THE DEVELOPMENT AND TESTING OF A FIREPROOF BOOM[1]

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ABSTRACT: In situ *burning of crude oil on water can be an extremely effective oil spill countermeasure, particularly in remote offshore areas and on cold water where conventional countermeasures are limited. In order for* in situ *burning to be an efficient mitigative technique, the oil must be contained and thickened. A novel fireproof boom has been researched, developed, and tested that can: (1) survive, without damage, long-term exposure to the heat generated by burning crude oil* in situ; *(2) contain burning crude oil in at least sea states up to three and at current speeds up to 0.4 m/s without loss of combustion intensity; (3) survive without damage for long periods at sea; and (4) withstand contact with small ice features.*

The Ixtoc I incident, the sinking of the *Atlantic Empress,* and the *Burmah Agate* spill provide evidence that it is possible to burn oil on open water with some success.[12, 6, 5] Much work has been conducted on the fundamentals of *in situ* burning of oil both on ice and open water.[3, 1, 4, 13] One conclusion of this work has been that for oil to be efficiently burned *in situ* it must be contained and thickened. The use of *in situ* burning as an offshore oil spill cleanup technique offers a tremendous advantage over conventional containment, skimming, storage, and disposal. The use of a fireproof boom would permit the containment and disposal of oil in one step using only one piece of equipment which, depending on the circumstances, could dispose of tens of thousands of barrels of oil per day (BOPD).

Several studies in the past in Canada[10, 11, 7] have investigated the use of booms to contain and thicken oil so that it could be burned on the water. Each proposed design, however, failed to be an operationally feasible device for one reason or another.

As a result of its work on a fireproof boom constructed from empty drums, Dome Petroleum, through the Canadian Offshore Oil Spill Research Association (COOSRA), decided to undertake a project to research, develop, construct, and field test a fireproof boom that had the following design criteria:

- Able to withstand flame temperatures of 980° C for extended periods of time in a salt-water environment and be reuseable
- Able to contain burning oil in a "U" configuration at sea state 4 and survive sea state 5
- Be as compact as possible and remain flexible down to −20° C and storable to −50° C
- Have good abrasion resistance so as to be able to withstand frequent handling and some contact with ice
- Be easily deployed using supply vessels and easily towed at two knots
- Have a tensile strength of at least 110,000 Newtons (N)

This paper documents the three-year, $500,000 program that was undertaken to develop the fireproof boom, including an analysis of the preliminary offshore trials, and a description of the final design of the boom and its potential for offshore oil spill cleanup.

Initial boom design

In order to meet the design criteria, an extensive search for suitable materials of construction was instituted, using Roberts and Chu[11] as a starting point. It became apparent that there were very few materials that could meet the design requirements and that only two were relatively inexpensive, these being high chromium stainless steels, such as type 309 and 310[9] and a refractory blanket material manufactured by the Carborundum Company, Fibrefrax L144, which is a cloth material woven with nichrome wire.

Using these materials a 12 meter section of prototype boom was constructed, (Figure 1) consisting of vented stainless steel flotation units of pentagonal cross-section with a "sail" to provide freeboard and a PVC coated nylon skirt underwater to provide draft. The use of stainless steel at the waterline ensures high abrasion resistance. Each 1.5 m long flotation unit was joined to a 0.75 m long flexible panel, to provide wave conformation. The panels were constructed of stainless-mesh-encased Fibrefrax blanket connected to a further section of PVC coated nylon skirt.

Tension members, consisting of 0.5 millimeter (mm) diameter stainless steel cables were added to ensure that no tension loads were placed on the flexible panels. The overall height of the boom was 1.77 m, with 0.66 m freeboard in calm water.

Each section of the boom was connected by means of a sliding joiner. These joiners fit inside slotted pipes fastened to both the free end of a flexible panel and the end of the next flotation unit.

Towing trials. Following successful static flotation trials that confirmed the stability of the flotation units, the boom was two tested in both straight line and catenary configurations. The straight line tests revealed that the boom could be towed successfully at speeds up to 5 knots, but that at this speed the prop wash tended to deflect the first section of the boom. Also, a significant prop wash tended to deflect the first section of the boom. Also, a significant bow wave was set up by the first section which resulted in a high drag force on the boom. We concluded that for an operational model a towing paravane should be included.

1. patents pending

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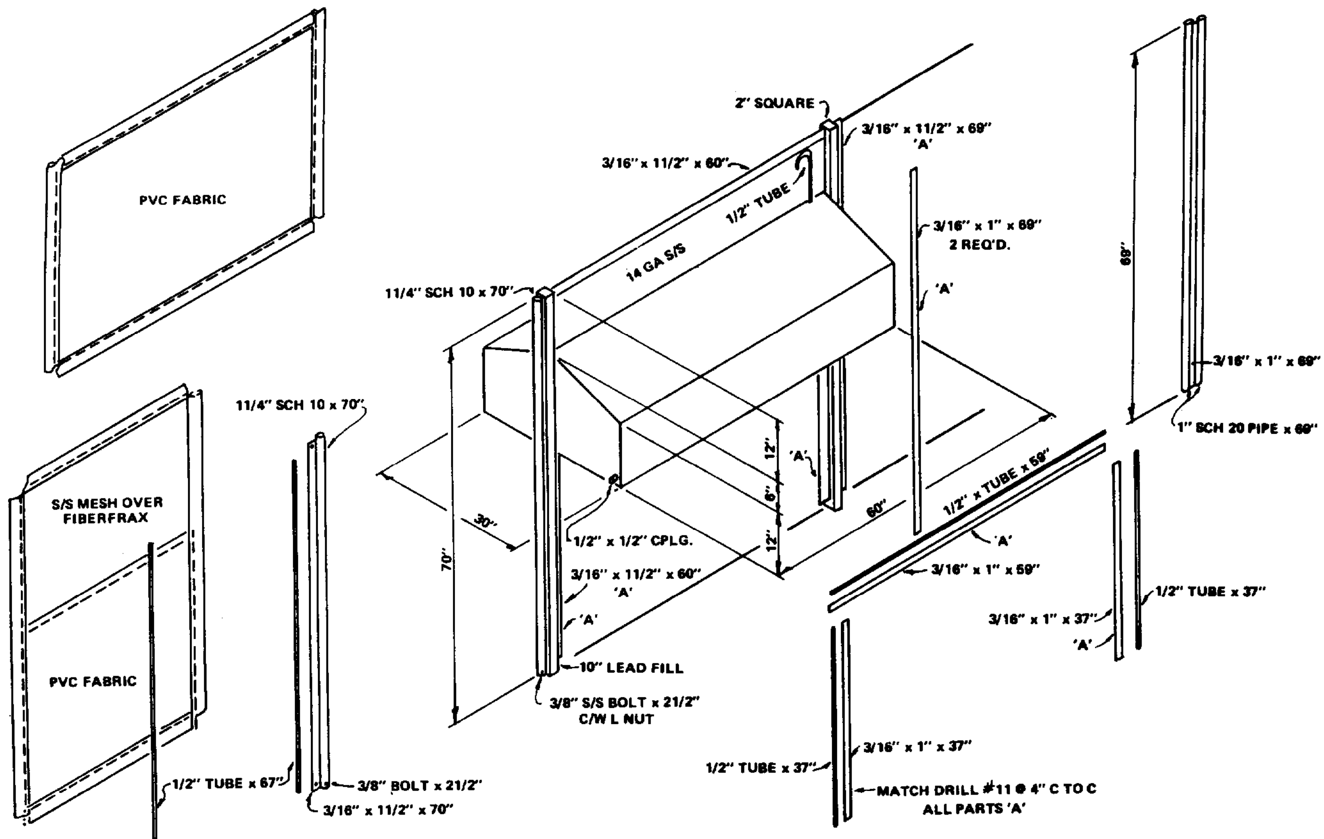
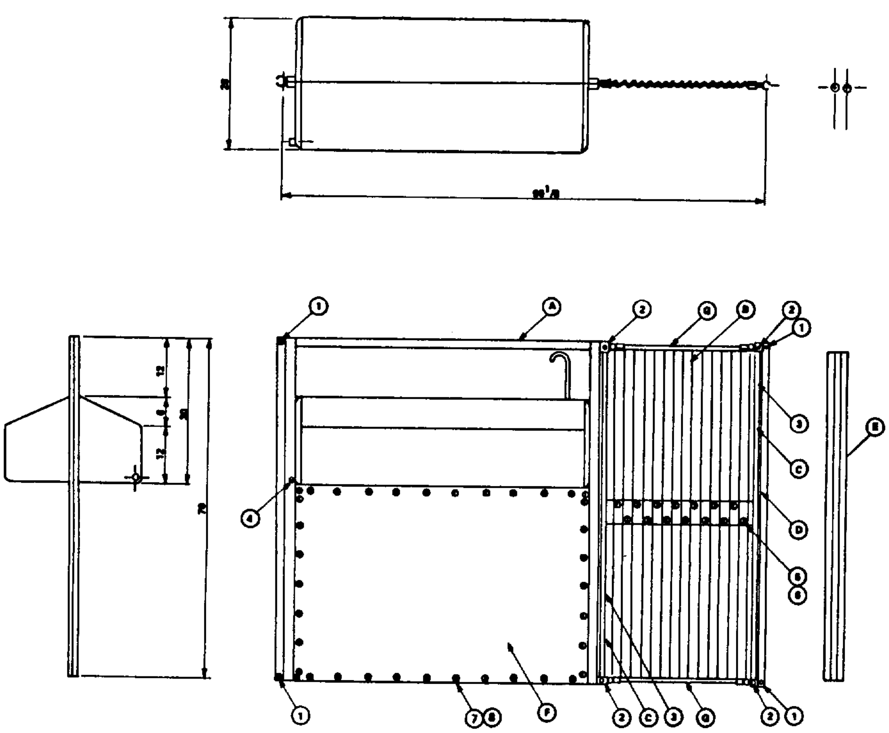


Figure 1. Initial fireproof boom design



LEGEND

A 1 FLOTATION UNIT (BUOYANCY CHAMBER) – DP – 81 – 01 – 02D
B 1 FLEXIBLE PANEL – 04D
C 2 FLEXIBLE PANEL SECURING BAR – 03D
D 1 FLEX. CONNN END – 03D
E 1 JOINER – 03D
F 1 BOTTOM PANEL – 04D
G 2 FLEX. CONNN CABLE – 03D

PURCHASED PARTS

1 4 3/8 NC S/S BOLTS C/W LOCK NUT
2 4 3/8 S/S SHACKLE – CHAIN
3 28 MD 665 BS POP RIVET
4 1 1/2 BE. PIPE PLUG
5 36 1" OD x 3/16 ID x 0.16 S/S WASHER
6 18 MD 419 BS POP RIVET
7 38 1" OD x 3/16 ID x 14 GA S/S WASHER
8 38 MD 650 BS POP RIVET
9 1 3/8 MS SHACKLE – ANCHOR

CUSTOMER
DOME PETROLEUM LTD.
PROJECT
FIREPROOF BOOM
DESCRIPTION
GENERAL ASSEMBLY
TYPICAL SECTION
DATE: 21/12/82
SCALE: 1/8 = 1
DRAWN BY: R. CANNING
DWG. NO. DP – 81 – 01 – 01D

Figure 2. Final design with corrugated steel connectors

Figure 3. Static burning trials

The catenary towing trials were held in a short, choppy sea with wave heights of approximately 1 m and a wind speed of 30 km/hr. The boom conformed well to the waves, demonstrated excellent stability, and was only overtopped once by a small amount of spray from a breaking wave.

Following these trials it was discovered that the Fibrefrax material had been seriously eroded by the action of the waves and it was apparent that the flexible panels, as originally designed, would not contain oil.

Flexible panel redesign. A further investigation of suitable construction materials showed that the flexible panels should be built from thin gauge (0.4 mm) type 321 stainless steel sheet, corrugated to provide the required flexibility (Figure 2). These panels were fitted to the boom, and a second towing trial confirmed that they did have the required flexibility. As redesigned, each boom section weighed approximately 125 kg, had a gross buoyancy of approximately 440 kg, and a buoyance-to-weight ratio of 3.5:1.

Static burning trials

In order to confirm that the design of the boom and the materials selected would withstand the temperatures of a crude oil fire, that no corrosion problems would occur, and to investigate the continuous combustion of crude oil on water a burning trial was held December 12, 1980 near Port Mellon, British Columbia.[8]

The boom, with the redesigned flexible panels, was connected in a circle and secured inside an area encircled by 0.9 m inshore boom and fender logs (Figure 3).

Thermocouples were mounted at various locations on one section of the boom and were monitored from a barge adjacent to the test site that served as a logistics and observation platform. Nine drums of Redwater crude oil (specific gravity, 0.839 at 26 °C; viscosity, 8 milli-Pascal seconds (mPas) at 21° C) supplied by Imperial Oil also were placed on the barge and a pump and hose were provided to pump the oil continuously under the skirt of the fireproof boom.

After a slick of 2-to-3 mm thickness had been pumped into the area enclosed by the fireproof boom, it was ignited by a burning oil-soaked sorbent pad. Over a two hour burning period, 1,545 liters (l) of crude were pumped into the boomed area. At the completion of the trial only 2 l of oil residue remained within the boom, giving a burn efficiency of 99.87 percent and a slick regression rate of 2.3 millimeters per minute (mm/min). Analysis of the burn residue revealed that it had a specific gravity of 0.933; before and after analysis of water column and sediments did not detect conclusive differences in hydrocarbon concentrations. Both these results led to the conclusion that no oil was lost to the water column during the burns.

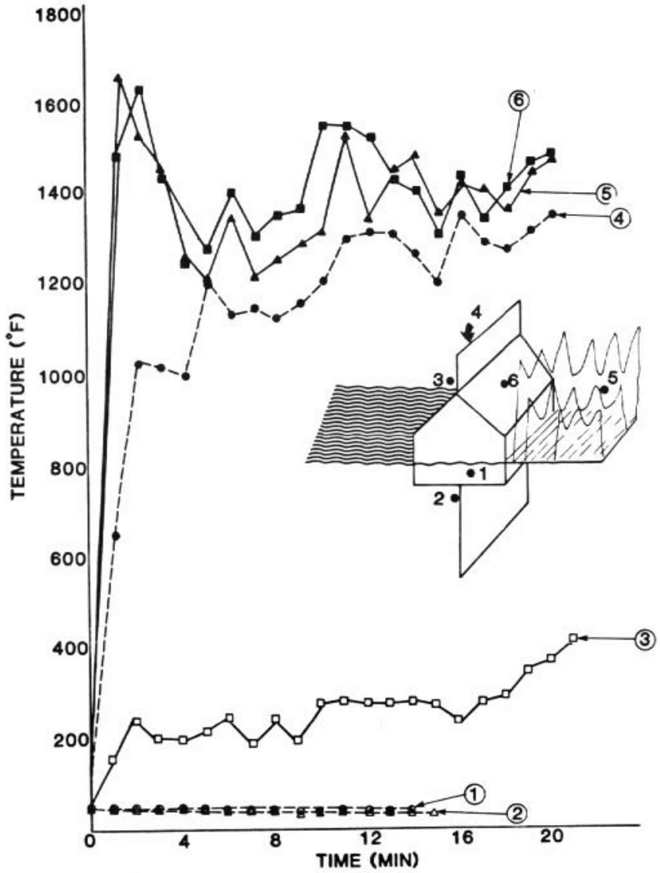


Figure 4. Burning trial temperature profiles

The temperatures measured at various points on and around the boom are shown in Figure 4. The maximum temperature measured was 905° C (1,660° F), well within the design maximum exposure temperature of 980° C (1,800° F).

It is interesting to note that the inside boom skin temperature was consistently recorded as higher than the temperature just above the slick. This may either be a calibration error or a reflection of the fact that, due to oxygen starvation, the combustion process was taking place at the edges of the boom and in the air space above it rather than immediately above the slick.

The thermocouples located in the water below the fire (numbers 1 and 2 on Figure 4) indicated that although some heat was being transferred to the water it was not raising the water temperature appreciably, even 4 cm below the burning slick. Presumably, much of the heat transferred into the water column was being absorbed in boiling off a thin surface layer of water. This was suggested by observations of some droplet carryover during the combustion, normally caused by boiling, and the fact that during gusts of wind that bent the flame over the side of the boom, the surface water near the flame could be observed boiling.

The smoke plume generated by the burn rose vertically to a height of approximately 300 m and then dispersed horizontally with visible smoke disappearing within 2–3 km downwind.

When the fire had extinguished itself the boom was examined and found to be in good structural condition. Some of the sheet metal was slightly warped and the exposed surfaces were covered with droplets of a hard asphaltic residue caused by the aforementioned droplet carryover. On removal from the water no further damage was observed and the boom was considered ready for immediate re-use.

Table 1. Text matrix and results

Test No.[1]	Tow Speed (m/s)	Wave Type	Wave Height X Length (m)	Wind Speed (m/s)	Wind Dir'n	Oil (Amount)	Remarks
1	0.25 - 1.0	calm	-	-	-	-	- stable in catenary, no rolling
2	0.25 - 1	swell	0.4 x 19	-	-	-	- stable, good wave conformance, no rolling
3	0.25 - 2.0	calm	-	-	-	Circo 75 l	- first loss at 0.4 m/s at vortex between floats; oil kept from boom by reflected waves
3R	0.25 - 1.25	calm	-	5	NE	Circo 38 l	- required 1.25 m/s to flush oil; at lower speeds oil not touching boom; first loss at 0.4 m/s as in 3
4	0.25 - 1.0	swell	0.4 x 19	5	NE	Circo 75 l	- first loss at 0.8 m/s; oil held out from boom by float backwash
7	0.25 - 1.0	harbour chop	0.2	5	NE	Circo 75 l	- first loss at 0.4 m/s; oil dispersed by turbulence in catenary
8	0.25	calm	-	8	NE	Murban 38 l	- intense burn for 5 min.; estimated greater than 90% efficiency; probably only 10 litres of Murban, not 38
9	0.15	calm	-	8	NE	Murban 38 l	- intense burn for 5 min. 51 sec.; estimated same efficiency as 8
10	0.35	calm	-	12	WNW	Murban 38 l	- flames had some difficulty spreading upwind; intense burn after for 4 min 43 sec.
11	0.25	harbour chop	0.2	12	WNW	Murban 38 l	- no ignition of oil, igniter pushing oil away by bobbing
11R	0.25	harbour chop	0.2	12	WNW	Murban 38 l	- no ignition of oil using flare
18	0.25	swell	0.2 x 19	12	WNW	Murban 38 l	- ignited in calm condition, intense burn for 3 min. 39 sec., more residue than 7, 8 and 9
14	0.25	swell	0.4 x 19	12	WNW	Murban 38 l	- ignited in calm, intense burn for 2 min. 29 sec., more residue than 18
15	0.25	swell	0.4 x 19	12	WNW	Murban 57 l	- ignited in waves, intense burn for 2 min. 54 sec., approx. same residue as 14
16	0.35 - 0.5	swell	0.4 x 19	12	WNW	Murban 57 l	- ignited in waves, intense burn for 2 min. at 0.35 m/s, poor burn for 1 min. 59 sec. @ 0.5 m/s
19	0.35 - 1	calm	-	10	W	Murban 57 l	- intense burn for 3 min. 10 sec. no difference in burning with increased speed
11R'	0.25	harbour chop	0.2	7	S	Murban 57 l	- successful ignition, pool flame spread, poor combustion extinguished by breaking wave
20	0.25	calm	-	7	S	Murban 57 l	- emulsified oil from 11R' successfully burned for 7 min. 10 sec.
21	0.25 - 0.75	calm	-	7	S	Circo 3800 l	- first loss at 0.4 m/s through vortex, extensive loss by entrainment at 0.5 m/s
22	0.25 - 1	harbour chop	0.6 m	7	S	Circo 3800 l	- durability trial - survived well excellent stability - minor damage to skirt observed on removal

1. For identification only, not necessarily in consecutive order

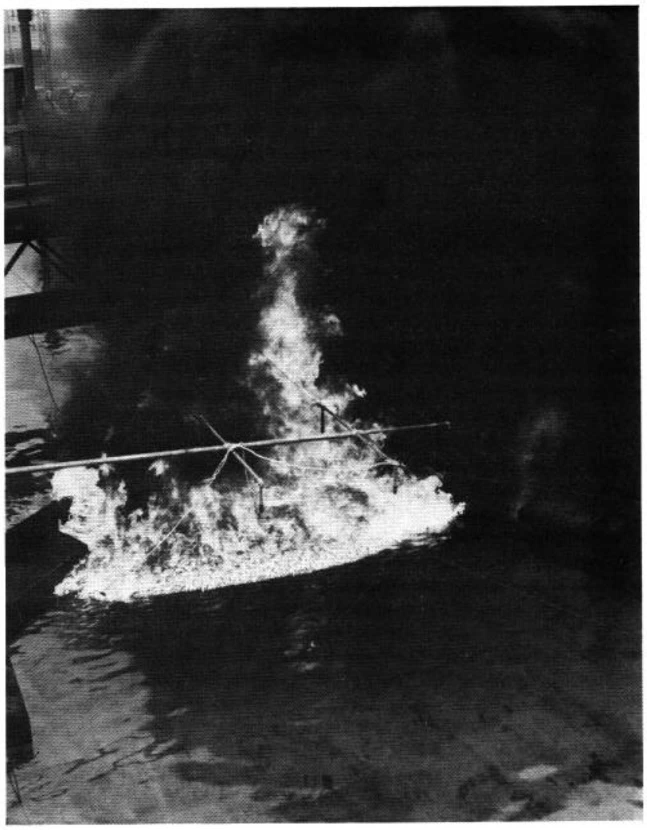


Figure 5. *In situ* burning in waves and current

OHMSETT trials

Following the burn trials, the prototype boom was tested at the U.S. Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility to further confirm its towing and stability characteristics, define its oil containment characteristics in controlled wave and current conditions, and investigate the effects of waves and currents on *in situ* combustion.[2]

Two oils were used in tests: a Circo 4X light oil (specific gravity, 0.9; viscosity, 11 mPas @ 22° C) for the containment trials; and Murban crude oil (specific gravity, 0.85; viscosity, 9mPas @ 14° C) for the *in situ* combustion trials. Table 1 summarizes the test matrix and the results obtained from the program.

As can be seen from Table 1 the boom exhibited excellent stability in all the wave conditions tested and was found to contain oil at speeds up to 0.4 m/s (0.75 knots). At this speed, a vortex formed between adjacent flotation units that drew small quantities of oil beneath the skirts. The anomalous containment of oil by the boom at up to 1.25 m/s tow speeds observed in Runs 3R, 4, and 19 was presumably due to the small volumes of oil used in these runs.

Runs 8, 9, 10, and 19 showed that in calm conditions the combustion was not adversely affected by increased tow speed up to 1 m/s. However, it is probable that had larger volumes of oil been used, at speeds exceeding 0.5 m/s the combustion efficiency would be reduced due to entrainment of the oil beneath the boom. A comparison of runs 8, 18, 14, and 15 shows that increasing swell height did not affect the ability to ignite the slick or the intensity of the resulting *in situ* combustion (Figure 5). However, the amount of residue that was left increased with increasing swell height. This was a function of the relatively small volumes of oil used in these trials and is not expected to seriously affect overall combustion efficiencies on a large scale.

The results of runs 15 and 16 illustrate the fact that in the swell wave condition the intensity of the burn was not affected until the tow speed reached 0.5 m/s (1 knot) at which point it was drastically reduced,

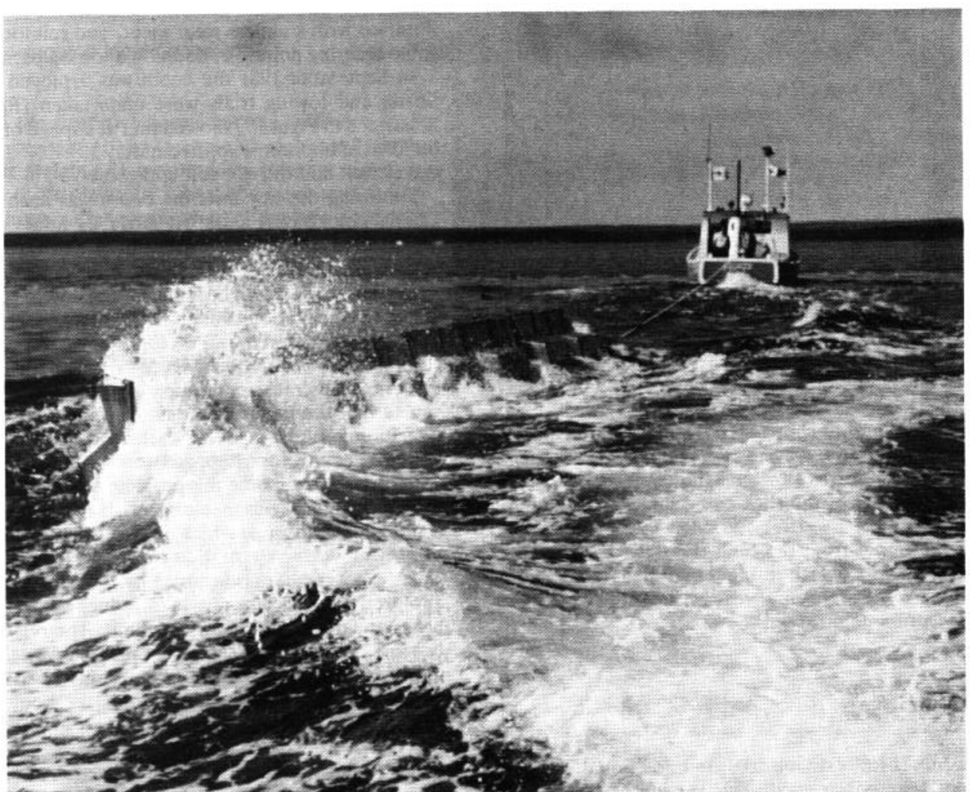


Figure 6. Boom towing and wave response trials

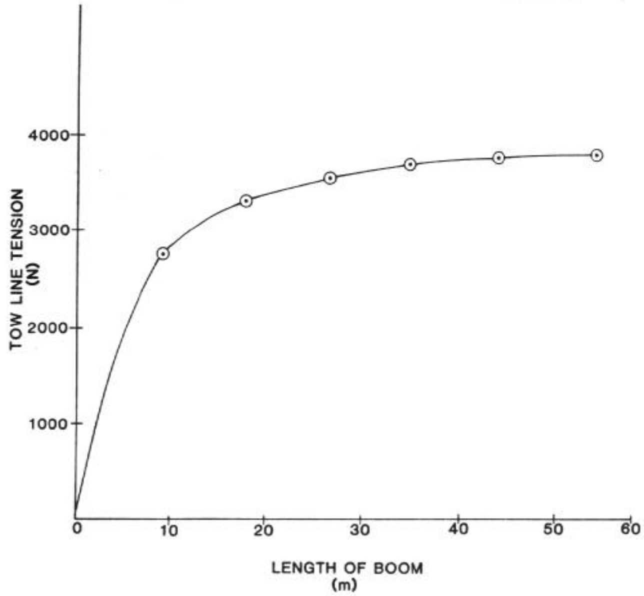


Figure 7. Results of two-knot towing test (straight line tow behind work boat)

Figure 8. Boom deployed offshore

presumably by the turbulence set up inside the catenary by the small waves reflected off the boom at this speed.

Of the three runs done in harbor chop (11, 11R, and 11R′) ignition was achieved only once (11R′) by increasing the oil volume and using two igniters. The flame spread was slow and the combustion poor. Before the entire surface area of the slick could ignite, a breaking wave extinguished the flames.

Upon removal of the boom from the tank the only damage observed was the loss of six rivets, which resulted in a slight bending of one of the skirt holding rods, and some wear on the upper flexible panel tension cable securing points.

Preliminary offshore trials

As a result of the successful test tank trials, an additional 20 sections (60 m) of boom were constructed. This version of the boom incorporated several minor modifications, including rounded corners on the flotation sections, replacement of the PVC skirt beneath the

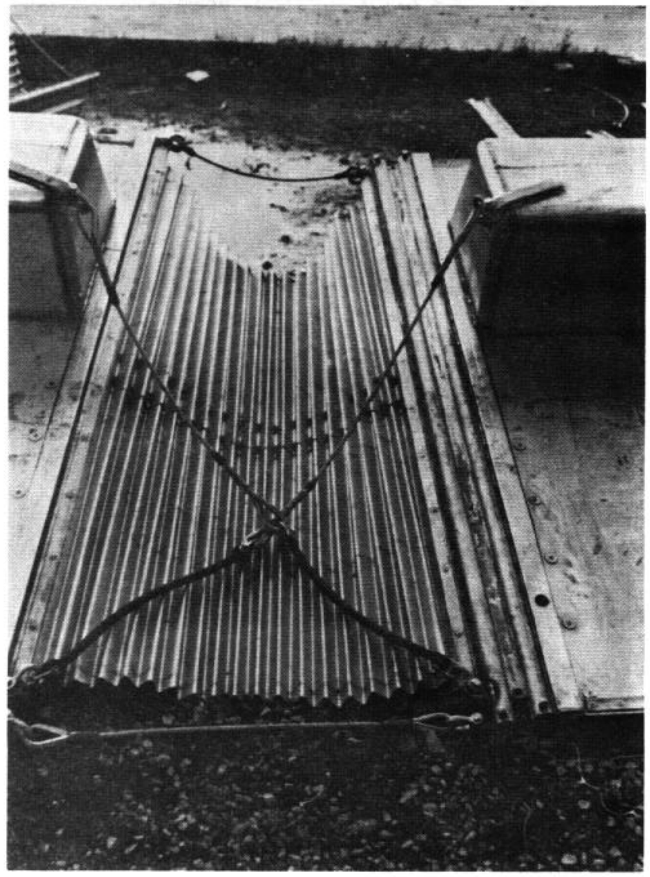


Figure 9. Cross cables

flotation with stainless steel sheet, and reinforcement of the tension cable securing points. In addition a towing paravane was constructed.

In September 1981 the boom was deployed near Mulgrave, Nova Scotia and towing trials were undertaken (Figure 6). The results, illustrated in Figure 7, showed that at a speed of 2 knots the drag force on 55 m of boom was approximately 3,800 N. The boom followed the waves well and did not roll appreciably.

Following the tow tests the boom was anchored in a catenary on Chedabucto Bay (Figure 8). After 24 hours exposure to sea state 3-to-4 with a 4 second wave period several of the flexible panels cracked vertically.

Initially it was thought that this was due to relative vertical motion of adjacent flotation units as waves passed beneath the boom. The boom was recovered and a cross-cable arrangement installed to restrict this vertical motion (Figure 9). When the boom was redeployed, however, the cracks continued to appear. Metallurgical analysis revealed that the failure was due to stress cracking caused by the flapping motion of the flexible panel. In a 24 hour exposure to a 4 second wave the connector "flapped" some 22,000 times.

In order to overcome this problem a more robust flexible connector was designed. This connector consists of a sheet of pleated light gauge stainless steel through which is passed a universally jointed box beam to provide tensile strength to resist towing and ice loads (Figure 10). The pleat bends are reinforced by the addition of a tubular backing and are of a sufficient radius to reduce stress concentrations to well below the material's endurance limit. The relative vertical motion of two adjacent flotation sections is restricted by the use of a guide shoe mounted on the universally jointed tongue. Stainless steel hinges on either end of the connector permit the boom to form a curve to contain oil.

Extensive bench testing of this connector was performed in a jig specially constructed to simulate the action of waves on the connector (Figure 11). The design finally selected was subjected to 502,232 cycles over a period of 10 days (equivalent to approximately 25 days in 4 second waves) without sign of any fatigue or damage.

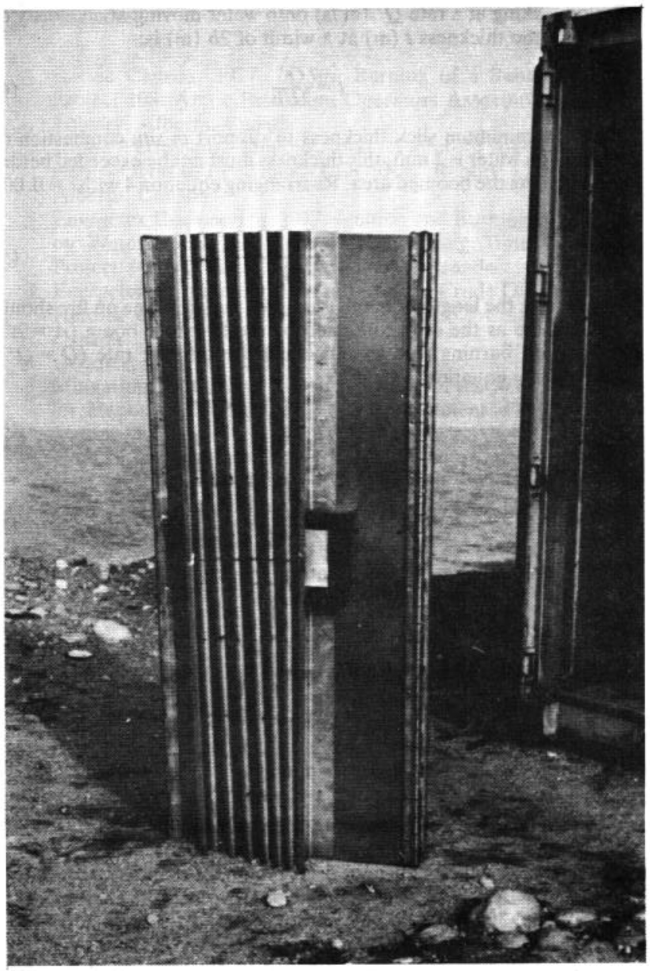


Figure 10. The new corrugated steel connector

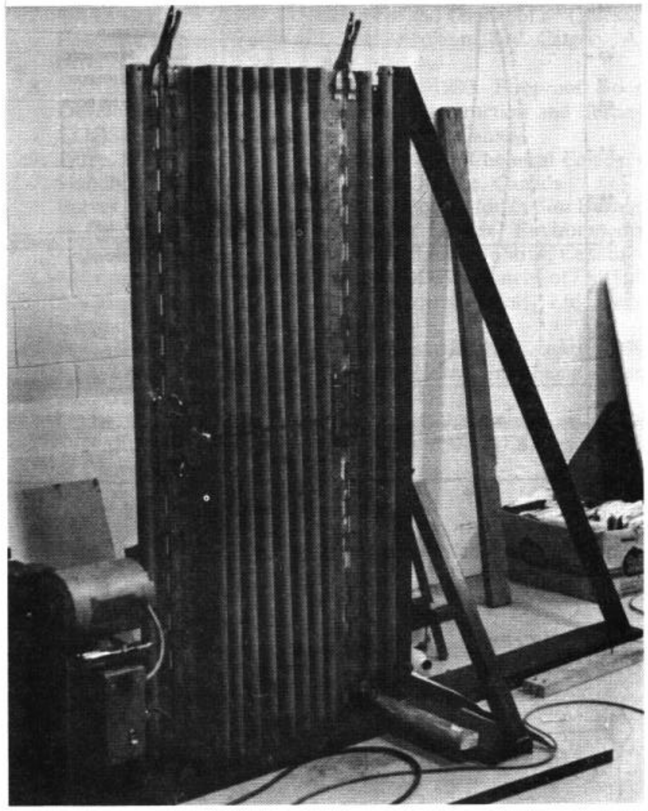


Figure 11. Bench testing of final connector design

The final design of the fireproof boom has the following major characteristics: section weight, 210 kg (boom and connector); section length, 2.58 m; linear weight, 81 kg/m; gross buoyance, 440 kg; buoyance/weight ratio, 2.1 to 1; draft, 1.2 m; and freeboard, 0.57 m.

At the time of writing a sufficient number of the new connectors were being constructed to permit offshore durability testing of 50 m of the boom. These trials were scheduled for the fall of 1982 near Vancouver, B.C.

It should be noted that this fireproof boom has been designed to operate and survive severe offshore conditions. Such booms for use in less severe conditions could be dramatically less massive.

Potential for offshore *in situ* burning

The existence of an offshore boom capable of operating and surviving on the sea for extended time periods offers an efficient new technique for oil spill cleanup. *In situ* burning is a one-step removal process that can dispose of large volumes of oil on water. Based on the results of trials with the fireproof boom, Figure 12 shows the dependence of oil combustion rate on burning area. In an area of only some 2,000 m^2, 6,600 m^3 of oil could be burned daily.

Assuming that the boom, when deployed in a current, takes the shape of a half ellipse, the length of boom required to contain a certain burning area can be calculated as:

Slick burning rate:

$$Q = rA' = 3.8 \times 10^{-5} A' \qquad (1)$$

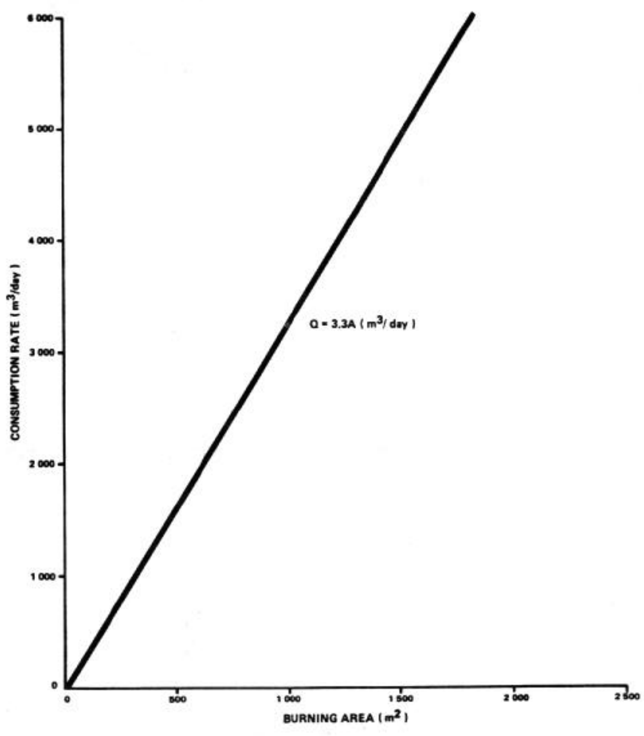


Figure 12. *In situ* burning oil consumption rate

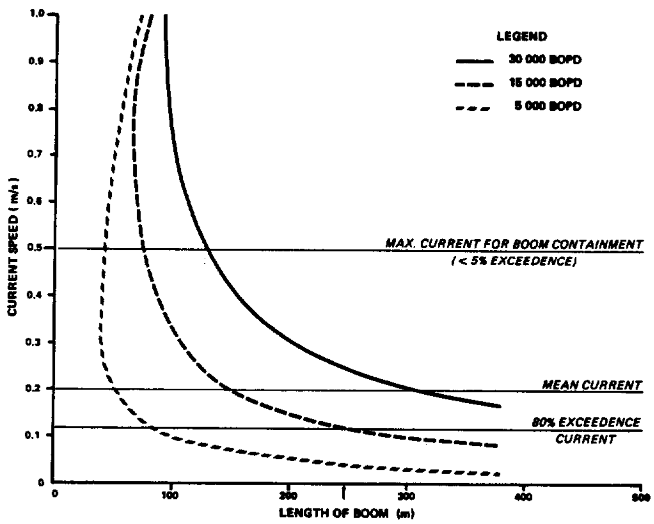


Figure 13. Lengths of boom required

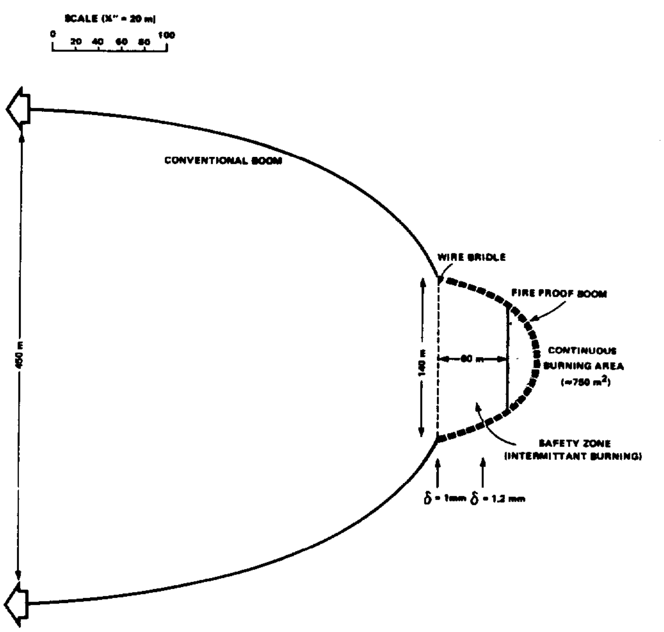


Figure 14. Example of boom configuration (15,000 bbl oil/day)

Where: Q = oil burning rate (m³/s)
A' = slick area on fire (m²)
r = slick regression rate, 2.3 mm/min or 3.8×10^{-5} m/s

Area of half ellipse:

$$A = \frac{\pi ab}{2} \tag{2}$$

Where: A = area of half ellipse (m²)
a = length of semi-major axis of ellipse (m)
b = length of semi-minor axis of ellipse (m)

Perimeter of half ellipse:

$$x \simeq \pi[\tfrac{1}{2}(a^2 + b^2)]^{1/2} \tag{3}$$

Where: x = perimeter of half ellipse or length of fireproof boom (m)

For oil leaking at a rate Q' (m³/s) onto water moving at a velocity of U (m/s), the thickness t (m) at a width of $2b$ (m) is:

$$t = \frac{Q'}{2Ub} \tag{4}$$

Since the minimum slick thickness to support *in situ* combustion of fresh oil on water is 1 mm, this thickness must not be exceeded before the oil enters the boomed area. Rearranging equation 4 with $t = 0.001$ yields:

$$b = \frac{500\,Q'}{U} \tag{5}$$

To optimize the length of boom required, the slick area on fire should be the same as the area contained by the fireproof boom ($A = A'$) and the oil burning rate should equal the oil leak rate ($Q = Q'$). Rearranging equation 2 yields:

$$a = \frac{2A}{\pi b} \tag{6}$$

Substituting equation 5 into equation 6 gives:

$$a = \frac{AU}{250\pi Q} \tag{7}$$

Substituting equation 1 into equation 7 yields:

$$a = 33.5U \tag{8}$$

Finally, substituting equations 5 and 8 into equation 3 gives:

$$x \simeq \pi\left[\frac{\left(1{,}100\,U^2 + \left(\frac{500Q}{U}\right)^2\right)}{2}\right]^{\frac{1}{2}} \tag{9}$$

Figure 13 shows the lengths of boom required for three burning rates as a function of current speed. As an example, surface current statistics for the southern Beaufort Sea are superimposed on Figure 13. It can be seen that 250 m of fireproof boom would be sufficient to burn 5,000 BOPD in excess of 80 percent, 15,000 BOPD for 75 percent, and 30,000 BOPD for approximately 50 percent destruction during the open-water period.

Figure 14 illustrates one possible configuration for use of the boom in response to a blowout offshore. Conventional offshore boom is anchored or held by supply vessels to direct the oil toward a pocket of fireproof boom. As the oil moves toward this pocket, it thickens; however, the overall slick thickness will not exceed 1 mm until the oil enters the pocket. As the oil moves toward the back of the pocket, it continues to thicken until it reaches the area of burning slick and then ignites.

Conclusions

A durable offshore fireproof boom has been researched, developed and tested that can:

- Survive, without damage, long-term exposure to the heat generated by burning crude oil *in situ*
- Contain burning crude oil in at least sea states 2–3 and at current speeds up to 0.4 m/s without loss of combustion intensity
- Survive, without damage, for long periods at sea
- Withstand contact with small ice features

Although the boom is necessarily massive, it offers a significant advantage over conventional offshore spill cleanup systems in that it can collect and dispose of large flow-rates of oil in one self-sustaining step with a minimum of logistics support. Once the final offshore trials are complete the boom will be commercially available.

Acknowledgments

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