"-19 Reg	0.6+ (1.2+)			
20	Critical Tow	none	1.5 (3)	none	started planing at 0.75 m/s	
21	Critical Tow	none	1.5 (3)	none	Globe boom influence very stable	

1. 3"-30 means 3-in. wave paddle stroke with a frequency of 30 cycles per minute; HC means harbor chop (i.e., wave beach lowered to allow reflection), Reg means wave beach raised to minimize reflection

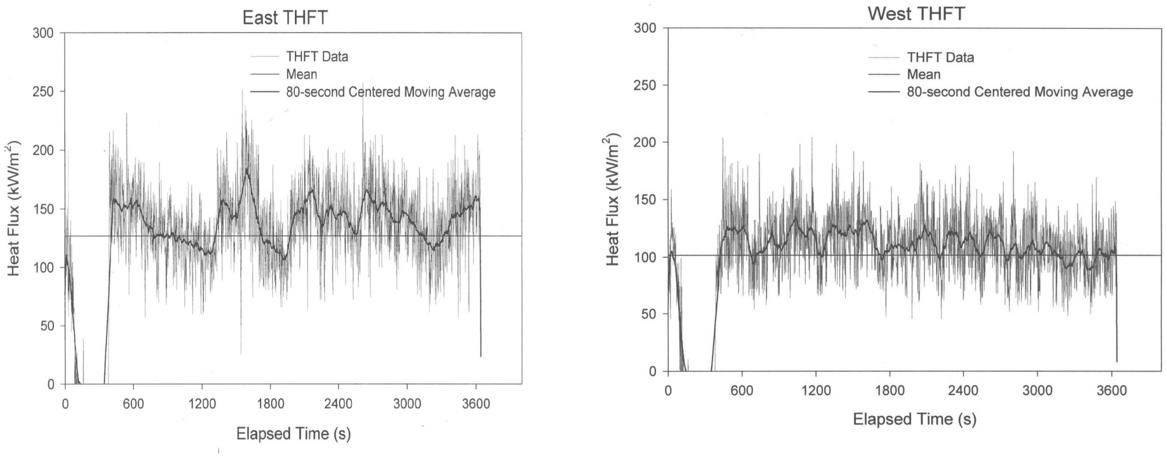
Section 8

ENHANCED PROPANE BURN TESTS AT OHMSETT

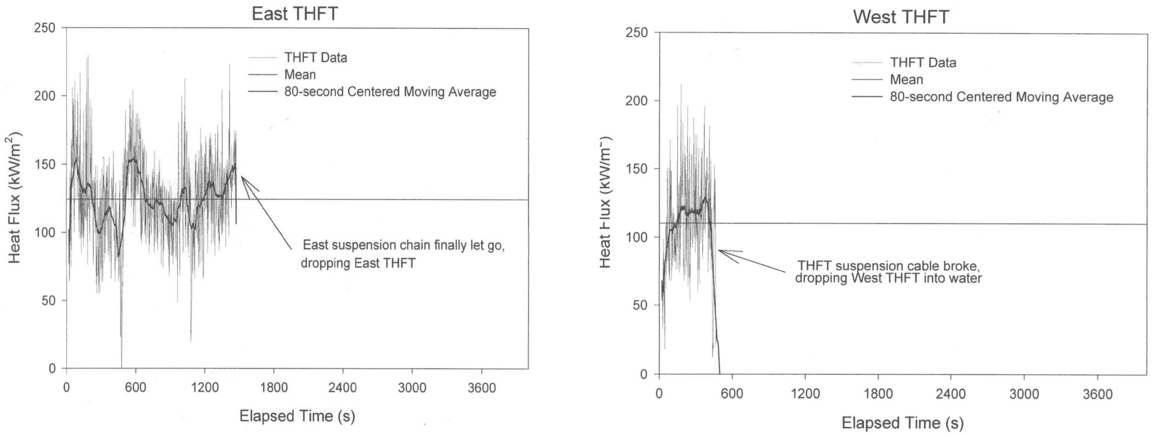
On November 24, 1998 the prototype Pocket Boom was put through Ohmsett's new enhanced propane fire test protocol (see McCourt *et al.* 1999). These tests involved three cycles of one hour of exposure to compressed air-enhanced propane flames in waves, followed by a one-hour cool-down period in waves alone. The tension on the boom was maintained at 1560 N (350 lbf). The test plan and data may be found in Appendix F. Figure 8-1 shows the burn during a test cycle and Figure 8-2 shows the total heat flux to the two sides of the boom during each of the three test burns. After several of the fire tests the boom was observed to be glowing bright cherry red in the daylight, an indication that the boom had reached temperatures on the order of 900 C (1650 F).

Figure 8-1. Pocket Boom in Enhanced Propane Flames at Ohmsett.

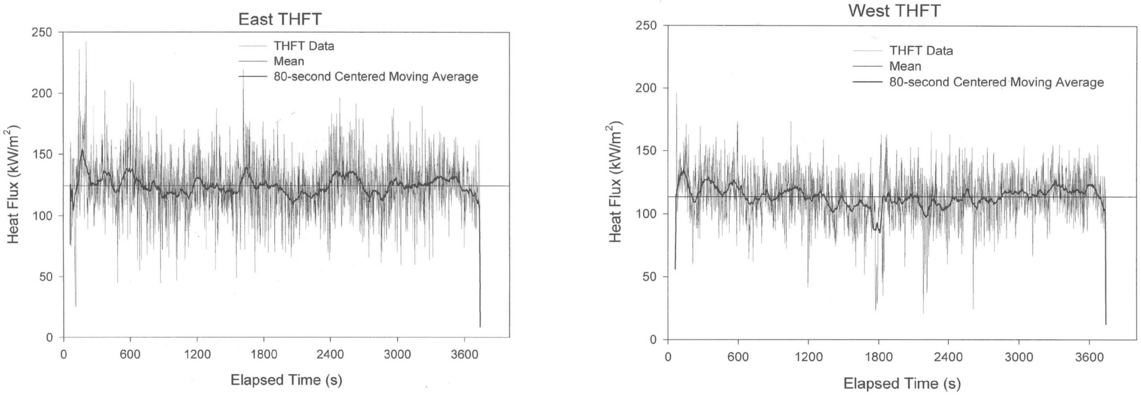
For the first two tests at Ohmsett the total heat flux transducers (Medtherm model 64-20-20, the same as those used in the diesel burn test in Mobile, AL) were suspended by chains from a cable passing across the center of the boom. The total heat flux transducers (THFT) were oriented to look across the boom at the flames on the other side.



Total Heat Flux from First Burn



Total Heat Flux from Second Burn



Total Heat Flux from Third Burn

Figure 8-2. Total Heat Flux Readings for Enhanced Propane Test.

During the second burn the wire cable holding the transducers failed (due to heating) and much of the data for this test was lost. For the third hour of burning, the transducers were mounted at the top of the hinge at opposite ends of the connector section in the middle of the flames. Again, the transducers looked at the flames on the other side of the boom. During the tests the winds were generally from the NW and averaged 30 km/h (15 mph).

In the first burn, the mean heat flux was 125 kW/m^2 at the East THFT (looking upwind) and 100 kW/m^2 at the West THFT (looking downwind). Over the time span of the recording for the second burn, the East THFT averaged 125 kW/m^2 and the West THFT averaged 110 kW/m^2. For the third burn the means for East and West were 125 and 115 kW/m^2 respectively. These averages are within the 110 to 130 kW/m^2 target being considered for the draft test protocol on fire boom testing being prepared by the ASTM F20.15 sub-committee on *In Situ* Burning. Comparison of the heat flux exposure with the enhanced propane system in Ohmsett and the diesel fire exposure in the tank in Mobile, AL, (see Section 6) shows that the two test protocols produced virtually identical total heat fluxes.

The Pocket Boom performed well during these tests. No failures or apparent expansions or contractions of the flotation sections were observed.

Following the completion of the tests the boom was examined closely. The state of a typical float and connector section from the portion of the boom exposed to the propane flames is shown in Figure 8-3. Note the heat-induced discoloration and slight warpage. Three instances of degradation were found:

- Three of the six connectors had developed a small (3 to 6-cm) crack or tear extending down from the top of the 321 stainless steel sheet at the first or second pleat. One of these is known to have resulted from tearing during the July critical velocity tow tests (see Section 6). None of the cracks/tears would have compromised the containment integrity of the boom.
- The second degradation was the detachment and deformation above the water-line of several of the steel hinge cover-strips at each end of the connector sections. This

too was considered to be minor damage.

- The third and final degradation observed was the substantial deterioration of the "omegas" covering the hinges at each end of the connector sections. Much of the refractory fiber material was gone, leaving behind only the inner stainless steel mesh matrix. A better, more durable grade of "omega" material will be specified for subsequent versions. The damage noted was minor and it was clear that the boom could have successfully contained oil after the completion of the enhanced propane burn test protocol.

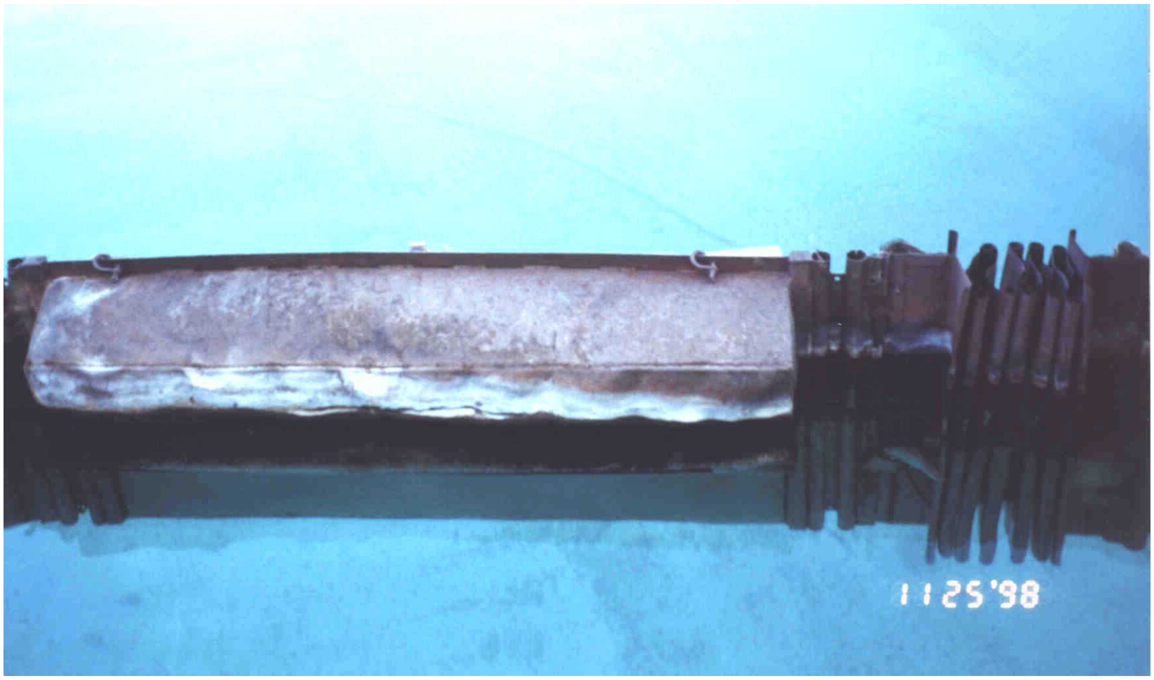


Figure 8-3. State of Pocket Boom after Ohmsett Burn Test.

Section 9

COMPONENT DESTRUCTIVE TESTING AND STEEL SELECTION

One of the key components of the Pocket Boom are the pleated connector sections. Over the month of January 1999, five of the pleated connector sections were tested, three to failure. The test involved mounting the connector in a specially-constructed jig that held one side of the connector (the side opposite the universal bearing) immobile and cycled the other side through its range of motion in the vertical plane. One end of the connector was cycled by a push rod mounted on an off-center wheel driven by a variable-speed electric motor (Figure 9-1). All five connector sections had been exposed to a total of six hours of flames, three during the diesel fire tests in Mobile, AL and three during the enhanced-propane fire tests at Ohmsett.

Figure 9-1. Jig for Cycling Connector Sections (connector is mounted upside down).

All the connectors showed distinct signs of heat stress, including slight warping of the deflector panels, dimpling of the pleated sheet metal, and oxidation and embrittlement of the pleated 321 stainless sheet exposed to the flames. Three of the connector sections already had small cracks at the tops of the pleated sheet metal, one of which was the result of a tear that occurred during the critical tow speed tests at Ohmsett in July 1998 (see Section 5).

The test jig cycled the connector at a rate of approximately 1 Hz. The lengthening of cracks in the pleated sheet was measured periodically. Failure was defined as the intersection of any crack with the water-line (340 mm = 13.7 in. down from the top of the boom). The first three connectors were cycled with a 15-cm (6-in.) stroke; defined as the total linear movement of the one side of the top of the pleated connector. Full data may be found in Appendix G.

Figure 9-2 shows the results for the first three connectors. The first connector failed after 572,000 cycles (equivalent to 26.5 days in Sea State 3, which has an average wave period of 4 s). The second failed after 348,00 cycles (16 days) and the third failed after 451,000 cycles (21 days). The mean time to failure was 457,000 cycles, approximately equivalent to 21 days in Sea State 3. Figure 9-3 shows the cracking at the top of the pleat of Connector 1 around Tube 1 on the near side (NS in Figure 9-2) after approximately 500,000 cycles.

The fourth connector was operated with a stroke of 10 cm (4 in.). This connector survived 1,000,000 cycles (equivalent to 45 days in Sea State 4) without any cracking (Figure 9-4). At 1,000,000 cycles the stroke was increased to 15 cm (6 in.); cracks began to appear and propagate in the next 100,000 cycles. The fifth connector was cycled with a stroke of 13 cm (5 in.). Afer 1,000,000 cycles only minor cracks, the longest being 57 mm, had appeared (Figure 9-5). The final design of the connector through-beam has been modified to restrict the stroke to 13 cm (5 in.). This will not impede the ability of the boom to respond to waves in its design operating environment (protected and semi-protected waters, up to Sea State 3 with a 1-m, 4-s significant wave).

In addition to these tests, a series of tensile tests were conducted on the perceived weak links in the boom design - the connector hinges and the Navy slide connector - to determine their strength. The data from these tests may also be found in Appendix G. The hinges, as built with one tack weld holding each knuckle shut, proved to have a yield strength of 2.2 x 10^5 N/m (1250

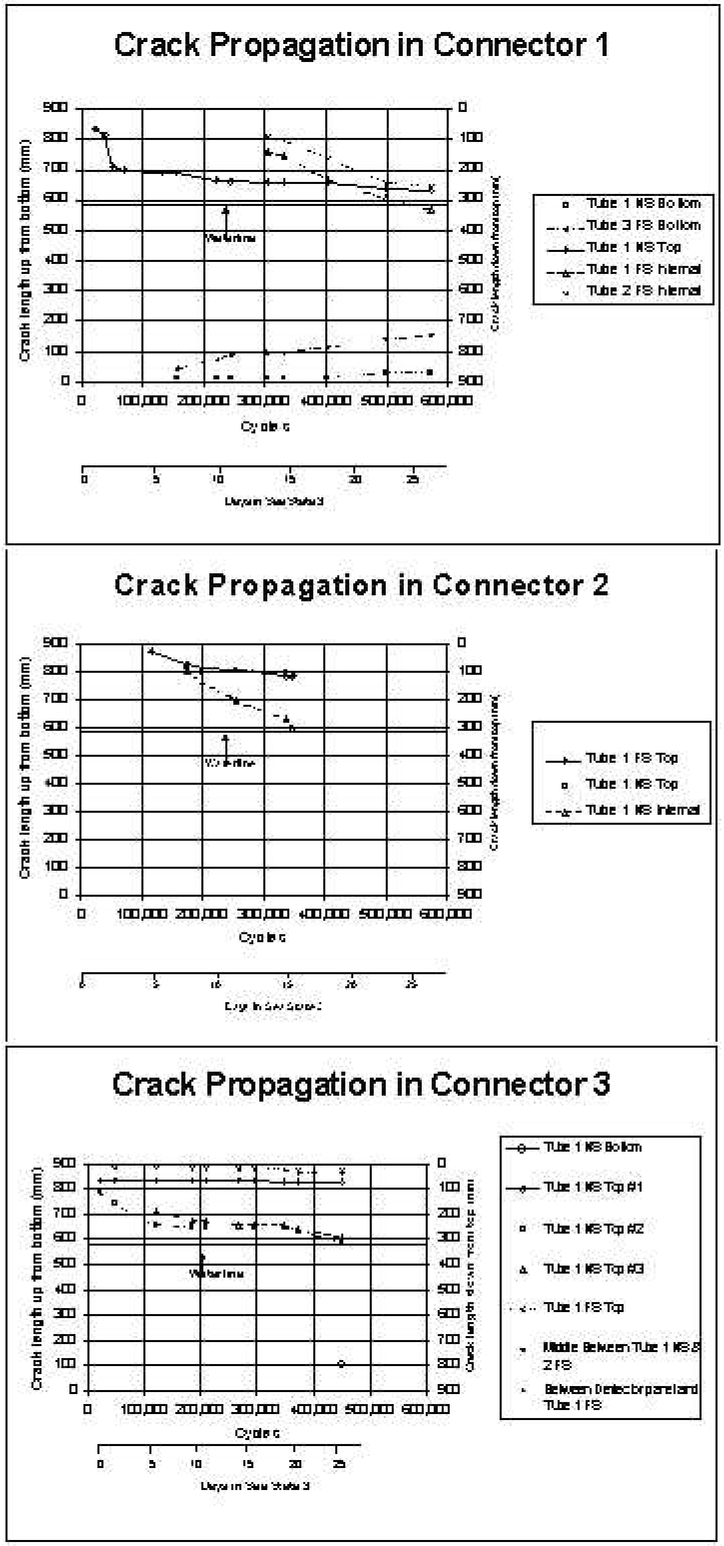


Figure 9-2. Crack Propagation in Connectors Cycled Through a 15-cm (6-in.) Stroke.

Figure 9-3. Crack in Pleat Material of Connector 1 after 500,000 Cycles with a 15-cm (6-in.) Stroke.

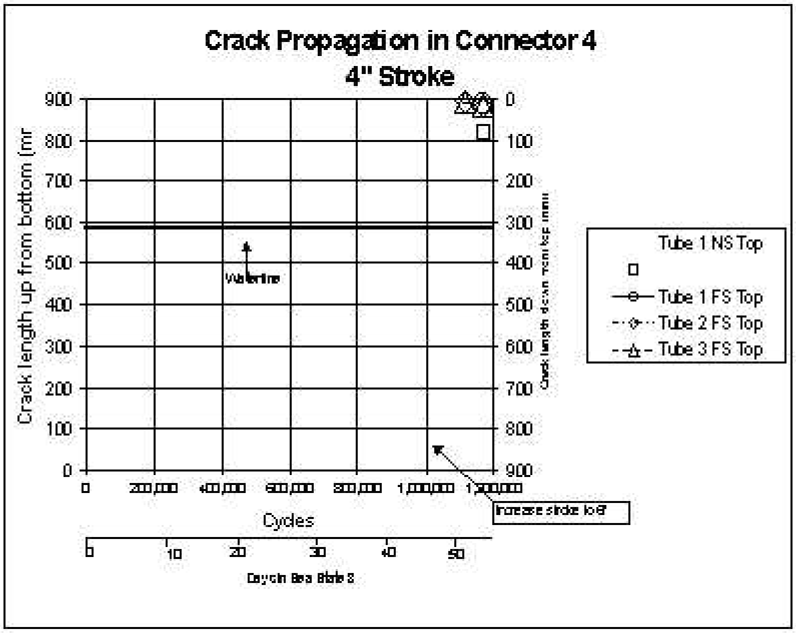


Figure 9-4. Crack Propagation in Connector Cycled Through a 10-cm (4-in.) Stroke.

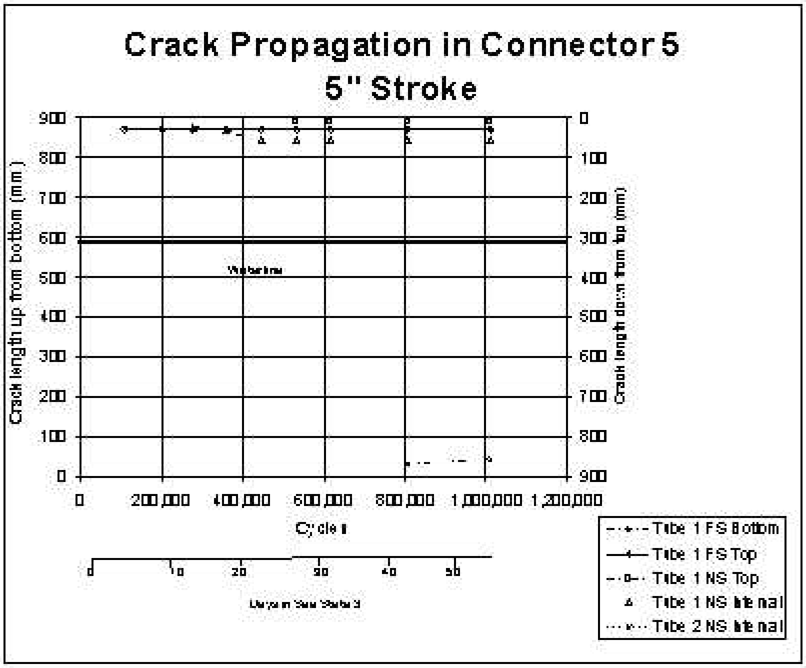


Figure 9-5. Crack Propagation in Connector Cycled Through a 13-cm (5-in.) Stroke.

lbf/in.) as desired. The mode of failure was the hinge knuckles uncurling. Without the tack weld the strength of the hinge was only 9 x 10^4 N/m (500 lbf /in.), well below specification. The yield strength of the Navy slide connector proved to be 2.2 x 10^5 N/m (1260 lbf/in.). The mode of failure was the male pipe pulling through the slot in the female pipe.

These component tests are not a substitute for the prescribed tensile testing using ASTM F 1093 standard methods; however, the results, and the design of the remainder of the structural elements of the Pocket Boom do indicate that its strength should be in the range of 1.8 x 10^5 N/m (1000 lbf/in.).

Several of the flotation units were constructed of 304 stainless steel, rather than the specified type 310.

There was no visible difference in the performance or degradation of the two types of steel during the tests. During these burn tests the flame temperature and the temperature of the boom occasionally exceeded 930 C (1700 F) - see Section 6 -, and flame temperatures as high as 1100 C (2000 F) have been reported in the literature (Fingas *et al.* 1995, Lazes 1994). Type 304 stainless has a maximum continuous operating temperature of 930 C (1700 F); which would be marginally acceptable. Type 310 has a maximum continuous operating temperature of 1150 C (2100 F), which would provide a margin of safety, and perhaps longer operational life, albeit at a higher cost. The melting temperature of all austentic/chrome-nickel (300-series) stainless steels is 1400 C (2550 F), well in excess of any recorded *in situ* oil burn temperature.

It is recommended that type 310 stainless steel be retained as the material of choice, where specified.

Type 321 stainless steel is specified for the pleated portion of the connectors, as was the case for the prototype, because:

- Type 310 is not available in the 27 gauge sheets required for this component.
- Although the maximum continuous operating temperature of type 321 is specified

as 930 C (1700 F), the same as type 304, the slightly higher nickel content of type 321 gives it superior high-temperature characteristics.

- Type 321 sheet can be obtained with higher yield strengths than type 304; this is important for resistance to cracking in the pleat bends.

Section 10

DEPLOYMENT AND RETRIEVAL

A typical (Allen 1990, Buist *et al.* 1994) fire boom system would consist of 150 m (500 ft) of boom towed in a U configuration with a gap ratio (the width of the mouth of the U divided by the length of the boom) of ⅓. The generally accepted operational procedeure would be to collect oil with the boom system until the back third of the U is filled. The boom system would then be moved to a safe location and the oil ignited and burned. Based on the formula for a parabola (which best predicts the shape of a boom under tow in the U configuration), 58 m (188 ft) of Pocket Boom would be needed to make up the back third of a combination fabric boom/Pocket Boom system.

The Pocket Boom has been designed so that long, pre-connected lengths of the boom can be removed from storage and deployed by crane. As designed, 58 m (188 ft) of pre-connected stainless steel boom, weighing 2600 kg (5600 lb), could be stored, ready for deployment in two pieces (on top of each other), in a standard 20-ft ISO container. Figure 10-1 is a sketch of the layout of one layer of the boom in such a container. The boom would be folded back on itself and each float section connected to a lifting beam with chains and snaps. The section is lifted from its container and into the water, the chains are unhooked, and the boom unfolded for connection to lengths of conventional boom. The process is reversed to retrieve the boom.

Figure 10-2 shows the prototype Pocket Boom being lifted from its wooden storage box in this manner. Over the life of the project the 15-m (50-ft) prototype was deployed and retrieved five times, using both cranes and forklifts, with relative ease using this system.

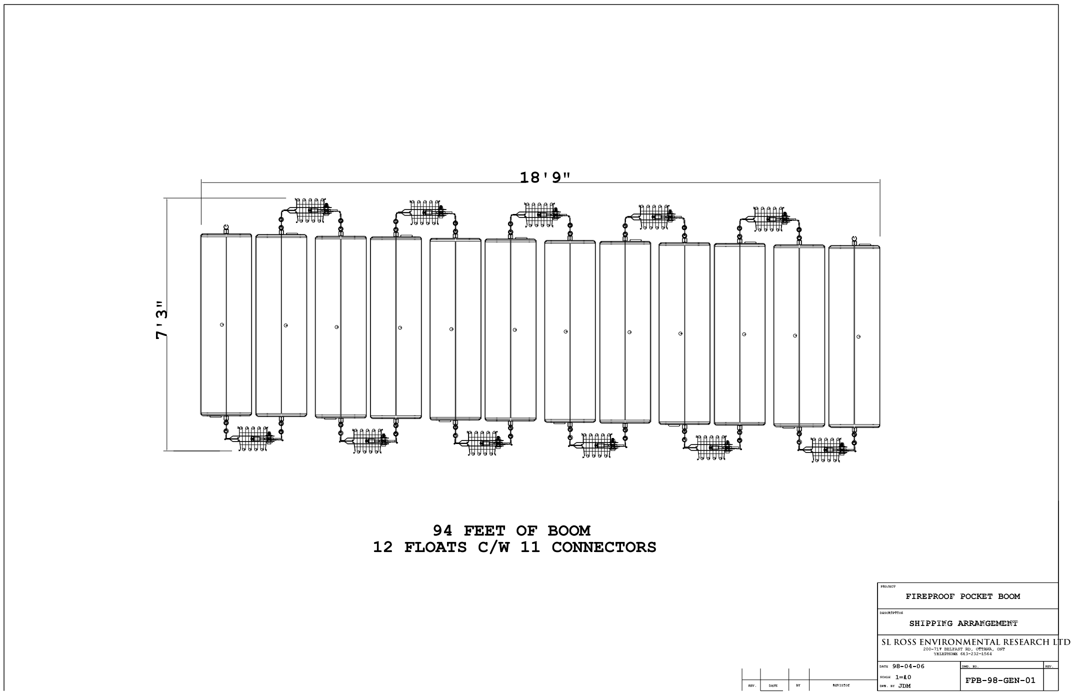


Figure 10-1. Sketch of Pocket Boom Layout Inside an ISO Container.

Figure 10-2. Deployment of 15 m (50 ft) of Pre-connected Pocket Boom.

Section 11

CONCLUSIONS

A large offshore stainless steel boom was redesigned to serve as a high-strength, durable, burn pocket to be inserted between two lengths of conventional fabric fire boom. The final design of the Pocket Boom has resulted in considerable cost, weight, and size reductions over the original design and a commensurate improvement in ease of handling. With a buoyancy-to-weight ratio of 3, a tensile strength in excess of 1.8×10^5 N (40,000 lbf), and an overall height of 100 cm (39 in.) the boom will perform well in its intended operating environment (calm or protected waters with waves up to 1 m [3 ft]) in conjunction with commercially-available fabric booms.

Deployment, sea-keeping, towing, and retrieval characteristics of the Pocket Boom are all good. Oil containment tests at Ohmsett showed that the boom will contain oil up to the normal limits (0.4 m/s = 0.75 knots) and can withstand catenary tow speeds up to 1.5 m/s (3 knots) without mechanical failure. Exposure to burning oil does not affect the oil containment characteristics of the boom.

The boom was exposed to six hours of fire with full-scale heat fluxes: three hours of diesel fires in Mobile, AL and three hours of enhanced propane fires at Ohmsett. The boom survived this heat exposure with only minor damage, none of which would have detracted significantly from its oil-containment capabilities. The final design of the connector section incorporates modifications to ensure that the boom will have a service life of at least 1,000,000 wave cycles, equivalent to more than 45 days at sea in Sea State 3.

For an operational system 150 m (500 ft) in length, 58 m (188 ft) of Pocket Boom would form the apex of a U. The arms of the U would consist of two 45-m (150-ft) lengths of conventional fabric fire boom connected to the Pocket Boom with suitably-adapted US Navy connectors.

The design of the boom is freely available, or the boom can be purchased commercially from Applied Fabric Technologies, Inc.

Section 12

REFERENCES

Alaska Clean Seas, “Long Duration Test Burn: 3M 8-inch Fire Containment Boom”, *ACS Newsletter*, Vol (1), No. 1, March 31, Anchorage, 1991.

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

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

Bitting, K.R. and P.M. Coyne, “Oil Containment Tests of Fire Booms”, *Proceedings of the Twentieth AMOP Technical Seminar*, Environment Canada, Ottawa, ON, pp 735-754, 1997.

Buist, I.A. ,S.L. Ross, B.K. Trudel, E. Taylor, T.G. Campbell, P.A. Westphal, M.R. Myers, G.S. Ronzio, A.A. Allen and A.B. Nordvik. *The Science, Technology and Effects of Controlled Burning of Oil Spills at Sea*, Marine Spill Response Corporation Technical Report Series 94-013, Marine Spill Response Corporation, Washington, DC, 382 p, 1994.

Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy and I.R. McAllister, “The development and testing of a fireproof boom”, *Proceedings of the 1983 Oil Spill Conference*, API/EPA/USCG, Washington, DC, pp 43 - 51, 1983.

Burkes, J.M., *Formulation of new fireproof boom designs*, Southwest Research Institute Project No. 06-6075, Draft Report to Marine Spill Response Corporation, Washington, DC, 1994.

Dome Petroleum Ltd., *Fireproof boom development - OHMSETT Trials*, Canadian Offshore Oil Spill Research Association Report CS3, Calgary, AB, 1981.

Dome Petroleum Ltd., *Fireproof boom field trials*, Canadian Offshore Oil Spill Research Association Report CS9, Calgary, AB, 1983.

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", *Proceedings of the 1995 Oil Spill Conference*, American Petroleum Institute, Washington, DC, 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", Spill Science and Technology Bulletin, Vol. 1, No. 1, Elsevier Science Ltd., Great Britain, pp 85-87, 1994.

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

McCourt, J., I. Buist, B. Urban, W. Schmidt, D. Devitis and J. Mullin. "Ohmsett's Propane-fuelled Test System for Fire-Resistant Boom". *Proceedings of the Twenty-Second AMOP Technical Seminar*, Environment Canada, Ottawa, ON, 1999.

Purves, W., "Design and Development of Equipment to Aid in the Burning of Oil on Water", *Proceedings of the First AMOP Technical Seminar*, Environment Canada, Ottawa, p190, 1978.

Roberts, D., and D.K.T. Chu, *Development of Oil Spill Burning Equipment*, Report by Bennett Pollution Control to Environment Canada, Ottawa, 1978.

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

SL Ross Environmental Research Ltd., *Demulsifiers and Modified Heli-torch Fuels to Enhance Burning of Emulsions,* Report to Alaska Clean Seas, Anchorage,1995.

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

Walton, W.D., W.H. Tilley, J.V. Mullin and R.R. Hiltabrand, "Evaluating a Protocol for Testing Fire-resistant Oil Spill Containment Boom", *Proceedings of the Twenty-First AMOP Technical Seminar*, Environment Canada, Ottawa, ON, pp 651-672, 1998.

APPENDIX A - BOOM DESIGN

APPENDIX B - SEA-KEEPING TRIALS

APPENDIX C - OIL CONTAINMENT TESTING

APPENDIX D - DIESEL FIRE TESTING

APPENDIX E - POST-BURN CONTAINMENT TESTING

APPENDIX F - ENHANCED PROPANE BURN TESTING

APPENDIX G - COMPONENT DESTRUCTIVE TESTING