PERFORMANCE TESTING OF OIL SPILL CONTAINMENT BOOMS

A Thesis

Presented to

the faculty of the Department of Civil Engineering

The University of Houston

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science in Civil Engineering

---

by

William A. Callegari

September, 1972

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This thesis was typed by Mrs. Barbara Wickline, who deserves special acknowledgement for an excellent job done under difficult conditions.

DEDICATION

This thesis is dedicated to my children, Butch, Robby, Cherry, and Chip, and especially to my wife, Ann, whose patience and assistance during the preparation of this manuscript and throughout this graduate program made its completion possible.

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ABSTRACT

This thesis consists of a comprehensive study of oil spill containment boom performance. It includes results of full scale tests under controlled current, towing, and wave conditions in the laboratory; towing and wave tests in an offshore environment; and evaluations of boom performance in actual oil spill service.

The text begins with an introduction into the basic oil spill problem, followed by a description of basic containment boom parameters, types of booms, and general usage. The containment booms are classified into three types; rigid, semi-flexible, and flexible, and the characteristics of each type are discussed. Next the test facilities are described and the procedures used in the testing program are reviewed. A detailed analysis of the test data and discussion of the test results follows. The results of tests on the three basic types of containment booms are analyzed, and the performance of each under varying conditions is discussed. Failure mechanisms are described and actual failure points in current, towing, and wave action are given. The last chapter reviews the generalized results of the tests, summarizes the limitations of each of the three types of booms, and discusses alternative methods of improving boom performance.

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CHAPTER I

INTRODUCTION

General

In this current age of ecological consciousness one of the most important challenges faced by engineers and the engineering sciences is the "fight against pollution". Of particular concern is potential damage to the environment due to oil spills in our rivers, harbors and oceans. As the need for petroleum and chemical products continues to increase, so does the need for controlling these undersirable effects of our industrial progress.

Oil pollution is not new. As long as records have been kept, natural oil seepages have been noted in lakes, rivers, and oceans. When the first commercial oil drilling operations were begun, "man-made" oil spills, resulting from a combination of insufficient knowledge and ineffective equipment, were originated. For many years these spills received little or no attention and were rapidly forgotten. However, in recent years man has become more conscious of his environment and has made concerted efforts to clean up the waters of the world. Notably, such disasters as the Torey Canyon in 1968, the Santa Barbara spill in 1969, and more recent spills in the Gulf of Mexico have focused attention upon the problems encountered in controlling and cleaning up oil spills. These spills have certainly pointed out the need and desire for development of efficient oil pollution control equipment and systems.

In recent years, numerous concepts have been developed for the containment, control, and recovery of oil spills. These include containment devices such as booms or air barriers; skimmers which mechanically remove oil from the water surface; sorbents which absorb the oil from the water; chemicals which react with the oil and water and speed up the normal degradation processes; and sinking agents such as sand which physically sink the oil to the bottom. The success or failure of these methods or devices is dependent upon environmental conditions, such as wind, waves, and currents, the type and volume of oil spilled, and man-made obstacles.

In this thesis attention is focused upon the problem of containing and controlling oil spills with mechanical containment booms so that efficient clean-up operations can be conducted. The basic characteristics of oil spill containment booms are described, and the results of performance tests on containment booms in varying environmental conditions are discussed. The booms are grouped in three major types according to degree of flexibility, and the advantages and limitations of each type are summarized. The performance of each of the three types of booms in current, towing, and wave service is analyzed, and several methods or designs for improving performance are proposed.

Previous Literature

Numerous reports about oil spill containment and control equipment have been presented by governmental agencies, universities, and private industry. However, the majority of these reports and papers are focused upon generalized oil spill control problems and do not deal specifically with containment booms. Reports of tests on commercially available booms are almost non-existent. Those articles which are directed towards containment booms consist primarily of mathematical analyses of boom response in current or wave action, or discussions of the basic parameters involved in oil spill containment, with little or no supporting test data. Many papers present discussions of the basic problems involved in controlling oil spills and discuss alternative methods of containing and removing spills, such as chemicals, sinking agents, sorbents, booms, and skimmers, but no actual performance data is available. Still others describe equipment and methods used in previous spills, such as the Torey Canyon and Santa Barbara spills, but again very little performance data is given. These reports generally comment on equipment which didn't work and give no specific failure points or other performance data. Those articles which do relate or contribute directly to the subject matter of this thesis are included in the Bibliography, either by way of footnotes in the text or as supplementary references.

CHAPTER II

GENERAL CONSIDERATIONS AND PARAMETRIC DESCRIPTIONS

General

In order to effectively control an oil spill it is necessary to prevent spreading of the oil. The most common method of preventing this spreading is by use of oil spill containment booms. Floating booms are generally used for the control of oil spills by holding or accumulating the oil in small areas so as to facilitate clean-up by skimmers, sorbents, or other methods.

There are generally two types of containment booms: air barriers and mechanical booms. Mechanical booms are generally more desirable, as they offer greater flexibility in use and effectiveness. Air barriers are expensive, difficult to operate and maintain, and are only effective in containing oil in calm water (no waves or current activity).

Floating booms can be used on confine oil within a specific area for skimming or other clean-up, to prevent spreading or passage of oil into critical areas, or for diverting an oil slick to or from a specific location. Experience indicates that booms are effective in still water and that performance deteriorates rapidly as water activity increases. Failure by current action occurs by passage of oil under the skirt, and the failure rate increases rapidly as the magnitude of the current increases. Failure in waves may be due to splashing of oil over the top or freeboard section of the boom or by complete "swamping" or tipping of the boom due to the forces exerted by the waves. In both wave and current action, structural integrity of the boom is important; however, loss of oil due to hydrodynamic failure or mechanical instability usually occurs before structural failure is evident.

Wind effects on boom performance are generally ignored, as experience has shown that mechanical booms are not susceptible to wind damage, unless high winds cause a "sail" effect and result in flattening of the boom. In some cases this effect coupled with vigorous wave action, can cause catastropic failure (complete swamping and loss of oil). However, high winds which are detrimental to boom performance are generally accompanied by significant wave activity and the wave effects greatly overshadow the wind damage.

Boom Components

Mechanical floating booms are rather characteristic in design: A typical boom, shown in Figure 1, consists of a buoyant section for flotation; a freeboard section, usually integral with the buoyant member, which extends above the surface of the water and prevents spillage of oil over the boom; a skirt which projects below the surface of the water so as to prevent leakage of oil under the boom; and rods, chains or weights at the bottom of the skirt for ballast. A longitudinal strength member consisting of chain or cable is attached at various points along the boom for structural integrity. Booms are normally manufactured in hinged sections which allow flexibility and conformance with wave action.

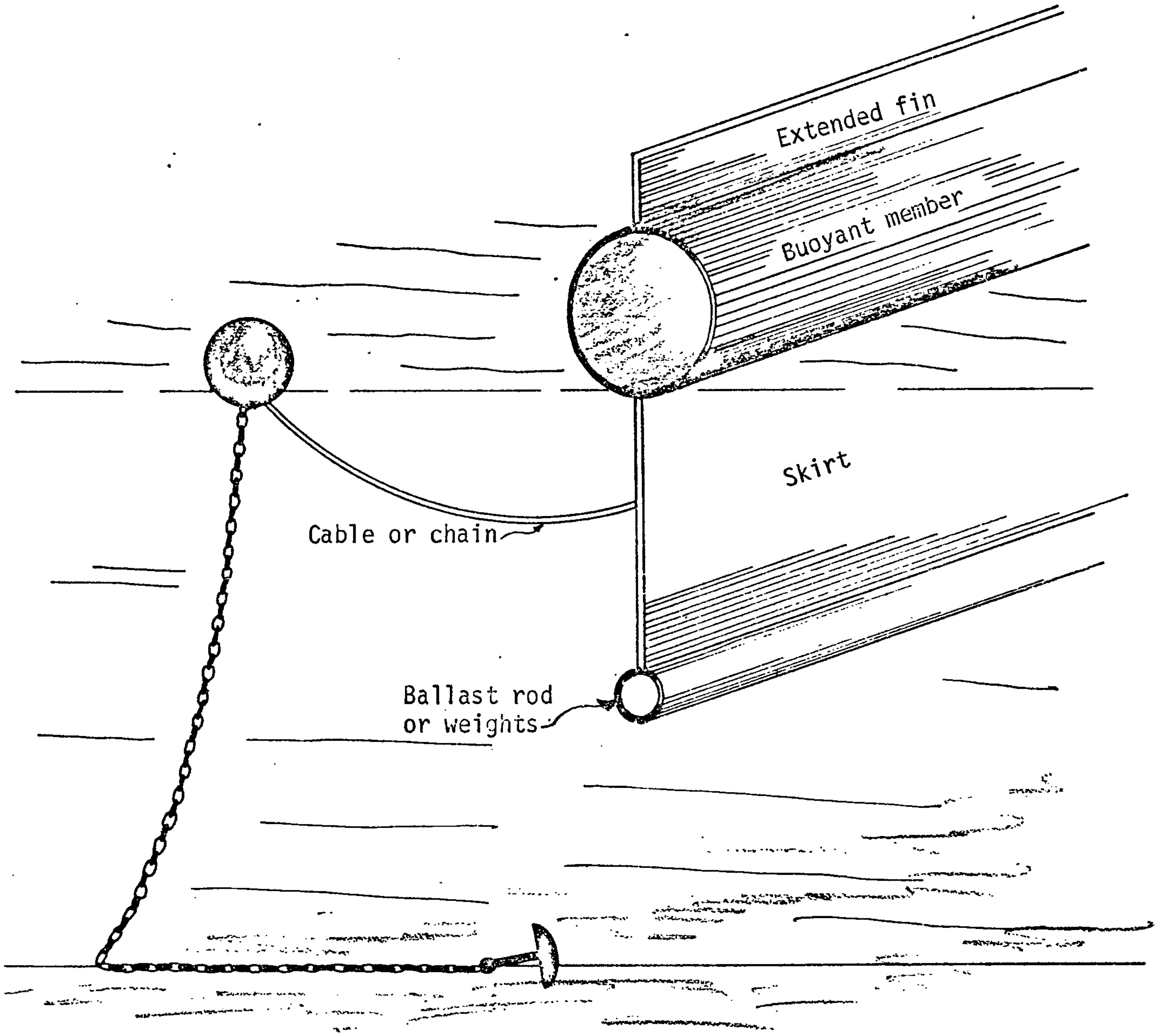


Figure 1 - TYPICAL OIL SPILL CONTAINMENT BOOM

Buoyancy of spill booms is normally provided by solid foam cylinders or by air or foam filled tubes constructed from vinyl or plastic materials. Tube diameters range from 4 to 12 inches for inshore booms and up to 36 inches or more for offshore booms. The amount of net positive buoyancy of the boom section determines the height of barrier above the water surface. In some designs a fin is added above the buoyant section to provide greater freeboard height and protection against oil spillage over the top of the boom. In other designs foam or metal floats ranging from 3 inches to 3 feet in diameter are attached at regular intervals along the length of the boom to provide buoyancy.

The skirt projects from 6" to 30" below the surface of the water, and is normally constructed of flexible vinyl-fabric or semi-flexible plastic material. However, some booms have been constructed of metal, wood, or rigid elastomer skirts, with flexible connectors at regular intervals along the skirt to facilitate conformance to the wave action.

Tensile strength is normally provided by chains, steel cables, or ropes ranging from 3/16" to 3/4" in diameter which run along the length of boom. These longitudinal members are generally attached via gromets or pockets at the lower edge of the skirt, but in some cases may be located at the middle of the boom section, slightly below the flotation member. In addition the buoyant section may provide tensile strength of up to 300 lbs. per inch of width and the skirt material may provide longitudinal strength up to 50 lbs. per inch of width.

In order to maintain the boom in a vertical position, the skirt or fin is ballasted by lead weights riveted to the bottom of the skirt, chain connected to the bottom of the skirt at evenly spaced intervals, or weighted rods sewn into pockets on the skirt bottom.

Boom sections generally range from 3 to 100 feet in length and are connected by steel or plastic plates, interlocking and overlapping snaps, or rope lashing. Although in most cases flexibility is provided within each section, the connections may provide additional flexibility, allowing the boom to conform to the wave action rather than cresting between successive waves.

Connections are normally provided at each end of the boom and at each joint for anchoring or stabilizing the boom. It is usually necessary to anchor the boom to prevent drifting or to hold it in a desired configuration or location. For stationary or semi-permanent service the ends of the boom are connected to boats, buoys or other structures, and intermediate anchor points are provided at 50 to 100 foot intervals as required.

<u>Boom Classification</u>

Although there are numerous designs of booms available today, they can be grouped into three general types based upon construction; rigid, semi-flexible, and flexible. Following are detailed descriptions of these three types of booms:

<u>Rigid Booms</u> - This boom, as the name implys, is built for structural stability, having been designed to withstand high

hydrodynamic forces without yielding. As shown in Figure 2, it is constructed of rigid materials, with metal, wood, or rigid elastomer skirts interconnected at 50 to 100 foot intervals to form a continuous barrier. Buoyancy is provided by formed metal cylinders or solid foam floats which are solidly connected to the skirt and extend along the full length of the boom on both sides of the skirt. The flotation members provide buoyancy only and do not contribute substantially to the structural integrity of the boom. The freeboard section normally extends 4" to 12" above the buoyant members. Because of its rigidity, this type of boom is highly susceptible to splashover in waves, due to its inability to absorb the energy exerted by the waves. Instead, the wave forces are dissipated by breaking up into smaller particles which splash over the boom, much the same as witnessed when waves contact a breakwater along a shoreline. The rigid booms are generally heavy and bulky, and therefore are very difficult to deploy. Accordingly, they are normally selected for use in permanent service where frequent redeployment is not required. Approximate cost is $10-$25/ft.

Semi-Flexible Booms - As shown in Figure 3, the semi-flexible boom consists of a flexible plastic or fabric-reinforced vinyl skirt with a single continuous flotation section which is an integral part of the skirt. The flotation member is made up of solid foam, beaded foam or air filled tubes, and is normally encased in or rigidly attached to the skirt material. Since the flotation member also serves as the freeboard section, the effective height

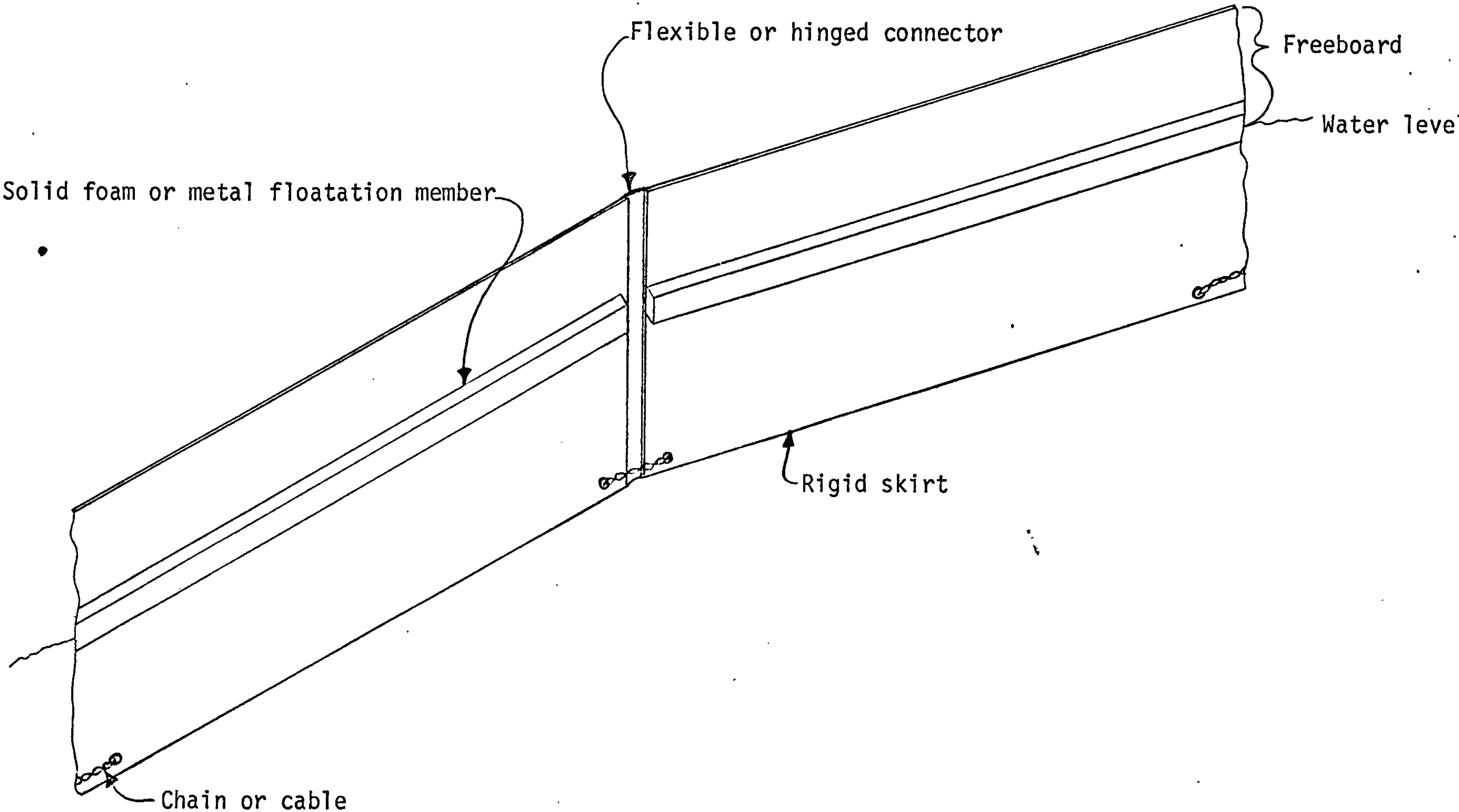


Figure 2 - RIGID BOOM

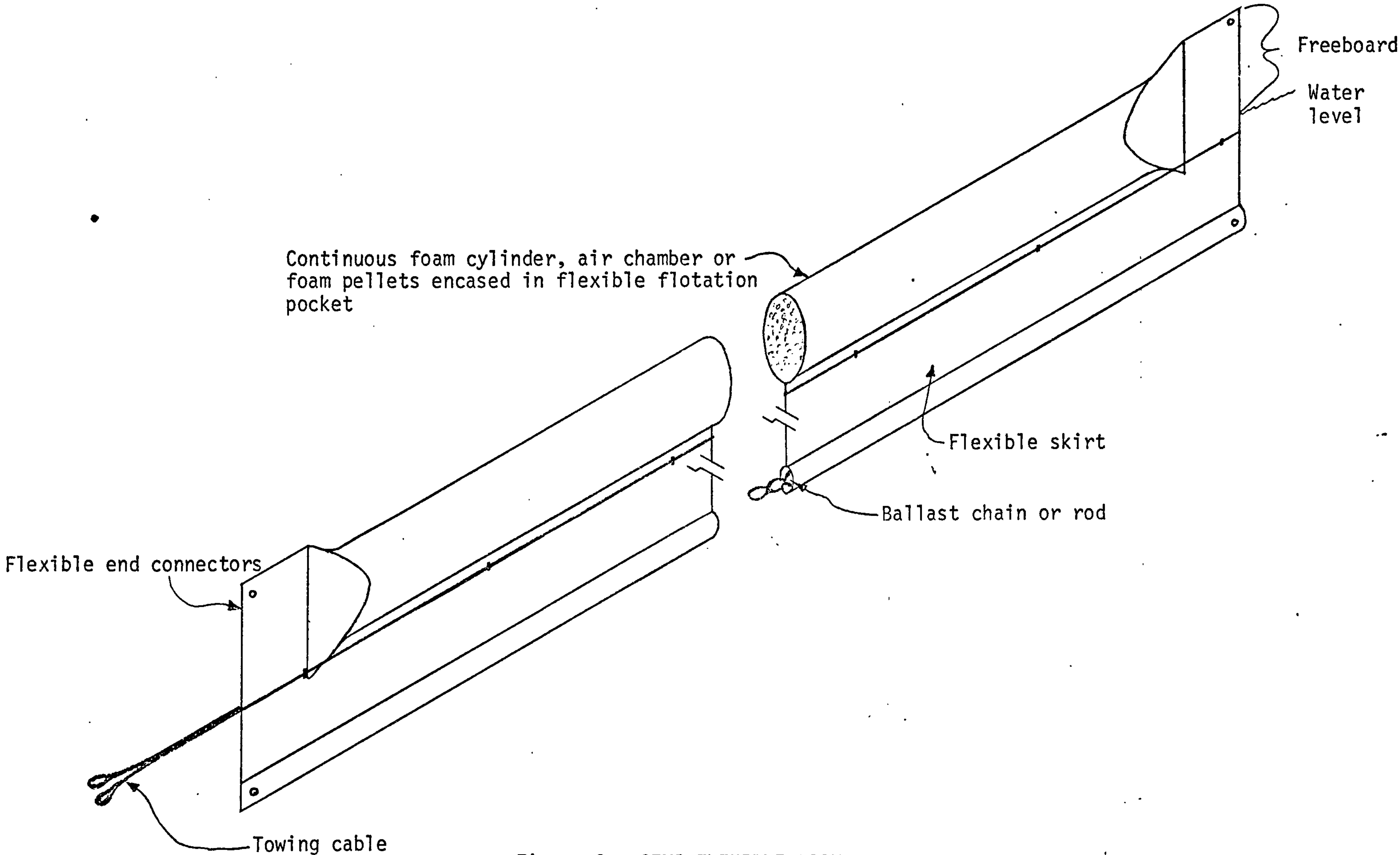


Figure 3 - SEMI-FLEXIBLE BOOM

of the boom is a direct function of the float diameter and buoyancy. The flexibility of this boom is derived from the flexible skirt, while the flotation member imparts a degree of rigidity to the design. It is generally made up in 50 to 100 foot lengths with flexible or hinged connections between sections. This type of boom is very compact and is easy to store and deploy. Because of its favorable handleability characteristics, it is desirable for use in small spill service in harbors, rivers, lakes, or where rapid deployment from a small boat is necessary. This design is generally favored for towing or current service, as the combination of flexible skirt and continuous semi-rigid flotation member appear to offer a stable configuration. The majority of the containment booms which have been marketed to date fall into the semi-flexible category. This is probably due to the fact that this design is readily conceived as a practical solution to the containment problem, and/or because this configuration generally offers more simplified and economic methods of fabrication. Price range is $5-$25/ft.

Flexible Booms - This type of boom, shown in Figure 4, is characterized by lightweight design and a high degree of flexibility at all points along the boom. The skirt is constructed of continuous vinyl-fabric or other pliable material, and short individual floats are attached at two to four foot intervals along the length of the skirt to provide buoyancy. The buoyancy members are generally hard foam cylinders or metal cans ranging from 4" to 12" in length and 3" to 6" in diameter. Each float is attached to the skirt by a

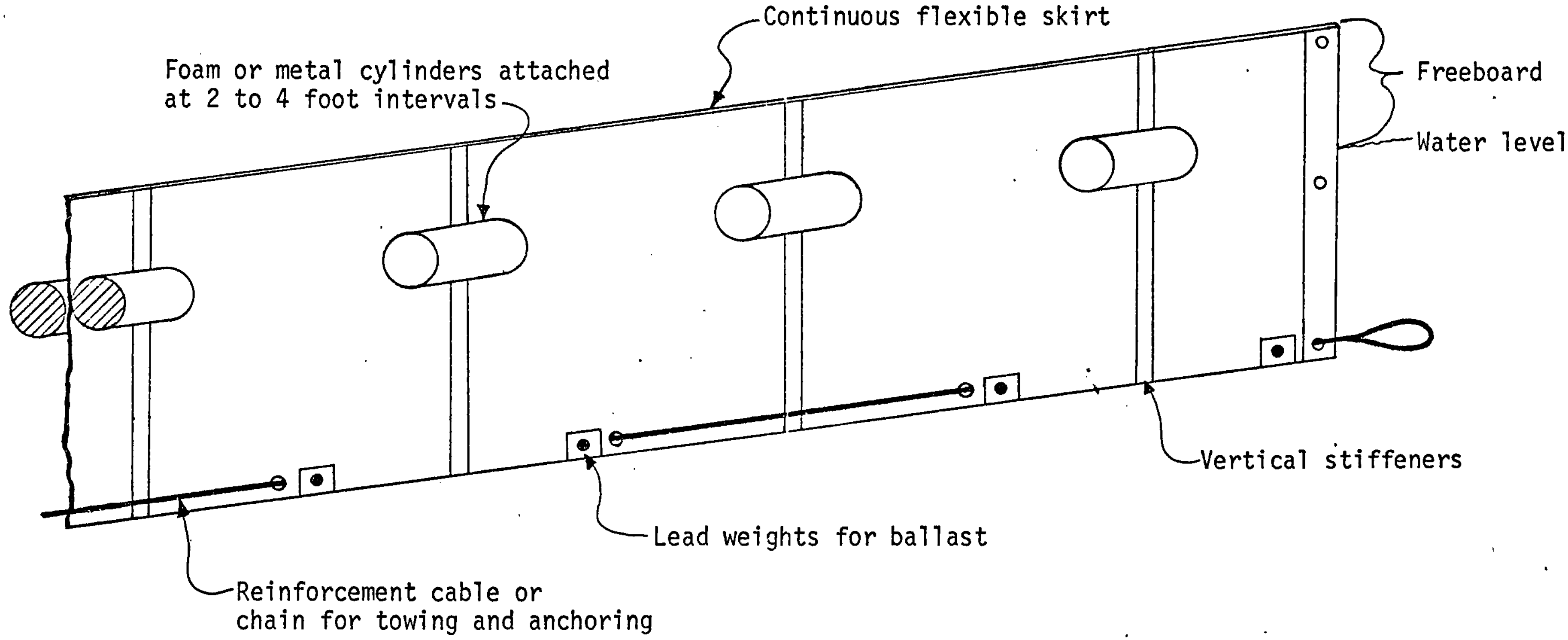


Figure 4 - FLEXIBLE BOOM

single point connection, so as to allow freedom of motion while still providing excellent buoyancy. The buoyant members are located on both sides of the skirt giving a pontoon effect and providing for increased stability. The flexible design allows the boom to conform readily to wave action and to absorb the wave energy rather than resist the waves. This has a damping effect on the waves, reducing the tendency of the wave and accompanying oil to splash over the top of the toom. In some instances, however, this flexibility may offer a disadvantage, as large waves can more easily "swamp" the light, flexible boom, and may result in catastrophic failure in severe offshore conditions. A particular advantage of this boom lies in its ease of handling and deployment. It is not as heavy as the other two types and is relatively easy to deploy from a boat, giving it a distinct advantage in offshore service. The floats can be easily removed to facilitate storage; however, in this case deployment becomes more difficult, since the floats must be reattached before the boom can be used. The cost of this type of boom is \$8-\$15/ft.

CHAPTER III

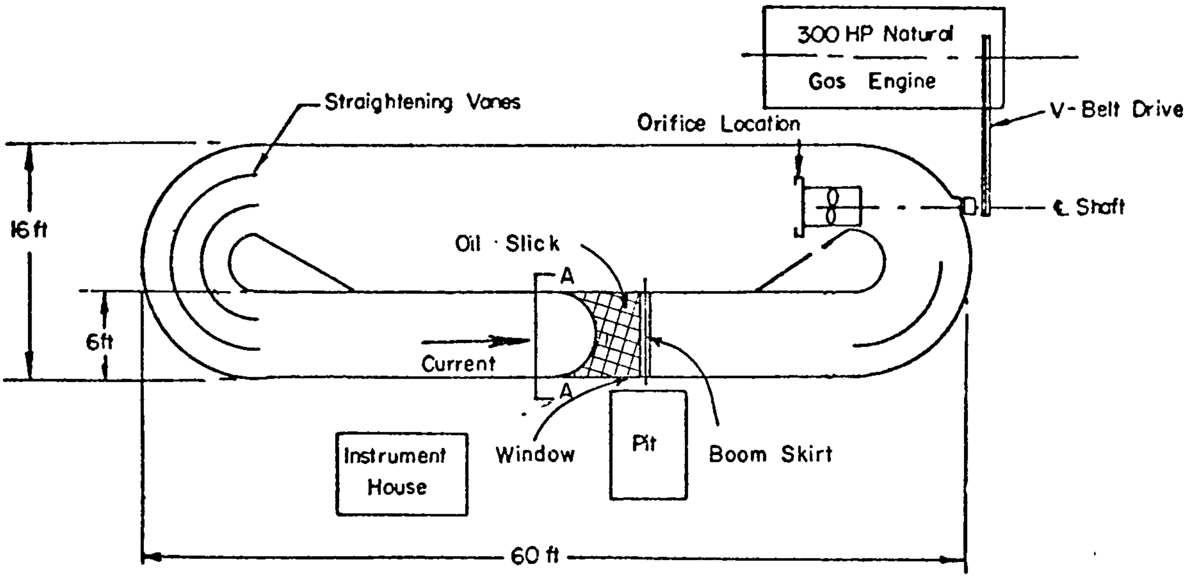
EXPERIMENTAL METHODS

General

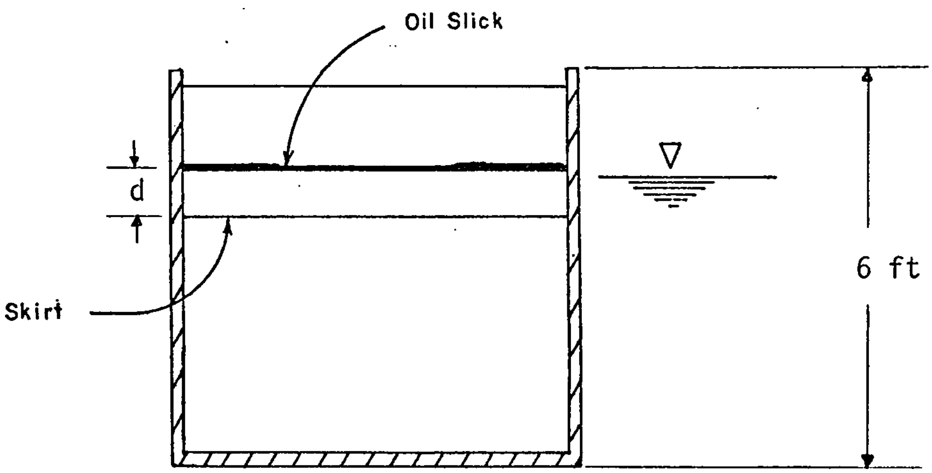
Tests were conducted in three separate categories: (1) laboratory tests under controlled conditions, (2) performance tests in an offshore environment, and (3) qualitative observations of booms under actual operating conditions in inshore and offshore service. The laboratory tests were conducted at Shell Pipe Line Corporation's Research and Development Laboratory at 5515 Gasmer, Houston, Texas. Offshore wave and towing tests were conducted near Shell Oil Company's Buccaneer Platform "A" in the Gulf of Mexico, utilizing existing wave staff and recording equipment for measurement. Performance of the three types of booms was observed in actual oil spill service in the Houston Ship Channel and in the Gulf of Mexico, off the Louisiana Coast. The latter evaluations were of a qualitative nature, since wave and current measurement equipment were not available when these observations were made. The information thus obtained was used to verify the results which had been observed in the earlier tests under controlled conditions.

Test Facilities

Current Tank - Current tests were conducted in a 6 foot wide x 6 foot deep x 40 foot long open channel, recirculating current tank, shown in Figure 5. Circulation was produced by a 3-blade,



Plan view of current tank



SECTION A-A

Figure 5 - SKETCH OF CURRENT TANK WITH BOOM SECTION IN POSITION PERPENDICULAR TO CURRENT FLOW SHELL PIPE LINE CORPORATION, HOUSTON, TEXAS

36-inch diameter, engine driven propeller. The propeller engine speed could be varied to yield currents of 0.5 to 8 feet per second. A plexiglas window in one side of the test section allowed visual observations of boom performance in current action. Current speed was measured with a Marine Advisors Inc. Model Q-8 ducted-impeller current meter connected to a Honeywell Model 1508 Visicorder.

Wave Tank - Wave and towing tests were conducted in a wave tank, shown in Figure 6, which consists of a 50 foot wide x 125 foot long x 6 foot deep fiberglas-lined pit filled with water to a depth of approximately five feet. Regular waves were generated by an engine driven Gaso pump connected through linkages to a 48 foot x 6 foot flapper. Engine speed and flapper stroke could be varied independently to yield a wide range of wave heights and lengths, as shown on Table 1. A capacitance probe with a Honeywell Model 1508 Visicorder was used for recording wave heights and periods. Wave lengths were measured via gauge marks on the sides of the wave tank.

Towing Apparatus - The towing apparatus, shown in Figure 7, consisted of a set of variable speed, double-drum winches mounted at either end of the wave tank. Cables were attached from each drum to either end of the test boom, allowing it to be pulled alternately from one end of the tank to the other at velocities ranging from 0.5 to 3.5 feet per second. Towing speed was determined by measuring winch speed with a tachometer. The speed was verified at frequent intervals by determining the time required to move the boom over the measured run.

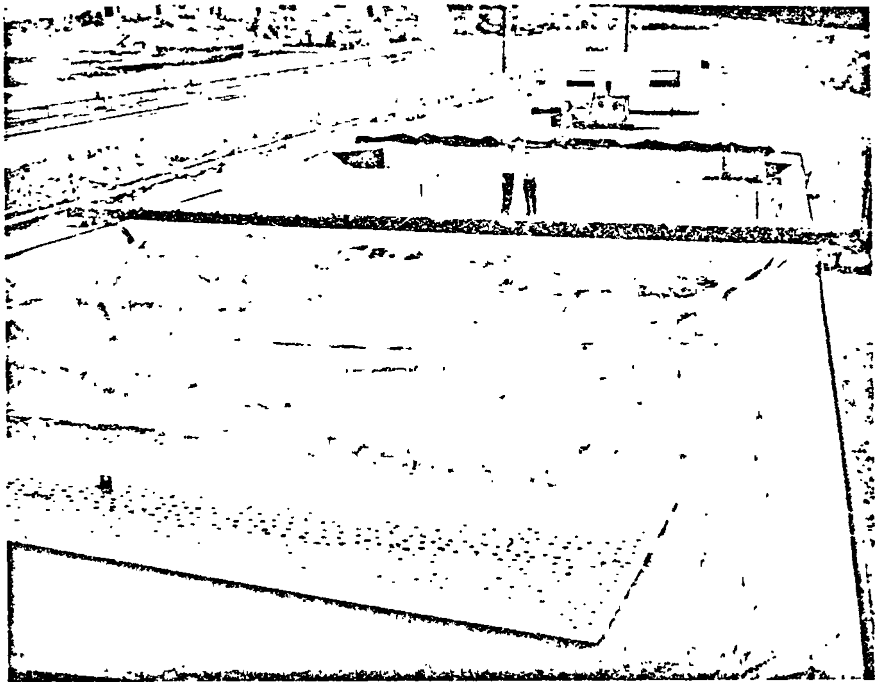


Figure 6 - VIEW OF WAVE TANK SHOWING THE WAVE ABSORBER IN THE FOREGROUND, THE WAVE GENERATOR IN THE BACKGROUND, AND A BOOM IN POSITION FOR WAVE TESTS SHELL PIPE LINE CORPORATION, HOUSTON, TEXAS

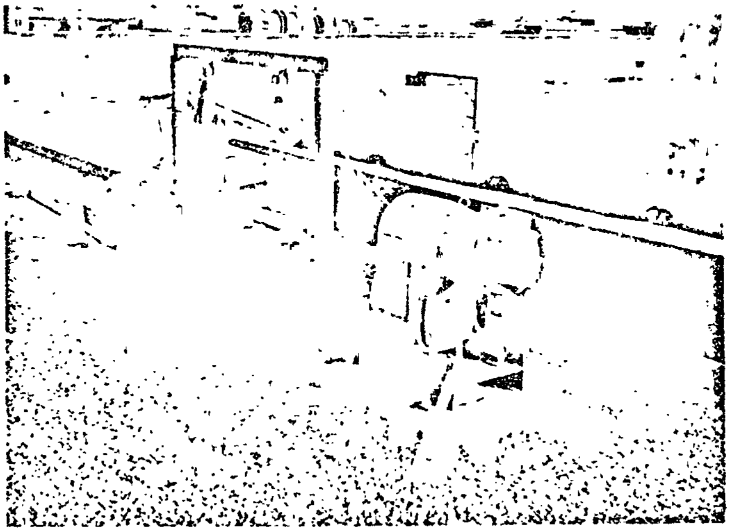
TABLE 1-TYPICAL WAVES AT VARYING FLAPPER STROKE LENGTHS AND SPEEDS

Wobble Bar Hole Setting	ENGINE RPM	PUMP RPM	STROKES PER/MIN	WAVE HEIGHT INCHES	WAVE LENGTH FEET	WAVE DESCRIPTION
2	600	200	35	3	-	Long swells, no form or pattern, relatively calm
2	700	237	44	4	9	Swells, shorter length - higher wave
2	800	263	49	7	8	Rolling swells, starting to form higher pattern
2	950	317	55	7	6	Rolling waves, very near peak stage
2	1000	337	59	9	5	Small whitecaps, waves forming sharp peak
3	600	200	35	6	15	Long surging swells, no real pattern
3	700	232	44	9	11	No sharp crest,
3	800	263	49	9	9	high rolling waves
3	950	316	55	11	6	High sharp peaks, just beginning to form whitecaps
4	600	200	35	4-8	12	Rollers - no crest, no pattern, flat rolling swells
4	700	237	44	10	11	Rough flat topped rollers, no peak or rounded crest
4	850	277	50	9	10	Waves peaked very near whitecapping

TABLE 1-TYPICAL WAVES AT VARYING FLAPPER STROKE LENGTHS AND SPEEDS (CONT.')

WOBBLE BAR HOLE SETTING	ENGINE RPM	PUMP RPM	STROKES PER/MIN	WAVE HEIGHT INCHES	WAVE LENGTH FEET	WAVE DESCRIPTION
5	600	200	35	7-9	-	No pattern, unable to determine crests, rolling and surging waves
5	700	237	44	10	11	Sharp peaks, forming good pattern
5	800	267	49	12	10	Very near white-capping sharp peaks formed
6	550	184	33	6	-	Rollers and swells
6	650	217	39	11	15	Very near peaking point, forming pattern flat topped rollers
6	700	237	44	13	12	Sharp peaks, some whitecaps, sharp breaking rollers
7	550	184	33	8	11	Occasional white-caps, choppy irregular rollers
7	650	217	39	13	15	Sharp breaking peaks, whitecaps, distinct peaked breakers

Towing winch - "Generator" end of wave tank



Towing winch - "Absorber" end of wave tank

Figure 7 - TOWING WINCHES
SHELL PIPE LINE CORPORATION
HOUSTON, TEXAS

Current Test Procedure

Current tests were made by installing a 6-foot long section of a boom across the current tank as shown in Figure 5. The ends were restrained to assure a vertical attitude, and vortex baffles were installed near the ends of the boom on the surface of the water to minimize vortex action due to boundary layer effects along the walls of the current tank. The boom was set up so that the skirt depth could be varied from 6" to 12". A predetermined amount of crude oil (see Table 2 for properties) was carefully poured onto the water approximately 25 feet upstream of the boom. The oil slick profile was observed through the plexiglas window, and the slick thickness noted. The current velocity was increased gradually and the failure characteristics were observed. The current was increased until definite failure occurred; i.e., a significant volume of oil escaped under the boom. The failure velocity was recorded and appropriate comments were made. An oil trap was installed downstream of the propeller to prevent recycling of the oil.

The initial current tests were conducted to allow observation of modes of failure for short sections of booms in a current environment. After the failure mechanism and approximate failure points were defined, current testing was carried out in the wave tank by using a towing apparatus to simulate current action. Since longer boom sections could be towed in the wave tank, the end vorticity problems encountered in the narrow test channel were averted,

TABLE 2-OIL PROPERTIES - SHALLOW YATES CRUDE

WAVE TESTS

Test Temp., °F	Viscosity c.s. at 77°F	DENSITY g/ml at 77°F	OIL SURFACE TENSION, dyne/cm	INTERFACIAL TENSION, dyne/cm	SPREADING PRESSURE, dyne/cm
80	348	0.938	31	3	36

CURRENT AND TOWING TESTS

Test Temp., °F	Viscosity c.s. at 77°F	DENSITY g/ml at 77°F	OIL SURFACE TENSION, dyne/cm	INTERFACIAL TENSION, dyne/cm	SPREADING PRESSURE, cyne/cm
80	37	0.932	32	11	27

and a more realistic interpretation of boom performance could be obtained.

Towing Test Procedure

Towing and current effects under full scale conditions were evaluated by towing the boom in the previously described wave tank. A series of runs without oil were made initially to allow observation of boom mechanical and structural performance, and to verify that the boom was being used to its optimum advantage; i.e., checking end connections, location of anchor points, etc. The results were evaluated and necessary corrections or adjustments were made. Another series of tests were made with oil on the water. These tests were used to determine the point of incipient failure; that is, the towing speed at which a significant volume of oil escaped past the boom, due to either hydrodynamic or mechanical failure. The results were tabulated and appropriate comments made.

Each test was started by accumulating approximately 5 gallons of crude oil in front of the boom. Then a fifty to sixty-foot section of boom was towed from one end of the tank to the other, and observations were made from a walkway located at the center of the tank. The speed was increased in succeeding runs until failure was reached. The failure point was determined by noting the velocity at which oil escaped under the boom or the point at which the boom failed mechanically by tipping over.

Wave Test Procedure

Standard test procedure was to evaluate boom performance (stability and splashover) at a given wave generator stroke and to vary engine speed several times at 50 to 100 RPM intervals within this stroke setting. The stroke was then increased or decreased as desired and another series of runs made at various engine speeds to yield a different range of wave vs frequency data. Fifty to sixty-foot boom sections were stretched across the wave tank in a U-shaped configuration and observations were made for each wave condition. The hydrodynamic and stability characteristics of each boom were observed, and the ability of the boom to contain oil was evaluated in accordance with the failure criteria described in Chapter IV.

Preliminary tests without oil were conducted for each boom in order to determine the effect of anchor point location on mechanical and structural stability. After the most desirable anchor arrangement was selected, 5 to 10 gallons of crude oil were poured in front of the boom, and its performance was evaluated by observing the point at which a significant amount of oil splashed over the top of the boom or mechanical instability occurred. Wave measurements were taken and appropriate comments were made for each run.

Offshore Tests

Wave and towing tests were conducted in the Gulf of Mexico near Shell Oil Company's Buccaneer Platform "A", approximately 30 miles south of Pelican Island, near Galveston, Texas. These tests were performed over a 5-day period with the following objectives: (1) To extend wave tank test data to cover more severe conditions; (2) To evaluate boom performance in irregular seas, since wave tank tests were restricted to regular waves; and (3) To evaluate the handling and deployment characteristics of the booms under realistic conditions.

Two sixty-foot work boats were utilized for deployment, towing, and observation of the booms during these offshore wave and towing tests. For the wave tests several booms were connected together in a U-shaped configuration to form a continuous boom and the ends were anchored to the platform legs. This allowed direct comparisons of different types of booms under identical conditions. Observations of wave conditions and performance were made and recorded at regular intervals, and long range effects of the wave forces on the structural integrity of the booms were noted. Inasmuch as the sea was relatively calm during the test period, the propeller wash from the boats was used to simulate more severe wave conditions. Measurements of wave height was accomplished by utilizing Shell's existing wave staff and strip chart recorder on Buccaneer Platform. A manual gauge on the platform leg was used for calibration and for measuring wave height due to propeller wash.

Towing tests were conducted by attaching the opposite ends of the booms to the two boats. A small quantity of oil was poured into the boom area and the boats were towed at varying speeds until failure occurred. Towing speed was determined by measuring the time required to tow the boom between two fixed points. The point at which the unit began to lose oil was noted by an observer who trailed the boom in a small boat, and the failure point and overall performance of the boom in tow were recorded. Individual boom lengths of approximately 200-feet were used for each test.

Observations Under Actual Spill Conditions

Observations of boom performance in actual service were made during several oil spills in the Houston Ship Channel and in the Gulf of Mexico, at Main Pass, approximately 35 miles off the Louisiana Coast. Models of each of the three major types of booms were observed at various times over a six-month period. Qualitative observations of performance under "real life" conditions were made in order to supplement the quantitative data which had been accumulated in previous tests. They also allowed comparisons of the performance of several hundred feet of boom to that of the short, single sections which were evaluated in the lab tests. In addition, information regarding deployment characteristics and structural stability of the booms was obtained by observing the problems encountered in actual oil spill service.

CHAPTER IV

ANALYSIS OF DATA AND DISCUSSION OF TEST RESULTS

CURRENT AND TOWING TESTS

General

In the early stages of containment boom development researchers theorized that the oil collected behind the boom in a triangular shape, with the thickest portion adjacent to the boom, as shown in Figure 8.[1,2,3] Under this theory, oil loss occurs by draining of the oil past the skirt due to the formation of a vortex, similar to the phenomenon which occurs when a liquid is drained from a tank such as a bathtub.[4,5] In this case the oil is assumed to be pulled under the water surface and to escape under the skirt where it is entrained into the stream. The major effect of this theory was the use of skirt depth as the major parameter in designing a containment boom for protection against oil loss in a current environment.

However, results of these current tests and others[6] indicate that the "draining" mode of failure is not the significant failure mode. Rather, it was found that in the presence of a current the oil collects behind the boom in a configuration just opposite to that described previously. As shown in Figure 9, the thickest portion of the slick occurs at the leading edge of the slick, at some distance from the boom. This leading edge is

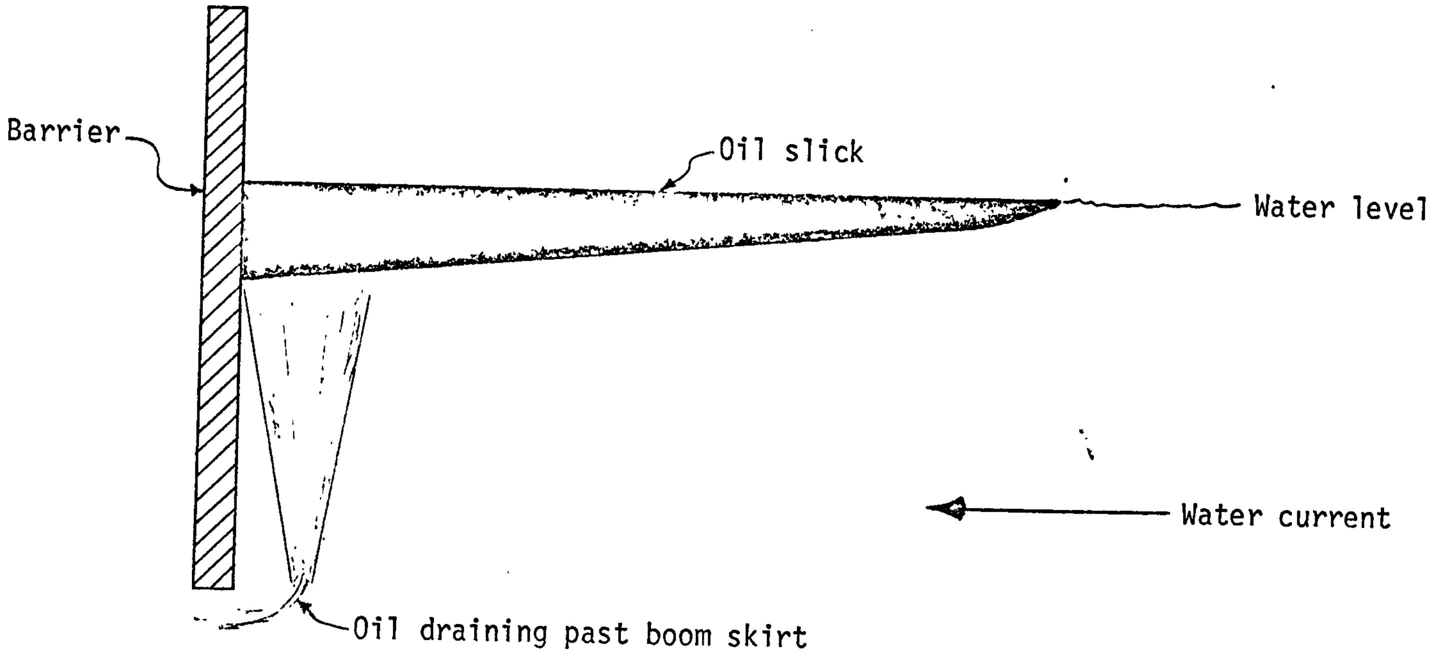
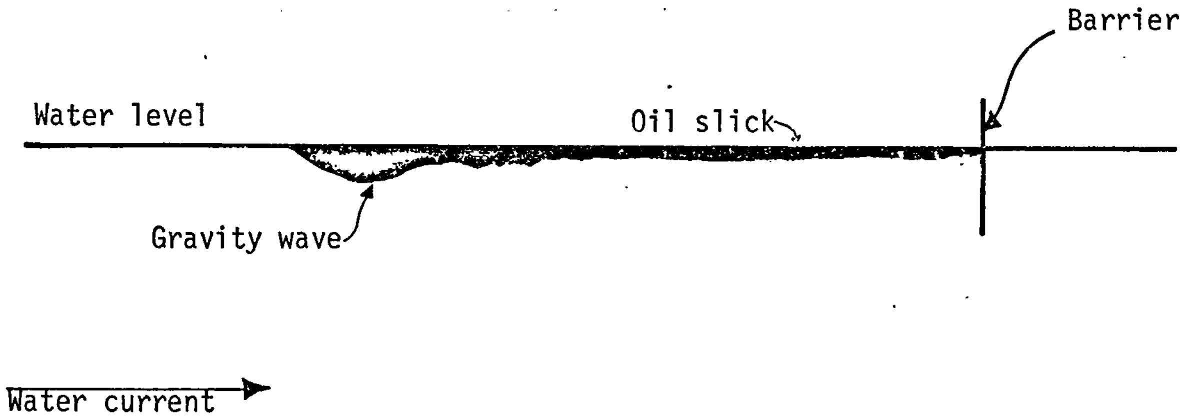
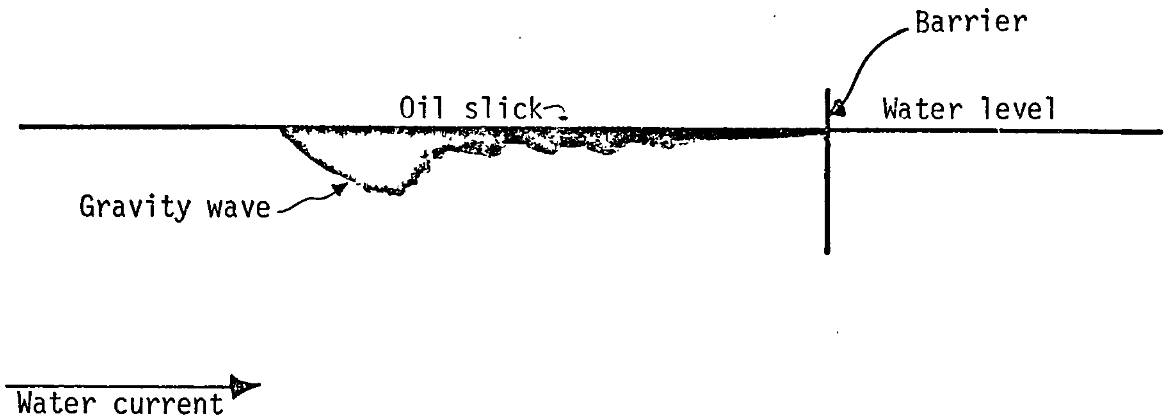


Figure 8 - OIL SLICK ACCUMULATION IN CURRENTS AS THEORIZED BY EARLY RESEARCHERS



(a) Current Velocity = 0.8 Ft./Sec.



(b) Current Velocity = 1.0 Ft./Sec.

Figure 9 - ACTUAL OIL SLICK ACCUMULATION BY A CONTAINMENT BOOM IN CURRENT ACTION

characterized by a reverse standing wave or gravity wave whose thickness is a function of the current velocity and the ratios of the oil and water densities.[7,8] The slick tapers to a minimum thickness at the boom interface. The thickness of the gravity wave increases with current velocity, and the distance of the gravity wave to the boom decreases as the current velocity increases.

The significance of the gravity wave phenomenon becomes apparent by analyzing Figure 10, which shows the typical failure mode for crude oil. The test results observed in the current tank showed that failure is due to the loss of oil coated water droplets under the skirt. As verified by these observations through the current tank window, the gravity wave is very unstable and wavelets are formed on the rear edge of the wave by the current action. Droplets are torn from the rear edge of the gravity wave, where they are entrained into the water stream and escape under the boom skirt. The droplets were found to be oil coated water droplets rather than solid oil bubbles, and droplet size ranged to a maximum of approximately 3/4-inches in diameter. This failure mechanism was also observed and reported by March[5] in a U. S. Coast Guard development project.

As one would expect, the failure rate increases with current velocity; i.e., more droplets are lost at higher velocities. However, the amount of oil loss was found to accelerate at a greater rate than that at which the current increased. Qualitative observations indicated that in addition to increased failure

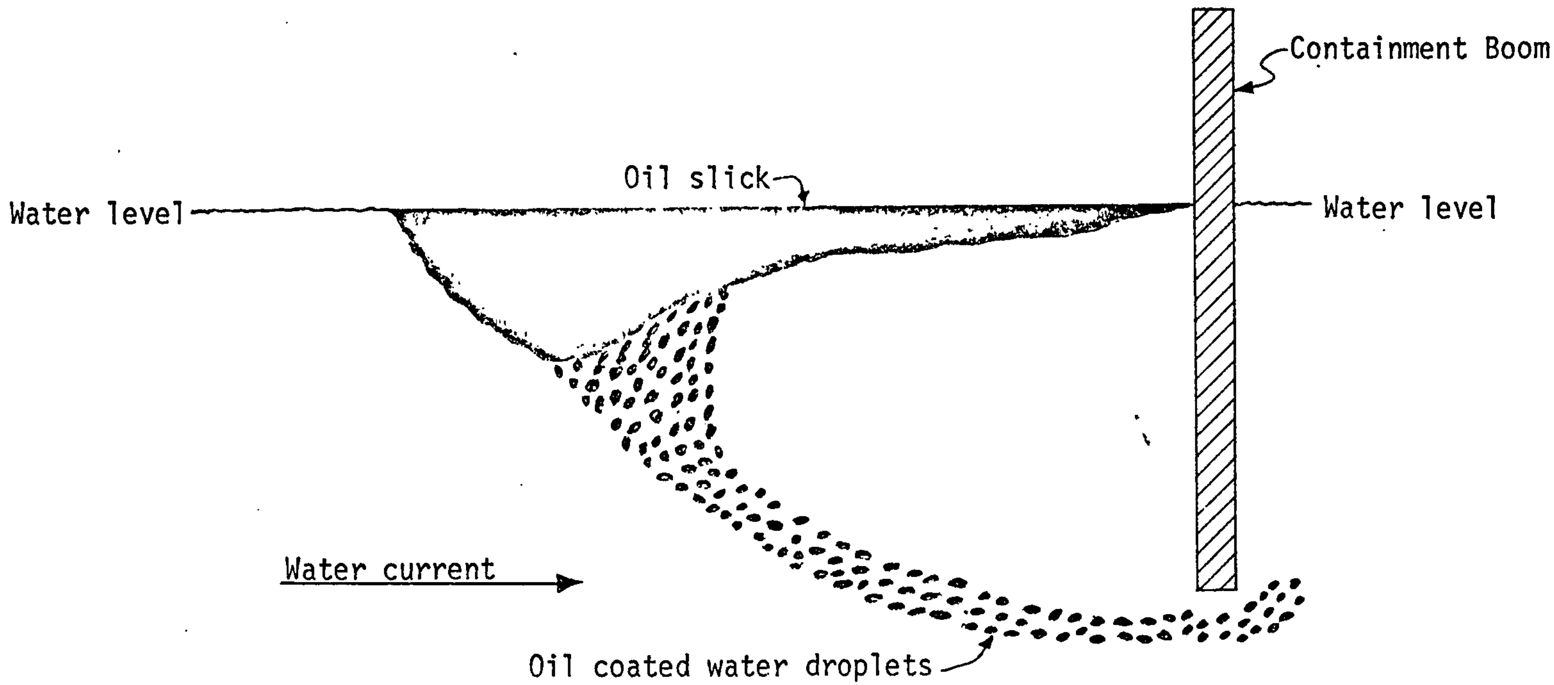


Figure 10 - TYPICAL FAILURE PROFILE OF A CONTAINMENT BOOM IN CURRENT ACTION

due to the loss of more droplets at higher velocities, the ratio of oil to water in the droplets changed with current velocity. At greater velocities, oil made up a larger percentage of the droplet and the droplet approached a 100 percent oil bubble. Thus, at increased current velocities a greater volume of oil is lost at an increased rate, substantially accelerating the overall failure rate.

As discussed previously, current tests were first conducted in the current tank to study the oil accumulation configuration and to define the failure mechanisms involved. Then a quantative measure of performance under full scale conditions was obtained by towing the boom in the wave tank and noting the point at which failure occurred. Two types of failure were noted; (1) escapement of oil under the boom skirt, and (2) mechanical failure of the boom due to planing on the surface of the water or submergence below the water surface.

Current Tank Test Results

Current tank test results are shown in Table 3. The gravity wave was evident at approximately 0.6 feet per second but no droplets were observed. At 0.8 feet per second, oil coated water droplets began to form and were entrained into the flow stream. This velocity did not constitute a failure point; however, as only a very small number of droplets were swept under the skirt. At this current speed most of the droplets were able to rise and coalesce into the oil slick before they were swept under the boom.

TABLE 3 - CURRENT TANK TEST RESULTS

Test No.	Current Velocity ft/sec	Skirt Depth (inches)	Comments
1	.6	6	No oil loss
2	.8	6	Few oil coated water bubbles popping up downstream of boom; no failure
3	.9	6	More droplets escaping; partial failure
4	1.2	6	Heavy oil loss under skirt; definite failure; droplets consist primarily of oil
5	.6	12	No oil loss
6	.85	12	Few oil coated water bubbles escaping; no failure
7	1.0	12	More droplets escaping; partial failure
8	1.2	12	Heavy oil loss; definite failure; droplets consist primarily of oil

As the current speed was increased, more droplets were swept under the boom and the incipient failure point was approached. Definite failure was observed at a current velocity of 1.2 feet per second.

The current tank tests were repeated with the boom skirt at depths ranging from 6" to 12" to evaluate the effect of barrier depth on performance. As shown in Table 3, the results were identical for all skirt depths. Failure occurred at 1.2 feet per second in each case and the rate of oil loss was approximately equal.

Towing Test Results

In most of the towing tests, failure was recorded at a slightly higher relative velocity (boom to water) than in the current tank tests. This is attributable to the fact that failure in the current tank tests could be observed precisely via the plexiglas window, while the actual towing test failure points were more difficult to define due to short time involved for each run and the inability to follow the boom at close range throughout each run. In addition, the velocity measurements in the current tank were more accurate than the towing speed measurements. Another problem experienced was that of maintaining a uniform towing speed with the boats in the offshore tests. This sometimes resulted in unequal towing forces at opposite ends of the boom and increased the tendency for planing.

Rigid Booms - Towing test results for a rigid boom with 12" freeboard and 24" skirt are given in Table 4. In the wave tank, at a velocity of 1.0 feet per second (0.59 knots), the skirt

TABLE 4 - TOWING TEST RESULTS - RIGID BOOM (12" FREEBOARD, 24" SKIRT)

Test No.	Location	Method of Attachment	Velocity Ft/Sec	Velocity Knots	Skirt Attitude	Comments
1	Wave Tank	Harness attached at top and bottom of boom	1.0	0.59	Vertical	No oil loss
2	Wave Tank	Harness attached at top and bottom of boom	1.3	0.77	West end started to plane at end of run	No oil loss
3	Wave Tank	Harness attached at top and bottom of boom	1.6	0.95	West end started to plane at end of run	Significant oil loss at west end
4	Wave Tank	Harness attached at top and bottom of boom	1.9	1.1	East end planed immediately and then entire boom planed	Heavy oil loss
5	Offshore	End Stabilizers- 3 point attachment	1.5	.89	Began planing at center, then entire boom planed	Heavy oil loss- complete fail- ure

assumed a vertical attitude and no oil loss occurred. At 1.3 feet per second (0.77 knots), the west end of the boom tipped and began to plane on the surface of the water. Again no oil loss was observed. At 1.6 feet per second (1.1 knots) the entire boom tipped over and all of the oil escaped. The latter two points were retested with identical results; planing and subsequent oil loss began at 1.6 feet per second, with complete failure at 1.9 feet per second.

The offshore tests revealed similar results. The entire boom planed and lost oil at a towing speed of approximately 1.5 feet per second (0.9 knots). In these tests, specially designed end stabilizers were used in an effort to reduce the tendency for planing. However, they were virtually useless, as the boom initially remained vertical at the ends but began planing at the center, and eventually the entire boom tipped over.

The performance of the rigid boom under actual operating conditions closely paralleled those discussed previously. In towing service at estimated speeds of less than 2 feet per second this boom could not maintain a vertical position. In mild current action in the Houston Ship Channel, approximately 1.0 feet per second, the rigid boom did successfully retain oil. However, when ships passed, inducing larger currents, some oil loss under the skirt was noted.

Analysis of the rigid boom test data indicates that its primary deficiency stems from mechanical rather than hydrodynamic failure. In all of the tests the boom failed by tipping over and planing on the water surface before oil could escape by the droplet failure mechanism noted previously. The basic problem with the rigid boom in current or towing service is instability caused by its flat, rigid configuration, which provides a large unyielding area upon which the current forces can act. The resulting force, exerted over the entire boom length, has virtually no resistance and the boom must yield by tipping over.

There is no evidence to indicate that this boom would offer better performance in tow if it could be made more stable so as to retain a vertical attitude. In this case failure would probably occur by loss of oil coated water droplets under the skirt at 1.2 to 1.4 feet per second, as was observed in the current tank and other boom tests.

Semi-flexible Booms - Towing tests indicated that the semi-flexible boom is not suitable for use in currents exceeding 1.4 feet per second (0.83 knot), with two point attachment through eyelets at the top and bottom of the boom. Results are shown in Table 5, test numbers 1-5. The observed failure velocity and failure mechanism compared favorably with results obtained on a model boom in the current tank. At a velocity of 0.82 feet per second (0.48 knot) the skirt remained vertical and no oil was lost. At 1.2 feet per second (0.71 knot) small droplets of oil began to seep under the skirt. At 1.4 feet per second (0.83 knot) large quantities of oil were lost under the skirt, constituting definite

TABLE 5 - TOWING TEST RESULTS - SEMI-FLEXIBLE BOOM (12" FREEBOARD, 16" SKIRT)

Test No.	Location	Method of Attachment	Velocity Ft/Sec	Velocity Knots	Skirt Attitude	Comments
1	Wave Tank	Two point attachment-top & bottom of boom	0.8	0.47	Vertical	No oil loss
2	Wave Tank	Two point attachment-top & bottom of boom	1.2	0.71	Vertical	Slight oil seepage under boom
3	Wave Tank	Two point attachment-top & bottom of boom	1.4	0.83	Vertical	Heavy oil loss under boom-definite failure
4	Wave Tank	Two point attachment-top & bottom of boom	1.8	1.06	45° from vertical skirt trailing flotation section	Failure-severe oil loss
5	Wave Tank	Two point attachment-top & bottom of boom	2.0	1.18	Planing-skirt horizontal	Only approximately 4-inches of skirt in water-severe failure
6	Wave Tank	Tension cable at bottom of skirt	0.80	0.47	Vertical-boom skirt concave in the direction of motion	No oil loss

TABLE 5 - TOWING TEST RESULTS - SEMI-FLEXIBLE BOOM (12" FREEBOARD, 16" SKIRT) (CONT.)

Test No.	Location	Method of Attachment	Velocity Ft/Sec	Velocity Knots	Skirt Attitude	Comments
7	Wave Tank	Tension cable at bottom of skirt	1.50	0.89	Vertical-boom skirt concave in the direction of motion	No oil loss
8	Wave Tank	Tension cable at bottom of skirt	1.90	1.12	Slight tilt angle forward-boom skirt concave in the direction of motion	Oil loss under boom-definite failure
9	Wave Tank	Tension cable at bottom of skirt	2.20	1.30	Skirt horizontal under water surface in the direction of motion	Heavy oil loss
10	Offshore	Tension cable at bottom of skirt	1.5	0.89	Boom vertical	Significant oil loss under the skirt
11	Offshore	Tension cable at bottom of skirt	2.0	1.18	Skirt tilted forward toward water surface	Heavy oil loss
12	Offshore	Tension cable at bottom of skirt	3.0	1.77	Entire boom horizontal under water	Heavy oil loss

failure. The failure mechanism was identical for all runs, and the amount of oil loss increased substantially at higher towing velocities. The boom began planing (floating horizontally on the water surface) at 2.0 feet per second (1.18 knots).

The towing tests were repeated with the towing cables attached to a tension cable at the bottom of the skirt. Results are shown in Table 5, test numbers 6-9. With this type of end attachment, the skirt assumed a concave configuration which seemed to result in slightly improved performance. At the lower velocities, there was no noticeable oil loss. At 1.5 feet per second (0.89 knots), the boom retained a vertical attitude with the skirt in a slight concave position, and no oil loss occurred. Failure was reached at a velocity of 1.9 feet per second (1.12 knots), with the boom skirt at a slight angle towards the water surface and significant droplet escapement under the skirt.

In the offshore test, at an estimated speed of 1.5 feet per second (0.89 knots), the boom retained its vertical (and slightly concave) configuration and experienced heavy oil loss under the skirt. At increased velocities (above 2.0 feet per second) the skirt began to lift upward towards the water surface and again heavy oil loss occurred. At approximately 3.0 feet per second, the skirt was in a horizontal position just below the surface of the water and the entire flotation section was slightly submerged.

Under actual operating conditions in mild current conditions the semi-flexible boom operated satisfactorily. In a current of approximately 1.0 feet per second, the boom contained a small spill with no significant oil loss. It was not observed in towing service during a spill, although dry runs (for training of personnel) with no oil on the water, indicated that this unit is relatively stable at speeds up to approximately 2.0 feet per second.

In contrast to the rigid boom the semi-flexible boom failed due to hydrodynamic effects and was not highly susceptible to planing. The cylindrical flotation member coupled with attachment via a tension cable at the bottom of the skirt gives it stability characteristics which other designs do not possess. However, although this design is more stable in tow than is the rigid boom and the modes of failure differ, the failure velocities for the two booms are approximately the same. Nevertheless, due to its greater stability the semi-flexible boom is preferred over the rigid type for towing or current service.

Flexible Booms - Towing test results for the flexible boom, shown in Table 6, indicate that this design may be even more unstable in currents than the rigid boom. With a two point harness attachment at the water level and at the bottom of the skirt, the boom remained vertical and no oil was lost at the initial velocity of 0.8 feet per second (0.47 knots). At 1.0 feet per second (0.59 knots), the west end began planing at the

TABLE 6 - TOWING TEST RESULTS - FLEXIBLE BOOM (12" FREEBOARD, 24" SKIRT)

Test No.	Location	Method of Attachment	Boom Speed Ft/Sec	Boom Speed Knots	Skirt Attitude	Comments
1	Wave Tank	Harness attached at water level and bottom of boom	0.8	0.47	Vertical	No oil loss
2	Wave Tank	Harness attached at water level and bottom of boom	1.0	0.59	West end planed	Significant oil loss at west end
3	Wave Tank	Harness attached at water level and bottom of boom	1.2	0.71	East end under water, center of boom planed	Heavy oil loss at east end and center
4	Wave Tank	Harness attached at water level and bottom of boom	1.4	0.83	East end planed	Heavy oil loss at east end
5	Wave Tank	Harness attached at water level and bottom of boom	1.6	0.95	East end planed, then entire boom planed	Heavy oil loss
6	Offshore	Harness attached to cylindrical paravanes bolted to boom	1.5	0.89	Center section of boom planed	Heavy oil loss complete failure

end of the run and significant oil loss occurred on that side. At 1.2 feet per second (0.71 knots), the east end of the boom was submerged and the center of the boom planed, allowing all of the oil to escape. The submergence may have resulted from a jerking action due to excess slack in the towing harness at the start of the run. At a slightly higher velocity of 1.4 feet per second (0.83 knots) the east end planed at the start of the run and heavy loss occurred. The center portion of the boom remained vertical for the remainder of this run, indicating that it may be possible to improve stability by reducing the total pressure on the boom skirt. At 1.6 feet per second (0.95 knots), the east end began planing and then the entire boom capsized, resulting in complete oil loss.

Due to the end stability problems encountered in the wave tank towing tests, the offshore tests were conducted with cylindrical paravanes attached to each end of the boom. The paravanes were constructed from 6-inch diameter x 4-1/2-foot long aluminum pipes, tapered at the leading edge in a bomblike configuration and welded to 3-foot x 4-foot x 1/4-inch aluminum plates. They were attached to the boom by hinged plates which were bolted directly to the skirt material. Use of the paravanes resulted in slightly improved performance by stablizing the end sections of the boom. The minimum uniform towing speed which could be attained was 1.5 feet per second, and the boom failed by planing of approximately 50 feet of the center section.

The planing may have been partially attributable to the 200-foot boom length used in this test. Note that even though the paravanes held the ends in a vertical position, the center section was still quite susceptible to planing due to the excessive length of the boom. This suggests that the flexible boom could possibly be used successfully for towing service if paravanes were employed and short boom sections were utilized. As discussed below, later evaluations of the boom in actual service confirmed this observation.

Tests in oil spill service in the Houston Ship Channel and at Main Pass in the Gulf of Mexico indicated this design can be used effectively in towing service under certain conditions. In actual service at the above locations, the flexible boom was towed successfully at speeds up to approximately 1.5 feet per second. Although it demonstrated a high degree of instability in previous tests, it was found that when paravanes are utilized for end stability, short sections (up to 50 feet) of flexible boom can be used successfully in towing service. In this type of service with velocities of approximately 1.0 feet per second, the boom was used several times to successfully contain oil for clean-up with mechanical skimming equipment.

The instability demonstrated by the flexible boom is somewhat similar to that of the rigid boom. In a flexible boom the skirt takes all of the tension in tow, and the boom apparently experiences tensile forces which impart a uniform, rigid characteristic similar to that of a rigid boom. This rigidity offers considerable resistance to current activity and results in mechanical rather than hydrodynamic failure for most current (or towing) applications. Although the flexible boom experienced mechanical failure at a lower velocity than the rigid boom, it is probably due to the instability of the flexible ends. The end instability can be improved with guide vanes as was done in the offshore tests and in actual oil spill service.

WAVE TESTS

General

The test data on Table 7 shows the relationships between the wave lengths and periods of the regular waves generated in the wave tank. These were found to closely approximate the calculated values obtained using mathematical relationships for wave length and periods for both intermediate and deep water conditions.[9,10,11]

"Deep water" is defined as

$$\frac{d}{L_o} > \frac{1}{2}$$

where d = water depth and L_o = deep water wave length. The relationship relating the wave length, L_o, and wave period, T, is

$$L_o = \frac{gT^2}{2\pi}$$

Intermediate water depth is defined as

$$\frac{1}{200} < \frac{d}{L} < \frac{1}{2}$$

where L is the wave length at any water depth and is defined as

$$L = L_o \tanh \frac{2\pi d}{L_o}$$

TABLE 7-TYPICAL WAVES GENERATED IN WAVE TANK

WAVE ACTION	WAVE HEIGHT (IN.)	WAVE LENGTH (FT.)	PERIOD (SEC.)
Rolling	13	18	2.1
Rolling	13	22	1.9
Rolling	14	14	1.9
Rolling	9	12	1.7
Rolling	8	14	1.5
Rolling	9	12	1.5
Rolling	9	12	1.5
Rolling	9	10	1.4
Sharp peaks, whitecaps	12	10	1.2
Rolling to sharp peaks	8	8	1.2
Sharp peaks, whitecaps	11	8	1.2
Choppy-irregular pattern-whitecaps	12	10	1.1
Sharp peaks to choppy whitecaps	12	7	1.1
Sharp peaks, whitecaps	10	6	1.1
Choppy-irregular pattern-whitecaps	6	6	1.0
Choppy-irregular pattern-whitecaps	7	6	1.0
Choppy-irregular pattern-whitecaps	6	5	1.0
Sharp peaks to choppy whitecaps	7	6	0.94

The corresponding relationship between wave length and wave period is given by

$$L = \frac{g}{2\pi} T^2 \tanh \left(\frac{2\pi d}{L_o}\right)$$

The comparison of the test data with these equations is shown in Figure 11.

In discussing wave conditions, the presence of breakers or whitecaps with significant wave heights of 2 feet or greater for sharp peaked choppy waves, and 3 feet or more for swells is defined as a severe condition and requires selection of high performance booms. Moderate conditions are characterized by choppy swells with some whitecaps and relatively low wave heights, 6 to 12 inches for relatively steep waves, and 2 to 3 feet for smoother waves or swells. Mild conditions are defined as calm waters with no whitecaps or choppiness, and wave heights of 1 to 3 feet.

In this testing program boom failure was determined qualitatively. In wave tests failure is defined as that point at which a significant amount of oil splashes over the top of the boom or mechanical failure (instability) of the boom occurs. Mechanical failure is easily understood. A boom might break-up structurally or it may tip over, laying horizontal on the surface of the water completely submerged by the wave action. Failure by splashover, however, is not easily defined. Splashover is defined in terms of slight, significant, or heavy. Slight splashover indicates occasional spraying over the top of the boom and

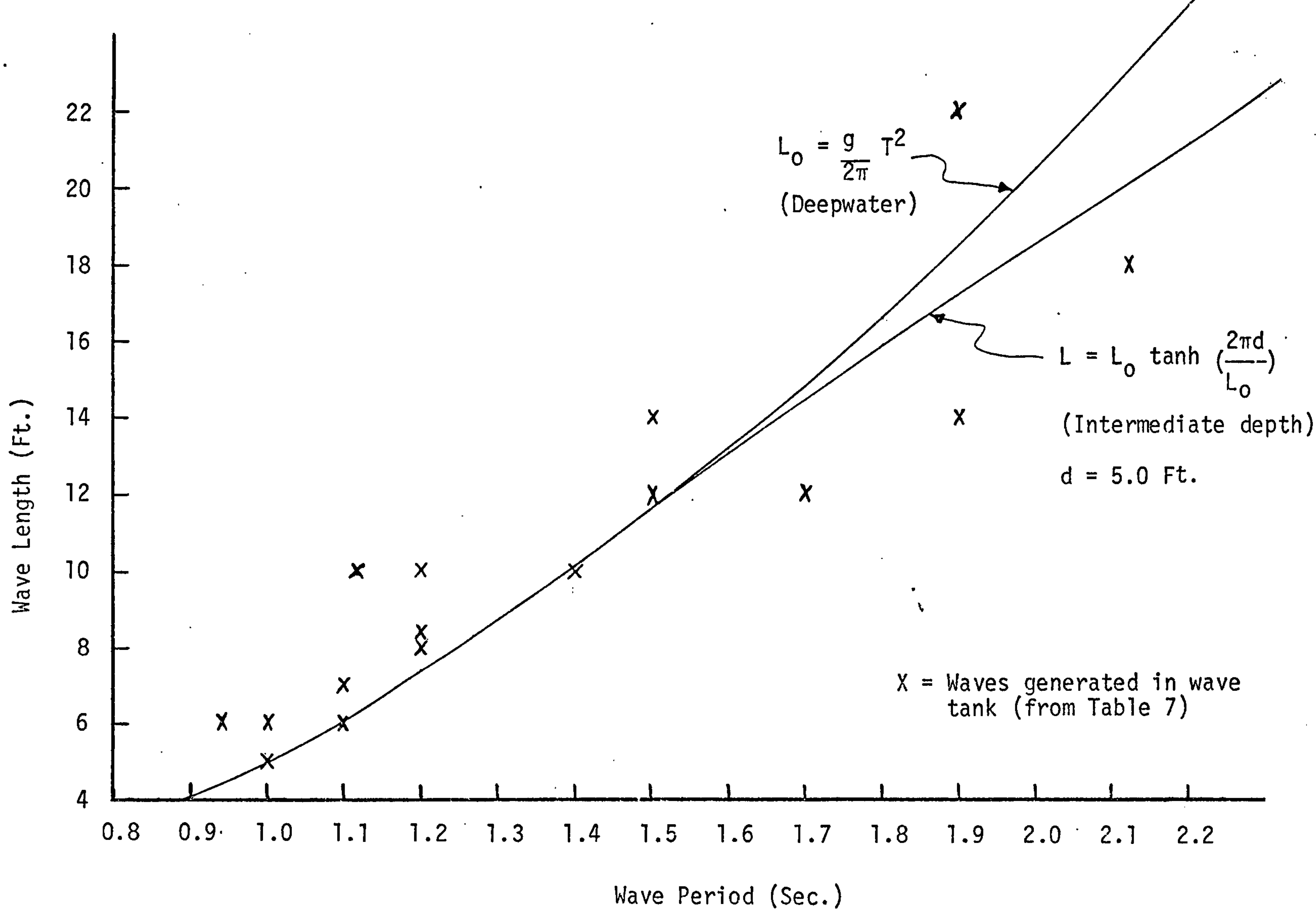


Figure 11 - COMPARISON OF TEST WAVES GENERATED IN THE WAVE TANK TO MATHEMATICAL RELATIONSHIPS FOR INTERMEDIATE AND DEEP WATER WAVES

generally does not constitute failure. Significant splashover denotes frequent splashing and oil loss over the boom and is considered the point of incipient failure by waves. Heavy splashover signifies almost constant splashing of oil and water over the boom and is generally characterized by "swamping" of the boom. In these tests, booms which allow "slight" splashover are considered to be satisfactory, whereas those which experience "significant" or "heavy" splashover are generally in the unsatisfactory performance range.

The term failure, of course, is subject to interpretation. Failure is defined to be the passage of a significant amount of oil either over or under the boom. The initial mode of failure by waves for all of the booms tested was the splashing of oil over the top of the boom, with the exception that some booms were marginally stable and capsized without righting themselves when the first group of waves hit. For severe wave conditions and wave heights substantially greater than the freeboard, most booms were completely swamped by the waves, as was expected.

A detailed analysis of the test data shows that the wave steepness ratio, which is defined as the ratio of wave height to wave length, is an important parameter in describing the wave conditions at which boom failure occurs. Failure by splashover is not likely to occur in regular waves when the wave steepness ratio, H/L, is 0.08 or less. However, for each boom type there is a critical steepness ratio beyond which failure will likely occur if the wave height is equal to or greater than the boom freeboard. Beyond this point the degree of failure increases as the steepness ratio and/or wave height increase.

Regular vs Irregular Waves

Regular waves, such as those generated in the wave tank, are characterized by a series of uniform undulations which repeat themselves in a uniform pattern, and which are readily describable in terms of wave height, length, and period. A sinusodial wave is an example of a regular wave. Irregular waves, as experienced in the offshore tests, are characterized by an irregular, random pattern of wave heights, lengths and periods, and are described in terms of an energy spectrum for a group of waves. Note that the wave steepness ratio discussed previously is not directly applicable in the case of irregular waves. For this condition boom performance is described in terms of the wave height and the physical description of the wave rather than by an absolute wave steepness value. In both regular and irregular wave conditions, as the significant wave height and/or wave steepness increase, a higher percentage of waves can be expected to contribute to boom failure.

Rigid Booms - As shown in Table 8, rigid booms are very unstable in moderate and severe wave action and are marginally effective in mild wave conditions. For a boom with 12" freeboard and 24" skirt, in mild rolling waves with a 0.062 steepness ratio and approximately 9-inch amplitude, the boom retained its vertical position and no splashover occurred. In more sharply peaked waves

TABLE 8 - WAVE TEST RESULTS - RIGID BOOM (12" FREEBOARD, 24" SKIRT)

Test No.	Location	Description of Wave Action	Wave Height (Inches)	Wave Length (Feet)	Steepness Ratio (H/L)	Comments
1	Wave Tank	Rolling	9	12	.062	No splashover
2	Wave Tank	Rolling	10	11	.076	No splashover
3	Wave Tank	Rolling	10	9-1/2	.088	Failure; boom completely swamped - horizontal on water
4	Wave Tank	Rolling with some sharp peaks	11	7	.13	Failure, boom completely swamped - horizontal on water
5	Offshore	Smooth, rolling swells	1-2ft			Boom vertical with slight splashover & boom tipped slightly when larger waves hit
6	Offshore	Moderate rolling swells, some whitecaps	2-4ft			Boom swamped when choppy waves hit; usually did not regain vertical position when waves slacked
7	Offshore	Propeller wash from boat; choppy with whitecaps	2-3ft			Boom swamped - horizontal on water surface

with steepness ratio of 0.076, the boom still maintained a vertical altitude and no splashover was observed with 10" waves; however, at this point the boom did exhibit a tendency to tip when larger waves (11" - 12") hit. As the wave steepness increased to 0.088, the boom capsized and was completely swamped by 10" waves. In the moderate sharp peaked waves of test No. 4 (0.13 steepness ratio and 11" height), the boom was again completely swamped. In this case, as in the previous run, the boom did not recover when the waves were stopped.

In the offshore tests, the boom exhibited similar instability characteristics. In mild conditions, with smooth rolling swells of 1 to 2 feet amplitude, the boom allowed slight splashover and occcasionally tipped over, without capsizing, when larger or sharper peaked waves were encountered. As wave steepness increased to the moderate conditions described previously, with 2 to 4 feet wave heights and occasional whitecaps, the boom was swamped and complete failure occurred. Propeller wash from the work boats created sharp peaked, severe waves of 2 to 3 feet amplitude, which resulted in complete failure by capsizing.

Performance of the rigid boom in actual spill service in the Gulf of Mexico supported the earlier observations. In moderate conditions with 2 to 6 foot waves, the boom was totally ineffective in containing oil. It failed severly by capsizing and twisted badly, resulting in structural failure at the interconnecting joints.

In wave action the rigid boom fails mechanically (by capsizing) rather than hydrodynamically (by splashing of oil over the top of the boom). It is theorized that hydrodynamic failure would have been experienced in moderate wave action, at steepness ratios greater than approximately 0.08 and wave heights of 11 to 12 inches if mechanical failure had not occurred first. This tendency was observed in isolated situations in the offshore tests when an occasional sharp-peaked wave in a wave train made up primarily of mild rolling waves hit the boom, but did not have sufficient force to cause mechanical failure. In these cases, significant splashover occurred when the wave height of the critical wave was approximately 12" or greater. It was also noted that the presence of the rigid boom appeared to enhance the tendency for splashover. Presumedly this is a function of the rigidity of the boom, and results from an inability to conform to the wave shape and absorb the wave energy.

In regular waves, failure by capsizing or splashover will probably occur when the steepness ratio is greater than 0.08 and the wave height is approximately equal to the boom freeboard (10 to 12 inches for a boom with a 12" freeboard). In irregular waves, failure will occur under any conditions other than mild rolling swells of 1 to 2 feet height.

<u>Semi-Flexible Booms</u> - The test results showed that semi-flexible booms are considerably more stable in wave action than are rigid booms. From Table 9 it is seen that failure by splashover

TABLE 9 - WAVE TEST RESULTS - SEMI-FLEXIBLE BOOM (12" FREEBOARD, 16" SKIRT)

Test No.	Location	Description of Wave Action	Wave Height (Inches)	Wave Length (Feet)	Steepness Ratio (H/L)	Comments
1	Wave Tank	Rolling	13	18	0.060	No splashover
2	Wave Tank	Rolling	10	12	0.069	No splashover
3	Wave Tank	Rolling	11	10-1/2	0.087	No splashover
4	Wave Tank	Rolling, sharp peaked	14	11	0.117	Slight splashover; incipient failure
5	Wave Tank	Rolling, sharp peaked, some whitecaps	14	9	0.129	Significant splashover, failure
6	Wave Tank	Choppy, white-caps	12	7-1/2	0.133	Significant splashover, failure
7	Offshore	Rolling swells, no whitecaps	1-3ft			No splashover
8	Offshore	Moderate swells, with whitecaps	2-4ft			Heavy splashover; definite failure
9	Offshore	Propeller wash from boat,choppy with whitecaps	2-3ft			Boom completely swamped by waves

occurred, but the boom did not experience catastrophic failure by capsizing as observed in the rigid boom tests. For a boom with 12" freeboard and 16" skirt, in mild rolling waves with steepness ratios less than 0.09, no splashover occurred (test Nos. 1 thru 3). On test No. 4, at a wave steepness of 0.117 and corresponding wave height of 14", slight splashover was observed, denoting the point of incipient failure. As the wave steepness increased to 0.129 in test No. 5, with the wave height remaining constant, definite failure by splashover occurred. Note the existence of whitecaps in this run, whereas no whitecaps were evidenced in the previous run which experienced only slight splashover. In test No. 6 the steepness ratio increased to 0.133 with a wave height of 12", and failure by splashover was even more significant than in the previous run. In all of the above tests, the boom remained in an upright position and exhibited no mechanical stability difficulties. In the more choppy waves with greater steepness ratios, the boom exhibited a slight tendency to dive into the crests and pull out of the troughs, suggesting a possible dynamic response deficiency. However, this effect was minimal and would only be significant under substantially more adverse conditions than were encountered in these tests. In addition, slight seepage was observed under the skirt at the interconnecting joints between adjacent boom sections. This seepage was in the form of oil-coated water droplets similar to that observed in current tests, and appeared to be the result of currents induced by the wave action. Losses by this mode were minimal and were not considered to constitute failure.

In mild offshore conditions with rolling swells of 1 to 3 feet, no splashover was observed and the boom assumed a stable attitude. In more vigorous moderate swells with wave heights of 2 to 4 feet and some whitecaps, heavy splashover occurred as the breakers contacted the boom. Propeller wash from the work boat created severe breaking waves of 2 to 3 feet amplitude, which completely swamped the boom. This latter test tends to support the earlier observation in the wave tank tests which pointed out a potential dynamic response problem in severe wave conditions. In this case improved boom response may have prevented complete swamping of the boom; however, it could not have prevented failure, since substantial splashover would still have occurred.

This boom was observed in actual oil spill service in an inshore facility only, in mild waves ranging from 3" to 9" in height. Performance under these wave conditions was satisfactory, as no oil was lost due to the wave action.

In contrast to the rigid boom, the semi-flexible boom fails hydrodynamically by splashing of oil over the top of the boom and appears to be relatively stable in waves. In regular waves failure is not likely to occur if the steepness ratio is less than 0.10, regardless of the wave height. However, if the wave height is equal to or greater than the boom freeboard and the steepness ratio is greater than 0.12, failure by splashover will result. This boom will probably perform satisfactorily in irregular waves under mild conditions with little or no chop and heights to 5 feet. Failure in irregular waves will occur in moderate conditions with wave heights of 2 to 4 feet, and in severe conditions with wave heights of 1 foot or more. The existence of whitecaps in both regular and irregular waves suggests that the wave is sufficiently steep to cause failure by splashover if the wave height is approximately equal to or greater than the boom freeboard.

Flexible Booms - The performance of the flexible boom in waves is superior to that of the two types discussed previously. As illustrated in Table 10, with 12" freeboard and 24" skirt, the boom contained oil satisfactorily with only slight splashover in sharp peaked waves up to 19" in height. In test Nos. 1, 2, and 3, in wave heights up to 15" and steepness ratios up to 0.114, no splashover occurred. Test No. 4, however, had a wave steepness approximately equal to that of test No. 3 and a lower wave height but experienced slight splashover. This is attributable to the difference in the wave characteristics, i.e., the rolling, peaked profile of test No. 3 versus the more vigorous, choppy breaking wave of test No. 4. In test Nos. 5 and 6, the wave height increased to 19" and steepness ratio increased to 0.122 and 0.144, respectively, with only slight splashover equivalent to that of test No. 4. The wave profile in test No. 7 changed to a steeper (0.179) breaking wave of approximately 15", but no significant increase in splashover was observed. However, in test No. 8 the wave steepness increased to 0.195 at a height of 14", with an accompanying increase in wave activity and breaking waves, and significant splashover occurred. Although definite hydrodynamic failure was established at this point, the boom maintained the

TABLE 10 - WAVE TEST RESULTS - FLEXIBLE BOOM (12" FREEBORAD, 24" SKIRT)

Test No.	Location	Description of Wave Action	Wave Ht.(In.)	Wave Len.(Ft.)	Steepness Ratio(H/L)	Comments
1	Wave Tank	Rolling	13	22	.049	No splashover
2	Wave Tank	Rolling, sharp peaked	9	8	.094	No splashover
3	Wave Tank	Rolling, sharp peaked	15	11	.114	No splashover
4	Wave Tank	Choppy, some whitecaps	10	7	.119	Slight splashover
5	Wave Tank	Rolling, sharp peaked	19	13	.122	Slight splashover
6	Wave Tank	Rolling, sharp peaked	19	11	.144	Slight splashover
7	Wave Tank	Choppy, some whitecaps	15	7	.179	Slight splashover
8	Wave Tank	Choppy, breaking waves	14	6	.195	Significant splashover, failure
9	Offshore	Rolling swells	1-3ft	-	-	No splashover
10	Offshore	Moderate swells, some whitecaps	2-5ft	-	-	Swamped badly when large waves hit
11	Offshore	Propeller wash from boat	1-2ft	-	-	No splashover
12	Offshore	Propeller wash from boat, whitecaps	2-4ft	-	-	Completely swamped

excellent stability characteristics which had been demonostrated throughout this series of tests.

The flexible boom performed satisfactorily in rolling offshore waves of 1 to 3 feet. However, in 2 to 5 foot moderate swells with whitecaps, the boom was completely swamped when the larger waves hit, exhibiting an instability characteristic which had not been observed in the wave tank tests with smaller waves. Tests with propeller wash from the boat yielded similar results. In 1 to 2 foot sharp peaked waves with few whitecaps, no splash-over occurred. With 2 to 4 foot breaking waves the boom was again completely swamped and failed mechanically in a fashion not dissimilar from the rigid boom failure. However, when the flexible boom capsizes, it has the ability to spring back to its original vertical configuration after the disturbing forces slack off, whereas the rigid boom normally remains in the failed position.

Numerous observations of the flexible boom were made in actual spill service in both inshore and offshore situations. In inshore service in the Houston Ship Channel and Boston Harbor, with wave heights up to 12", the boom successfully contained oil with no significant loss due to the wave action. Extrapolating from these experiences and the previous tests, this boom can probably be used successfully in most inshore applications in wave heights of 18 to 24 inches, depending upon the intensity of the wave activity. In offshore service in the Gulf of Mexico the boom performed satisfactorily, allowing slight splashover in 1 to 3 foot mild, rolling swells with a slight chop. In moderately choppy or severe waves 3 feet and above, this boom could not successfully contain oil.

When subjected to moderate waves up to 3 feet in height, the flexible boom fails hydrodynamically. In choppy waves greater than 3 feet and in severe wave conditions this boom fails mechanically by capsizing. In regular waves incipient splashover occurs at a steepness ratio of approximately 0.12 with wave height approximately equal to its freeboard. Significant splashover (or definite failure) is not evident until a steepness ratio of 0.19, with wave height approximately equal to the boom freeboard, is reached. Conversely, it is unlikely that the flexible boom will fail at any wave height if the steepness ratio is less than 0.12. Failure in irregular waves occurs at approximately 3 feet for mild conditions and 1 to 2 feet for moderate to severe conditions. In severe irregular waves (offshore service), the flexible boom experiences catastrophic mechanical failure rather than hydrodynamic failure.

CHAPTER V

CONCLUSIONS

General

Floating containment booms are in common use for the control of oil spills. Booms can be used to confine oil within a specific area for skimming, to prevent spreading or passage of oil or for diverting an oil slick. There are several commercial models of mechanical containment booms. In general these booms consist of a buoyant section, a freeboard section which projects above the surface of the water, a skirt which extends below the water surface, a longitudinal strength member, and chains or weights on the skirt for ballast. Mechanical booms can be grouped into three major types: rigid, semi-flexible and flexible. The three types of booms were tested in the laboratory under wave, current, and towing conditions, and under actual conditions in the Houston Ship Channel and the Gulf of Mexico. The booms performed satisfactorily in relatively calm water, but were not effective in high current or towing velocities (above 1.2 feet per second) or in high waves (1 to 3 feet, depending upon wave steepness). Booms which failed due to currents usually did so by permitting the oil to pass under the skirt or by planing on the water surface. Failure by waves was generally due to splashing or spilling of oil over the top of the freeboard section or capsizing of the entire boom.

The performance level of the three major types of containment booms is largely dependent upon the environmental conditions encountered. Generally, the semi-flexible boom yields better performance than the other types under current or towing conditions, while the flexible boom is more satisfactory in wave action. The rigid boom, on the other hand, performs unsatisfactorily in both current and wave environments.

Figure 12 gives a qualitative comparison of the performance of the three types of booms in wave and current action. As shown in this chart, none of the booms performed satisfactorily in current or towing service. Although the semi-flexible boom is preferred for current service due to its greater stability, it cannot contain oil above a current (or towing) speed of 1.7 feet per second, and therefore is also rated poor in that category. The last section in this chapter discusses deployment or diversionary tactics which can be employed to improve the performance of booms in current or towing service.

The comparison of performance in waves is broken into the three wave condition categories described in Chapter IV. Semi-flexible and flexible booms are rated excellent in mild waves, while the rigid boom is rated good. In moderate waves the superiority of the flexible boom is evident, while the performance of the semi-flexible and rigid booms approach unsatisfactory levels. In severe waves all booms show poor performance. In evaluating this chart note that in the previous discussion of wave test results the flexible boom was found to experience

PERFORMANCE

TYPE OF BOOM	Waves			Current	Towing
	Mild	Moderate	Severe		
Rigid	Good	Poor	Poor	Poor	Poor
Semi-Flexible	Excellent	Good to Poor	Poor	Poor*	Poor*
Flexible	Excellent	Excellent	Poor	Poor	Poor

*Performs better than other types, but not suitable for high current or towing service.

Figure 12 - COMPARATIVE EVALUATION OF BOOM PERFORMANCE

catastrophic mechanical failure in severe wave action, in a manner similar to the rigid boom failure. In similar service, although it experienced heavy failure by splashover, the semi-flexible boom demonstrated more favorable stability characteristics. Thus it becomes apparent that the performance of semi-flexible booms approaches that of flexible booms in severe wave action where mechanical stability rather than hydrodynamic effectiveness is the most important factor. Although the tests reported herein did not evaluate containment efficiency in terms of volume of oil lost, it is quite possible that semi-flexible booms are the most effective in this regard, especially in severe wave conditions.

Current and Towing Performance

There are two modes of failure for booms in current or towing service: (1) hydrodynamic failure due to passage of oil coated water droplets under the skirt, and (2) mechanical failure or planing of the boom due to instability characteristics. The towing test results for the rigid and flexible booms indicate that the actual failure mechanism may be insignificant; i.e., the mechanical failure point for these booms occurred just below the velocity at which hydrodynamic failure would be expected to occur if the booms had not failed due to instability.

Figure 13 shows a comparison of the performance of the three major types of containment booms in current or towing service. For rigid and flexible booms the current limitation resulted from

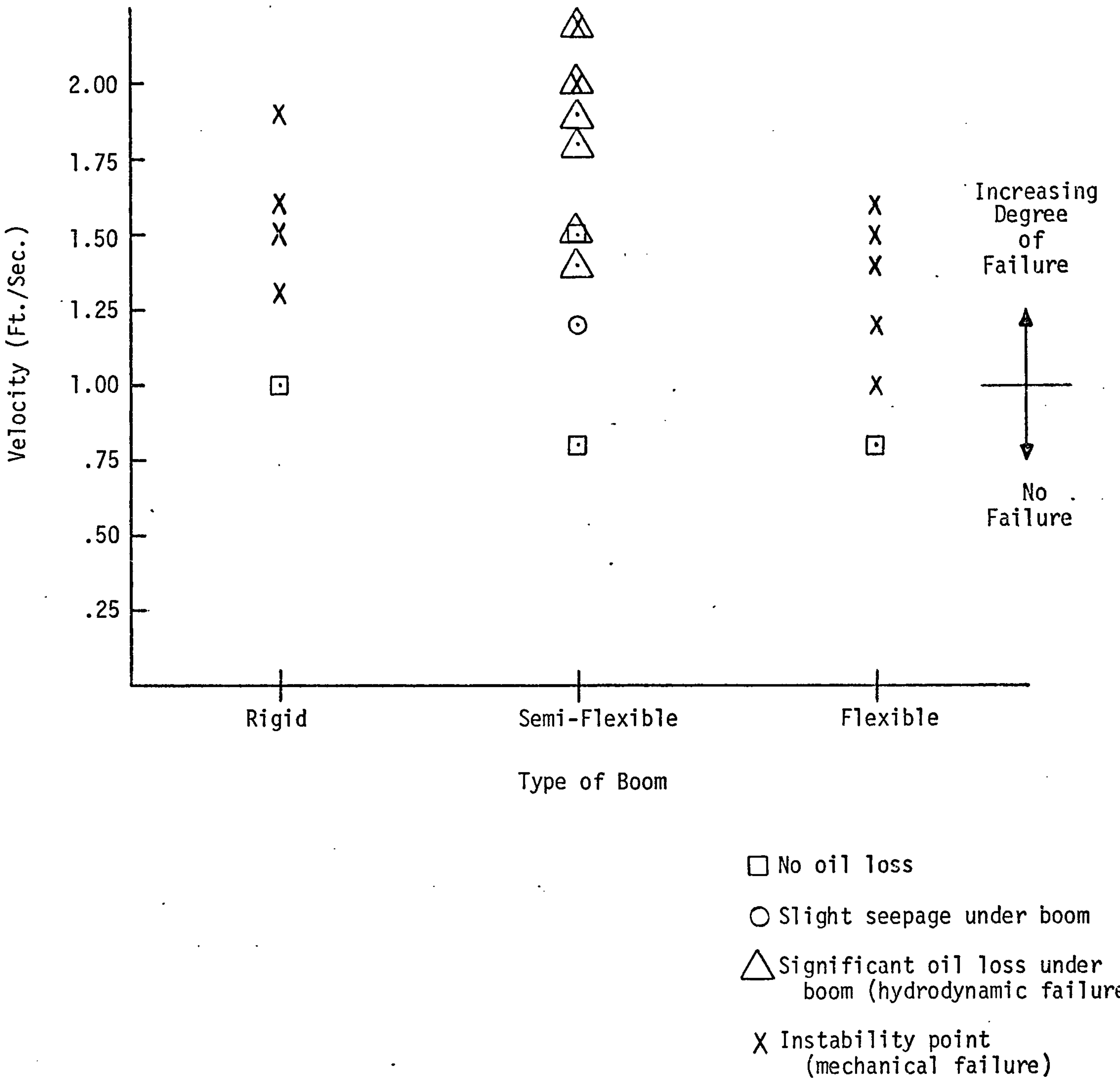


Figure 13 - BOOM PERFORMANCE IN CURRENTS (TOWING)

mechanical failure due to the unstable nature of the straight, thin skirts which offer a large area upon which the water forces can act, thus allowing or encouraging tipping and subsequent planing of the boom. The semi-flexible boom, on the other hand, failed hydrodynamically by loss of oil under the skirt at an incipient failure velocity of 1.2 feet per second. With an improved end connection with the tension cable at the bottom of the skirt, the failure velocity for the semi-flexible boom was shifted upward to approximately 1.7 feet per second. This improved performance is credited to the concave configuration assumed by the skirt which presumedly acts as a scoop, disrupting the fluid flow pattern and diverting entrained oil droplets back into the slick on the upstream side of the boom. Mechanical failure for the semi-flexible boom did not occur until a speed of approximately 2.0 feet per second was reached, and was not as catastrophic as in the case of the rigid and flexible booms. Although none of the booms are considered satisfactory in currents, the semi-flexible boom should be selected over the other types for current or towing service when velocities exceed approximately 1.0 feet per second and wave conditions do not completely overshadow current effects. In combined current and wave service, the effect of each environmental factor on boom performance must be evaluated and the proper boom selected in accordance with the guidelines discussed above for currents and in the next section for waves.

Performance in Waves

Boom failure by splashover is a function of the wave steepness ratio, which is defined as the ratio of wave height to wave length, H/L. A boom can withstand a relatively large wave height if the corresponding wave length is long; i.e., low steepness ratio. However, if wave height increases with respect to wave length so as to increase the steepness ratio, failure is more likely to occur. As the steepness ratio increases, the wave form changes from smooth rolling swells to sharp peaked breakers. It is the sharp peaked breakers which cause failure in most booms. A good rule of thumb for boom performance is that, in the presence of steep waves with whitecaps, failure by splashover will occur if the wave height is equal to or greater than the boom freeboard.

Figure 14 illustrates the effect of wave steepness on containment booms and compares the performance of the three types of booms in waves. As shown, all of the booms perform satisfactorily when subjected to mild rolling waves with steepness ratio less than 0.08. However, as the wave steepness ratio, H/L, approaches a critical value, failure is likely to occur. This critical ratio varies with each type of boom and increases as boom flexibility increases.

The rigid boom failure occurs by mechanical rather than hydrodynamic failure. The critical steepness ratio for rigid booms appears to be approximately 0.08. The boom will fail by capsizing at this point at a wave height slightly less

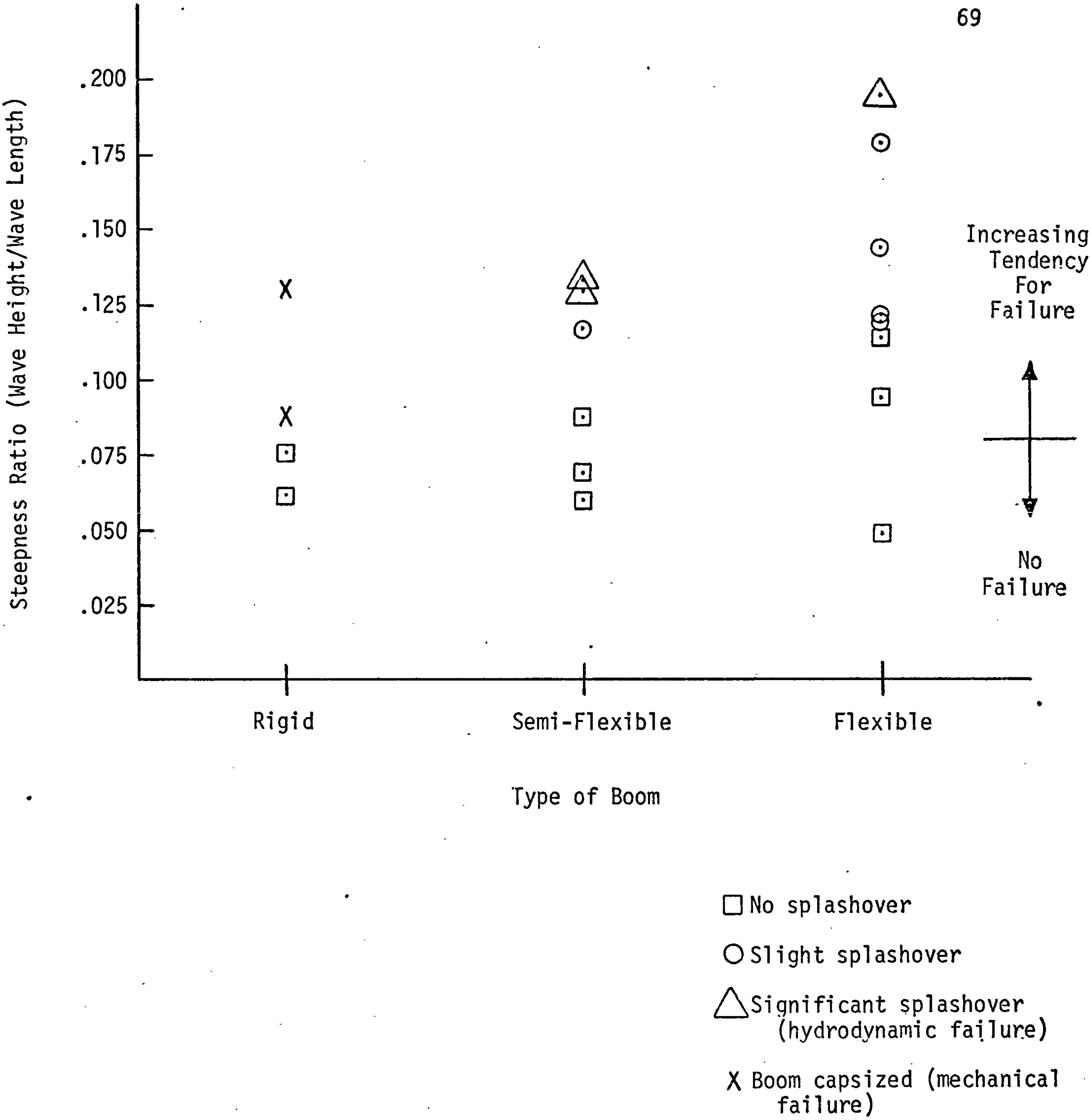


Figure 14 - EFFECT OF WAVE STEEPNESS RATIO ON BOOM PERFORMANCE

than the boom freeboard. Due to its instability, the rigid boom rarely reaches a splashover failure point. Even if it could be buoyed and anchored so as to prevent mechanical failure, failure by splashover would probably occur due to the "breakwater effect" of the rigid boom.

Semi-flexible booms have proven to be relatively stable in wave action. Failure occurs hydrodynamically by splashing of oil over the top of the boom at a critical steepness ratio of approximately 0.12. The failure wave height at the critical ratio is slightly greater than the boom freeboard. In an offshore environment failure by splashover can be expected to occur in moderate waves with whitecaps and significant wave height approximately equal to the boom freeboard. Dynamic response deficiencies may be experienced in severe offshore conditions, resulting in complete swamping of the boom.

Performance of the flexible boom is superior to the other types in mild to moderate conditions in inshore service. As shown in Figure 14, slight splashover begins at a steepness ratio of approximately 0.12; however, failure (significant splashover) does not occur until a steepness ratio of 0.195 is reached. Interpolating from the chart, a steepness ratio of 0.19 is designated as the critical ratio for flexible booms. The failure wave height at this steepness ratio is slightly greater than the boom freeboard. At lower steepness ratios comparable to the semi-flexible critical ratio, failure wave height can be expected to be 1-1/2 to 2 times the boom freeboard. In offshore service, however, the effectiveness of the flexible boom deteriorates rapidly as wave activity increases. In moderate breaking waves with significant wave height approximately twice the boom freeboard, the flexible boom will fail catastrophically by capsizing.

A basic guideline for the selection of containment booms is that the boom freeboard should be greater than the significant wave height in moderate sharp peaked waves with whitecaps. In mild waves the freeboard can be slightly less than the significant wave height, and in severe wave conditions it should be greater than the maximum wave height. The flexible boom is recommended for inshore service in moderate wave conditions with wave heights less than twice the boom freeboard. For offshore service and other severe conditions where catastrophic failure of the flexible boom may be anticipated, the semi-flexible boom is recommended due to its greater stability. Due to its poor stability characteristics, the rigid boom is not suitable for use in waves.

Methods of Improving Performance

Improving performance with the booms described herein is difficult without major design modifications and subsequent laboratory and field evaluations. However, some methods have been devised and found to be beneficial in controlling oil slicks. An interesting aspect is that even though the failure mechanisms differ for booms in current and wave action, methods which are effective in improving performance in one type of environment sometimes prove to be helpful in the other as well.

One method of improving boom effectiveness in waves is to spread hay, foam, gelling chemical, or other suitable material for 2 to 10 feet upstream of the boom so as to provide a pre-barrier and create a damping effect on the waves. This may also help in currents by moving the gravity wave (leading edge of the slick) farther away from the boom and disrupting the normal flow pattern which causes failure. The increased distance of the head wave to the boom may also increase the likelihood of the droplets to be entrained into the slick on the upstream side of the boom rather than escaping under the boom skirt.

Systems have been devised whereby booms are used to divert and allow recovery of oil in a current situation. One of the most successful methods proposed thus far for diverting oil from a high velocity to a low velocity area is to utilize a system of booms to direct the oil from the center of a stream where currents are high to the shoreline where currents are relatively low. When the oil is diverted to this point the booms are more likely to successfully contain it for recovery with skimming equipment. This system may require the use of several booms deployed at an angle to the current, so that any oil lost under one boom be picked up by the succeeding boom and directed towards the shoreline. A sketch of a possible arrangement is shown in Figure 15. Newman and Macbeth[12,13] also recommend this

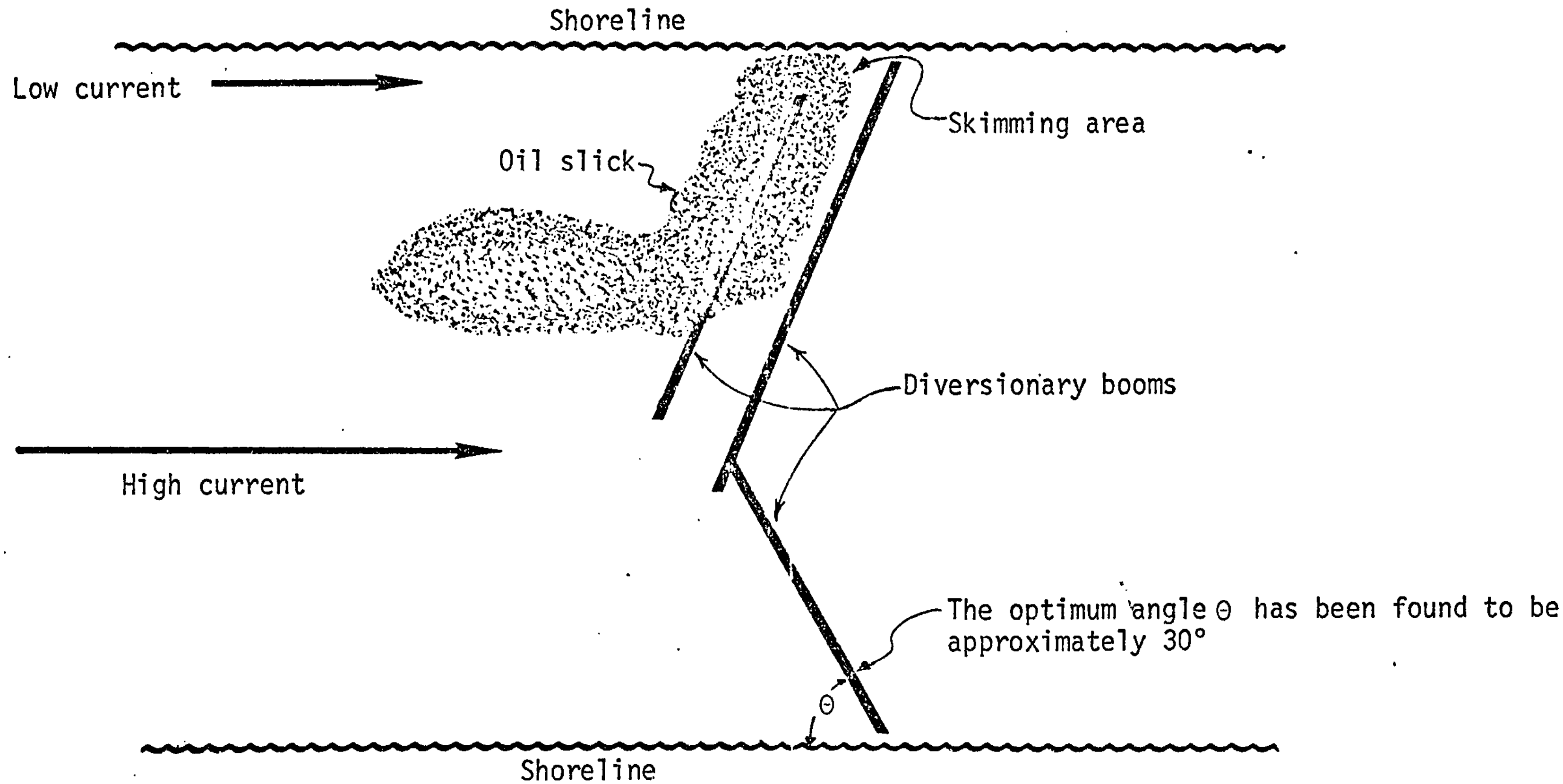


Figure 15 - DIVERSIONARY BOOMS IN A RIVER - USED TO DIVERT OIL FROM THE HIGH CURRENT AREA IN CENTER OF STREAM TO THE LOW CURRENT AREA NEAR SHORE FOR COLLECTION WITH SKIMMERS

method and have found that optimum performance in rivers can be obtained when the booms are placed at approximately 30° to the direction of flow.

Another possible but unproven method of improving performance in current or towing service is to utilize booms and skimmers in such a way as to take advantage of the tendency of oil to escape under the boom at the point of maximum current. The booms can be arranged in a V-shape, as shown in Figure 16, and the oil can be collected as it funnels towards the center of the drape at the point of maximum current where it is likely to escape first. A skimmer would be placed at the vertex to collect the oil. This funneling method has been attempted several times, but has not been successful because no one as yet has developed a suitable skimmer to collect and remove the oil. The success of this method can be enhanced by cascading several V-shaped boom sections in series, so as to channel the flow into successive funnel-shaped areas for ultimate collection at the final vertex where the skimmer would be located. A report by Banfield and Butterworth[14] recommends this method and lists 30° as the optimum cone angle.

A variation of the above system can be used to improve performance in waves. Although there appears to be no advantage in waves due to the funneling effect, the use of successive boom sections perpendicular to the waves will significantly improve the ability of booms to contain oil in waves. This leads to the

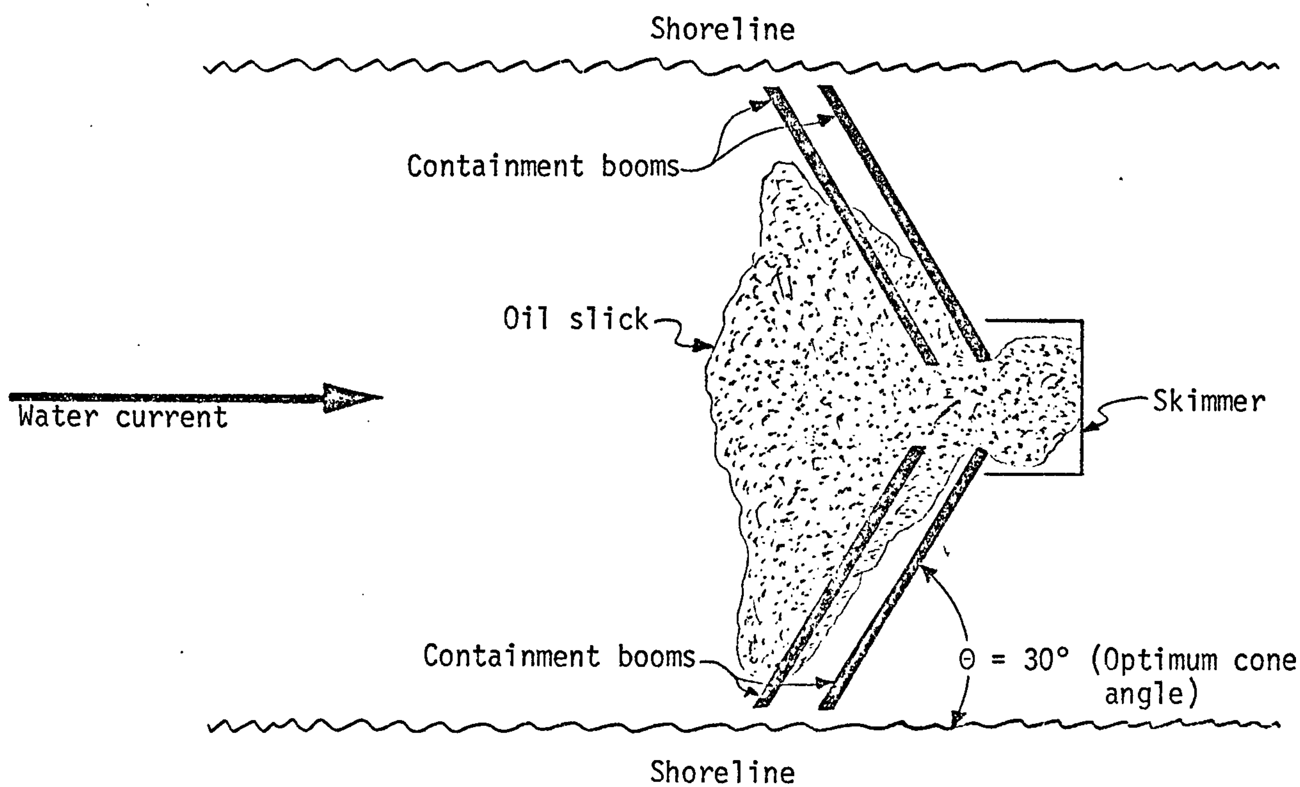


Figure 16 - V - SHAPED BOOM SKIMMING ARRANGEMENT

double boom concept which has been used successfully in actual spill service. Double booming involves the arrangement of two complete boom sections anchored in parallel, one behind the other, so that oil which splashes over the first boom is trapped between the two booms. The distance between the booms may vary from 3 to 10 feet, depending upon the amplitude of the waves and the level of wave activity. Regardless of the ambient wave conditions, the waves in the space between the booms will be damped considerably. The resulting level of wave activity inside the double boom area is not likely to cause significant splashover or other failure. This concept can also be used to reduce oil losses in currents. A double boom as described previously will increase the distance that the oil coated droplets must travel in order to escape the entire boom system, and therefore a large portion of the bubbles will pop up in the space between the booms. Skimmers can then be used to remove the oil collected in the double boom space. However, if a large amount of oil is allowed to accumulate in the boom space, a new slick with corresponding gravity wave may form, and newly formed oil droplets may escape under the second boom.

The above can be refined by designing a double boom skimmer system solely for containment in currents. This system would consist primarily of a permanent double boom, with a rigid, vertical lip which acts as weir as the leading edge and a conventional semi-flexible type boom as the second (or trailing) member.

As shown in Figure 17, the two sections would be rigidly connected so as to form a single unit with a horizontal screen or slotted skirt in the space between the two members. The weir allows water and oil to flow into the space between the two sections. The screen or slotted lower skirt allows the water to escape under the second boom while the oil is retained in the space for removal with skimmers or foam.

Performance can also be enhanced by design changes such as: (1) large pontoon floats for the flexible boom to provide increased stability in severe wave action; (2) a more flexible version of the semi-flexible boom with continuous but considerably more flexible flotation members; (3) a continuous boom comprised of absorbent flotation material which can absorb the oil during the containment process; and (4) other boom/skimming arrangements designed for specialized applications.

It appears futile to attempt to design a universal boom for use in every type of environment. Rather it is more practical to select containment booms for four specific types of service: (1) stationary use in a current environment (efficient collection system for rapid skimming in rivers, streams, etc.); (2) towing service (stable boom with optimum handleability and deployment characteristics); (3) inshore wave service (inexpensive, easily deployed, stable boom for choppy waves less than 2 feet in height); and (4) offshore service (large stable boom with high structural strength and sufficient flexibility for protection

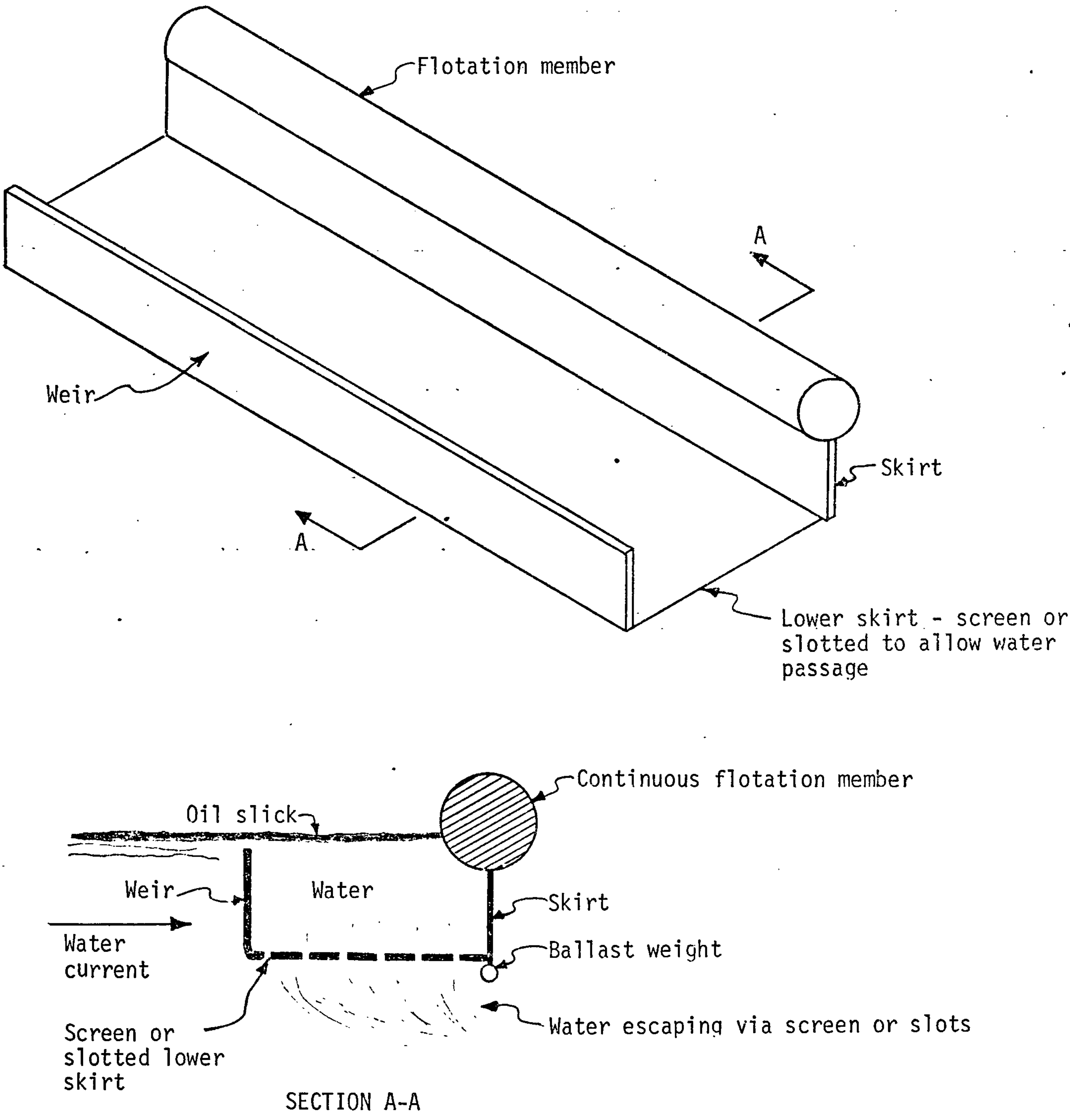


Figure 17 - DOUBLE BOOM SKIMMER

against splashover). Although several designs of containment booms are available today, none are really effective in high current or offshore environments. An excellent sequel to this thesis would be a design/evaluation program for development of efficient high current or offshore containment booms.

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