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Fabric Boom Concept For Containment and Collection of Floating Oil

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FABRIC BOOM CONCEPT FOR CONTAINMENT AND COLLECTION OF FLOATING OIL

By

Philip E. Bonz

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Program Element B12041

Project Officer

John S. Farlow
Edison Water Quality Research Laboratory
National Environmental Research Center
Edison, New Jersey 08817

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ABSTRACT

The feasibility of applying the concept of oil-water separation by means of woven hydrophilic fabric to a floating oil containment boom was investigated through a series of model tests. A preliminary model boom configuration was developed and towed at speeds to 0.686 meters/sec (2.25 ft/sec) in both calm water and waves. Oil retention performance of this model was clearly superior to that of a conventional flat plate boom of comparable draft in the environment investigated. A larger model of similar configuration demonstrated no oil leakage when towed at 0.77 meters/sec (1.5 kt) in calm water.

While further detailed analysis, engineering, and testing is required to fully examine this concept, it appears that a properly designed flexible boom which uses a hydrophilic skirt material offers significant potential both as a containment device for floating oil in high current situations and as a high-speed collecting device.

This report was submitted in fulfillment of Project Number 15080 FWM, Contract Number 68-01-0139 by CONSULTEC, Inc., Rockville, Maryland, under sponsorship of the U.S. Environmental Protection Agency. Work was completed as of August 1972.

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SECTION I

CONCLUSIONS

The following conclusions are based on preliminary efforts aimed at establishing the feasibility of utilizing the oil/water separation qualities of selected woven fabrics in a floating oil containment device and specifically determining whether such a concept could offer better performance than conventional flat plate booms. It should be recognized that this effort was primarily exploratory in nature and that a final or prototype design was neither developed nor tested.

The results of this effort, although limited, were encouraging. The concept of employing a woven fabric in a flow-through containment boom was demonstrated to be feasible. Towing tests of a preliminary model showed that the oil retention capability of such a device in calm water was superior to that of a conventional flat plate boom of comparable draft at the speeds and with the oil tested. Towing tests conducted in the presence of waves indicated that the preliminary model conformed well with the wave profile and that no oil losses were caused by wave action.

Although it is not possible as a result of these efforts to accurately predict full-scale performance, they do indicate the potential of such a device for containment of floating oil in currents where the conventional flat plate boom is of limited effectiveness and the adaptability of such a device to high-speed oil collecting.

While the preliminary design showed promise, it was far from optimum. Design refinements both in fabric selection and cross-section configuration are expected to result in improved performance.

In terms of oil containment capability, the boom concept tested during this effort possesses the following advantages over a conventional flat plate boom under conditions of current and waves:

- Entrainment losses are reduced (or eliminated) since water flow under the oil slick must pass through the separation fabric which rejects penetration by entrained oil droplets.
- Losses by drainage are eliminated (or reduced) through proper selection of the throat opening such that the bag draft is at least as great as the oil slick depth at the boom.

- The inherent buoyancy of the oil-filled bag contributes to the wave conformance capability of the total boom, reduces the requirements for floatation, and minimizes oil loss due to wave action.

Because oil encountered by the boom is swept by the current into the bag where it is contained, this fabric boom concept appears to offer potential as an oil-collecting device. While details of this application were not addressed, only a minor modification to the configuration tested would be required for the bag to act as the sump for suction hoses of an oil removal system. In this situation, throat opening can be significantly less than that required for a retention boom since a large buildup in slick depth is precluded by continual (or periodic) oil removal.

SECTION II

RECOMMENDATIONS

Additional detailed fabric analysis and testing should be conducted. Critical to any further consideration of a hydrophilic fabric for the separation of oil and water is a complete understanding of the flow and rejection process through these fabrics. Detailed analysis - theoretical supplemented by laboratory testing - should be undertaken to identify and quantify those factors which influence fabric behavior as an oil/water separator. Factors which should be addressed include fabric characteristics, fluid properties, fluid interfacial properties, and the degradation of fabric performance due to presence of probable solutes and suspended solids. The results of this effort would provide a sound basis for fabric selection and for predicting the optimum and limiting operating conditions for oil separation for various type oil in various environments.

Detailed engineering analysis to support optimization of the boom configuration should be conducted concurrently with fabric analysis and testing. The initial purpose of this effort should be to develop the capability to predict dynamic pressures, internal and differential across the fabric, for various values of current, slick profile, and internal oil volumes as a function of bag configuration. Upon the completion of the fabric analysis effort wherein the optimum operating conditions for oil separation are defined, an optimum bag configuration would be developed and its performance capability analytically assessed.

If it appears at this time that indeed the fabric boom concept has sufficient performance potential to warrant further investigation, then the following major efforts should be undertaken sequentially:

- Full-scale two-dimensional testing in calm water of the predicted optimum configuration for a variety of oils.
- Engineering design of a complete boom assembly including optimization of the floatation and mooring/towing systems.
- Full-scale three-dimensional testing in both calm water and waves for a variety of oils.
- Design, development, and testing of an oil removal system.

SECTION III

INTRODUCTION

Under Federal Water Quality Administration Contract Number 14-12-878, CONSULTEC, Inc. demonstrated the basic feasibility of separating oil from water using selected woven fabrics, reference (1). Among the potential applications of this phenomenon is the concept of utilizing oil-separating fabrics in oil containment boom systems. Under Environmental Protection Agency Contract 68-01-0139, CONSULTEC developed and tested a preliminary design of a fabric oil containment boom system which makes use of this concept. Due to its improved hydrodynamic behavior and the ability of the fabric to pass water while retaining collected oil, the fabric boom system has the potential to perform better than currently available flat plate boom systems. It has successfully done so at speeds up to 0.77 meters/sec (1.5 kt).

Efforts under the current contract were conducted as follows:

(1) Initial testing in both calm water and waves of very preliminary boom concepts which employed fabrics identified in reference (1) as having the best oil-water separation characteristics, and the analysis of those test results.

(2) Identification of boom configuration criteria, limited additional fabric analysis, and development of a refined preliminary boom design.

(3) Preliminary testing.

(4) Demonstration testing.

Initial tests, and analysis of the results of those tests, are discussed in Appendix A. All other efforts are described in Sections V through VIII. A discussion of the characteristics of various oils is provided in Appendix B.

SECTION IV

GENERAL CONCEPT

OF FABRIC OIL CONTAINMENT BOOM

A literature search revealed that existing (1971) oil containment booms all behave essentially as flat plate systems (references 2, 3, 4, 5, 6, 7, 8, 9, and 10). Some configurations are rigid plates, and some consist of flexible flat skirts. Some rigid and semi-rigid systems, although not being actually configured as flat plates, behave much as a flat plate boom would behave in currents. Flat plate booms have been shown to be effective only in low currents, i.e., currents of 0.515 meters/sec (1 kt or less). At moderate and high current velocities stripping occurs, wherein collected oil is entrained in the water and carried under the boom by the water flow. In currents, non-porous flat plates cause flow streams to accelerate as water passes under the boom. The higher velocity flow causes lower pressures at the submerged base of the boom and collected oil is sucked into this low pressure region and allowed to escape under the boom. In addition to this "drainage" there is a second mode of failure wherein, above a certain critical current speed (for given oil and water properties), droplets of oil are torn off the headwave and "entrained" in the water. If gravity and buoyant effects are not sufficient to cause the oil droplets to rise and regain the slick before reaching the boom, the flow will carry the oil droplets under the boom.

The fabric boom concept improves upon the performance of flat plate systems through the use of a porous fabric skirt which, by permitting water flow through skirt, reduces the tendency for oil to be sucked under the boom. This also redirects entrained droplets into, and not under, the boom. The flexible fabric skirt is in the shape of a bag and is held open at the mouth. The fabric is a "hydrophilic" fabric, which exhibits the property to "wet" with water and not with oil. With an appropriate configuration of fibers, the surface tension properties of the oil are sufficient to preclude its penetration of the water-wetted fabric. Thus, the fabric boom system redirects flow lines and carries entrained oil into the fabric skirt, where it will be separated from the water and allowed to return to the surface slick due to gravity and buoyant effects.

Except for those droplets of oil entrained in the entering water flow which have not yet risen to join the surface oil slick within the bag, and those droplets which may be temporarily torn off from that slick by local internal turbulence, the oil contained within the bag takes the form of a surface slick, the buoyancy of which causes the bag to float with its top or upper portion above the water surface. Because water-wetting of a hydrophilic fabric is an essential factor in its rejection of passage by oil, this upper portion of the flexible skirt is constructed of a non-porous fabric. The collected oil, floating under this non-porous fabric, provides a significant degree of floatation for the boom system.

Water flowing into the bag through the mouth flows out through the bottom of the bag. In currents, the bag assumes a bulged shape toward the back. The increase in bag depth causes accelerated flow under the bag and results in a low pressure region on the underside of the bag. This increases the water flow through the fabric skirt and thus enhances flow into the bag.

Being flexible and lightweight, the fabric boom conforms readily to wave shapes, thereby minimizing oil losses over the top of the boom, as well as under the boom. In more advanced applications, oil collected in the bag-shaped fabric skirt could be pumped out, thus providing a high rate oil collection and separation device.

SECTION V

MATHEMATICAL ANALYSIS

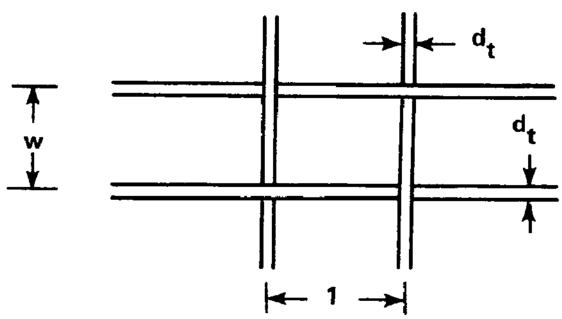
Bag design equations were developed on theoretical grounds as an assist in the overall boom concept development. From the standpoint of cloth selection, three conditions apply:

(1) The effective hole diameter between threads must be sufficiently small that entrained bubbles of some designated size will not pass through the cloth.

(2) The stagnation conditions experienced by oil bubbles of a larger size will not produce extrusion of oil through the cloth opening.

(3) The head loss for water flow through the cloth must be equal to that occurring in adjacent streamlines so that there is no diversion of flow around the cloth.

For purposes of illustration, consider a cloth with thread diameters and spacing when wet as shown in the sketch below:



The free face area for a single stream of flow is

$$A_1 = w \cdot 1$$

The contracted area through which the flow stream must pass is

$$A_2 = \left(w - d_t\right)\left(1 - d_t\right)$$

For convenience sake, the contracted area may be redefined as

$$A_2 = d_w \cdot d_1$$

where d_w and d_1 are the smaller and larger (respectively) dimensions of the individual fabric hole.

In consideration of the first condition listed above, the maximum diameter, d_o, of an oil droplet that will pass through in the flow stream, disregarding hydrophilic action, will be

$$d_o < d_w < d_1$$

If the droplet is distorted from spherical shape, then

$$d_o < \frac{2d_w d_1}{d_w + d_1}$$

Although the effect is not well understood, hydrophilic action is believed to surround the threads with a cloud of water molecules, increasing the effective thread diameter with respect to the passage of oil. Thus for hydrophilic fabrics the maximum oil droplet size would be somewhat less than that defined above.

While this approach seemed relatively straightforward, further analytical determination of fabric dimensions to meet this first consideration was thwarted by the lack of theoretical or empirical data necessary to predict size distribution of oil droplets generated by the headwave of an oil slick under the range of conditions to be encountered.

The second condition has to do with the surface tension characteristics of oil in water. In order for the oil to pass through the cloth, there must exist a pressure differential across the cloth sufficient to produce an oil bubble the size of the opening in the cloth. From elementary mechanics the pressure difference, ΔP, must be greater than $4\sigma/d$, where σ is the surface tension of oil in water and d is the equivalent diameter of the opening.

Considering a stream of water of velocity V_1 and cross-sectional area A_1 passing through a contracted section of area A_2, the pressure difference between the free flow and contracted flow will be

$$\Delta P = \frac{\rho_1 V_1^2}{2} \left[1 - \left(\frac{A_1}{A_2} \right)^2 \right]$$

(where ρ is the mass of water per cubic foot).

If the entering flow is suddenly blocked by a glob of oil, the contracted flow pressure remains the same (at least instantaneously), but the entering water flow stagnates, resulting in a pressure increase equal to the kinetic energy of the flow. The resulting pressure difference acting to force oil through the contraction increases to

$$\Delta P = \frac{\rho V_1^2}{2} \left(\frac{A_1}{A_2} \right)^2$$

The cloth selection criterion, then, is that this pressure difference remain less than that required to create an oil bubble, or expressed mathematically:

$$\Delta P = \frac{\rho V_1^2}{2} \left(\frac{A_1}{A_2} \right)^2 \leq \frac{4\sigma}{d}$$

This inequality may also be expressed in terms of V_2, the water flow velocity in the contracted region, which is equal to V_1 (A_1/A_2):

$$\Delta P = \frac{\rho V_2^2}{2} \leq \frac{4\sigma}{d}$$

and rewritten in terms of the Weber number, i.e.,:

$$W = \frac{\rho V_2^2 d}{\sigma} \leq 8$$

In consideration of the third condition, the head loss through the cloth can be expressed as

$$\Delta h = \left(\frac{A_1}{A_2} - 1 \right)^2 \frac{V_1^2}{2g}$$

or, in terms of pressure drop, as

$$\Delta P = \frac{\rho V_1^2}{2} \left(\frac{A_1}{A_2} - 1 \right)^2$$

These expressions are quite simplistic and assume that $A_2 = d^2$ and there is full flow through A_2. In point of fact, the effective value of A_2 in the head loss equation is a function of the cloth's geometry and the Reynolds number of the flow. To further complicate the issue, the effective values of d and A_2 in the extrusion equation depend as well upon the hydrophilic characteristics of the cloth used. The actual behavior of a specific cloth must be determined by experiment, but the equations given above were used for initial design; and the second and third design conditions can be achieved by meeting the following basic design equation:

$$\frac{\rho V_1^{\ 2}}{2} \left(\frac{A_1}{A_2} \right)^2 \leq \frac{4\sigma}{d}$$

Given a design headwave thickness and a bag draft, b, sufficiently large to collect all oil bubbles generated by the headwave in a current of velocity V, the bag design must meet the constraint given above. Assuming the head loss ratio is sufficiently small, the flow entering the bag is q = Vb (cubic feet per second per unit width). From continuity considerations, this flow is maintained at the cloth face. Therefore

$$q = Vb = V_1 L \text{ or; } \frac{b}{L} = \frac{V_1}{V}$$

where L is the bag length and V_1 satisfies the inequality given above.

The adequacy of this analysis for initial design efforts was reasonably confirmed by the tests reviewed in subsequent Sections.

SECTION VI

FABRIC SELECTION

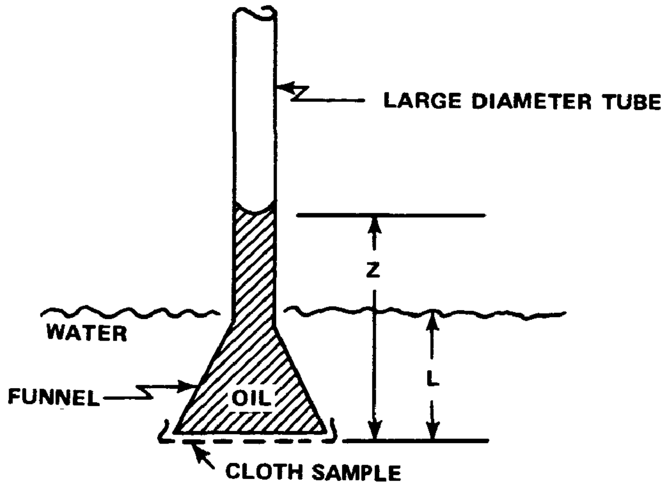
Under EPA direction, minimum effort was to be expended in fabric analysis and testing during the conduct of this contract. Although it was recognized that the performance of the flow-through boom is directly dependent on the characteristics of the fabric employed, it was felt that if the concept could be demonstrated to be attractive without optimization of the fabric, then later efforts could be undertaken in this area. Following unsuccessful initial tests (see Appendix A), a modest effort was undertaken to identify additional basic fabric selection criteria and to select a fabric(s) for further demonstration testing. The fabric selection process was restricted by EPA to the quick appraisal of a limited number of readily available fabrics and the selection of the most promising from that group.

Based on prior laboratory testing, and the limited analysis presented in the preceding section, the following criteria were developed for the initial selection of fabrics for evaluation:

- The thread diameter should be as small as possible.
- The fabric should be a plain weave.
- A cloth count (numerical ratio of warps to wefts per square inch) should be close to 1.0 (square count).

Following discussions with various fabric manufacturers, it was decided to concentrate on various cotton fabrics, and five sample fabrics were obtained for evaluation.

Weave type, cloth count, and fabric dimensions were obtained by viewing water-soaked specimens of each fabric with a compound microscope. A simple test was then conducted on each fabric to determine its capability to resist oil extrusion. The setup for this test is shown in the sketch on the following page.



A tube of sufficient diameter to minimize capillary effects was attached to a funnel on which a cloth specimen was mounted. The funnel was placed in water so that the cloth face was a defined distance, L, below the water surface. The cloth specimen was allowed to become water-soaked and water was allowed to seek its own level in the funnel. SAE 30 weight additive-free test oil was then slowly added in the tube from the top, displacing water until the funnel was filled with oil. Additional oil was carefully added until minute oil bubbles was extruded from the cloth. At that point the total oil height, Z, was measured. Under the test setup the bubbles formed were stable and of minimum size. The differential pressure at which oil will extrude was calculated as

$$\Delta P = (\rho \text{ oil})\ (Z) - (\rho \text{ water})\ (L)$$

A summary of the properties of the five cotton fabrics investigated is provided in Table 1. Geometric characteristics of the fabrics used in the initial (unsuccessful) tests discussed in Appendix A are also shown for comparison.

From a review of that data, fabric No. 5 was selected as having the best overall performance potential in terms of <u>concurrently</u> providing the greatest resistance to oil extension (maximum ΔP) and the smallest head loss due to water flow through the fabric (maximum A_2).

TABLE 1 – SUMMARY OF FABRIC CHARACTERISTICS

Sample No.	Fiber	Manufacturer & Pattern	Nominal Thread Count	Measured Thread Count	Measured Number of Holes/in^2	Measured Thread Diameter (10^{-3} in)	Measured Minor Hole Dimension (10^{-3} in)	Measured Major Hole Dimension (10^{-3} in)	Calculated Area of Individual Hole (10^{-4} in^2)	Calculated Percent of Fabric Area Open to Flow (%)	Measured ΔP at Which Extrusion Occurs (10^{-2} psi)
1	100% Cotton (Unbleached)	Burlington Industries Leslie, Catlin #13766	60 x 64	56 x 63	3528	7.15	8.60	10.80	0.93	32.8	3.81
2	100% Cotton (Bleached)	Lowenstein #88815-59	64 x 56	70 x 56	3290	8.60	5.71	9.30	0.53	20.8	5.89
3	100% Cotton (Bleached)	Lowenstein #N-3982	80 x 80	93 x 93	8649	7.86	2.86	2.86	0.08	7.1	11.82
4	100% Cotton (Organdy with Heberlin Finish)	Logantex #1235	72 x 80	64 x 70	4480	4.30	10.00	11.40	1.14	51.0	2.94
5	65% Polyester 30% Cotton	West Point Pepperell #24140	56 x 54	56 x 61	3294	5.72	10.70	12.85	1.38	45.0	3.34
A/1	Linen (plain)	(unknown)	---	47 x 34	1598	10-25	---	---	0.53	8.5	---
B/2	Linen (Irish)	Couturier Fabric WPL 9893	---	20 x 28	560	30-45	---	---	1.43	8.1	---

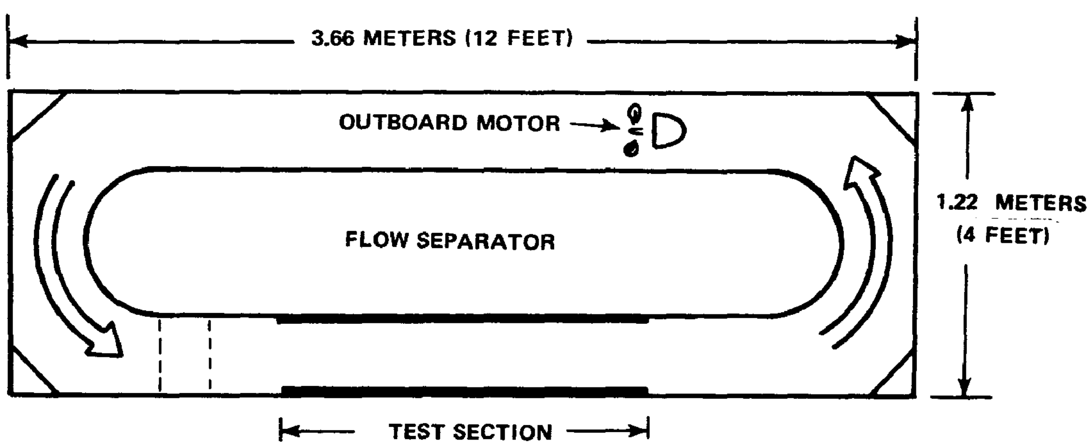
/1 Fabric used for initial model testing of preliminary boom configurations (fixed fabric models) described in Appendix A.
/2 Fabric used for initial model testing of preliminary boom configurations (free-to-float fabric model) described in Appendix A.

SECTION VII

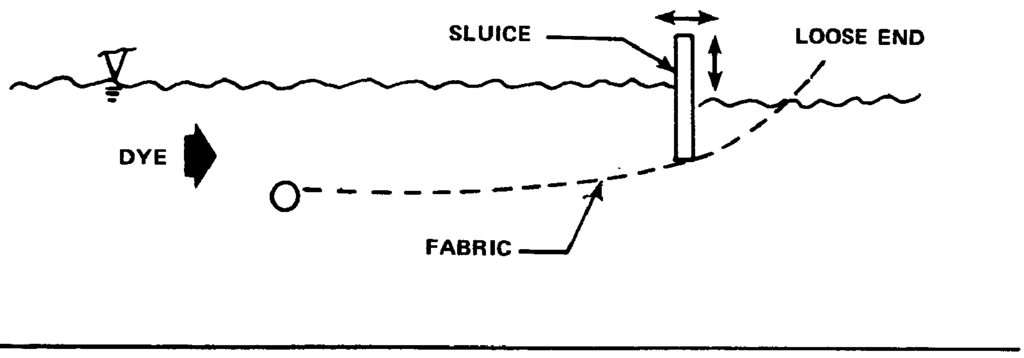
LABORATORY TESTING

In addition to the testing involved with fabric selection, a series of laboratory tests was conducted to determine a reasonable cross-sectional configuration for the flow-through boom. Based on the analysis of initial configuration testing (see Appendix A), it was decided to employ an impervious (to both oil and water) fabric as the material for the upper portion of the bag, and to control the throat opening of the boom by rigid separation of the lower leading fabric edge from the upper leading edge (boom floatation). The objectives, then, of this test series were to identify water flow lines into and through the bag and to determine the influence of various parameters such as bag length, throat opening, location of rear seam, and shape of the lower spacer bar on those flow lines.

To support this testing, CONSULTEC funded the construction of a simple flow tank shown in the sketch below. An insert in the tank provides a test section 30.48 cm (12 in) wide, 137.16 cm (54 in) long, and up to 25.40 cm (10 in) deep. Cross-sectional viewing in this test section is provided by vertical plexiglass windows. A variable speed electric outboard motor was used to create controlled flow in the tank and, with this configuration, current speeds of up to 0.23 meters/sec (0.75 ft/sec) were obtained. Flow speeds were monitored with an accurate flow velocimeter.



In the first flow test, a piece of test fabric was positioned in the flow channel as shown in the sketch on the following page. One end of the fabric was held under water by means of a dowel inserted through a sewn seam, while the other end was positioned above the water by hand. Dye was injected into the stream to study the behavior of the flow through the fabric. The length of the bag was varied by moving the loose end. A bag with an impervious back was simulated through the use of a flat plate or



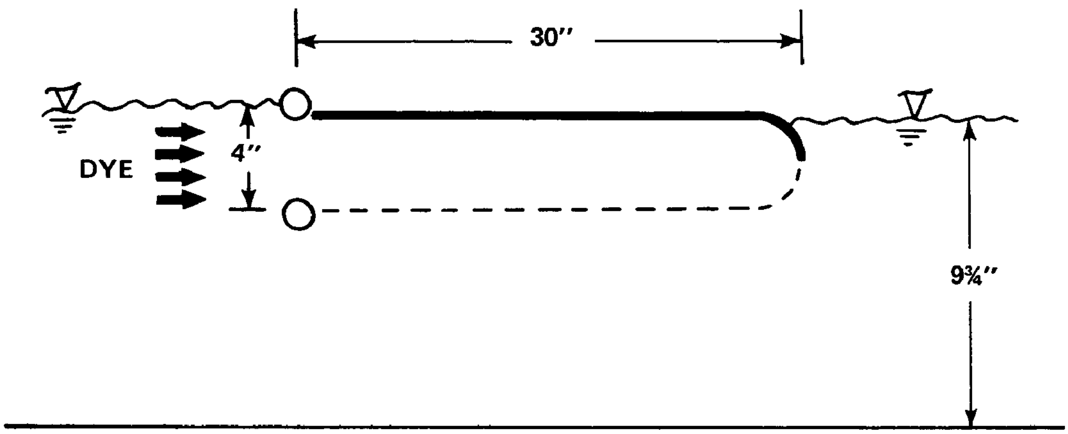
sluice which could be positioned to any combination of immersion depth and distance from the fixed leading edge of the fabric. With this technique, various bag configurations could be investigated; for example, a bag of cross-sectional symmetry with an impervious upper section and a fabric lower section could be represented by immersing the sluice to a depth half as deep as the leading edge fixed dowel.

In the absence of the sluice, flow through the bag was seen to be very good and essentially straight. When the sluice was inserted, dye traces revealed that flow streams were directed downward and through the bottom of the bag. The sluice was held at various depths to observe the effects of the depth of the impervious portion of the back of the bag. This test provided basic insight into the influences of bag length and an impervious upper and rear section of the bag.

Concurrently, a limited examination was conducted into the effect on flow patterns of the shape of the lower support rod. Support rods of various cross-sectional shapes were inserted into the leading edge fabric seam and their effect on flow lines was observed through the use of dye trace. Shapes tested included triangular, oval, streamline foil and circular, all of various sizes. Because no advantage was observed for shapes other than circular, and since it was felt that lower support in the prototype design could most easily be provided by a cable, a circular cross-section was utilized in all further tests.

Based on the results of these tests, a tentative bag configuration was developed and tested. In this configuration, bag length was 76.20 cm

(30 in), throat opening was maintained at 10.16 cm (4 in) by two 2.54 cm (1 in) diameter dowels, and the top of the bag was fabricated of an impervious polyethylene fabric which extended halfway down the back of the bag, while the remainder of the bag was fabricated of the selected cloth fabric. Dye was injected at various depths upstream of the bag. The test arrangement is shown in the sketch below.

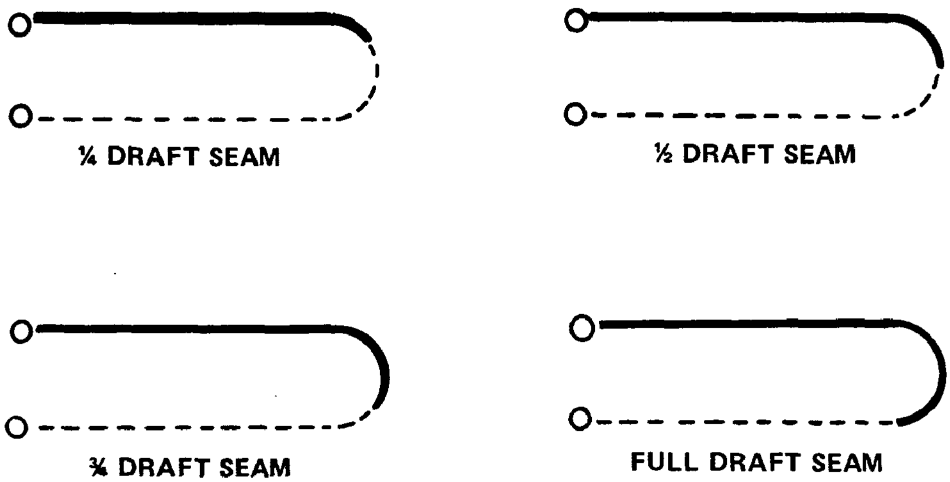


The dye traces showed that all flow streams to a depth of 10.16 cm (4 in) were directed into the bag; and that flow inside the bag was uniform and went well into the back of the bag before exiting through the cloth fabric. However it was noted that at the upper velocity range, the maximum draft of the bag exceeded one-half test channel depth. Since, as discussed in Appendix A, this is a limiting test condition, it was felt that additional testing should be conducted with shorter bags and smaller throat openings. Additionally, it was concluded that the effect of the fabric seams on internal flow should be determined more precisely.

A third series of tests was conducted using a bag length of 25.40 cm (10 in) and a throat opening of 5.08 cm (2 in). Throat opening was maintained by using two 1.27 cm ($\frac{1}{2}$ in) dowels. For this series, four models were constructed--identical except for the fabric seam, which was located at 1/4, 1/2, 3/4, and full bag draft, respectively--as shown in the cross-sectional sketches on the following page.

These tests conducted in a 0.23 meter/sec (0.75 ft/sec) current, indicated that the best flow lines as shown by dye injection occurred when the fabric seam was located midway between the top and bottom (i.e., at bag's longitudinal centerline). With that configuration, all water flow lines above the lower support passed into the bag and were smoothly directed out of the bottom of the bag through the entire length of the woven fabric. (As noted previously, in tests of the longer bag, water/

flow lines passed well into the bag before exiting through the woven fabric.) Maximum bag draft was observed to be 10.16 cm (4.0 in).



As a result of these laboratory tests, the influence of various design parameters on water flow lines into and through the bag were identified and basic criteria for subsequent bag configuration were established.

SECTION VIII

DEMONSTRATION TESTS

The primary purpose of efforts conducted under this contract was to demonstrate the feasibility of applying the concept of oil/water separation by means of a hydrophilic fabric to a floating oil containment system. At different stages of the contract effort, various model tests were conducted to examine and/or demonstrate the performance of an evolving boom concept in oil. These tests are summarized in this section.

With one exception, testing was limited to SAE 30 weight motor oil, since that oil was used in prior efforts, reference (1). Additionally, no effort was under taken to Weber-scale the oil by addition of surface active agent, since the effect of such a procedure on the oil rejection characteristics of the fabric was unknown.

First Test Series

Initial model tests of preliminary boom designs were conducted in the Hydronautics 24.4 meter (80 ft) towing tank. Models for these tests were fabricated using fabrics identified in previous efforts, reference (1), as displaying desired oil/water separation characteristics. However, these fabrics, while resisting penetration by oil, offered excessive resistance to water flow at moderate current velocities. Because of this, preliminary booms behaved essentially as flat plates. In addition, instabilities due to tank configuration were observed. The results of this test series are discussed in detail in Appendix A.

Second Test Series

Following the initial tests, analysis of those initial tests and further laboratory testing led to the development of an improved boom configuration. Oil containment tests of this configuration were conducted in the Consultec flow channel to observe performance in oil; to demonstrate superiority of that design over the configuration originally tested; and to provide a basis for further design refinement and testing at higher speed.

Two models were constructed for this test series, the dimensions of which are provided in Figure 1. Both models were identical except for the woven fabric: in the first model, one of the two fabrics employed in the initial tests described in Appendix A was used (Fabric B, Table 1); the second model was constructed using a fabric (Fabric No. 4, Table 1)

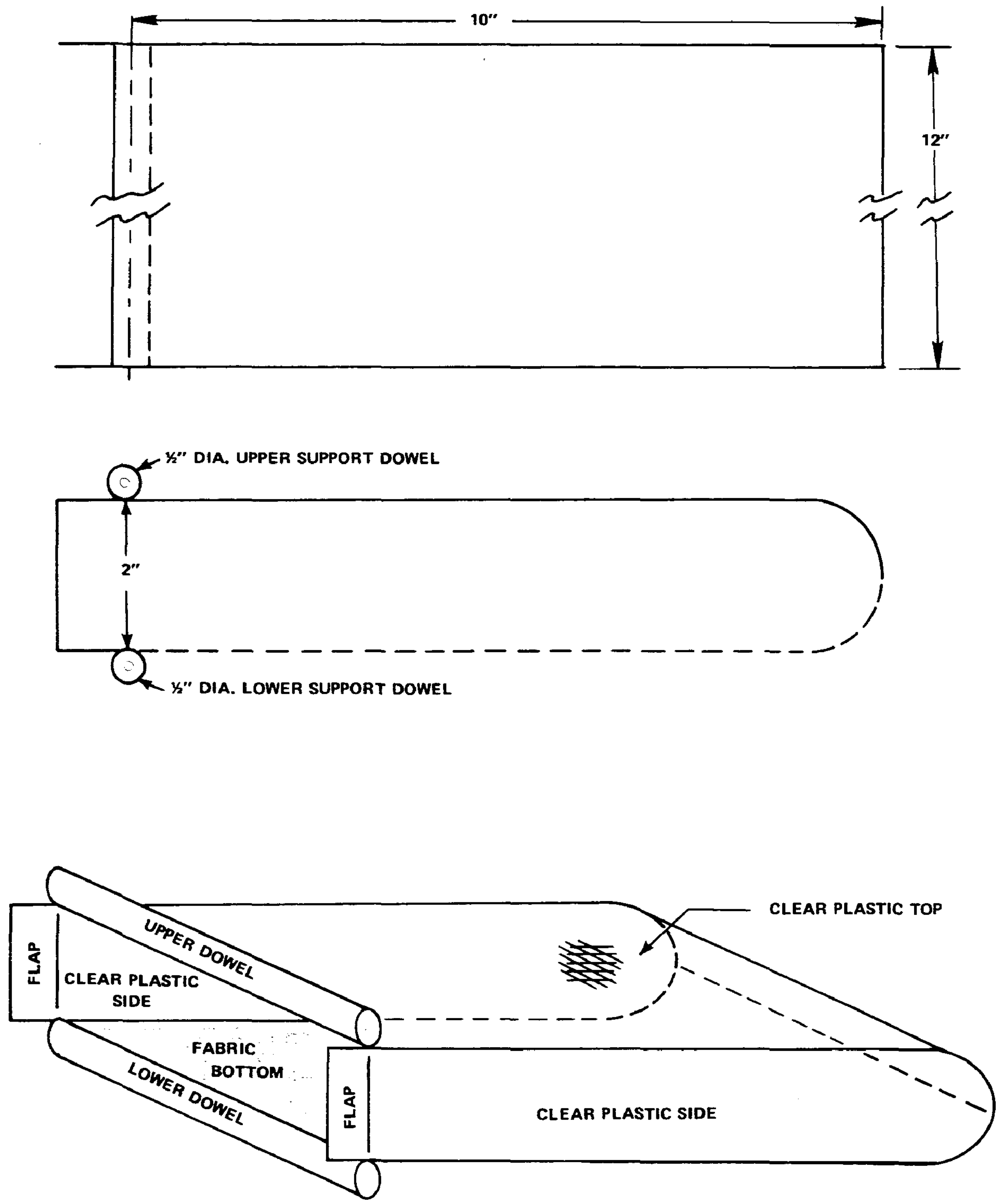


FIGURE 1 – CONFIGURATION DETAILS OF TEST MODELS, SECOND TEST SERIES

which by the selection process described in Section VI was determined to have suitable characteristics. (It should be pointed out that the fabric selection efforts had not been completed, and that based on those efforts a different fabric was selected for subsequent demonstration testing.)

Although no attempt was made in the development of these demonstration models to carefully scale the properties of the boom, a rough estimate of the scale of the boom can be obtained by comparison with typical prototype boom systems. If the 5.08 cm (2 in) mouth opening of these demonstration models is compared to the draft of existing flat plate booms (using an average draft of 76.20 cm (30 in)), the scale of the demonstration model would be approximately 1/15.

The models were held in a plexiglass fixture which provided a flow channel 30.48 cm (12 in) wide and approximately 24.77 cm (9.75 in) deep upstream of the model. Flow velocities were monitored upstream and downstream of the model. Dye was injected into the flow upstream of the model to study the behavior of the flow around and through the model booms. For the oil containment tests, oil was poured into the water just upstream of the boom. Entrained oil droplets were created by dropping the oil from a height above the water, in front of the boom.

The following demonstration tests were conducted:

<u>Test No. 1</u> Flow test with the first model. No oil was used in this test, but dye was used to observe the flow conditions.

<u>Test No. 2</u> A similar test with the second model.

<u>Test No. 3</u> An oil containment demonstration test using the second model and SAE 30 weight oil (Sears additive-free).

<u>Test No. 4</u> An oil containment demonstration test using the second model and No. 2 Diesel fuel oil.

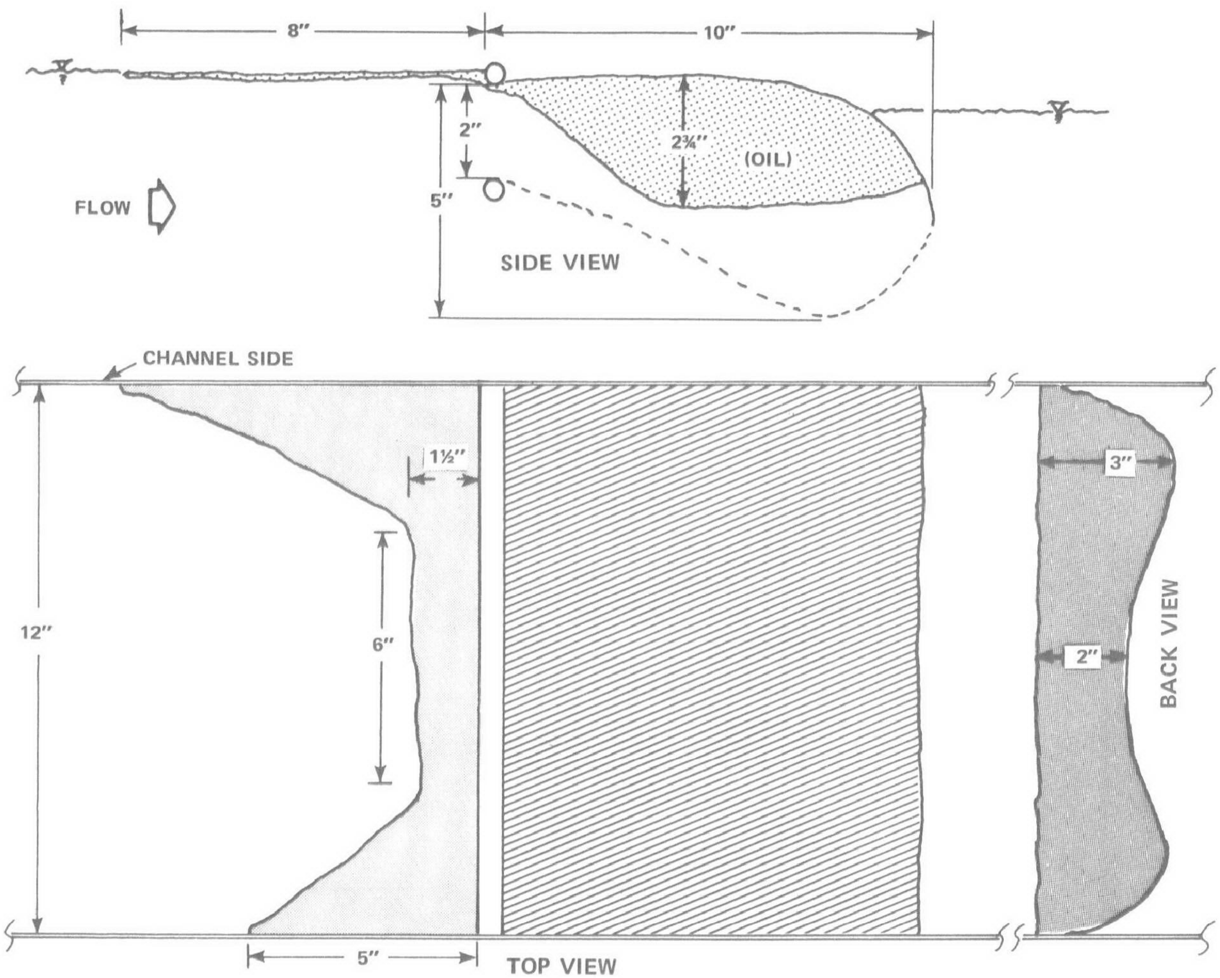
Test No. 1, conducted at a current velocity of 0.17 meters/sec (0.55 ft/sec), demonstrated that with a skirt made of Fabric B, very little flow occurs through the fabric, and flow is primarily directed under the lower dowel of the model. Some dye, however, did flow through the mouth of the boom, and the behavior of the dye showed that the conditions in the bag were almost stagnant. The conclusion is that an oil retention boom which uses Fabric B for the skirt, results in essentially stagnation in front of the boom and does not behave much differently than a flat plate boom of the same draft.

Test No. 2, conducted at the same current velocity, demonstrated that with Fabric No. 4 for the skirt, flow was directed through the mouth of the bag and through the fabric. Dye traces indicated that flow went almost all the way to the back of the bag before passing through the fabric.

Test No. 3 demonstrated the oil retention capability of the fabric boom. SAE weight motor oil was added until a total of 5400 ml was held by the boom. While it appeared that the model could contain a greater volume of oil without failure, a limiting bag draft of half channel depth was reached with 5400 ml of oil. Based on the analysis presented in Appendix A, it was felt that test results with a greater amount of oil would provide false performance indications because of test channel blockage. The 5400 ml test volume corresponds to a specific volume of oil of 17.65 liters/meter (0.19 ft^3/ft) of boom. If the scale factor of the demonstration model is assumed to be 1/15 and if the specific volume of the oil is assumed to scale up geometrically, then the full-scale specific volume of oil would be 3.96 $meters^3/meter$ (42.6 ft^3/ft). If the estimated current speed of 0.17 meter/sec (0.55 ft/sec) is assumed to Froude scale up, then the simulated prototype speed would be 0.65 meter/sec (2.13 ft/sec) or 1.26 knots.

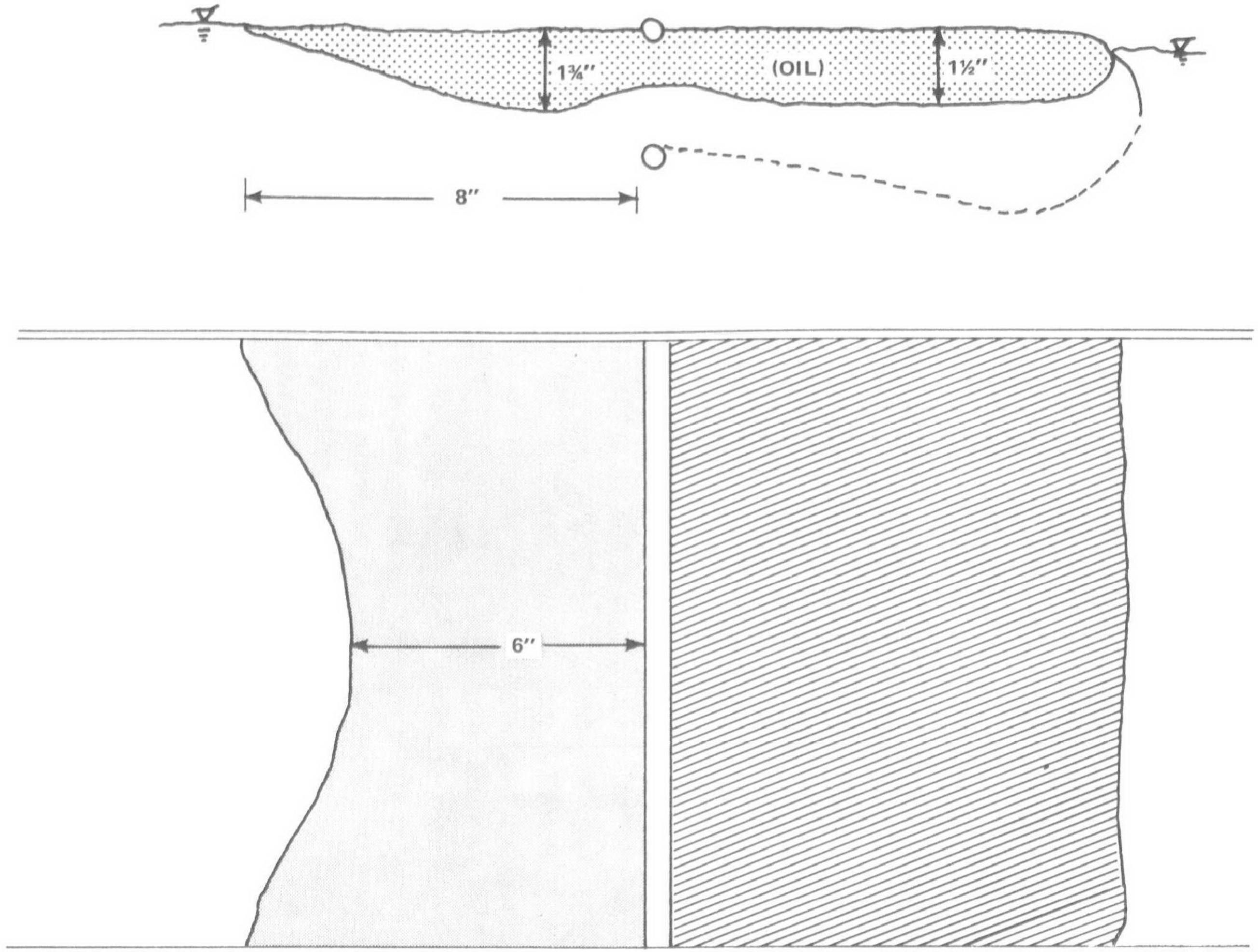
Figure 2 shows the configuration of the boom and that of the oil slick at 0.17 meters/sec (0.55 ft/sec) and 5400 ml of oil. In this test, a headwave about 6.35 cm (2.50 in) deep existed inside of the bag, and the slick extended all the way to the back of the bag. Figure 2 indicates that the bag assumed a bulged shape under these flow conditions. This shape is a desirable feature, since, by creating higher velocities (and resultant low pressures) under the bag, flow through the fabric and, thus, into the mouth of the boom is enhanced. Due to edge effects in the flow channel, and possibly also to surface tension effects, the slick configuration was not uniform across the width of the channel. The current speed was lowered from 0.17 meter/sec (0.55 ft/sec) to approximately 0.14 meter/sec (0.45 ft/sec) to allow the oil slick to form more in front of the boom. Under these conditions, a headwave formed just forward of the boom, and the depth of oil inside of the bag decreased. A sketch of the slick configuration of 5400 ml of oil and 0.14 meter/sec (0.45 ft/sec) current velocity is shown in Figure 3.

Test No. 4 was conducted to look at the effects of the viscosity of the oil on the oil retention ability of the boom. No. 2 Diesel fuel has a viscosity which is of the order of 1/100 that of the SAE 30 oil used in Test No. 3. The oil was added until the oil retention limit of the boom was reached. The No. 2 Diesel fuel oil slick extended beyond the mount of the boom and the primary headwave was outside of the bag. After 1400 ml of oil



SPECIFIC OIL VOLUME = 17.65 LITERS/METER (0.19 $FT.^3/FT.$)
CURRENT VELOCITY = 0.17 METERS/SEC. (0.55 FT./SEC.)

FIGURE 2 - OIL SLICK PROFILE, SECOND TEST SERIES (SAE 30 WEIGHT OIL)



SPECIFIC OIL VOLUME = 17.65 LITERS/METER (0.19 $FT.^3/FT.$)
CURRENT VELOCITY = 0.14 METERS/SEC. (0.45 FT./SEC.)

FIGURE 3 – OIL SLICK PROFILE, SECOND TEST SERIES (SAE 30 WEIGHT OIL)

was poured into the channel, the headwave was so deep--approximately 5.08 cm (2.0 in) deep--that oil droplets which were torn off the trailing edge of the headwave did not rise and rejoin the slick, but were swept under the boom. Because of the test facility configuration, once any oil got past the boom, it was carried into the propeller of the outboard motor and dispersed into the current as tiny droplets. Unless these droplets rose to the surface before reaching the boom, they were swept under the boom in succeeding passes. With Diesel oil this effect was particularly limiting, and further testing was prevented by oil droplets entrained in the water flow itself. Figure 4 shows the slick configuration for 1400 ml of No. 2 Diesel fuel at an estimated 0.17 meter/sec (0.55 ft/sec) current velocity. If the demonstration model results are scaled up to prototype size in the same manner as described for Test No. 3, it would correspond to a specific volume of 2.07 meters^3/meter (22.3 ft^3/ft) at a current velocity of 0.65 meters/sec (2.13 ft/sec) or 1.26 knots.

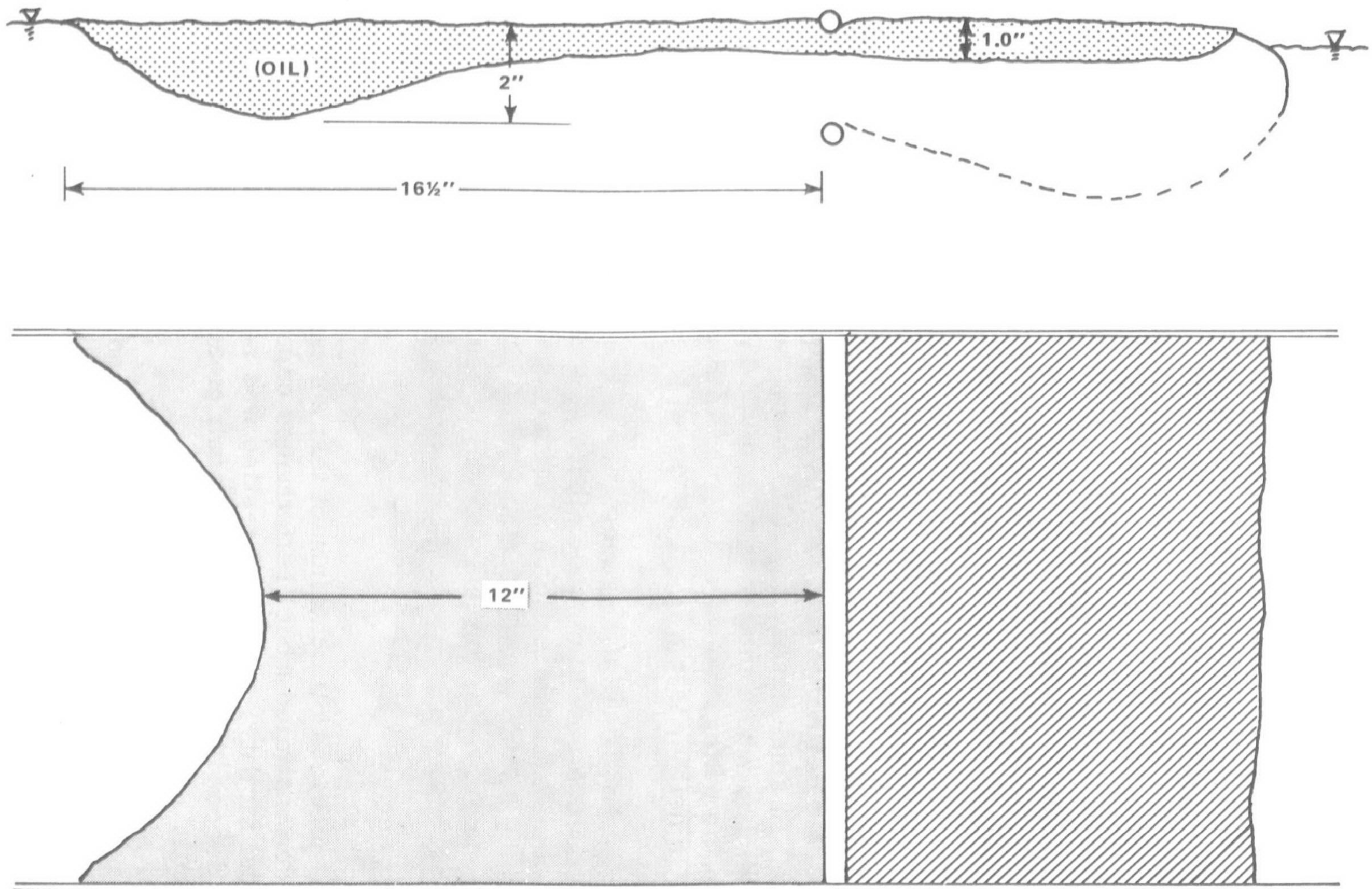
In both Tests 3 and 4, oil droplets carried into the bag by the water flow were observed, either to rise directly to, and join, the oil slick within the bag or, in some cases, to "roll" along the woven fabric toward the back of the bag where they rose to join the slick. No oil droplets entrained in the water flow were observed to pass through the fabric. Additionally, in neither test was oil observed to extrude through the fabric.

In addition to demonstrating feasibility of the basic concept and indicating performance potential, these tests provided the opportunity to evaluate various model fabrication and mounting techniques and provided the basis for developing model configuration (in terms of throat opening, throat-to-length ratio, and plastic/fabric seam location) for further testing.

Third Test Series

While the previous oil containment test series conducted in the flow channel demonstrated model performance capability within the limitations of that test facility, additional testing was necessary at higher speeds and in a deeper tank which would permit greater boom drafts and greater oil volumes.

A series of final demonstration runs was conducted in the 24.4 meter (80 foot) Hydronautics oil test tank. These tests consisted of essentially two events--a comparison of the fabric boom and flat plate in calm water using SAE 30 weight motor oil, and a performance demonstration of the fabric boom in waves also using SAE 30 weight motor oil. The rationale for the selection of these tests was as follows:



SPECIFIC OIL VOLUME = 9.20 LITERS/METER (0.099 $FT.^3$/FT.)
CURRENT VELOCITY = 0.17 METERS/SEC. (0.55 FT./SEC.)

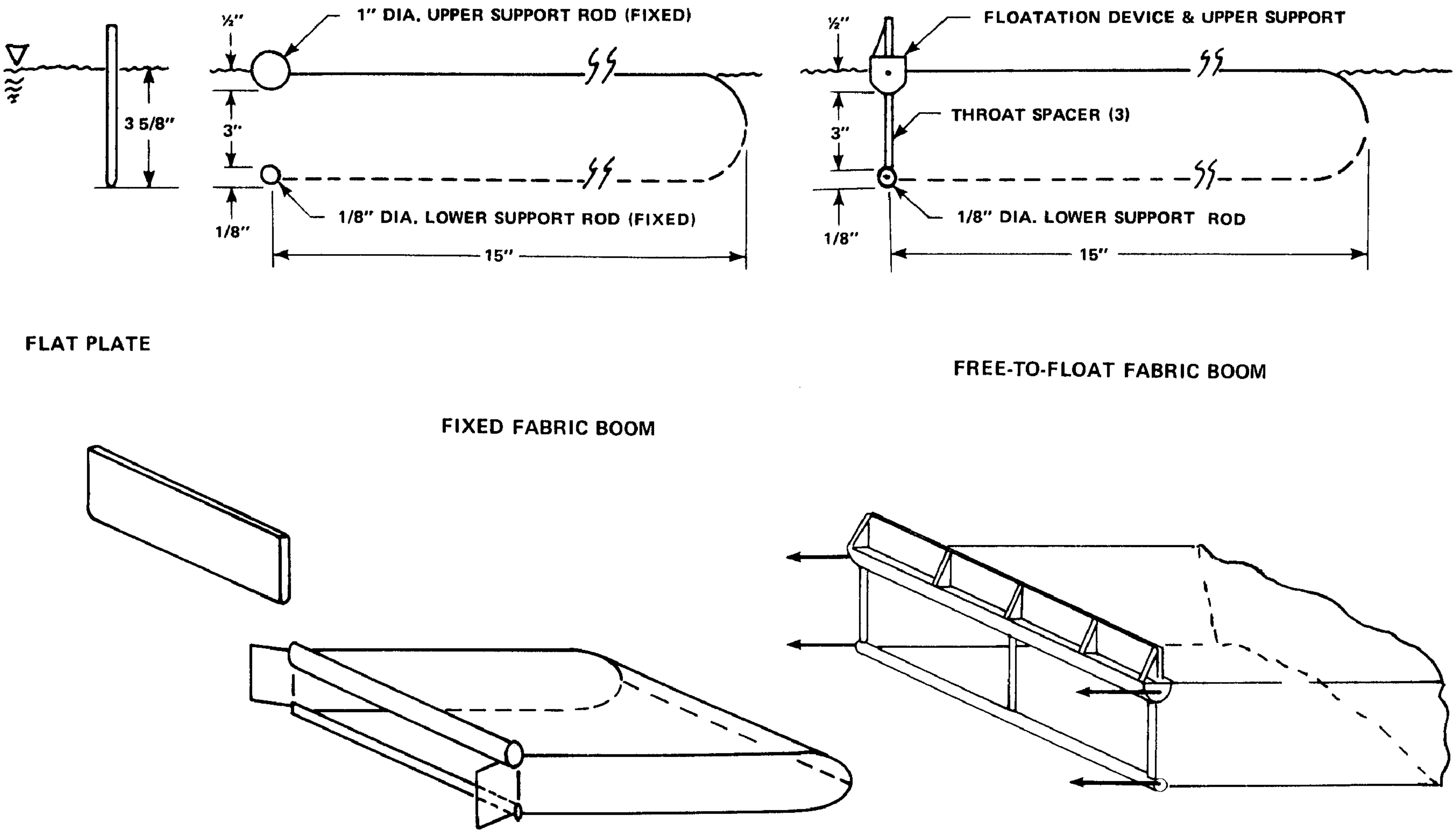
FIGURE 4 – OIL SLICK PROFILE, SECOND TEST SERIES (NO. 2 DIESEL FUEL)

- By comparing performance in calm water, the significant engineering effort necessary to accurately model the flat plate for wave response was eliminated.
- If the fabric boom performed better than the flat plate in calm water and the fabric boom could be shown to perform successfully in waves, then it may be assumed that the fabric boom will perform better than the flat plate under all conditions.

The Hydronautics towing tank is 0.61 meters (24 in) wide and was filled to a depth of 0.48 meters (19 in) for this test series. One side is made of clear acrylic for viewing. A rubber-tired carriage rides on steel rails along the top of the tank walls and is pulled by an electric motor-driven endless cable. Waves are generated by a wave maker installed at one end. Photographic coverage of all runs was provided by a 16mm camera mounted on an outrigger attached to the tow carriage.

Three models were fabricated for this test series: a flat plate boom, a calm water fabric boom, and a free-to-float fabric boom. Sketches of these models are provided in Figure 5. Except for the floatation and the support and mounting systems, both fabric boom models were identical and employed a cotton polyester fabric, Fabric No. 5 of Table 1, as the lower bag material. As pointed out previously, fabric testing efforts had not been completed when the second demonstration tests were conducted. Although in that demonstration series, the boom configuration which used Fabric No. 4 (considered at that time to be the best available) performed satisfactorily to the limits of the test facility and no oil penetration of the fabric was observed, it was recognized that the higher speeds of the third demonstration test series could result in greater differential pressures across the fabric and thus an increased probability for oil penetration of the fabric. Therefore, based on the final results of the fabric selection effort described in Section VI, Fabric No. 5 was chosen for use as the lower bag material in this demonstration series since, while its weave was slightly less open than Fabric No. 4 (calculated percentage of open fabric area of 45% versus 51%), the differential pressure at which oil extrusion occurred was greater (3.3 psi versus 2.9 psi).

It should be noted that the floatation and support systems of the free-to-float model were derived empirically and thus do not necessarily represent an optimum configuration. The basic purpose of the free-to-float test was to demonstrate concept performance in other than calm water and, specifically, to show the inherent response of the oil-filled boom to wave action.



NOTE: 23 INCH BOOM WIDTH FOR ALL THREE TEST MODELS

FIGURE 5 – CONFIGURATION DETAILS OF TEST MODELS, THIRD TEST SERIES

All models were mounted in a clear plexiglass support assembly which, in turn, was suspended from the wheeled tow carriage. This carriage was capable of speeds to 0.69 meters/sec (2.25 ft/sec) with the model boom installed. The flat plate and calm water fabric boom models were rigidly mounted directly to the sides of the plexiglass support assembly. The free-to-float model was towed by four nylon threads which, at one end, were attached to either end of the floatation device and to either end of the lower spacer bar. At the other end these lines were secured to the inside of plexiglass support device at a height such that the angle of pull was horizontal. Sufficient length was provided so that the ability of the model to follow the wave profile was not inhibited by the tow system.

The fabric boom models were constructed with clear polyethylene sides which were equipped with frontal flaps. These flaps were taped to the inside of the plexiglass support structure to prevent oil from passing between the boom and that structure, and thus invalidating test results. Passage of oil between the plexiglass support structure and the tank was prevented by installing flexible wipers on exterior leading edges of the plexiglass.

All tests were conducted using the constant volume technique. In this technique all of the oil to be encountered by the model is collected and contained just ahead of the model by a cofferdam which is removed just prior to boom acceleration. Steady state is achieved after the desired carriage velocity is reached and the oil slick has adjusted to a constant length. When oil losses are large, no steady state condition is achieved.

In the two-day period available for testing, a total of 33 test runs were conducted with oil volumes of up to 30,000 ml and at speeds of up to 0.69 meters/sec (2.25 ft/sec). The superior oil retention capability of the fabric boom over the flat plate in calm water was demonstrated; and the free-to-float boom was shown to be capable of oil retention while exhibiting stable performance and satisfactory wave response at all speeds tested. Since the primary purpose of these tests was demonstration rather than engineering testing, oil losses (when they occurred) were measured in only a few instances and estimated in others, and all runs were filmed. The results of these tests are summarized in Table 2.

In addition to clearly demonstrating the feasibility of applying the concept of oil/water separation by means of a hydrophilic fabric to a floating oil containment system, these tests provided valuable data for developing an improved boom configuration and an indication of the adaptability of this concept to a floating oil collection system.

TABLE 2 - SUMMARY OF THIRD TEST SERIES

Model	Oil Volume (ml)	Carriage Speed (meters/sec)	Carriage Speed (ft/sec)	Wave Characteristics	Oil Loss	Run No.
Flat Plate	5,000	0.23	0.75	Calm	None	21-1
↓	5,000	0.30	1.00	↓	65%[1] [3]	21-2
↓	5,000	0.38	1.25	↓	85%[1] [3]	21-3
↓	10,000	0.23	.75	↓	30%[2] [3]	20-1
↓	10,000	0.30	1.00	↓	64%[2] [3]	20-3/21-15
↓	10,000	0.38	1.25	↓	95%[1] [3]	20-2/21-4
Fixed Fabric	10,000	0.23	0.75	Calm	None	20-4/21-5
↓	10,000	0.30	1.00	↓	None	20-5/21-6
↓	10,000	0.38	1.25	↓	None	20-6/21-7
↓	10,000	0.46	1.50	↓	Possible Minute Extrusion[4]	21-8
↓	10,000	0.53	1.75	↓	Minute Extrusion[5]	21-9/21-10[10]
↓	10,000	0.61	2.00	↓	2%[2] [6]	21-11
↓	10,000	0.69	2.25	↓	2%[1] [6]	21-12
↓	20,000	0.23	0.75	↓	None	20-8
↓	20,000	0.30	1.00	↓	None	20-9
↓	20,000	0.38	1.25	↓	None	20-10[7]/21-13
↓	20,000	0.46	1.50	↓	Possible Minute Extrusion[4]	20-11[7]/20-12[7]/21-14
↓	30,000	0.38	1.25	↓	5%[1] [8]	20-13
Free-to-float Fabric	10,000	0.23	0.75	[9]	None	21-19[11]
	20,000	0.23	0.75	[9]	None	21-20
	20,000	0.30	1.00	[9]	None	21-20

[1] Estimated
[2] Measured
[3] Oil loss continues throughout duration of run.
[4] Although no oil droplets could be seen extruding, 6-10 small droplets were visible on water surface aft of the boom at conclusion of run.
[5] 10-12 tiny droplets were observed to extrude through fabric during run.
[6] Loss appeared to have been caused by extrusion.
[7] Some oil passage occurred due to vortex action at junction of model and plexiglass support plates.
[8] Loss occurred near end of run when, as bag became full, internal flow pattern caused spillage out of mouth of bag. No loss through fabric.
[9] Length - 1.83 meters (8 ft); Height - 3.18 cm (1.25 in).
[10] Run No. 20-7 experienced large oil loss due to vortex action. Corrected in 21-series runs by repositioning model within plexiglass support plates.
[11] Runs 21-16, 21-17, and 21-18 were conducted without oil to establish towing and mounting techniques.

As shown in Table 2, oil extrusion through the fixed fabric model was noted at speeds above 0.46 meters/sec (1.50 ft/sec). If the 9.21 cm (3.63 in) throat draft is compared to an average flat plate boom draft of 76.20 cm (30 in), the scale of the fabric model would be approximately 1/8.3. Under conventional Froude scaling the model velocity of 0.46 meters/sec would represent a full-scale velocity of 1.32 meters/sec (4.32 ft/sec) or 2.6 knots. However, the applicability of Froude scaling to extrusion is not clear since the fabric characteristics would not be changed in a full-scale system. Furthermore, the draft of a full-scale fabric boom will not necessarily be 76.20 cm (30 in)--further analysis and testing must be conducted before a full-scale configuration can be developed. One of the factors causing oil extrusion is the differential pressure across the fabric. For a given fabric, differential pressure can be reduced by increasing the bag length/throat opening ratio, thus providing a greater fabric area for water discharge.

Table 2 also shows that the maximum volume of oil which could be contained by the fabric model configuration before loss by spillage or drainage occurred was between 20,000 and 30,000 ml. An oil volume of 20,000 ml equates to a specific volume for the fabric model of 34.24 liters/meter (0.37 ft^3/ft), which is far greater than the oil retention capability of the flat plate model, and represents a full-scale specific volume of 2.36 $meters^3/meter$ (25.49 ft^3/ft)--again, assuming a scale factor of 1/8.3. While the full-scale specific volume predictions appear to exceed a prototype design goal of 0.93 $meters^3/meter$ (10 ft^3/ft), the design of a full-scale configuration has not been developed and thus the scaling laws are not completely valid. However, it is clear that the specific volume contained by the boom before spillage or drainage occurs can be increased by increasing the bag length, thus providing a greater holding volume.

It was concluded from these tests that, with minor configuration changes, the oil retention capability of the fabric boom could be improved in terms of increasing the specific volume of oil contained and increasing the speed at which loss by extrusion commences.

Fourth Test Series

Following the successful demonstration of the basic fabric boom concept at Hydronautics (third test series), CONSULTEC was asked to investigate the applicability of that concept to high-speed oil collecting. The initial phase of that effort was to be the demonstration of the capability of the fabric boom to retain a "pumpable" volume of oil at a towing speed of four knots (2.06 meters/sec, 6.76 ft/sec): the basic considerations being that the boom must retain some specified, but undefined, quantity of oil; and that as this entrapped volume of oil is increased by sweeping, the excess oil would be removed at the same rate it is collected.

The approach envisioned for this phase was the development of an acceptable or preferred bag configuration through iterative testing and modifications of both design and procedures based on the review of test results. Upon the determination of an acceptable bag configuration, a compatible oil pump-out system would be developed and incorporated for demonstration purposes. (However, as will be pointed out, due to funding constraints, only one series of bag configuration test runs was conducted.)

The tow tank at EPA, Edison Water Quality Research Laboratory, was selected as the test facility for this phase. This tank is 30.48 meters (100 ft) long, 3.66 meters (12 ft) wide, and can be filled to a water depth of 0.91 meters (3 ft). A wheeled carriage which spans the tank width and runs on rails mounted on the tank sidewalls can be towed at speeds to 4 knots by means of a variable speed electric motor and can carry both test equipment and an observer/operator.

In the conduct of this phase it was desired to utilize the results of previous testing to the maximum extent possible. Since the majority of prior test efforts were in calm water with no appreciable effort expended on the analysis and design of boom floatation and towing systems, preliminary testing was planned for calm water using the same type of carriage/boom support employed in previous testing. Additionally, in order to compare performance with previous efforts, the first boom selected for testing was fabricated from the same material, Fabric No. 5, Table 1, and was similar in configuration to the boom used successfully at Hydronautics. The frontal width of the model was increased from 58.42 to 116.84 cm (23 to 46 in) to take advantage of the wider tank, while the throat opening was decreased from 7.61 to 5.08 cm (3 to 2 in) and the length was increased from 38.10 to 142.24 cm (15 to 56 in) because of the increased towing speed: however, the rear plastic-to-fabric seam was maintained at the same (mid-draft) relative position.

Upon completion of necessary modifications to the test facility, the installation of required underwater lighting and viewing systems, and the preliminary debugging of both equipment and procedures during tests without oil, one series of calm water tests using SAE 30 weight oil was conducted on August 11, 1972. In these tests, the boom configuration described above was held rigidly between two plexiglass plates, suspended from the tow carriage. Underwater performance was observed and recorded via periscope by the portable SONY "Rover" TV camera mounted on the carriage. A total of seven runs was conducted at carriage speeds ranging from 1 to 2 knots (0.52 to 1.03 meters/sec; 1.69 to 3.38 ft/sec).

Because these tests were considered at the time to be the first in a series of iterative tests, emphasis was placed on evaluation of procedures and qualitative performance rather than on the gathering of quantitative data. However, since no additional testing of the fabric boom was performed under this contract, and since this test series represents the most severe testing to which the fabric boom concept has been exposed, it is considered appropriate to discuss these tests in some detail.

As in the case of all prior testing, the oil to be encountered by the boom during the test run was contained in a small area just ahead of the boom. For these tests, the oil was contained by the vertical plexiglass plates (to which the boom was mounted) and by a removable athwart-tank cofferdam which was lifted clear as the carriage began to accelerate. (At the termination of the run, the cofferdam was dropped back into place to retain the oil contained by the boom which otherwise would have been lost during deceleration.) No physical measurement of the oil which got by the boom was undertaken although, at the end of each run, the oil on the water surface behind the boom was swept and collected at the extreme (starting) end of the tank. It should be pointed out that while estimates of oil loss are given in the following discussions, these extremely crude estimates are based on visual impressions of the relative amount of oil floating on the water surface following the passage of the boom. In addition to oil which penetrated the fabric or otherwise legitimately escaped from the boom, these estimates include oil losses which may have been artificially induced by the test set up such as oil loss over the boom or oil loss between the boom and the plexiglass side plates due to vortex action.

Run No. 1. A speed of 2 knots (1.03 meters/sec or 3.38 ft/sec) was selected for the first run since it represented a compromise between maximum previous test speeds and the desired goal of this phase, and thus the first step of a bracketed approach. Initial oil volume was 9.46 liters (2.5 gal). Although the periscope, lights, and TV camera had been adjusted to provide full coverage of the bag during a preliminary two-knot run without oil, the introduction of oil caused the bag to submerge such that during this run only the plastic top of the bag was in the camera's field of view. Consequently, although oil droplets were noted by tank-side observers to rise in the wake of the boom, the source and cause of this oil loss could not be determined. Total oil loss was estimated at 15 to 20 percent.

Run No. 2. After adjusting TV zoom to increase field of vision, 28.39 liters (7.5 gal) of oil were added to the residual oil from Run No. 1 and another two-knot run was conducted to determine the path of oil loss. Again, although oil droplets were noted rising to the surface in the boom's wake and an oil loss of 15 to 20 percent was estimated, the TV camera position was unsuitable to determine the source of oil loss.

Run No. 3. The positions of the periscope and underwater lights were lowered to provide underwater TV viewing of the entire rear portion of the bag and another two-knot run was conducted using only the residual oil from Run No. 2. During this run the pattern of oil droplet movement within the bag indicated that the water flow was essentially from front to rear. Additionally, extreme turbulence in the rear portion of the bag was noted. Oil droplets caught both in the straight flow lines and in the turbulence were observed to penetrate the fabric in the after section of the bag and escape. Total oil loss was again estimated at 15 to 20 percent.

Run No. 4. In order to confirm results of prior test efforts, the carriage speed was reduced to 1.0 knot (0.52 meters/sec or 1.69 ft/sec) for this run. An additional 18.93 liters (5 gal) of oil was added to the residual oil remaining from Run No. 3. During this run, internal turbulence was significantly less than that noted at 2 knots and oil droplets could be seen drifting along inside the bag (sometimes "rolling" along the fabric) and rising to join the oil slick within the bag. This would indicate that the water exit flow lines were more evenly distributed along the length of the fabric. No oil droplets were seen to pass through the fabric and no oil loss was observed.

Run No. 5. Carriage speed for this run was increased to 1.5 knots (0.77 meters/sec or 2.53 ft/sec). No oil was added to the residual oil of Run No. 4. Although internal turbulence was considerably greater than that observed during the previous run, no oil was observed to pass through the fabric and no oil loss was observed.

Run No. 6. In an attempt to bracket the speed at which oil loss is initiated, the carriage speed for this run was increased to 1.75 knots (0.90 meters/sec or 2.96 ft/sec). No new oil was added. Again, an increase in internal turbulence was noted and some passage of oil through the fabric was observed. Total oil loss was estimated at 5-10 percent.

Run No. 7. With an estimated 35 liters (9.25 gal) of oil remaining from the previous run, the final run of this series was conducted at a carriage speed of 2 knots, with the desire to more accurately determine, if possible, the mechanics of failure. As expected, internal turbulence was greater than that observed at 1.75 knots. During this run, oil droplets were observed to "hang" in position on the inside of the fabric toward the rear of the bag and then suddenly be forced or extended through. Total oil loss was estimated at 15-20 percent.

Analysis of the results of this test series can be summarized as follows:

- The boom tested appeared to retain oil at speeds to 1.5 knots (0.77 meters/sec, 2.53 ft/sec).
- Oil leakage occurred at 1.75 knots (0.90 meters/sec, 2.96 ft/sec) and at two knots (1.03 meters/sec, 3.38 ft/sec).
- Oil leakage rate of 2.0 knots appeared greater than at 1.75 knots.
- The boom support system employed for those tests was not satisfactory for high-speed operations.
- Underwater viewing is a necessity for performance analysis.

The failure of the boom to retain oil at speeds in excess of 1.5 knots can be attributed to the following factors:

- Because the upper boom support was fixed, the boom itself was not floating on the surface of the water. In fact, the water surge wave generated at higher velocities increased both the pressure and the water flow into the bag itself due to the rigidity and shape of the upper support. This surge wave was estimated to be as high as 6.35 cm (2.50 in) at a carriage speed of 2 knots.

- Flow inside the bag was far from optimum. Successful boom performance is dependent on flow distribution across the entire bag length. From review of the television tapes of these tests, it appears that water flow within the bag at speeds in excess of 1.5 knots was essentially from front to back with little flow exiting along the bottom of the bag. Additionally, because of this flow pattern, extreme turbulence was generated within the after-end of the bag itself.

- The location of the plastic/fabric seam at the rear of the bag directly influences the water flow pattern. While positioning this seam at the mid-point produced best results at low speed in terms of retention capacity, this location may not be optimum for high-speed collection operation.

Other factors which may have influenced performance were the fact that the boom tested was installed for numerous checkout runs during the preceding month, and thus was repeatedly exposed to water of high chlorine content. Although the deterioration aspect of the fabric has never been examined, all prior tests were conducted with "new" booms.

Although this test series did not result in the immediate demonstration of a boom configuration which could be directly applied to high speed oil collecting and additional testing could not be conducted due to funding constraints, it should be recognized that these tests were only the first step in an iterative test/design effort. Further analysis and evaluation of the results of these and preceding tests will provide valuable input for future efforts. CONSULTEC is confident of the adaptability of the fabric boom concept to high-speed oil collecting.

SECTION IX

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SECTION X

APPENDICES

APPENDIX A

INITIAL MODEL TESTING OF PRELIMINARY BOOM CONFIGURATIONS

Test Program

Model tests of the initial boom designs were conducted in the 24.4 meter (80-foot) towing tank at Hydronautics, Inc., (Laurel, Maryland). This program consisted of the following tests:

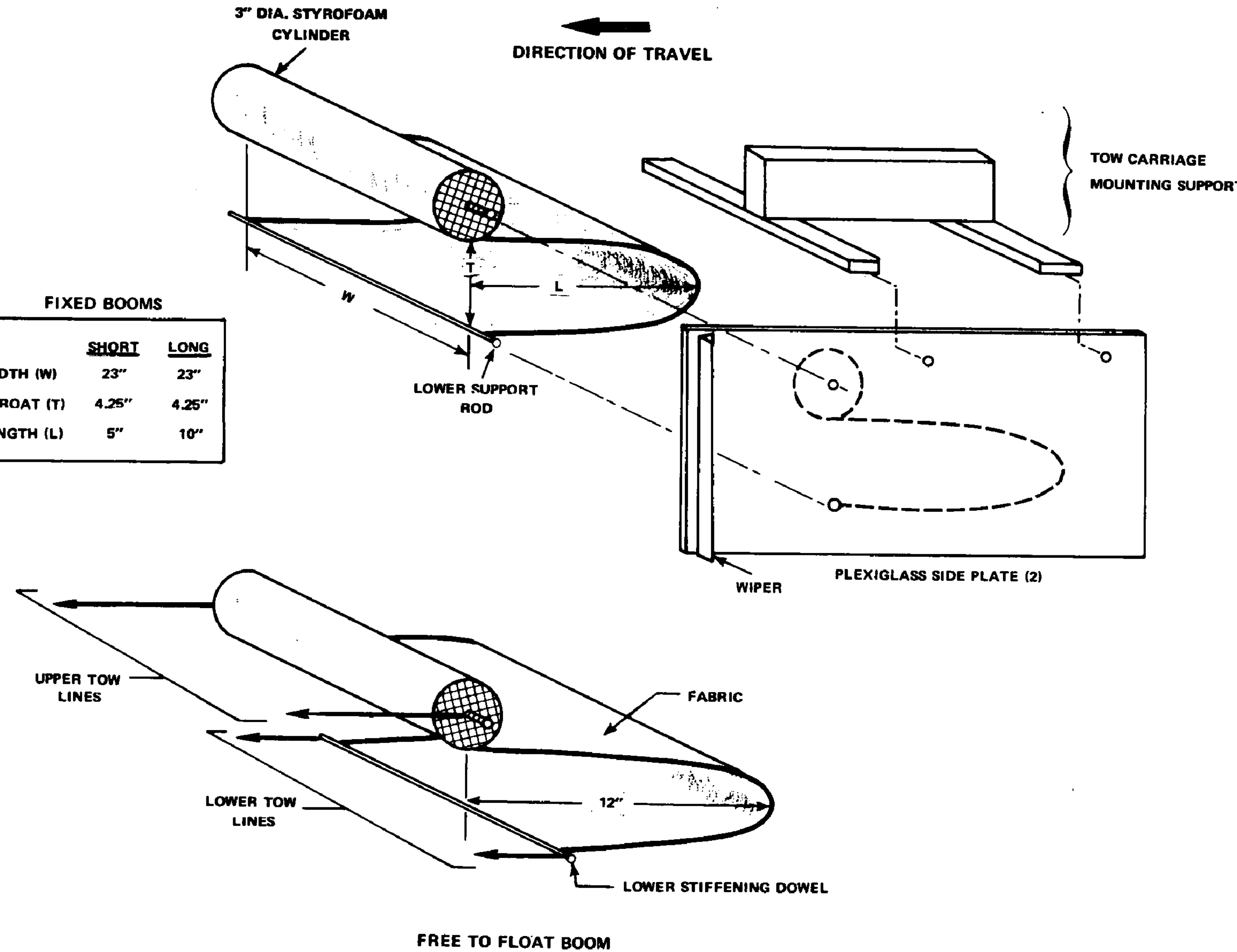
a. Exploratory two-dimensional tests of two boom configurations in calm water to measure their oil containment ability at various speeds for different quantities of oil.

b. Tests of a rigid flat plate boom of the same draft as the models tested in (a), above, to obtain oil containment properties for comparison with the fabric boom designs.

c. Tests in waves of a free-to-move fabric boom model to determine the effect of waves on the oil containment properties of the system.

Four models were employed during this test series: a fixed flat plate boom, a fixed short fabric boom, a fixed long fabric boom, and a free-to-float fabric boom. Configuration details of the fabric booms are provided in Figure A-1. The flat plate model was fabricated of plywood and had a draft equivalent to that of the fixed fabric models (5.75 in). The fixed fabric booms were fabricated from a plain linen fabric previously determined as having the best oil-water separation properties of the fabrices examined--reference (1), fabric sample no. 0701. In an attempt to improve on the performance of the fixed booms, a coarser linen fabric, Couturier Fabric WPL 9893, was used for the free-to-float boom model. Geometric characteristics of these fabrics, designated A and B, respectively, are listed in Table 1 of the basic report.

The Hydronautics towing tank is 24.4 meters (80 ft) long, 0.61 meters (24 in) wide and was filled to a depth of 0.46 meters (18 in) for the tests. Models were towed at steady speeds ranging from 0.15 to 0.69 meters/sec (0.5 to 2.25 ft/sec). A flat-plate wavemaker at one end of the tank was used to generate regular waves which varied in length from 0.61 to 2.44 meters (2 to 8 ft) and were 3.18 or 6.35 cm (1.25 or 2.50 in) high. Using the constant oil-volume method of testing, the specified quantity of oil was placed just ahead of the boom. After each run, the amount of oil



FIXED BOOMS

	SHORT	LONG
WIDTH (W)	23"	23"
THROAT (T)	4.25"	4.25"
LENGTH (L)	5"	10"

FIGURE A-1 – CONFIGURATION DETAILS OF INITIAL TEST MODELS which passed the boom was measured. Sixteen mm film coverage was obtained for each of the tests.

This initial test program is summarized in Table A-1. While the performance of the free-to-float fabric model was such as to preclude the reporting of any meaningful data, oil loss rates for the flat plate model and the fixed fabric models (in calm water) are shown in Figure A-2.

The flat plate boom tests provided engineering data on oil slick geometry and oil loss characteristics for flat plates in currents. SAE 30 weight motor oil was used for all the tests. Fabric boom tests of both the fixed and free-to-float models showed that due to excessive resistance to water flow through the fabric, the boom system did not behave as intended. Flow in the bags was almost stagnant for the fixed-bag configurations, and the overall behavior of the boom was much like that of a flat plate.

The fixed-bag tests provided engineering insight into the effect of the bag and influence of bag length on oil slick characteristics. These tests demonstrated that having a hydrophilic material on the top side of the bag is not an advantage. It is, in fact, a disadvantage because the top of the bag is pushed out of the water by the floating oil. Since this prevents water-wetting of the hydrophilic fabric and reduces its effectiveness in preventing oil passage, collected oil passed through the top. This situation can be prevented by using a non-porous fabric on the upper portion of the bag.

The free-to-move model did not assume the anticipated shape when towed in calm water; and in waves, the opening of the mouth of the bag became extremely unstable. These observations have led to the conclusion that the mouth of the bag should be held mechanically to the appropriate dimension.

Film coverage of the tests was analyzed using a photo-optical data analyzer. Oil slick characteristics, oil dynamics and boom behavior were studied. Figures A-3 and A-4 show the characteristic shapes of the oil slicks formed by a flat plate boom at various speeds for different specific volumes of oil. Figures A-5 and A-6 show slick geometry for the fixed short cloth boom and Figures A-7 and A-8 show the same data for the fixed long cloth boom. Comparison of the cloth boom data with the flat plate data shows that the slick geometry is essentially the same for equal speeds and specific volume of oil, and supports the assertion that these cloth booms behaved essentially as flat plates. Figure A-9 compares the long cloth boom to the short cloth boom for a given speed and

TABLE A-1 – INITIAL PROGRAM OF TWO-DIMENSIONAL MODEL TESTS OF PRELIMINARY BOOM CONFIGURATIONS CONDUCTED IN THE HYDRONAUTICS TOWING TANK

Test Number	Model	Wave Condition (Length x Height) (meters x cm)	Wave Condition (Length x Height) (ft x in)	Specific Oil Volume (liters/meter)	Specific Oil Volume (ft^3/ft)	Velocity Range (meters/sec)	Velocity Range (ft/sec)
1 A to E	Fixed, Short, Fabric	Calm	Calm	9.29	0.1	0.15-0.61	0.50-2.00
2 A to E	Boom	↓	↓	46.46	0.5	0.15-0.61	0.50-2.00
3 A to E	↓			18.58	0.2	0.23-0.53	0.75-1.75
4 A to E	Fixed, Flat Plate			18.58	0.2	0.23-0.53	0.75-1.75
5 A to E	Boom			9.29	0.1	0.23-0.53	0.75-1.75
6 A to G	Fixed, Long, Fabric			9.29	0.1	0.23-0.69	0.75-2.25
7 A to E	Boom			18.58	0.2	0.30-0.61	1.00-2.00
8 A to E	Free, Long, Fabric			9.29	0.1	0.23-0.53	0.75-1.75
9 A to D	Boom with Wooden	0.61 x 3.18	2 x 1.25	↓	↓	0.15-0.46	0.50-1.50
10 A to D	Dowel	0.91 x 3.18	3 x 1.25			0.23-0.46	0.75-1.50
11 A to D	↓	1.22 x 3.18	4 x 1.25			0.23-0.53	0.75-1.75
12 A to D		1.83 x 3.18	6 x 1.25			0.23-0.53	0.75-1.75
13 A to D		2.44 x 3.18	8 x 1.25			0.23-0.46	0.75-1.50
14 A to D		0.61 x 6.35	2 x 2.50			0.23-0.38	0.75-1.25
15 A to D		0.91 x 6.35	3 x 2.50			0.23-0.46	0.75-1.50
16 A to D		1.22 x 6.35	4 x 2.50			↓	↓
17 A to D		1.83 x 6.35	6 x 2.50				
18 A to D		2.44 x 6.35	8 x 2.50				
19 A to D		0.61 x 3.18	2 x 1.25	18.58	0.2		
20 A to D		0.91 x 3.18	3 x 1.25	↓	↓		
21 A to D		1.22 x 3.18	4 x 1.25				
22 A to D		1.83 x 3.18	6 x 1.25				
23 A to D		2.44 x 3.18	8 x 1.25				
24 A to D		0.61 x 6.35	2 x 2.50				
25 A to D		0.91 x 6.35	3 x 2.50				
26 A to D		1.22 x 6.35	4 x 2.50				
27 A to D		1.83 x 6.35	6 x 2.50				
28 A to D		2.44 x 6.35	8 x 2.50				
28 E	w/Aluminum Dowel	2.44 x 6.35	8 x 2.5			0.30	1.00
28 F	w/Steel Dowel	2.44 x 6.35	8 x 2.5			0.30	1.00

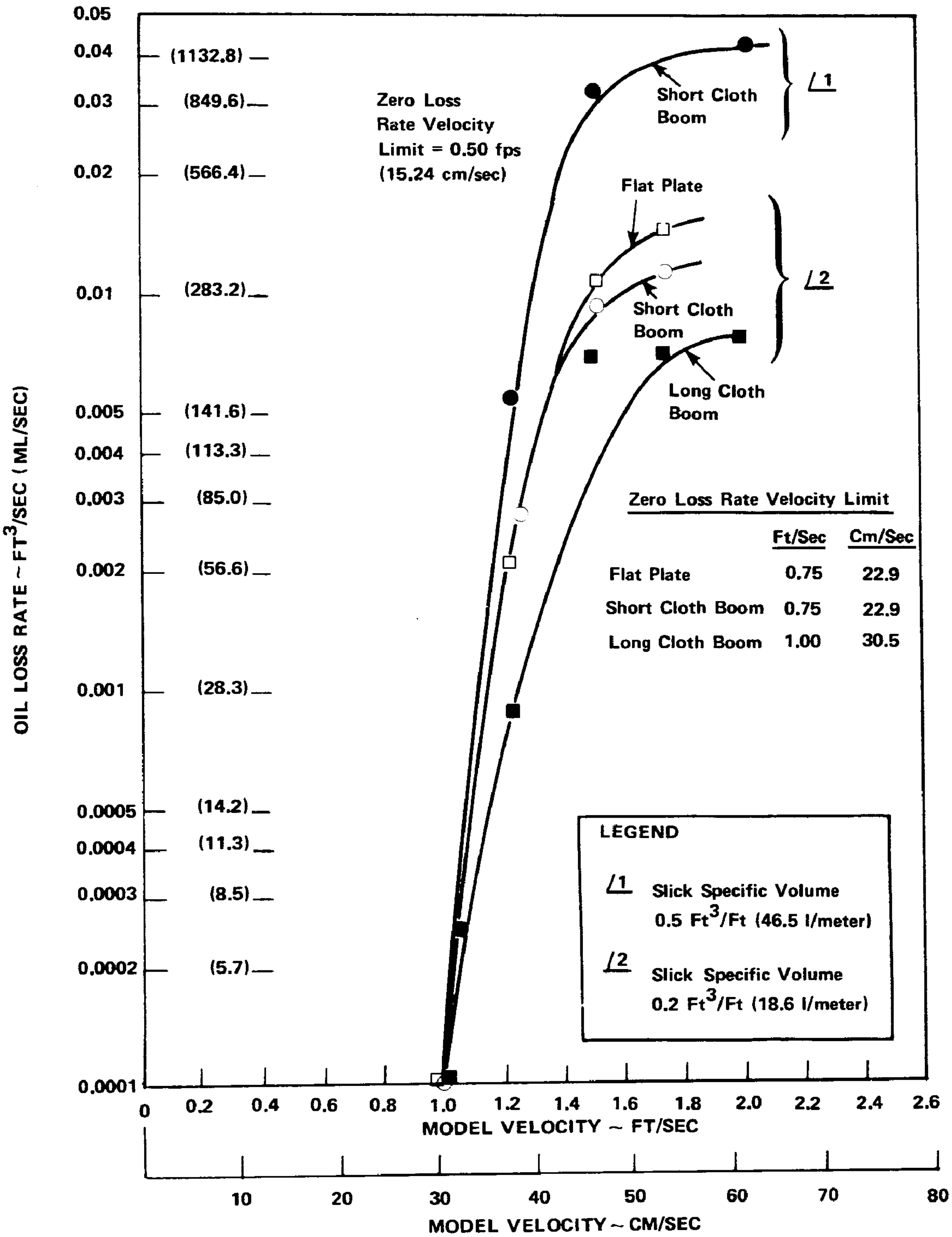


FIGURE A-2 – OIL LOSS RATE AS A FUNCTION OF BOOM VELOCITY IN CALM WATER

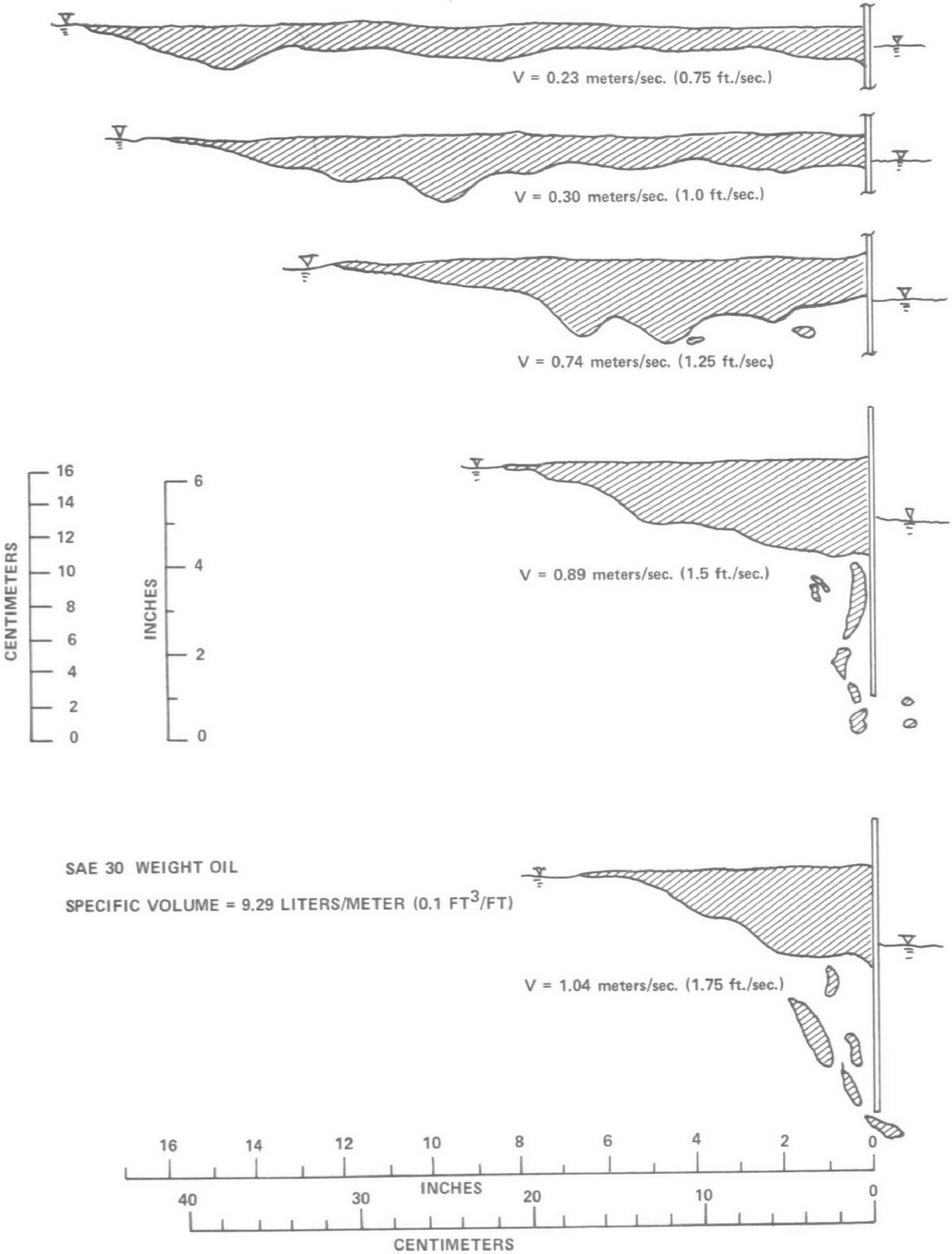


FIGURE A-3 – OIL SLICK CHARACTERISTICS FOR FLAT PLATE BOOM

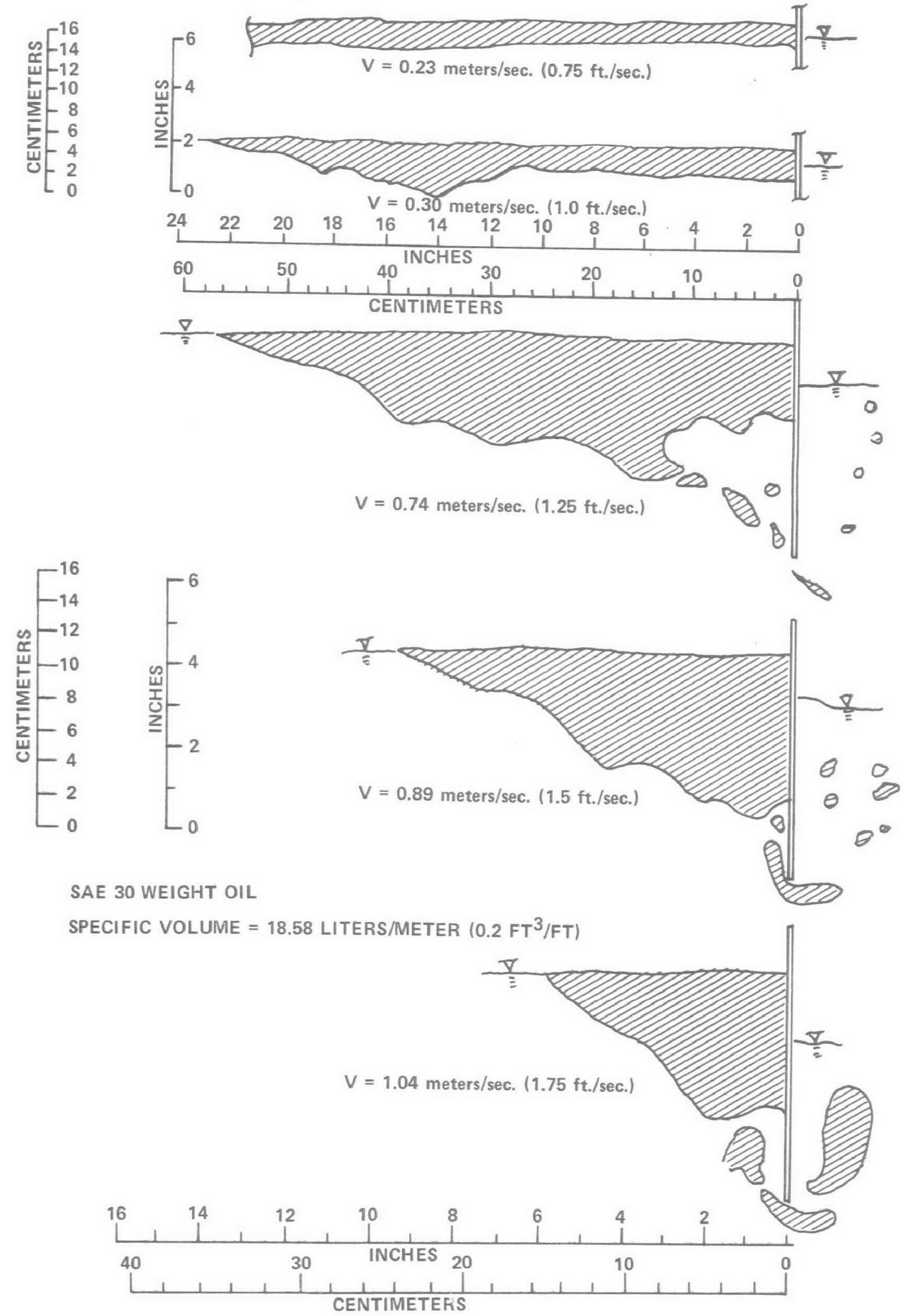


FIGURE A-4 – OIL SLICK CHARACTERISTICS FOR FLAT PLATE BOOM

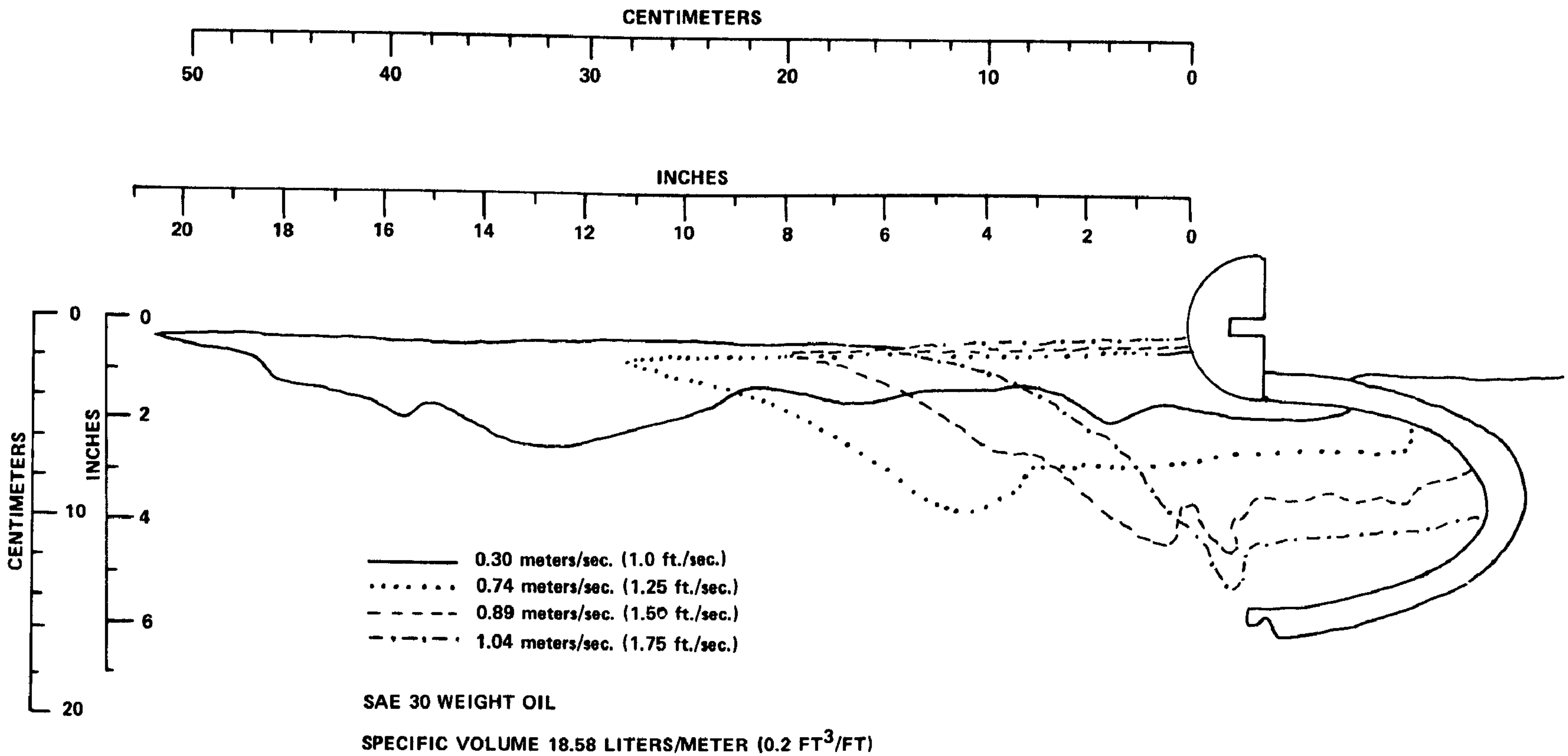
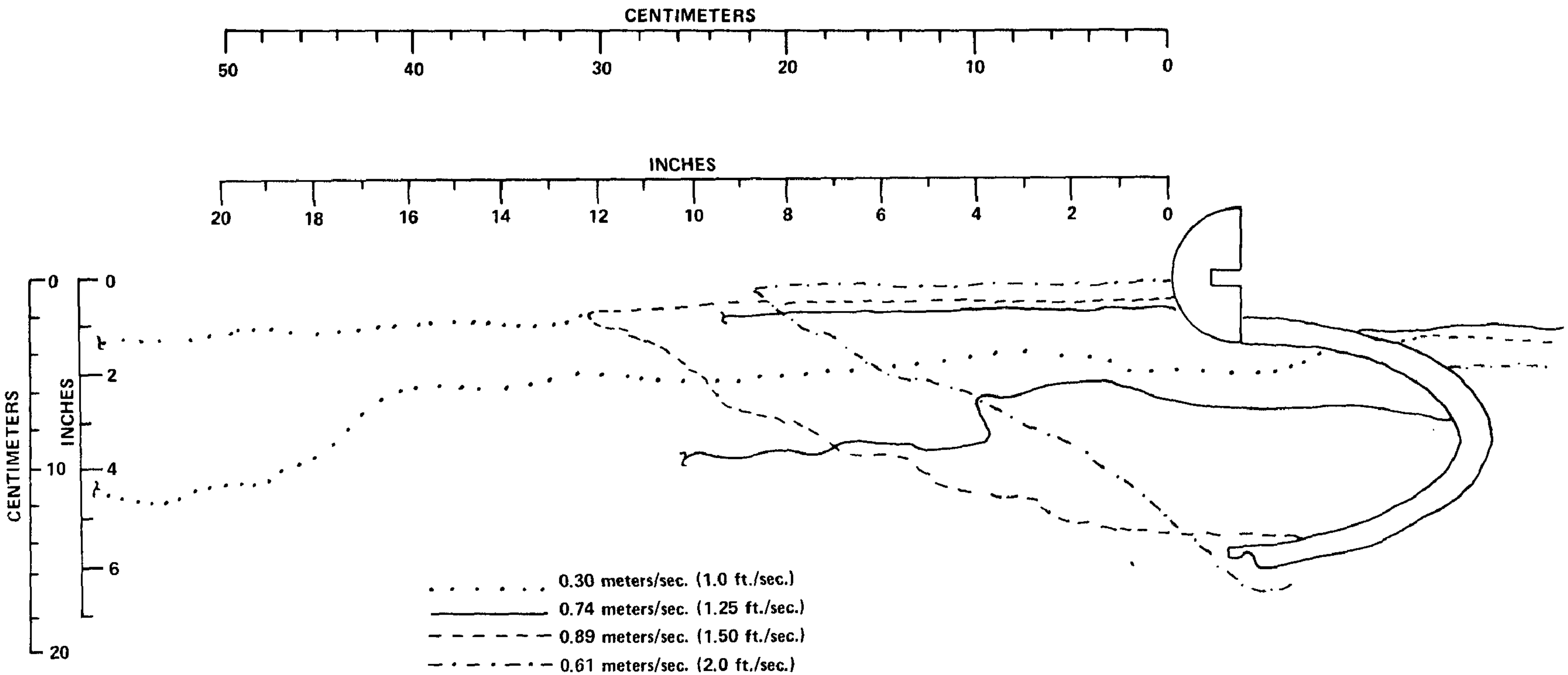


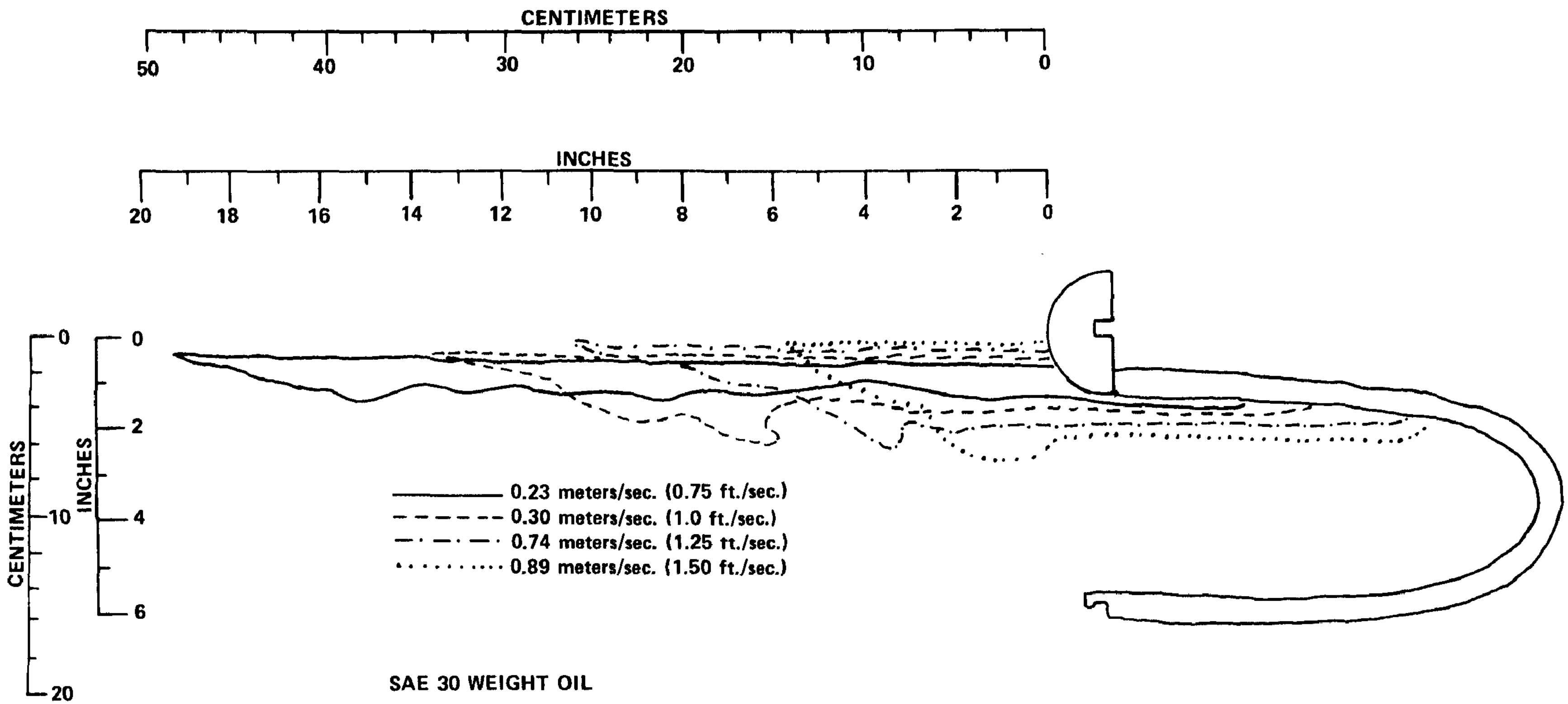
FIGURE A-5 – OIL SLICK CHARACTERISTICS FOR FIXED SHORT FABRIC BOOM



SAE 30 WEIGHT OIL

SPECIFIC VOLUME = 46.46 LITERS/METER (0.5 FT^3/FT)

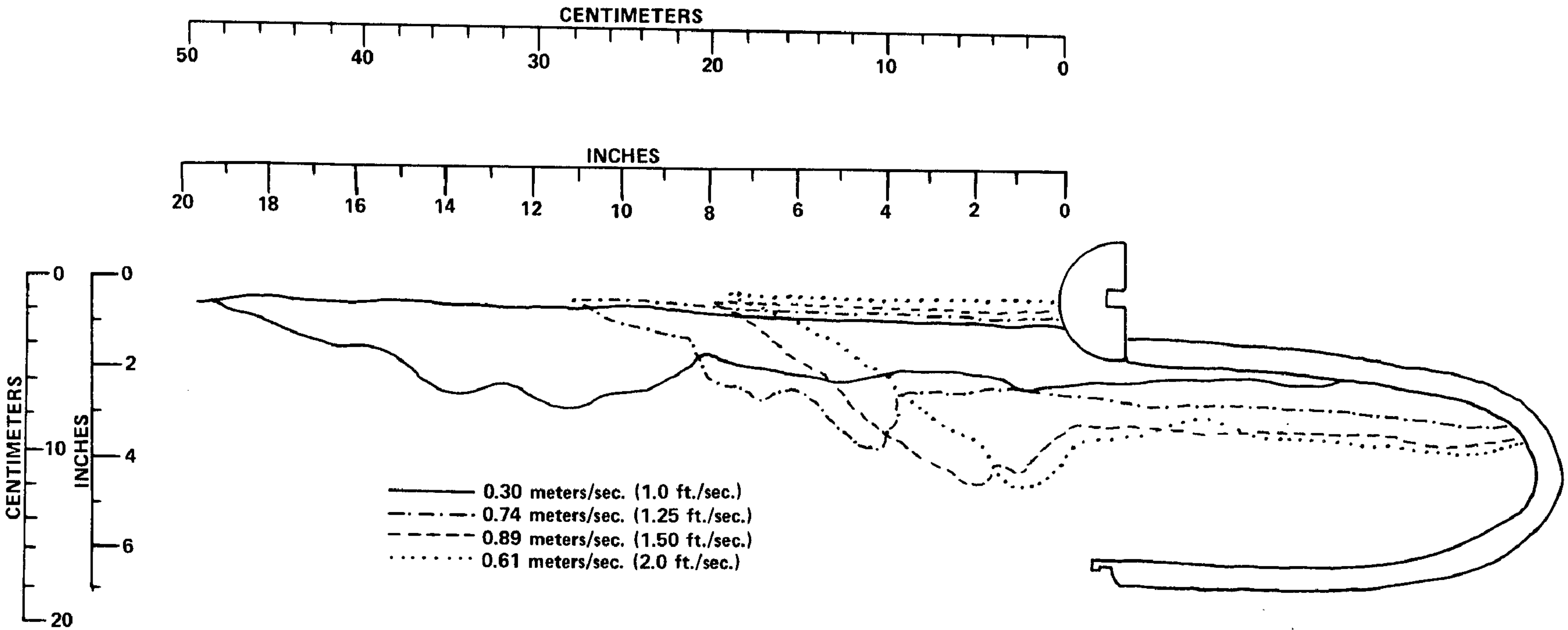
FIGURE A-6 – OIL SLICK CHARACTERISTICS FOR FIXED SHORT FABRIC BOOM



SAE 30 WEIGHT OIL

SPECIFIC VOLUME = 9.29 LITERS/METER (0.1 FT^3/FT)

FIGURE A-7 – OIL SLICK CHARACTERISTICS FOR FIXED LONG FABRIC BOOM



SAE 30 WEIGHT OIL

SPECIFIC VOLUME = 18.58 LITERS/METER (0.2 FT^3/FT)

FIGURE A-8 – OIL SLICK CHARACTERISTICS FOR FIXED LONG FABRIC BOOM

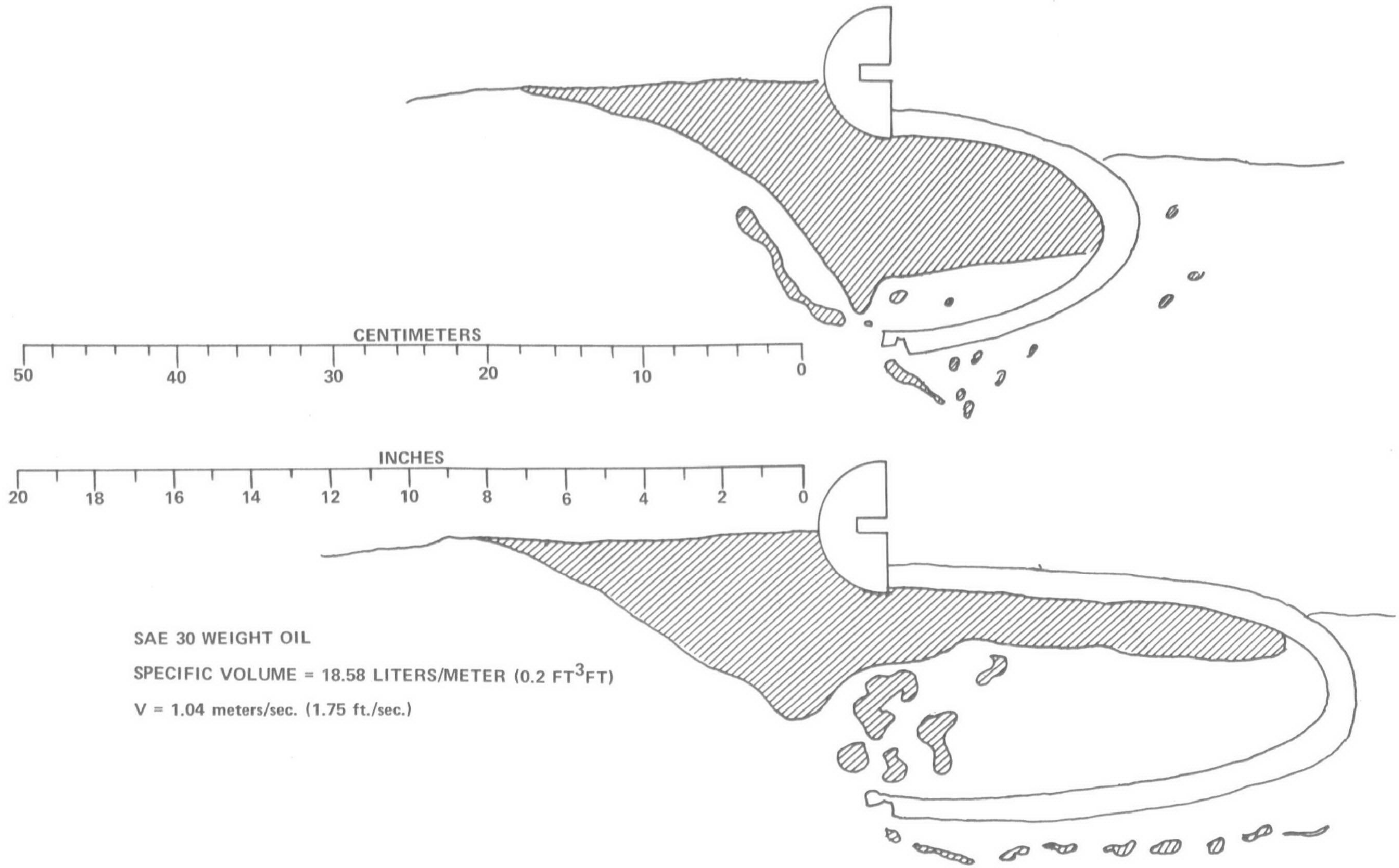


FIGURE A-9 – COMPARISON OF OIL SLICK CHARACTERISTICS FOR FABRIC BOOMS quantity of oil. This figure shows that the configuration of the slick outside of the bag is essentially the same for both bag lengths, and consequently the depth of oil inside the bag increases as the bag length decreases. Even with poor water flow through the bag, the oil slick extends well into the bag. It appears that water flow conditions at the back of the bag prevented the slick from going all to the back of the bag for the long cloth configuration. The analysis of the film data provided insight into behavior of flexible fabric booms, and useful engineering information for the design of an improved system.

Films of the free-to-move boom in waves were studied, but due to the angle of the camera it was not possible to accurately measure the slick geometry.

The flat plate test data is in general agreement with the experimental and analytical results of references (2) and (3). The headwave is generally not smooth. Interfacial instabilities arising from viscous shear forces cause interfacial waves to grow along the headwave, reference (3). This causes inaccuracies in the measurement of the headwave geometry. Comparison of the headwave geometry for the flat plate tests using SAE 30 weight motor oil with the results presented in reference (2) for No. 2 Diesel Fuel shows the effect of viscosity. Increased viscosity apparently causes the headwave to be shorter and thicker. The viscosity of the SAE 30 weight motor oil is of the order of one hundred times that of No. 2 Diesel Fuel.

Understanding Some Observed Flow Phenomena

In some of the free-to-float model tests, the boom was subject to wild oscillatory motions. Subsequent analysis led to a satisfactory explanation of this behavior in both qualitative and mathematical terms. This explanation lies rather in the tank geometry than in a fundamental instability in the design of the boom itself.

Qualitative Discussion

The combination of bag material and the testing geometry produced a sluice-like flow condition. The high velocity and consequently low pressure region under the bag caused the lower edge of the bag to drop closer to the bottom of the tank. This constriction in flow areas, with no compensating head increase (due to the fixed upper edge), produced a net decrease in total flow. The normally stable hydraulic jump downstream of the bag then became an advancing surge wave, filling the low pressure area behind the bag with an onrush of water sufficient to cause back pressure and the restoration of the lower bag lip to its previous position.

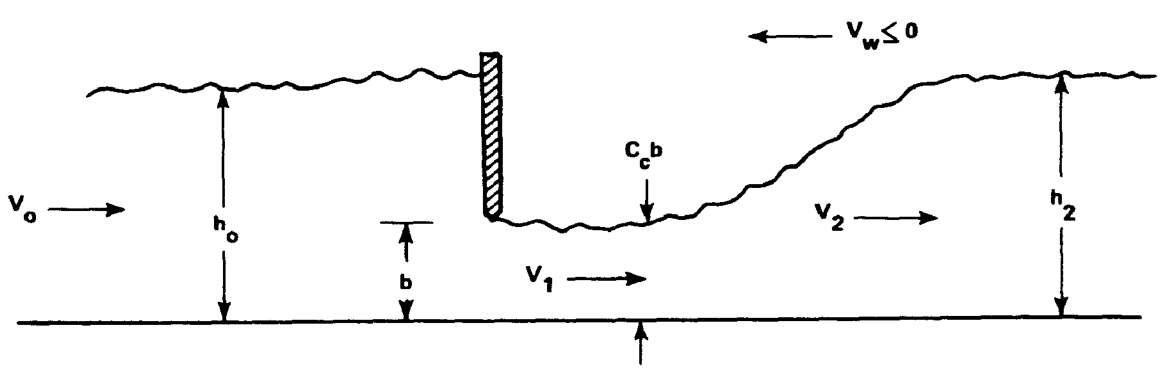
This cyclical behavior could have been prevented by either limiting the lower free edge to less than one-half the tank depth (limiting the sluice effect) or fixing the relative distance between the bottom and top edges and freeing the whole assembly. The latter would have been self-compensating and consequently stable, i.e., an initial decrease in flow would have increased the upstream depth, lifting the entire boom and reopening the flow area.

The extension of the instability analysis to further testing was based on the sluice/hydraulic jump phenomenon. The Froude number for flow beneath the bag characterizes the form of the hydraulic jump behind the bag. Under general flow conditions, the Froude number is a direct function of the ratio of water depth below the bag to the total water depth and is independent of velocity. In very deep water the Froude number approaches 1.0 for a free-floating boom, inducing a very smooth standing wave behind the boom. (With a Froude number of between 3 and 6, the standing wave is called a "smooth prejump", converting to wild oscillation between 6 and 20, as observed in the Hydronautics tests.) To maintain this same characteristic condition in a shallow tank, the Froude number must be restricted to less than 3. This can be readily done by keeping the depth below the bag somewhat greater than one-half the total water depth.

Analysis of Instability

Assuming that the booms tested in the Hydronautics tank were relatively impenetrable to water flow, their behavior moving in the tank is analogous to that of water flow past a fixed sluice.

The assumed condition is illustrated below:



Under steady flow conditions

$$V_o h_o = V_1 C_c b = V_2 h_2 \qquad (1)$$

where $C_c b$ is the sluice contraction coefficient and

$$C_c = f\left({}^{b}/h_o\right)$$

From continuity considerations

$$V_1 = \sqrt{2gh_o} \;/\; \sqrt{1 + C_c b/h_o} \qquad \text{(2) for the sluice}$$

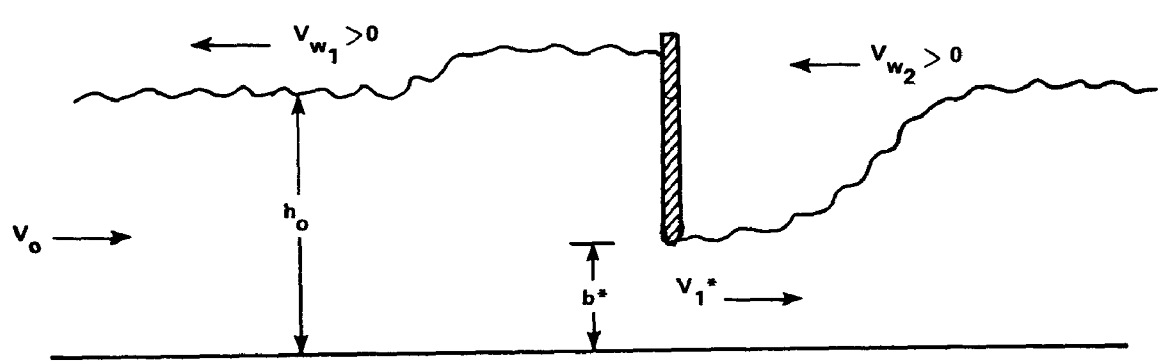
$$V_1 + V_w = \sqrt{gC_c b} \cdot \sqrt{\tfrac{1}{2}\left(1 + C_c b/h_2\right)} \qquad \text{(3) for the hydraulic jump}$$

where $V_w = 0$ for a standing wave

$V_w < 0$ for a receding surge wave

Since the bag was not in fact a flat plate, the venturi effect produced by the high velocity, V_1, underneath the bag and the more or less stagnant region in the bag combine to push down the lower edge, reducing the dimension b.

The resulting constriction in flow creates the unsteady condition shown below:



Although the increase in head due to water storage increases the flow velocity ($V_1^* > V_1$), the total flow decreases due to the reduction in flow area. Since the boom top is fixed and lower edge unrestricted, there is no compensating lift of the entire boom to restore steady flow conditions.

The surge wave, V_{w_2}, advances into the boom, drowning the sluice and restoring the static pressure balance for a repeat of the cycle. At high velocities, the advancing surge wave is not a smooth jump, but a wild oscillating wave. Under these circumstances the surge is violent enough to propagate forward of the boom, resulting in the phenomenon referred to as "galloping" when seen in the test films.

Numerical spot checks, based on observed velocities and boom configurations and using the equations given, provide the basis for the narrative description given above.

Extension of Analysis for Test Design

Under deep water conditions

$$\frac{C_c b}{h_o} \simeq 1$$

and the tail wave will be a smooth standing wave.

The tail wave, or hydraulic jump, is known to be a function of the Froude number of the flow, V_1. By definition, a standing wave occurs when $V_w = 0$. Therefore, using equation (3) and defining the Froude number, F_1, as

$$F_1 = \frac{V_1^2}{gC_c b} = 2gh_o/gC_c b\left(1 + C_c\frac{b}{h_o}\right)$$

$$F_1 = \frac{2}{\frac{C_c b}{h_o}\left(1 + \frac{C_c b}{h_o}\right)} \qquad (4)$$

For a deep water condition the tail wave is a standing wave, corresponding to a Froude number of near 1. This same characteristic tail wave is retained up to a Froude number 3, changes to a "smooth prejump" until $F_1 = 6$, becomes wildly oscillatory for F_1 between 6 and 20, and becomes a well-formed hydraulic jump for F_1 greater than 20, reference (11). In order to simulate the deep water conditions in a shallow tank, the Froude number should be kept below 3. Solving (4) iteratively we find $C_c b/h_o \geq 0.457$. Since the analysis is based on a sharp-edged sluice gate, we can assume that in our case $C_c = 1$ and require that $b/h_o \geq 0.5$ as a design constraint consistent with observed tests.

APPENDIX B

OIL CHARACTERISTICS

The quantity of oil to be retained by a boom may be specified in terms of the specific volume, or the volume of oil contained per unit length of boom. The full-scale tests of reference (12) involved a calculated average specific volume of .316 meters^3/meter (3.4 ft^3/ft); and based on the shape of the boom and the oil slick under towing conditions, the peak value could have been as high as .929 meters^3/meter (10 ft^3/ft).

The constant volume method is better suited for tank testing than the continuous slick method, and a scaled volume of oil corresponding to a full-scale specific volume of .929 meters^3/meter (10 ft^3/ft) is considered to be a reasonable design goal.

A literature search has revealed that the fluid properties of the oil can have a significant influence on the dynamic behavior of the oil slick and the ability of a boom to retain oil. Specific gravity, viscosity and interfacial tension (between oil and water) vary for different oils. A list of some of the oils that have been used in previous testing is given below:

Test Oil	Reference
No. 2 Diesel Fuel	(2, 3, 7, 9, 13)
No. 4 Fuel Oil	(13)
No. 5 Diesel Fuel	(9)
No. 6 Fuel Oil	(9)
SAE 30	(3)
Industrial Lubricating Oils	(3, 13)
Soybean Oil	(12)
Crude Oils	(9, 14)

Properties of various test oils are provided in Table B-1. Specific gravities and interfacial tensions do not appear to vary over a wide range, whereas viscosities do. Studies reported in reference (3) indicate that viscosity has an effect on the headwave. Comparisons between No. 2 Diesel Fuel and SAE 30 motor oil show that increased viscosity apparently causes the headwave to have greater thickness at a given speed.

The velocity of the current at which oil droplets are torn off the headwave is dependent on the interfacial tension between the oil phase and the water phase, and is characterized by a critical Weber Number,

TABLE B-1 – PROPERTIES OF VARIOUS TEST OILS

Type of Oil	Kinematic Viscosity (centi-stoke)	Viscosity (Saybolt Universal Seconds-at 40°F)	Absolute Viscosity (centi-poise)	Specific Gravity	Surface Tension of Oil (dynes/cm)	Interfacial Tension Oil/distilled water (dynes/cm)	Interfacial Tension Oil/sea water (dynes/cm)	Source
No. 2 Diesel Fuel	4.3			0.860	28[2]		27[2]	Ref.(3)
No. 2 Fuel Oil	6.45	47	5.6	.868	26.8		20.6	Ref.(2)
(ESSO) Faxom 35	19			.883				Ref.(3)
(ESSO) Faxom 50	100			.900				Ref.(3)
No. 4 Fuel Oil	113.2	525	99.6	.880	28.1		27.3	Ref.(2)
(Humble) Nuso 38	118			.954				Ref.(3)
Soybean Oil	120.8	560	111.5	.923	31.4		23.6	Ref.(2)
SAE 30	380			0.906	33.5[3]	42.5[3]		Ref.(3)
Kuwait Crude					28		22	Ref.(6)
Intermediate Sweet Crude			4.6	.821	24	31	18[1]	Ref.(9)
Mercy Crude			30	.812	27	29	10[1]	Ref.(9)
Shallow Yates Crude			61	.910	28	31	14[1]	Ref.(9)
Fullerton Crude		45.8		.81	24.9		18.7	Ref.(14)
Tia Juana		297		.89	20.9		34.3	Ref.(14)
Urania		2591		.92	31.5		17.5	Ref.(14)
Safaniya		270		.87	27.3		30.1	Ref.(14)

(1) Synthetic Sea Water
(2) Reference (9)
(3) SEARS ALLSTATE regular motor oil SAE 30 (additive-free)

reference (15). In order to simulate oil entrainment in the small-scale demonstration model, the interfacial tension coefficient would have to be Weber-scaled if the model velocities are to be Froude-scaled. Simultaneous Weber and Froude scaling is achieved if the ratio $(\text{Velocity})^4/(\text{interfacial tension})$ is maintained constant. Surface active agents are available for reducing the interfacial tension of the oil. The effect, if any, that such additives to the oil would have on the hydrophylic properties of the boom fabric, must be explored.

No. 2 Diesel Fuel and SAE 30 weight motor oil were used in preliminary developmental tests and in tests to demonstrate the performance of the fabric boom system. Since the viscosity of these two oils varies by an order of magnitude of 100, and since they encompass the range of densities most likely to be encountered in actual cases, they represent realistic conditions for preliminary evaluation. In more advanced exploration, other oils should also be considered.

SELECTED WATER RESOURCES ABSTRACTS

INPUT TRANSACTION FORM

1. Report No.	
2.	
3. Accession No.	W
4. Title	FABRIC BOOM CONCEPT FOR CONTAINMENT AND COLLECTION OF FLOATING OIL
5. Report Date	
6.	
8. Performing Organization Report No.	
7. Author(s)	Bonz, Philip E.
9. Organization	Consultec, Inc. Rockville, Maryland
10. Project No.	15080 FWM
11. Contract/Grant No.	68-01-0139
13. Type of Report and Period Covered	
12. Sponsoring Organization	
15. Supplementary Notes	U.S. Environmental Protection Agency Report No. EPA-670/2-73-069, September 1973.

16. Abstract

The feasibility of applying the concept of oil-water separation by means of woven hydrophilic fabric to a floating oil containment boom was investigated through a series of model tests. A preliminary model boom configuration was developed and towed at speeds to 0.686 meters/sec (2.25 ft/sec) in both calm water and waves. Oil retention performance of this model was clearly superior to that of a conventional flat plate boom of comparable draft in the environment investigated. A larger model of similar configuration demonstrated no oil leakage when towed at 0.77 meter/sec (1.5 kt) in calm water.

While further detailed analysis, engineering, and testing is required to fully examine this concept, it appears that a properly designed flexible boom which uses a hydrophilic skirt material offers significant potential both as a containment device for floating oil in high current situations and as a high-speed collecting device.

17a. Descriptors

*Water Pollution Control, *Oil Spills, *Flow Separation, *Running Waters, *Fabric, Feasibility Study, Oil, Oil-Water Interfaces, Oil Pollution, Separation Techniques, High Flow

17b. Identifiers

*Floating Oil, *Oil Containment, *Oil Collection, *Oil Boom, Hydrophilic Fabric

17c. COWRR Field & Group 05F

18. Availability	19. Security Class. (Report)	21. No. of Pages	Send To:
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